ISSUE RESOLUTION STATUS REPORT

KEY TECHNICAL ISSUE:
THERMAL EFFECTS ON FLOW

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

Revision 3
November 2000

Significant changes to the TEF KTI IRSR

Revision #	Section/ Paragraph	Date	Modification
0	all	Sept 1997	None–initial issue
1	3.2/1	Sept 1998	Minor modification to discuss importance of relative humidity
1	3.2.1/1-3	Sept 1998	Minor modification to clarify discussion of corrosion
1	3.2.3/1	Sept 1998	Minor modification to refer to scope of near-field environment KTI
1	3.3/1	Sept 1998	Added reference to TSPA-VA and performance assessment Technical Exchanges
1	3.3.5/all	Sept 1998	Discussion of TSPA-VA added
1	3.3.6/all	Sept 1998	Discussion of performance assessment technical exchange added
1	3.4/all	Sept 1998	Discussion of sensitivity analyses results added
1	4.1.1/all	Sept 1998	Minor reorganization to break out each acceptance criterion for Subissue 1 separately, criteria have been regrouped
1	4.1.2/1	Sept 1998	Minor rewording of last sentence of paragraph
1	4.1.3/1	Sept 1998	Minor rewording of bullet items for clarification
1	4.2.1/all	Sept 1998	Minor reorganization to break out each acceptance criterion for Subissue 2 separately–criteria have been regrouped
1	4.2.1	Sept 1998	Inclusion of parameter uncertainty and variability in technical acceptance criterion 1
1	4.3.1/all	Sept 1998	Minor reorganization to break out each acceptance criterion for Subissue 3 separately–criteria have been regrouped

Change pages (cont'd)

Revision #	Section/ Paragraph	Date	Modification
1	4.3.3/1	Sept 1998	Additional references added to review method
1	5.0/all	Sept 1998	Material contained in status section was increased–entire chapter was reorganized to address each subissue separately
1	5.1/all	Sept 1998	New section added to describe status of issue resolution of Subissue 1
1	5.4/5-16	Sept 1998	Evaluation of the DOE response to three comments on thermohydrological testing sent by the NRC to the DOE has been added (these three open items are considered resolved)
1	App B	Sept 1998	Appendix B deleted–details about conceptual models in the NRC/CNWRA performance assessment code that describe the propensity for water to reflux into the WP environment will be provided in NUREG CR–5549 (TPA 3.1 Sensitivity and Uncertainty Analyses; in preparation)
2	3.3.6	Aug 1999	Revised last sentence in this section
2	3.3.7	Aug 1999	New section added
2	4.1.1	Aug 1999	Revised TAC's 1.1 and 1.4
2	4.1.1	Aug 1999	Added TAC's 1.7, 1.8, and 1.9
2	4.1.1	Aug 1999	Revised TAC 2
2	4.2.1	Aug 1999	Added TAC's 2.10 through 2.16
2	4.3.1	Aug 1999	Revised TAC 3.1
2	5.0	Aug 1999	Revised 1st, 2nd and 3rd paragraphs
2	5.1	Aug 1999	New discussion and Table 7 added.
2	5.1.1	Aug 1999	Updated evaluation of PAC 1. Status summary added.

Change pages (cont'd)

Revision #	Section/ Paragraph	Date	Modification
2	5.1.2	Aug 1999	Updated evaluation of PAC 2. Status summary added.
2	5.1.3	Aug 1999	Updated evaluation of TAC 1. Status summary added.
2	5.1.3	Aug 1999	Updated evaluation of TAC 1.2. Status summary added.
2	5.1.3	Aug 1999	Status summary added to TAC 1.3.
2	5.1.3	Aug 1999	Updated evaluation of TAC 1.4. Status summary added.
2	5.1.3	Aug 1999	Status summary added to TAC 1.5.
2	5.1.3	Aug 1999	Updated evaluation of TAC 1.6. Status summary added.
2	5.1.3	Aug 1999	Evaluations of new TAC's 1.7, 1.8, and 1.9 added.
2	5.1.4	Aug 1999	Revised TAC 2. Status summary added.
2	5.1.5	Aug 1999	Status summary added.
2	5.2	Aug 1999	New section added to describe status of issue resolution of Subissue 2
2	5.3	Aug 1999	New section added to describe status of issue resolution of Subissue 3
2	5.4	Aug 1999	Renumbered section (formerly section 5.2 in Rev. 1)
2	5.5	Aug 1999	Renumbered section (formerly section 5.3 in Rev. 1)
2	5.5	Aug 1999	Added new 2nd paragraph indicating two concerns related to The DOE TSPA-95 considered closed.
2	5.6	Aug 1999	Added 1997 to section title
2	5.7	Aug 1999	New section added
2	6.0	Aug 1999	New references added

Revision #	Section/ Paragraph	Date	Modification
3	Exec. Sum.	Nov 2000	Executive summary added
3	1.0	Nov 2000	Revised for consistency with ENFE IRSR
3	2.0	Nov 2000	Subissues revised. Other text revised for consistency with ENFE IRSR
3	3.0	Nov 2000	Test revised for consistency with ENFE IRSR. More detailed discussion of influence of TEF on related integrated subissues added.
3	3.1	Nov 2000	Updated DOE safety strategy
3	4.0	Nov 2000	Acceptance criteria of Rev. 2 consolidated into seven general acceptance criteria
3	5.0	Nov 2000	Sections 5.0 through 5.3 completely revised for revised subissues and acceptance criteria
3	Appendix B	Nov 2000	Appendix B added to provide cross-walk between acceptance criteria (and open items) applied in Rev. 2 and Rev. 3

EXECUTIVE SUMMARY

Thermal effects on flow (TEF) is a process that could affect the performance of the proposed geologic repository at Yucca Mountain. Features, events and processes that could affect repository performance are referred to as FEPs. Within the scope of the TEF Key Technical Issue (KTI) are environmental conditions in the near-field and within the drift that are important to degradation of engineered barriers. Parameters representing near-field environmental conditions include temperature and humidity. Also within the scope of the TEF KTI are perturbations to flow paths in the unsaturated zone resulting from heat produced by decaying radioactive waste. Perturbations to flow paths in the unsaturated are represented by thermal effects on saturation and flux. Heat given off by the decaying radionuclides will drive temperatures in the waste emplacement drifts above boiling for a period after repository closure. Above boiling temperatures will dry out the matrix of the repository host rock in the vicinity of the waste emplacement drifts. Water leaving the rock matrix as vapor will move away into cooler regions where it will condense and drain by gravity back through the fractures. Water above emplacement drifts, including both infiltrating water and water boiled out of the matrix, may cycle repeatedly as vapor and condensate in a refluxing phenomenon known as a “heat pipe”. If water is redistributed by thermal effects in such a way that it enters the emplacement drifts and contacts waste packages, such as by evaporation and condensation or by focusing of condensate drainage in fractures, it could contribute to degradation of engineered barriers and promote early release of radionuclides. The two subissues of the TEF KTI represent a systematic review of the adequacy of the U.S. Department of Energy’s assessment of the consequences of thermohydrologic effects on repository performance. The status of these subissues and path to their resolution are summarized in the following table.

Subissue	Status and Path to Resolution
Features, events, and processes related to thermal effects on flow	This subissue is open. To resolve this subissue, the DOE needs to: • Provide the final list of primary and secondary FEPs. • Provide the revised FEP screening analysis for thermohydrologic models. The screening analysis documentation should comprehensively address all primary FEPs. • Give greater visibility to secondary FEPs in the FEP screening documentation. • Provide a summary of the assumptions related to screening arguments for FEPs relevant to thermohydrologic models that need verification and the associated analyses planned to provide that verification. • Provide traceable references to previous analyses used as the technical basis for screening arguments for excluded FEPs.

Subissue	Status and Path to Resolution
Thermal effects on temperature, humidity, saturation, and flux	This subissue is open. To resolve this subissue, the DOE needs to: • Complete thermohydrologic modeling for the current repository design. • Include the process (FEP) referred to as the “cold trap effect” in the MSTHM process models. Subsequently, provide model support for implementation of the MSTHM “cold trap effect” model by comparison with past observations such as condensation in the ECRB under a thermal gradient imposed by the TBM. • Provide traceable references to MSTHM model input and output t allow review of such aspects as boundary and initial conditions and to confirm the mass balance of model results. • Consider measuring losses of mass and energy through the bulkhead of the DST. • Address (i) the potential for unmonitored mass and energy flow through test boundaries of the CDTT and (ii) the effect of unmonitored mass and energy flow through test boundaries of the CDTT on the usefulness of test results before the test begins. Consider designing and conducting the CDTT so as to avoid unmonitored mass and energy flow through test boundaries. • Provide data support for the ventilation model by completing the ongoing ventilation test. Subsequently, provide model support for the ventilation model by comparisons to the test data. • Evaluate data uncertainty in (i) measurement error, bias, and scale-dependence in the saturation, water potential, and pneumatic pressure data used for model parameter calibration, (ii) heterogeneity and spatial variability in thermohydrologic properties, and (iii) variability in model results using the various property sets found to be valid for thermohydrologic modeling and propagate this uncertainty through the thermohydrologic model abstraction. • Evaluate model uncertainty as seen in results from various alternative conceptual models such as the ECM, DKM, and AFM, and propagate this uncertainty through the thermohydrologic model abstraction. • Provide model support by predicting thermohydrologic results of the CDTT to verify the thermohydrologic

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ACKNOWLEDGMENTS

Revision 1

This report was prepared jointly by U.S. Nuclear Regulatory Commission (NRC) and Center for Nuclear Waste Regulatory Analyses (CNWRA) staff. Primary authors of the report are Jeffrey A. Pohle (NRC) and Ronald T. Green (CNWRA).

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Revision 2

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Revision 3

This report was revised by Debra L. Hughson and Jeffrey A. Pohle.

QUALITY OF DATA, ANALYSES, AND CODE DEVELOPMENT

DATA: No CNWRA-generated original data are contained in this report. Sources for other data should be consulted for determining the level of quality for those data.

ANALYSES AND CODES: TPA 3.1.1 and MULTIFLO Version 1.0 were used for analyses contained in this report. These scientific and engineering software are controlled under CNWRA Technical Operating Procedure–018, Development and Control of Scientific and Engineering Software. Calculations presented in this report were checked as required by Quality Assurance Procedure–014, Documentation and Verification of Scientific and Engineering Calculation, and recorded in a scientific notebook.

1.0 INTRODUCTION

Site characterization activities are specified in the U. S. Nuclear Regulatory Commission (NRC) geologic repository regulations and in the proposed Commission rule (U.S. Nuclear Regulatory Commission, 1999a). The Commission has noted that ongoing review of information from site investigation and characterization activities, particularly those activities with long completion schedules, allows for the early identification and resolution of potential licensing issues. Moreover, the NRC strategic planning assumptions call for the early identification and resolution of issues at the staff level. The principal means for achieving this goal is through formal, prelicensing consultation with the U.S. Department of Energy (DOE). These consultations are required by law and occur in an open manner that permits observation by the State of Nevada, Tribal Nations, affected units of local government, and interested members of the public. Obtaining input and striving for consensus from the technical community and interested parties helps the issue resolution process. The issue resolution approach attempts to reduce the number of, and to better define, issue that may be in dispute during any potential NRC licensing review.

Consistent with Title 10 Code of Federal Regulations (CFR) Part 60, proposed 10 CFR Part 63 and a 1992 agreement with the U.S. Department of Energy (DOE), staff-level issue 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 the license application. 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 have 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.

The NRC has identified three categories of resolution: closed; closed pending; and open. An issue is considered “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. Issue are “closed pending” if the NRC staff have 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 initial license application. 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.

The NRC high-level radioactive waste program was realigned during fiscal year 1996-1997. The realignment was in response to: (i) a reduction in Congressional budget appropriations for the NRC if fiscal year 1996; (ii) the reorganization of the DOE’s geologic repository program at Yucca Mountain, Nevada; and (iii) a 1995 report issued by the National Academy of Sciences to advise the U.S. Environmental Protection Agency regarding the technical bases for new geologic disposal standards for Yucca Mountain. In response to these developments, the NRC high-level radioactive waste program was realigned to focus prelicensing work on those topics most critical to the postclosure performance of the proposed geologic repository; these topics are called Key Technical Issue (KTIs). This approach is summarized in Chapter 1 of the NRC HLW Program Annual Report Fiscal Year 1996, NUREG/CR–6513 (Center for Nuclear Waste Regulatory Analyses, 1996).

The current Division of Waste Management approach is to focus most activities on issue resolution of the respective KTIs, at the staff level. The division's activities have been re-prioritized to streamline and improve the integration of the technical work necessary to achieve staff-level resolution. Regulatory attention is focused where technical uncertainties will have the greatest effect on the assessment of repository safety, and is achieved by identifying KTIs, integrating their activities into a risk-informed approach, and evaluating their significance for postclosure repository performance. Early feedback among all parties is essential to define what is known, what is not known, and where additional information is likely to make a significant difference in the understanding of future repository safety.

An important step in the staffs approach to issue resolution is to provide the DOE with feedback regarding issue resolution before the license application. Issue Resolution Status Reports (IRSRs) are the primary mechanism that we use to provide the DOE feedback on the progress toward resolving the subissues comprising the KTIs. This report is the third revision of the IRSR on Thermal Effects on Flow (TEF). This revision of this IRSR supersedes previous revisions. Previous IRSRs included: (i) acceptance criteria and review methods for use in issue resolution and regulatory review; (ii) technical bases for the acceptance criteria and review methods; and (iii) the status of resolution, including where the staff currently has no comments or questions, as well as where it does. The acceptance criteria and the review methods are now included in the Yucca Mountain Review Plan (YMRP) the staff is currently developing. Finally, open meetings and technical exchanges with the DOE provide opportunities to discuss issue resolution, identify areas of agreement and disagreement, and develop plans to resolve such disagreements.

Each IRSR contains five sections, including an Introduction in Section 1.0. Section 2.0 defines the KTI, the related subissues, and the scope of the particular subissue or subissues that are addressed in the IRSR. Section 3.0 discusses the importance of the subissues to repository performance, including: (i) qualitative descriptions; (ii) reference to total system performance; (iii) results of available sensitivity analyses; and (iv) relationship to the DOE Repository Safety Strategy (RSS) Revision 3 (U.S. Department of Energy, 2000), which supersedes the DOE RSS Revision 1 (U.S. Department of Energy, 1998a), which supersedes the DOE Waste Containment and Isolation Strategy (WCIS) (U.S. Department of Energy, 1996a). Section 4.0 provides notice that the acceptance criteria and review methods in Revision 2 of this IRSR are being used to develop the YMRP. Full discussion of the acceptance criteria and review methods will be contained in the YMRP and are no longer discussed in Section 4.0 of this IRSR. In developing the YMRP, the acceptance criteria have undergone slight modifications. The general acceptance criteria used in Section 5.0 are consistent with and reflect, to the extent practicable, those modifications. The acceptance criteria in future versions of this IRSR will continue to be modified, as needed, to reflect the acceptance criteria as developed in the YMRP. The acceptance criteria are used to conduct the regulatory review. The DOE may decide to follow approaches different from those outlined in this document. In such a case the staff will develop appropriate acceptance criteria and review methods applicable to those DOE approaches as these become known. Section 5.0 concludes the revision with the status of resolutions indicating those subissues resolved at the staff level or those subissues remaining open. These open subissues will be tracked by staff, and resolution will be documented in future IRSRs. The assessment of progress toward issue resolution documented in Section 5 is in part based on review of preliminary DOE Process Model Reports (PMR) and/or Analysis and Model Reports (AMR). The staff recognizes the preliminary nature of these documents; specifically, that they have not been accepted by the DOE. Because the preliminary PMR's and AMR's have not been accepted by the DOE, the staff have not used the information they contain to resolve any open items in this IRSR. To aid the issue resolution process, however, the staff may have reviewed and commented on the sufficiency of the information in the preliminary documents to address staff concerns. After receipt and review of the final PMR's or other documents that indicate the DOE acceptance of the information in the preliminary documents, we will consider whether it is appropriate to close any portion or all of the issues. Finally, Section 6.0 includes a list of pertinent references.

2.0 KEY TECHNICAL ISSUE AND SUBISSUES

Features, events and processes that could affect the performance of a geologic repository are referred to as FEPs. Thermal effects on flow is a FEP. Within the scope of thermal effects on flow are the estimation of parameters such as temperature, moisture content, and humidity within the drifts and at the waste package surface. Also within the scope of thermal effects on flow is the process of thermally driven water flux with respect to the transport of radionuclides from failed waste packages. Redistribution of moisture driven by heat may result in periods of dryness in the rock formation surrounding the waste emplacement drifts in the proposed repository. A key aspect of the Enhanced Design Alternative II (EDA II) (Civilian Radioactive Waste Management System, Management and Operating Contractor, 1999a) is that, aided by drift ventilation, rock temperatures midway between emplacement drifts remain below boiling to facilitate condensate drainage. However, depending on the amount of liquid phase flux and rock heterogeneities, redistribution of moisture driven by heat could also result in channeling moisture into the drifts and toward the waste package—a phenomenon referred to as "thermal reflux" in this report. As explained in Section 3.0, it is necessary to understand the spatial and temporal effects of the thermal load on liquid phase and gas phase fluxes as well as on temperature and relative humidity of the waste package environment at the proposed repository to have confidence in predictions of containment and long-term waste isolation.

The review methods and acceptance criteria being developed for the YMRP focus on fourteen model abstractions. These fourteen abstractions are equivalent to the integrated subissues in the Total System Performance Assessment and Integration IRSR (U.S. Nuclear Regulatory Commission, 2000a). Thermal effects on flow is a process relevant to four of these fourteen integrated subissues (abstractions). These four integrated subissues include: (i) degradation of engineered barriers, (ii) quantity and chemistry of water contacting waste packages and waste forms, (iii) radionuclide release rates and solubility limits, and (iv) flow paths in the unsaturated zone. Figure A-1 illustrates a flowdown diagram for a performance assessment that identifies the fourteen integrated subissues. The four integrated subissues relevant to thermal effects on flow are highlighted.

An objective of the staff review of the DOE's program is to assess aspects of thermal effects on flow that may affect the performance of the repository. In this revision of the IRSR, the staff reviews whether the DOE assessment of thermal effects on flow on repository performance includes: (i) important features, events, and processes, and consistent and appropriate assumptions, (ii) sufficient data to adequately define relevant parameters and conceptual models, (iii) parameter values used in the performance assessment abstractions that are consistent with site characterization data, design data, laboratory experiments, field measurements, and natural analog data, (iv) consideration of alternative conceptual models; and (v) performance assessment abstractions that are justified by comparison with process-level models and empirical observations. To accomplish the review objective, the staff have used a systematic approach to determine whether the DOE will adequately consider the process of thermal effects on flow in the four relevant integrated subissues within their performance assessment. This approach involves applying seven general criteria to the review. These seven criteria include: (i) identification of FEPs, (ii) screening of FEPs, (iii) system description and model integration, (iv) data and model justification, (v) data uncertainty, (vi) model uncertainty, and (vii) model support.

Previously, this KTI was divided into three subissues encompassing the DOE's consideration of the process of thermal effects on flow in their performance assessment. These subissues were:

- Is DOE's thermal testing program, including performance confirmation testing, sufficient to evaluate the potential for thermal reflux to occur in the near field?
- Is DOE's thermal modeling approach sufficient to predict the nature and bounds of TEF in the near field?
- Does DOE's total system performance assessment (TSPA) adequately account for TEF?

The systematic review of the DOE's consideration of thermal effects on flow in their performance assessment is provided by the seven general criteria discussed previously. Because these seven criteria duplicate the scope of the original three subissues, the statements of the subissues have been revised to reflect the specific parameters, features, events or processes within the technical scope of the thermal effects on flow KTI (see discussion in Section 3.0). The revised subissues are:

- Features, events, and processes related to thermal effects on flow.
- Thermal effects on temperature, humidity, saturation, and flux.

In Section 5.0, the status of resolution and resolution information needs are addressed with respect to these two subissues.

3.0 IMPORTANCE TO REPOSITORY PERFORMANCE

Thermal effects on flow is currently considered an important process in repository performance. The consequences of thermal effects on flow may affect many aspects of repository performance. These are discussed in detail in Section 3.2 of this IRSR. The DOE needs to adequately demonstrate and quantify the consequences of thermal effects on flow on repository performance. This demonstration requires the DOE to consider the interactions of thermal effects on flow both within and among key elements of the natural and engineered subsystems of the repository.

Our strategy for reviewing the performance of the potential high-level waste repository at Yucca Mountain is described in the Total System Performance Assessment and Integration (TSPAI) IRSR (U.S. Nuclear Regulatory Commission, 1998a, 1998b, 2000a). The performance assessment IRSR provides the framework and context for other KTI IRSRs, and integrates the results of those IRSRs. Its overall goal is to delineate a systematic approach for determining compliance with an overall system performance objective. The TEF KTI supports the resolution of the TSPAI KTI by describing the information needed in key elements of the natural and engineered subsystems within the performance assessment and by pursuing issue resolution with respect to those key elements. Those elements that are important to a postclosure performance assessment of a repository at the Yucca Mountain site are defined as integrated subissues (In Revision 2 of the TEF KTI, integrated subissues were referred to as Key Elements of System Abstraction - KESA). Therefore, the approach that we will use to independently evaluate the DOE's postclosure performance assessment will focus on integrated subissues. The integrated subissues are illustrated in Figure A-1 in Appendix A.

Acceptance criteria, for the key elements of the DOE TSPA, are under development and will be included in the YMRP. The review methods and acceptance criteria being developed for the YMRP focus on fourteen model abstractions. These fourteen abstractions are equivalent to the integrated subissues in the TSPAI IRSR. As highlighted in Figure A-1, thermal effects on flow is an important factor that the DOE need to consider in four key elements of the natural and engineered subsystems. The four integrated subissues, or "abstractions", that thermal effects on flow influences include:

- Degradation of Engineered Barriers — Thermal effects on flow is a FEP that will influence the waste package environment. Localized environmental conditions that are considered important to the calculation of degradation rates include: (i) temperature; (ii) in-drift gases (e.g., H_2O, O_2, CO_2, and N_2); (iii) chemistry of water and mineral films on the waste package (e.g., precipitates, salts, and pH); (iv) presence or absence of water dripping on the waste package surface; and (v) relative humidity (Civilian Radioactive Waste Management System, Management and Operating Contractor, 1999a). Of these key environmental conditions, temperature and relative humidity are a direct consequence of heat produced by the waste and are evaluated using dual-continuum models of thermal hydrology. Water films on waste package surfaces and the presence or absence of water dripping on waste packages are also strongly coupled to thermohydrologic processes. The temperature and relative humidity of the waste package and drip shield environment are dependent on the liquid phase and gas phase fluxes through the repository. In addition, liquid water that refluxes into the underground facility and interacts with waste packages and drip shield can affect the integrity of canister material by accelerating corrosion mechanism, thereby leading to potential premature release of radionuclides from the waste package. Detailed staff review of the degradation of engineered barriers is provided in the Container Life and Source Term (CLST) IRSR (U.S. Nuclear Regulatory Commission, 1999b).

- Quantity and Chemistry of Water Contacting Waste Packages and Waste Forms — This integrated subissue also pertains to the waste package environment that is influenced by thermal effects on flow. Degradation of the waste form and release from waste packages is a function of the amount of liquid water available whether as incident percolation flux during the isothermal period or as thermal reflux. Additional staff evaluation of the quantity and chemistry of water contacting waste packages is provided in the Evolution of the Near-Field Environment (ENFE) IRSR (U.S. Nuclear Regulatory Commission, 2000b).

- Radionuclide Release Rates and Solubility Limits — Radionuclide release from waste forms and from the engineered barrier system (EBS) depends on the near-field and waste package environment, which will in turn be conditioned by heat produced by waste and thermally driven water flow. Staff evaluation of DOE abstractions, models, and analyses of radionuclide release rates and solubility limits is provided in more detail in the CLST IRSR, Revision 2 (U.S. Nuclear Regulatory Commission, 1999b).

- Flow Paths in the Unsaturated Zone — This integrated subissue is concerned with flow paths in the unsaturated zone both above and below the repository. Perturbations to flow paths in the unsaturated zone can be expected as a result of heat produced by decaying radioactive waste. Perturbations result from: (i) condensate shedding through fracture systems; (ii) dry-out of matrix pore water in the near-field; (iii) development of heat pipes (refluxing); and (iv) buoyant gas-phase advection. Although the heat produced by decaying radioactive waste is a transient process, permanent changes to flow paths in the unsaturated zone may result as a consequence of coupled thermal-hydrologic-chemical and thermal-hydrologic-mechanical alteration of near-field permeabilities and porosities. These potential effects are discussed in detail in the ENFE (U.S. Nuclear Regulatory Commission, 2000b) and Repository Design and Thermal-Mechanical Effects (RDTME) (U.S. Nuclear Regulatory Commission, 2000c) IRSRs.

3.1 U.S. DEPARTMENT OF ENERGY REPOSITORY SAFETY STRATEGY

The DOE presented a waste containment and isolation strategy (WCIS) for the proposed Yucca Mountain repository in its 1988 site characterization plan (SCP) (U.S. Department of Energy, 1988). Since that time, additional site characterization data have been obtained and the engineered system design has advanced. The DOE updated the WCIS to incorporate additional site characterization information, newer repository and waste package designs, more realistic performance predictions, and changing regulatory considerations (U.S. Department of Energy, 1996a). The WCIS was updated again and renamed “The Repository Safety Strategy” (RSS) (U.S. Department of Energy, 1998a). The RSS was revised in January, 2000 (U.S. Department of Energy, 2000; Revision 3). Revision 3 of the DOE’s RSS defines key attributes of the HLW disposal system important to performance. These attributes include:

- Limited water contacting waste package
- Long waste package lifetime
- Low rate of radionuclide release from the EBS
- Delay and dilution of radionuclide concentrations during transport away from the EBS

Revision 3 of the DOE's RSS also identifies the principal factors assumed to be important to quantitative estimates of postclosure performance with respect to the key attributes of the repository. The determinations of importance of the factors were based on subjective judgment of the participating experts (U.S. Department of Energy, 2000; pg. D-5). The principal factors in the DOE's postclosure safety case include:

- Limited seepage of water into the emplacement drifts
- Performance of the drip shield
- Performance of the waste package
- Solubility limits of dissolved radionuclides in Yucca Mountain water
- Retardation of radionuclide migration in the unsaturated zone
- Retardation of radionuclide migration in the saturated zone
- Dilution of radionuclide concentrations during migration

Of these principal factors, the TEF KTI is primarily concerned with limited seepage of water into the emplacement drifts. The TEF KTI is also concerned with the performance of the waste package and drip shield because temperature, humidity and thermal reflux may affect performance of the engineered barriers. The DOE technical bases for seepage into drifts are summarized in the Unsaturated Zone Flow and Transport Process Model Report (PMR) (CRWMS M&O, 2000a). The DOE technical bases for performance of the waste package and drip shield are summarized in the Waste Package Degradation PMR. The DOE identified these principal factors based on a review of all factors potentially important to repository performance. Although the DOE examined preliminary performance assessments and barriers importance analyses in this review, essentially the conclusions were based on the subjective judgment of persons involved with site characterization and previous performance assessments. Factors judged to be less important to repository performance, termed other factors and potential principal factors, relevant to the TEF KTI are

- Effects of coupled processes on unsaturated zone flow
- Effects of coupled processes on seepage
- Environments on drip shield
- Environments on waste package
- Environments within waste package
- Unsaturated zone flow and transport-advective pathways

Technical work conducted by the DOE for supporting the site recommendation and license application will concentrate on evaluating factors deemed by expert subjective judgment to be principal factors.

Revision 3 of the DOE's RSS states that "[t]he determinations of importance of the factors were based on subjective judgment of the experts participating in this step. At the same time, the numerical results from the preliminary barriers importance analyses ... were considered." While opinions of those involved with site characterization and performance assessments may screen out factors that contribute significantly to dose and assist in allocating limited site characterization resources, opinions are a weak technical basis upon which to found a repository safety case. Staff have a concern that, if a factor above were judged incorrectly not to be important to repository performance and resources are not allocated for further study, then how would this error be identified? There is a possibility that important factors could be neglected without adequate investigation based solely on this preliminary screening.

Within those factors identified as principal factors for repository performance, there is clearly a definite reliance on engineered barriers. This reliance is shown in Figure E-2 of the barriers importance analysis-nominal scenario (U.S. Department of Energy, 2000). If both water diversion by drip shields and containment by waste packages are neutralized, annual dose using expected or deterministic values for parameters reaches the 25 mrem/yr proposed dose limit shortly after 1000 yr and exceeds it by more than two orders of magnitude within the 10,000-yr compliance period. With both the Alloy-22 waste package and the titanium dripshield included, calculated annual dose is zero for more than 100,000 yr. Furthermore, the waste package is expected to show little sensitivity to the range of expected conditions and is modeled as remaining intact for more than 100,000 yr. Reliance on the EBS appears to be the main motivation for determining that coupled processes such as thermohydrologic effects are not important to performance as indicated by the following quote:

"Current information suggests the performance of these barriers (i.e., waste package and dripshield) depends weakly on these environments over their expected ranges. Therefore, their environments were not considered to be principal factors. In this same light, coupled effects that might impact these environments (e.g., thermohydrologic effects) or the unsaturated zone flow system are expected to play only a minor role in determining expected postclosure system performance."

The adequacy of the technical bases for these assumptions is addressed in the Container Life and Source Term (CLST) IRSR (U.S. Nuclear Regulatory Commission, 1999b).

Of the components of the natural system identified as potential barriers, diversion of seepage away from drifts due to the capillary barrier effect is most relevant to the TEF KTI. Current performance assessments are based on the concept that water is held in fractures by capillary forces and that water will not enter emplacement drifts unless percolation at the repository level is above a seepage threshold. This model is currently based on limited water injection tests conducted in the zone around the Exploratory Studies Facility (ESF). Test results were affected by ventilation dryout and the limited scales of time and space. The tests did not fully account for effects of storage or evaporation (U.S. Department of Energy, 2000). However, because diversion of seepage away from drifts has a significant effect on performance, it may become an important part of the safety case as outlined in the following excerpt from Section 3.2.1 of the RSS Revision 3.

“The seepage threshold concept will be pursued through field and laboratory testing, improved models, and sensitivity analyses. If the seepage threshold concept becomes sufficiently defensible, seepage will be specified to be zero except when and where extreme flow conditions or adverse conditions (e.g., significant changes in drift geometry that could affect the seepage threshold) are present. Otherwise, the amount of seepage into the drifts will be estimated using the current seepage model and values of input parameters.”

In summary, the RSS depends upon engineered barriers to comply with the proposed dose limit. These barriers are expected to last longer than the 10,000 yr compliance period over the range of expected repository conditions. Seepage into drifts is believed to be limited by capillarity of the fractures in the proposed repository host rock. However, the seepage threshold concept is presently not sufficiently established by data collected under expected repository conditions to be defensible.

3.2 IMPORTANCE OF TEMPERATURE, MOISTURE CONTENT, AND RELATIVE HUMIDITY ON REPOSITORY PERFORMANCE

The influx of water, as liquid or vapor, into emplacement drifts can potentially affect repository performance by degrading the integrity of the waste package, by transporting radionuclides released from waste packages, or by altering hydraulic or transport pathways in the ground control structures, inverts, or host rock.

The effect of heat emanating from waste packages will cause the container environment to become dynamic by vaporizing liquid water near the heat source and condensing liquid water in regions where temperatures are below boiling. There are two principal sources of water in the repository environment: ambient rock-bore water and infiltrating water (incident percolating water). Ambient rock water is water in the matrix and fractures of the repository block prior to the onset of heating by waste emplacement. This water is mobilized into the vapor phase as rock temperature elevates, particularly in regions where rock temperatures exceed boiling. The volume of ambient rock water mobilized by vaporization from waste package-generated heat could be significant. As much as 8000 m^3 of water can be vaporized per container for thermal loading scenarios that result in a dry-out zone that extends 100 m above the repository horizon. Dry-out zones that do not extend far above the repository horizon will vaporize a smaller quantity of rock water, however, liquid water refluxing through the dry-out zone to the emplacement drifts will have a shorter distance to travel for this scenario. Vaporized/condensed rock-pore and fracture water and the downward flux of percolating water can form convecting cells near the waste packages. Water that has entered a vaporization/condensation cell encompassing a waste package can cycle between boiling and condensation, possibly interacting with a container, or exit the cell as vapor or liquid with or without contacting a waste package. This source of water will be available for refluxing as liquid or for contributing to relative humidity as vapor until rock temperatures are no longer increasing and all vaporized rock water has left the vaporization/condensation cell containing the waste package. The actual volume of rock water active in refluxing, however, may decrease significantly after the first several hundred years after emplacement when the boiling isotherm has migrated a sufficient distance from the waste packages and negligible amounts of vaporized rock water succeed in returning as condensate to the waste package environment.

The ultimate fate of ambient rock-pore water or percolating water in the waste package environment is a function of the heterogeneity of the system, the strength of the heat source, and flux of all waters introduced into the repository environment. Infiltration or deep percolation can provide water continuously or episodically to the waste package environment, most likely through preferential pathways located along fractures. The pathways for flux from percolating water can vary both spatially and temporally in response to changes in surface infiltration and due to repository-induced alterations in the geologic environment.

3.2.1 Effect of Thermally Driven Water on Waste Package Integrity

The propensity for waste packages to corrode from exposure to water as a liquid or vapor is a complex function of temperature, water chemistry, rock heterogeneity, mineralization, container design, material selection, duration, and frequency of container exposure to water (Mohanty, et al., 1997). Because of the uncertainty in most of these factors, the effect of water on container corrosion cannot be easily determined.

Corrosion of waste packages may occur with or without the presence of water. Corrosion in the absence of water, referred to as dry-air corrosion, is considered by the DOE and also by the NRC to be negligible in container corrosion (TRW Environmental Safety Systems, Inc., 1995). Corrosion is considered to occur only when the waste package is in contact with water in the vapor or liquid phase. The DOE treats corrosion of the outer waste package layer of corrosion allowance material (CAM) differently from the inner layer of corrosion resistant material (CRM). The DOE assumed two corrosion regimes for the CAM: humid air corrosion and aqueous corrosion, differentiated by degree of relative humidity (TRW Environmental Safety Systems, Inc., 1995). Humid air corrosion occurs in the presence of a thin film of water in environments (i.e., relative humidity from about 65–75 percent to 85–95 percent). Similarly, aqueous corrosion occurs when relative humidity exceeds 85–95 percent, a condition in which metal is assumed to be in contact with bulk water. Differentiation between humid air and aqueous corrosion environments is also assumed in the EBSFAIL module of TPA Version 3.0. (Mohanty, et al., 1997).

The staff currently considers two corrosion regimes (i.e., humid air and aqueous) for both the CAM and CRM, similar to DOE's approach detailed in TSPA 1995 (TRW Environmental Safety Systems, Inc., 1995), although the threshold levels of relative humidity at which humid air corrosion or aqueous corrosion are experienced may differ. In addition to these two corrosion regimes, the DOE directly considers the effect of bulk water on corrosion of the CRM. The effect of bulk water is only indirectly considered in the total performance assessment (TPA) code by increasing the chloride concentration of water on the container surface. In addition, the effect of dripping may be indirectly incorporated into future NRC performance assessments by lowering the threshold of relative humidity at which the onset of humid air or aqueous corrosion begins.

Although corrosion of waste package materials may occur by a variety of different processes (i.e., crevice corrosion, stress corrosion cracking, microbial influenced corrosion, and galvanic corrosion), only two of these processes are considered potentially important for corrosion of the waste packages—general corrosion and localized corrosion in the form of pitting. General corrosion typically occurs over large areas, whereas localized pitting corrosion is restricted to limited surface areas. General corrosion can occur nonuniformly under low pH (i.e., less than 7) and at a chloride concentration significantly greater than minimum $[Cl^-] \gg [Cl^-]_{min}$. General corrosion can also occur uniformly as passive (pH > 8.5) or active (pH < 8.5) corrosion. Passive corrosion in the presence of $[Cl^-] \gg [Cl^-]_{min}$ provides an environment conducive for pitting. For the inner container material (i.e., a Ni-Fe-Cr-Mo alloy), adequate O_2 must be present for any corrosion mechanism to be active.

In addition to relative humidity, the occurrences and rates of general and pitting corrosion are dependent on temperature and chloride concentration. Formulas describing the relationship among relative humidity, temperature, and chloride concentration can be found in Mohanty, et al. (1997) for example. In general, corrosion rates increase with temperature, relative humidity, and chloride concentration. One notable exception to this generalization is corrosion in the presence of wetting/drying cycles (i.e., periods within wetting/drying cycles when relative humidity may be decreased), which may lead to accelerated corrosion rates (Tsuru, et al., 1995).

The waste package design formerly consisted of an outer barrier of CAM (i.e., carbon steel) and an inner barrier of CRM. Alloy 825 was the candidate CRM in TSPA–95, but Alloy-22 is used in the new waste package design (Civilian Radioactive Waste Management System, Management and Operating Contractor, 1999a).

Physical and chemical factors dictate which corrosion mechanism will prevail in a particular environment. Dominant parameters in the context of the geologic repository include pH, chloride concentration, and oxygen concentration. The states of these factors determine the corrosion potential, $E_{Corr.}$, of the waste package environment. If $E_{Corr.}$ exceeds the repassivation potential, E_{rp}, localized corrosion is assumed to occur, otherwise, general corrosion under passive conditions will be experienced. Passive corrosion implies a low rate of corrosion.

The introduction of bulk water onto a waste package by dripping can affect corrosion mechanisms and rates in several ways (Walton, 1993). First, water dripping from the rock-support structures or rock mass can provide significant quantities of strong anions, in general, and chloride, in particular, to the waste package surface, whereas water films that attach to the container surface as vapor will be essentially pure water. Second, water that tends to drip continuously or intermittently at a specific location would lead to degradation at that localized site. Finally, cyclic wetting/drying of the container surface can accelerate the rate of corrosion relative to conditions where moisture (thin film or bulk) adheres to the waste package surface (Tsuru, et al., 1995). Corrosion products, when dried during the wetting/drying cycle, can then act as oxidizing agents for additional corrosion when the surface is re-wetted. The rate of corrosion is thereby greater than for conditions where corrosion products remain continuously wet. One example of corrosion in a wet/dry environment is metal piers located in off-shore marine environments. Rates of corrosion for the piers are observed to be significantly greater in the splash zone than any other segment of the piers, including that segment that is continuously submerged (Dexter, 1992). In summary, these conditions could potentially accelerate the rate of general or pitting corrosion, although the rate of one would tend to exceed the other for a particular set of circumstances.

3.2.2 Effect of Thermally Driven Water on Radionuclide Transport from Failed Waste Packages

Water that enters into emplacement drifts can alter the temperature, relative humidity, and flux of (vapor or liquid phase) water proximal to the waste packages. Process-level models should consider all the potential water entering emplacement drifts, including refluxing, when predicting the heat and mass transfer near the waste package. Results from process-level models and performance assessments may be used to develop a basis for inclusion or exclusion of the refluxing phenomenon in predicting radionuclide transport so that liquid phase transport of radionuclides from waste packages is conservatively estimated.

3.2.3 Effect of Thermally Driven Water on Hydraulic and Transport Pathways

The design of the emplacement drifts for the license application is the EDA II (Civilian Radioactive Waste Management System, Management and Operating Contractor, 1999a). Details of design options including backfill, support structures, and shape of drip shields, are still subject to modification. Liquid water entering the emplacement drifts has the potential to transport significant quantities of minerals to the waste package surface as part of vaporization/condensation cells driven by waste package heat. Resulting dissolution/precipitation can cause changes to the hydraulic and transport pathways present in the engineered structures (i.e., ground control features, inverts, backfill materials, etc.) and the host rock. The geochemical processes that govern these changes are a complex result of temperature, moisture content, and the minerals present in the repository environment. Consequently, prediction of the geochemical processes that might result in pathway alterations will require an understanding of heat and mass transfer mechanisms affected by water refluxing into emplacement drifts. Assessment of the geochemical alteration of hydraulic and transport pathways is a component of the ENFE KTI.

3.3 CONSIDERATION OF THERMALLY DRIVEN WATER IN PREVIOUS PERFORMANCE ASSESSMENTS

The performance of the waste package and the transport of radionuclides released from failed waste packages are affected by the thermal-hydrology of the environment in the vicinity of the waste packages. Predicting heat and mass transfer in the near field of the waste packages has been an integral component of recent performance assessments of the proposed repository at Yucca Mountain. The following are most notable of these performance assessments: (i) two performed by the DOE, the *1993 Total System Performance Assessment* (TSPA–93) (Wilson et al., 1994) and the *1995 Total System Performance Assessment* (TSPA–95) (TRW Environmental Safety Systems, Inc., 1995); (ii) one prepared by the Electric Power Research Institute (EPRI)—*Yucca Mountain Total System Performance Assessment, Phase 3* (EPRI 96) (Kessler and McGuire, 1996); and (iii) one prepared by the NRC—*Iterative Performance Assessment, Phase 2* (IPA Phase 2) (Wescott, et al., 1995). The manner in which each study incorporates the thermohydrologic effects resulting from heat generated by the decay of HLW is summarized in the following sections. Included in this summary are the DOE and NRC program modifications as described at the May 1998 DOE/NRC Technical Exchange on performance assessment held in San Antonio, Texas.

3.3.1 U.S. Department of Energy Total System Performance Assessment 1993

Mechanisms and parameters that affect waste package integrity

TSPA–93 uses a source term module, YMIN, to determine the flux and time history of radionuclides released from the waste packages. The integrity of the waste packages is calculated in YMIN as a function of temperature and whether the waste packages are dry or wet. Wet waste packages are defined as those in which the 96 °C isotherm (i.e., the temperature of boiling at the repository horizon) is within 5 m above the center of the waste package. Corrosion will proceed for those containers that are wet.

Fuel and canister temperatures for in-drift loading were numerically calculated using the conduction-only code COYOTE (Gartling, 1982), an analytical solution, or the numerical simulator ANSYS. The extent of the dry-out zone was calculated with an analytical model and VTOUGH, a numerical code (Nitao, 1989). Flow through fractures only is calculated using WEEPTSA. Because WEEPTSA is an isothermal simulator, this preliminary estimate of mass transfer is solely a function of liquid water flux. In this performance assessment, container corrosion can occur as air oxidation, general aqueous corrosion, or localized pitting corrosion. All three corrosion mechanisms are directly or indirectly (via property dependence) functions of temperature. Both general aqueous corrosion and localized pitting corrosion require the presence of liquid water (which will only occur at sub-boiling temperatures) to proceed. Therefore, liquid water flux is required to determine container performance, but the presence of water is indirectly indicated by temperature only. Relative humidity is not considered a factor in waste package performance in TSPA–93.

Effect of pore water and infiltration on released radionuclides

The contribution of gaseous radionuclides to dose is accounted for in TSPA–93. Therefore, fluxes of air and vapor movement, in addition to liquid water fluxes, are calculated for the assessments. Two models are used to predict liquid water and gaseous flow through partially saturated fractured rock: TOSPAC (Dudley, et al., 1988), a composite-porosity model, and WEEPTSA. Both are coupled to the radionuclide source program YMIN. WEEPTSA is an isothermal simulator, therefore, the dry-out fraction and volume are determined externally using VTOUGH. Heat flow for both analyses is predicted using COYOTE, or an analytical heat-conduction solution. In summary, liquid transport of radionuclides released from failed waste packages is a function of spent fuel, waste package, and host rock temperatures and the flux of liquid water through the repository environment. Transport of gaseous radionuclides is dependent on the fluxes of air and water vapor, which in turn, are dependent on temperature and liquid flux.

3.3.2 U.S. Department of Energy Total System Performance Assessment 1995

<u>Mechanisms and parameters that affect waste package integrity</u>

TSPA–95 assesses the likelihood of corrosion of the outer barrier CAM and the inner barrier CRM. For both barriers, the primary conditions for corrosion are thought to be humid air (thin film) corrosion and aqueous (bulk water) corrosion. Only general corrosion and localized pitting corrosion are considered in TSPA–95. In general, the outer barrier will degrade by general corrosion alone or by a combination of general corrosion and localized pitting corrosion. The inner barrier will degrade solely by localized pitting corrosion under aqueous conditions.

General corrosion is highly dependent on relative humidity but only weakly dependent on temperature. Conversely, pitting corrosion is highly dependent on temperature with increased temperature leading to increased corrosion. Pitting corrosion, which requires aqueous (bulk water) conditions, is assumed to occur at temperatures less than 100 °C and relative humidity greater than 85–95 percent. Thus, the contact with liquid water is not explicitly considered in container performance.

<u>Effect of pore water and infiltration on released radionuclides</u>

Subsequent to the failure of waste packages, radionuclides are transported from the point of release to the saturated zone in the liquid phase. Geosphere transport of radionuclides in the gaseous phase of the unsaturated zone is not considered in TSPA–95. TSPA–95 relied on the RIP abstraction, a code that samples flux distributions and other user designated distributions, to solve advection-only or advection/dispersion transport through one-dimension (1D) columns connecting the ground surface with the saturated zone. Liquid flux through the unsaturated zone is a function of both fracture and matrix flow. Predictions of flux using RIP are compared with matrix/fracture flux calculated using FEHM (Zyvoloski, et al., 1995), a dual permeability process-level model, to increase confidence in flux predictions. Temperature and relative humidity are only indirectly important to flux predictions in the manner in which they affect mass balance and liquid flux calculations.

3.3.3 Electric Power Research Institute Yucca Mountain Total System Performance Assessment 1996

<u>Mechanisms and parameters that affect waste package integrity</u>

EPRI used the code Integrated Multiple Assumptions and Release Calculations (IMARC) to assess the performance of the individual components that contribute to the performance of the repository system (Kessler and McGuire, 1996). The performance of the containment barrier system (CBS) is a direct function of temperature, humidity, and microbiologically influenced corrosion. The presence or absence of liquid water during the heating period is incorporated into CBS performance calculations in IMARC as a probability weighing coefficient. Twelve scenarios are considered in the EPRI performance assessment, four moisture settings each at three different temperature regimes. The four moisture settings are: (i) dry—the waste package does not contact liquid water; (ii) wet-drip—separate droplets of water fall across an air gap onto the waste package; (iii) episodic—liquid water contacts the waste package intermittently for limited periods of time; and (iv) moist-continuous—liquid water is in continuous contact with the waste package. The three temperature regimes are: (i) waste packages whose surface temperatures rise substantially above boiling; (ii) waste packages whose surface temperatures rise to approximately the boiling point; and (iii) waste packages whose surface temperatures remain well below boiling. Fractions (or weights) are assigned to each of the seven components to determine the probability of each scenario occurring. Therefore, wet conditions are considered in waste package failure by assigning probability factors that reflect a greater failure than dry conditions. The general approach to waste package failure taken in EPRI 96 is similar to the approach on refluxing in the REFLUX1 and REFLUX2 abstractions included in TPA Version 3.1.1 (see Section 3.4 of this report).

Effect of pore water and infiltration on released radionuclides

The effect of dripping water and advective liquid water transport of radionuclides from the waste package is considered in the EPRI source-term code, IMARC: COMPASS (Zhou and Salter, 1995). The rate at which advective liquid water leaves the waste package is equivalent to the rate of water dripping into the waste package. On encountering the concrete barrier below the waste package, radionuclides can be transported by a combination of diffusion and advection. The movement of pore water and infiltration driven by thermal effects can, therefore, influence the transport of radionuclides released from the waste packages subsequent to container failure. Temperature and relative humidity are not directly incorporated into radionuclide transport (source-term) analyses, other than their inherent coupling with water flux in nonisothermal flow calculations.

3.3.4 U.S. Nuclear Regulatory Commission Iterative Performance Assessment Phase 2

Mechanisms and parameters that affect waste package integrity

Temperature is explicitly used in three places in IPA Phase 2: (i) gas velocity for the ^{14}C transport model; (ii) onset of corrosion in the source-term model; and (iii) release of ^{14}C from the spent fuel under dry conditions. The repository temperature model used in IPA Phase 2 considers only heat transfer by conduction in a uniform, semi-infinite medium and does not include two-phase flow or radiative heat transfer.

The performance of the waste package is contingent on waste package corrosion. The waste packages are assumed to remain dry and no corrosion of the waste packages occurs until the temperature falls below the boiling isotherm in the repository environment, 96 °C. The integrity of the waste package in IPA Phase 2 is not directly dependent on relative humidity or liquid water.

Effect of pore water and infiltration on released radionuclides

Several mechanisms that can lead to water contact with waste packages are discussed in IPA Phase 2: (i) dripping fractures—fracture flow in the rock that occurs where infiltration exceeds the hydraulic conductivity of the rock matrix; (ii) direct contact of the waste package with rock or rubble infilling material—the air gap surrounding the waste package becomes filled with rubble material or the waste package is tilted against the borehole wall; (iii) condensation of water onto surface of the waste packages—liquid water could be present at temperatures in excess of 100 °C if salts are present in the condensed water at high concentrations; and (iv) immersion of the waste package—the unlikely occurrence where the waste package would become immersed in liquid water due to a rise in the regional water table or to igneous activity. This last category was not considered to be a credible scenario in IPA Phase 2. The source for water in these mechanisms can be ambient rock water or infiltration.

The inflow of water into a waste package and the threshold of water in the waste package that must be exceeded before outflow occurs are functions of the first three mechanisms listed previously. Advective transport of radionuclides from the waste package to the natural environment is solely a function of the outflow of water from the waste package and independent of any other liquid water contributions that may be present.

3.3.5 U.S. Department of Energy Total System Performance Assessment—Viability Assessment Methods and Assumptions (Civilian Radioactive Waste Management System, Management and Operating, 1997)

Mechanisms and parameters that affect waste package integrity

As indicated in the DOE's TSPA-VA Methods and Assumptions Document, the DOE will use thermohydrologic modeling results to provide relative humidity, air mass fraction, gas-phase flow rate in the drift, temperature of the waste package, and the liquid saturation and temperature of the concrete liner and invert. Results from the thermohydrologic modeling will be used in combination with results from the unsaturated zone flow models to develop a model of seepage into emplacement drifts, which will be used by the near-field models.

The abstraction of seepage into TSPA calculations is not defined in this document. There are no data currently available to calibrate process-level models for seepage. Information from drift-scale unsaturated zone flow and thermohydrologic modeling, mountain-scale unsaturated zone flow and thermohydrologic modeling, and past results from the WEEPTSA model may be used to define a response surface abstraction for seepage. Although the exact nature of the response surface is not known, the desired outputs of the seepage model are the fraction of waste packages contacted by weeps and the range or distribution of seep flow rates, both of which will be transient because of thermal effects and climate changes. The response surfaces are anticipated to be functions of the local fracture flux, and possibly the fracture hydraulic properties, and a measure of the fracture/matrix connection area. The response surface may be a function of temperature because evaporation can alter the occurrence and rate of seepage.

The DOE subsystem model for evaluating degradation of the waste package in the Total System Performance Assessment for the Viability Assessment (TSPA-VA) is WAPDEG (Civilian Radioactive Waste Management System, Management and Operating Contractor, 1997a). Corrosion of the outer barrier is based on an empirical formulation. Mechanistic models of corrosion are under development. These models will be incorporated into WAPDEG when available.

The DOE model in TSPA-VA for outer barrier corrosion includes both humid air corrosion and aqueous corrosion as functions of time of exposure and temperature, and only aqueous corrosion as a function of relative humidity. Objectives for the updated corrosion plan for the outer barrier in the TSPA-VA are to include the following models: (i) humid-air general corrosion; (ii) aqueous general corrosion; and (iii) localized corrosion (or variation in general corrosion depth) of the outer barrier in humid-air and aqueous corrosion conditions. Pitting may be incorporated as a multiplier of general corrosion. Spalling may also be included in the DOE's model. Microbial corrosion is expected to be modeled in the TSPA-VA as localized corrosion incorporating additional constraints due to temperature, water availability, nutrient availability, and pH.

The inner barrier is assumed to corrode only by aqueous pitting corrosion dependent only on temperature. Objectives for the updated corrosion plan for the inner barrier in the TSPA-VA include a model to predict the rate of penetration of the inner barrier as a function of temperature, relative humidity, and in-drift dripping. In addition, a simple galvanic protection model has been used that only allows pitting corrosion of the inner barrier after a specified percentage of the outer barrier has corroded. This later model is to be significantly revised.

<u>Effect of pore water and infiltration on transport of released radionuclides</u>

Thermohydrologic results will be used to provide liquid-phase flow fields for the unsaturated zone zone below the repository during the period of thermal disturbance. These mountain-scale calculations might be used to provide liquid-phase, flow-field multipliers for the thermal period for this flow field. The multipliers would be used to approximately correct ambient unsaturated zone flow fields. As an example, fracture flux would be increased when the thermohydrologic calculations indicate the potential for increased or decreased condensate drainage during the period of thermal disturbance. The modified flow fields can be used to account for thermohydrologic effects in the radionuclide transport calculations.

3.3.6 U.S. Department of Energy/U.S. Nuclear Regulatory Commission Performance Assessment Technical Exchange—May 1998

<u>Mechanisms and processes that affect waste package integrity</u>

Information exchanged between the DOE and NRC at the May 1998 Technical Exchange on performance assessment indicates that both the DOE's and NRC's approaches to incorporating TEF into their respective performance assessments have been modified. The DOE recognizes that waste package failure is affected by dripping. Seepage, which can lead to dripping, will be calculated using a three-dimensional (3D) stochastically generated heterogeneous, fracture continuum, drift-scale model. Thermal effects will be included in the model in an approximate fashion. Thermohydrologic uncertainties will be investigated by using different weighting factors for process models. The DOE approach incorporates the effects of liquid water by dripping on corrosion predictions for the inner layer (e.g., CRM) of the waste package. In particular, the candidate material for the inner barrier, C-22, is subjected to general and localized corrosion in the presence of dripping but only general corrosion if dripping is absent. Threshold levels for temperature and relative humidity, at which corrosion of the outer barrier is experienced, will be specified by expert elicitation. Microbial-induced corrosion is not considered.

Greater detail was provided on the role of thermohydrologic predictions in the TSPA process. Mountain-scale thermohydrologic models using TOUGH2 will provide predictions of gas flux and air mass fraction. This information is used in geochemical models to predict CO_2 and O_2 compositions used in corrosion calculations. Drift-scale thermohydrologic models using NUFT will provide predictions of temperature, relative humidity, and liquid saturation to the near-field geochemical models (EQ3/6) and predictions of temperature and relative humidity to WAPDEG. Temperature and relative humidity will be obtained for each of the six zones. It is not clear if liquid saturation will be obtained from NUFT for each zone. A possible inconsistency from other presentations at the performance assessment technical exchange is the flow chart for the TSPA-VA code configuration dated February 1998, which has no indication of the drift-scale thermohydrologic model providing liquid saturation to WAPDEG. Other inconsistencies are implied in the logic diagram for the basecase TSPA-VA waste package degradation model, which indicates the drift-scale thermohydrologic model will provide information on waste package temperature, relative humidity, and in-drift drips to WAPDEG. The logic diagram further indicates that dripping is included in corrosion calculations of the CAM outer barrier. It is important to note that these interpretations are inferred from diagrams, and the actual model may perform differently. Additionally, the diagrams may provide a snapshot of a version of WAPDEG that differs from the version to be used in the TSPA-VA. Although not a nonisothermal calculation, drift-scale unsaturated zone flow models (TOUGH2) will calculate the fraction of waste packages with seeps.

The DOE will also employ a multi-scale thermohydrologic modeling approach that includes a 3D mountain-scale model and 1D, two-dimensional (2D), and drift-scale models. It is not clear how the multi-scale modeling approach is incorporated into the TSPA-VA design discussed in the previous paragraph. In particular, how will the drift- and mountain-scale, thermal-conduction model predictions (for temperature only) be included into the TSPA-VA process?

The NRC program currently considers humid air corrosion separately from aqueous corrosion but does not directly incorporate the effects of liquid water on waste package corrosion. Both the DOE's and NRC's programs acknowledged the importance of assessing the propensity to corrode the outer layer (e.g., CAM) of the waste package by exposure to liquid water. Both programs indicated intentions to address the issue.

<u>Effect of pore water and infiltration on transport of released radionuclides</u>

Radionuclides will be transported from the waste packages by advection only when drips are present; otherwise, transport is by diffusion. The drift-scale thermohydrologic model using NUFT will provide predictions of temperature and liquid saturation to waste-form degradation and radionuclide transport calculations by the RIP code. The nonisothermal drift-scale unsaturated zone flow model (TOUGH2) will provide values for the fraction of waste packages with seeps and the seep flow rate. The nonisothermal, mountain-scale unsaturated zone flow model (TOUGH2) will provide liquid flux values to RIP.

3.3.7 U.S. Department of Energy Total System Performance Assessment—Viability Assessment and Technical Basis Document

The DOE conducted a VA (U.S. Department of Energy, 1998b) of the proposed repository to provide information on the progress of the Yucca Mountain Site Characterization Project. The VA also identified critical issues that must be addressed before a decision is made to recommend the Yucca Mountain site for a repository. From a technical perspective, the TSPA portion of the VA (Volume 3 of the VA, referred to as TSPA-VA) and the Technical Basis Document (TBD) (TRW Environmental Safety Systems, Inc., 1998), which contains supporting analyses used in the TSPA-VA, have the most relevance to the TEF KTI. Of these two documents, the TBD contains greater detail. A summary review of those items in the TBD that relate to TEF is contained in this section. The summary includes that portion of Chapter 2 that addresses seepage, Chapter 3 (Thermal Hydrology), and Chapter 5 (Waste Package Degradation Modeling and Abstraction). These documents were reviewed in terms of their relevance to the TEF IRSR. A greater level of detail is extracted from Chapter 3, Thermal Hydrology, which describes the DOE approach for thermohydrologic processes to be used in the TSPA-SR and TSPA-VA.

3.3.7.1 Technical Basis Document—Chapter 2: Unsaturated Zone Hydrology Model

Chapter 2 of the TBD addresses the unsaturated zone hydrology model, which describes how seepage is incorporated into the TSPA-VA. From the DOE perspective, seepage is a critical contributor to repository performance. Therefore, considerably more effort was devoted to modeling seepage in the TSPA-VA than had been done in earlier TSPAs. In short, the DOE adopted a more process-based method to estimate the amount of seepage onto waste packages. The method used a dual permeability model (DKM) and a geostatistical description of the fracture heterogeneity.

The 3D unsaturated zone flow model was used to calculate the percolation flux and seepage velocity. In the unsaturated zone model it was assumed that hydrogeological units are homogeneous (i.e., that heterogeneity within a unit was not included). It is noted elsewhere (TRW Environmental Safety Systems, Inc., 1998, pg 2-92) that fracture permeability is heterogeneous. This approach does not consider the potential consequences of inter-layer heterogeneity on flow through the unsaturated zone (TRW Environmental Safety Systems, Inc., 1998, pg 2-34). As a result predictions of focused fracture flow may be suppressed. Although the DOE states that a range of percolation fluxes into the seepage block was considered in the analyses, it is not clear if the full effect of potential focused flow from media heterogeneity was accommodated in the predictions.

The DOE notes that groundwater travel times are insensitive to variations in fracture van Genuchten air-entry values (i.e., van Genuchten α) (TRW Environmental Safety Systems, Inc., 1998, pg 2-37). The fracture air-entry values are determined from fracture aperture values, which were originally determined using air-injection testing. This insensitivity suggests that the van Genuchten α characterization may not be appropriate for fracture flow. For example, rapid episodic fracture flow may not be controlled by capillarity, therefore, capillarity may not be the appropriate mechanism to describe rapid fracture flow. It is possible that surface film or groove flow may dominate fast flow down fractures. If so, fracture flow characterized by a capillary retention curve may not be appropriate (Stothoff, et al., 1999). Also, fracture porosity values of 1.24×10^{-4} based on Exploratory Studies Facility (ESF) fracture mapping may not be justified (TRW Environmental Safety Systems, Inc., 1998, pg 2-91). Recently reported fracture porosities by the DOE using results from gas tracer tests and retention curves from the niche studies significantly exceed those porosities based on mapping (Hughson, 1999a).

Observations of seepage in the niche studies are used to support conceptual models and model predictions. Interpretations of the niche studies results are predicated on the assumption of near 100 percent relative humidity in the niche air space (TRW Environmental Safety Systems, Inc., 1998, pg 2-103). This assumption is not justifiable in the presence of ventilation and its effect on relative humidity. The less than 100 percent relative humidity in the niche will diminish, if not completely eliminate, the formation of moisture on the drift wall and dripping from the drift wall surface that would occur under otherwise expected ambient conditions. Both a low relative humidity (i.e., less than 100 percent) and ventilation are highly effective in removing moisture that enters the drift from fractures (Lepalla, et al., 1998: Danko, et al., 1996). The impacts of ventilation and low relative humidity on moisture at the drift interface is well demonstrated by comparing the dry walls of the ESF through which desert air is ventilated to the moist walls within niche 3566 that was sealed from the drying effects of ventilation. Therefore, if either the relative humidity is reduced or if ventilation is present in the niche air space, seepage into the niche will be substantially curtailed. Accordingly, a ventilated drift is an inappropriate analog of seepage that would occur in a shut-in drift with high humidity and no ventilation. The absence of seeps in the ESF cannot be interpreted to imply that seepage through that portion of Yucca Mountain would not exist under pre-existing, ambient or nonventilated, ambient relative humidity conditions. The DOE acknowledged that the lack of seeps in the ESF may be partially due to ventilation; however, it should be recognized that the ventilation of the ESF using low relative humidity desert air would, in itself, completely obviate the possibility of seeps in the ESF.

The DOE recognized the need to investigate the possibility of episodic flow and discrete-fracture effects at the repository (TRW Environmental Safety Systems, Inc., 1998, pg 2-11). It is stated "… local equilibrium implies that the liquid saturation in the fractures will remain near zero until the matrix saturation approaches values close to 100%" (TRW Environmental Safety Systems, Inc., 1998, pg 2-93). Based on this reasoning, under steady-state conditions, liquid flow in fractures will become significant only for matrix saturations close to 100 percent. It should be noted, however, that localized episodic flow can happen where the rock pores at the drift wall are not at full saturation as observed at the 1988–89 G-tunnel heater test (Ramirez, 1991; Buscheck, et al., 1991). This condition can occur when the fracture/matrix interface has diminished permeability due to the combined effects of fracture coating, reduced contact area, and rapid fracture flow. This occurrence of seepage through fractures in rock whose matrix is less than fully saturated is inconsistent with the DOE conceptual model that assumes rock pores must be fully saturated for fracture flow to occur (TRW Environmental Safety Systems, Inc., 1998, pg 2-93). The presence of fracture flow through a less than fully saturated rock matrix is exhibited in niche 3566 where matrix saturations at the proposed repository horizon are about 0.92 and dripping was observed. The presence of bomb-pulse isotopes at repository depth provides additional evidence of water flow through fractures in rock whose matrix saturation is less than 1.0.

The prospect of a capillary barrier at the drift wall is considered important in the TBD (TRW Environmental Safety Systems, Inc., 1998, pg 2-92 and 2-95). However, there is insufficient evidence to support that the drift wall behaves wholly as a capillary barrier. This is particularly the case for a drift wall with a high degree of asperities resulting from an irregularly shaped drift wall surface (i.e., due to rock fall) and ground support structures (i.e., rock bolts, steel sets, mesh, etc.). Asperities whose height exceeds the pressure column height equivalence (i.e., a column of water whose height equates to the matrix pore size or fracture aperture in the asperity) to the fracture apertures will drip rather that divert flow to the side of the drift. Flow in rock not controlled by capillarity cannot be expected to keep moisture out of the drift by capillary diversion. Therefore, capillary diversion cannot be expected to divert all flow around the drift opening. In addition, treating the drift ceiling as a geometrically shaped smooth surface is not valid because actual mined surfaces are rarely, if ever, smooth. Capillary diversion resulting from flow around a geometrically smooth circular surface is a nonconservative approximation of a drift excavated into welded tuff that exhibits an irregularly shaped surface.

Results from 2D simulations of dripping into a drift were based on a porous medium continuum model with flow driven by capillary forces (TRW Environmental Safety Systems, Inc., 1998, pg 2-97). Simulations that indicate water flows symmetrically downward around the two sides of the drift are not representative of a flow system dominated by gravity-driven flow through heterogeneous media.

Sensitivity analyses indicate that for a given infiltration rate the amount of seepage depends mostly on fracture α and permeability (TRW Environmental Safety Systems, Inc., 1998, pg 2-101). This observation is an artifact of the conceptual model that has flow controlled solely by capillary forces. This assumption may be acceptable for most flow through partially saturated fractured rock at the proposed repository with the exception of the region where significant thermal conditions are present.

The possibility for gravity-driven flow at the drift wall interface was considered in the TBD for occurrences in which discrete features connect the drift opening to a continuous fracture network (TRW Environmental Safety Systems, Inc., 1998, pg 2-102). This prospect is believed to increase seepage from that predicted for a capillary-driven system. The phenomenon is controlled by aperture, roughness, spatial orientation of the fracture, length of fracture section, and the amount of flux diverted into the fracture. The discrete features are vertically oriented with no lateral connections. An increased density of vertical features is envisioned to result from excavation activities and long-term alteration processes. This arrangement allows water in the fractures to flow into the drift opening and not flow laterally. A significant increase in seepage flux was realized using this conceptual model. The effect of not having a capillary barrier at the drift interface was also investigated by allowing water to readily drain into the drift (TRW Environmental Safety Systems, Inc., 1998, pg 2-105). A significant increase in seepage into the drift was again experienced. These results should be incorporated in the TSPA.

Repository heating is assumed in the TBD to have a significant effect on seepage. Seepage is reduced to zero during the time that the temperature of the drift-wall above the waste package exceeds boiling (TRW Environmental Safety Systems, Inc., 1998, pg 2-115). This nonconservative assumption neglects the possibility of penetration of the boiling isotherm by flow down a fracture. Penetration of the boiling isotherm has been experimentally observed (Wilder, et al., 1998; Green and Prikryl, 1998) and theoretically predicted (Phillips, 1996; Pruess, 1997). A conservative prediction must accommodate the potential for liquid water to enter the drift prior to the collapse of the boiling isotherm below the drift interface.

In the TSPA analysis, seepage was found to be important to the overall repository performance for periods ranging from 10,000 to 1 million years (TRW Environmental Safety Systems, Inc., 1998, pg 2-127). The lack of importance of seepage for the first 10,000 years after emplacement is quite possibly an artifact of this particular conceptual model used to predict seepage because alternative DOE conceptual models predict seepage during this time frame. Additional evidence is required to justify the assumptions inherent in the conceptual models used to eliminate seepage prior to 10,000 years after emplacement.

This review concurs with the DOE observation that there remains a need to assess the effects of episodic percolation pulses, the potential increase in seepage during drainage of thermally mobilized water, the effects of chemical or mechanical alterations in hydrological properties around the drifts, and the effects of drift collapse or emplacement of backfill (TRW Environmental Safety Systems, Inc., 1998, pg 2-128).

3.3.7.2 Technical Basis Document—Chapter 3: Thermal Hydrology

The DOE uses a multiscale modeling approach to abstract thermohydrologic processes into its TSPAs. The multiscale approach combines 1D, 2D, and 3D drift-scale thermal models and thermohydrologic models with a conduction-only 3D mountain-scale model. These models were used in the TSPA-VA to estimate waste package corrosion rates, waste-form dissolution rates, and transport of radionuclides through the EBS. The use of conduction-only models is anticipated to introduce small errors in the abstracted performance measures. The magnitude of these errors can be estimated by comparing abstracted results with direct simulations. Where possible, conduction-only models are used to calculate temperature differences instead of absolute temperatures; this method minimizes the abstraction errors (TRW Environmental Safety Systems, Inc., 1998, pg 3-60).

Four different models are used in the thermohydrologic multiscale modeling and abstraction method: SMT, SDT, LDTH, and DDT. In this terminology, S denotes smeared heat source, M denotes mountain scale, the first D denotes drift scale, T denotes heat flow by conduction, TH denotes thermal-hydrological coupling, L denotes line loading, and the second D denotes a discrete heat source. In addition, a smeared-heat source, drift-scale, thermohydrologic model (SDTH) has been used during the course of model abstraction testing. The SDTH model is used to determine thermal conductivity relationships for the conduction-only models. With SDTH and the SDT submodel, a thermal conductivity as a function of temperature is developed to estimate the effect on the heat transfer rate by conduction (TRW Environmental Safety Systems, Inc., 1998, pg 3-61).

The major components of the multiscale approach are summarized in the following paragraphs (TRW Environmental Safety Systems, Inc., 1998, pg 3-10):

- LDTH is a 2D line-averaged-heat-source, drift-scale, thermohydrologic submodel that computes average temperature and relative humidity at the drift wall. It is also used to compute the average liquid saturation in the drift invert. The LDTH submodel has DKM capability. Radiant heat flow within open drifts is modeled explicitly. 1D heat flow in the unsaturated zone is equivalent to that of the SDT and DDT models. The water table is assumed to be a constant temperature boundary. LDTH and SDT are used for hydrology corrections to the SMT model. Point-load and line-load designs are considered using this model. Designs with and without backfill are evaluated. The circular drift and waste package are represented with rectangular geometry. Radiative heat transfer is included. Local topography, hydrostratigraphy, thermal properties, hydrological properties, boundary conditions, and initial temperature are consistent with unsaturated zone site-scale model. Thermal and hydrological properties are homogeneous within hydrostratigraphic units. Heat source is an average of the seven individual waste packages (i.e., six full packages and two ½ packages) represented in the DDT model. DKM is used. One primary role for the LDTH model in the thermohydrologic multiscale modeling and abstraction method is to provide a functional relationship between repository host-rock temperatures predicted with a thermal-conduction-only model and the perimeter-averaged drift-wall temperature predicted by a thermohydrologic model. This relationship allows the mapping of the LDTH perimeter-averaged drift-wall temperature onto the SMT-predicted repository host-rock temperature. This approximates a drift-wall temperature prediction from a mountain-scale model with a finely resolved, line-averaged heat source, which can be readily computed for locations throughout the repository area. LDTH includes the hydrology of the system indirectly through the functional relationship developed with the LDTH and SDT submodels. The LDTH submodel calculations are made in parallel with the SDT calculations (TRW Environmental Safety Systems, Inc., 1998, pg 3-68). Results from the LDTH submodel that are input into the thermohydrologic multiscale modeling and abstraction method include the following:

  - Perimeter-averaged, drift-wall temperature
  - Perimeter-averaged, drift-wall relative humidity
  - Perimeter-averaged, drift-wall liquid-phase saturations
  - Liquid-phase flux three meters above the drift
  - Liquid-phase saturation in the invert.

- SMT is a 1D smeared-heat-source, mountain-scale, thermal-conduction submodel designed to establish temperature relationships accounting for the influence of repository edges, topography, and mountain-scale variability in hydrogeological layering. The SMT submodel neglects gas-phase transport. SMT is coupled with SDT to determine differences between edge and center locations. Relative humidity is calculated using temperatures. Conduction-only predicted temperatures over-predict temperature relative to a thermohydrologic model; however, conduction-only allows for finer spatial discretization. In the TSPA-VA design, the length of the repository is 2912 m, and the width is 1109 m. There are 104 emplacement drifts with spacing of 28 m such that the center of the emplacement drift is 3 m higher than east and west sides. Local topography, hydrostratigraphy, thermal properties, hydrological properties, boundary conditions, and initial temperature are consistent with the unsaturated zone site-scale model. Heat conduction below the water table is included (TRW Environmental Safety Systems, Inc., 1998, pg 3-65).

- SDT is a 1D smeared-heat-source, drift-scale, thermal-conduction submodel designed to establish temperature relationships accounting for the influence of repository edges, topography, and mountain-scale variability in hydrogeological layering. The SDT submodel is coupled with SMT to determine differences between edge and center locations. It also gives abstracted drift-wall temperatures and relative humidities. Vertical heat flow in the SDT is equivalent to that in the LDTH and DDT models. The water table is a constant temperature boundary. The SDT and LDTH models are used for hydrology corrections to the SMT model. Local topography, hydrostratigraphy, thermal properties, hydrological properties, boundary conditions, and initial temperature are consistent with the unsaturated zone site-scale model. Thermal properties are homogeneous in each unit. The primary role for the SDT submodel in the multiscale approach is to provide a functional relationship between repository host-rock temperature predicted with the SDT submodel and the perimeter-averaged drift-wall temperature predicted by a LDTH model. This functional relationship allows estimation of the perimeter-averaged drift-wall temperature using the calculated conduction-only, mountain-scale temperature. The SDT submodel input to the thermohydrologic multiscale modeling and abstraction method is repository host-rock temperature. The SDT submodel calculations are made in parallel with the LDTH model calculations (TRW Environmental Safety Systems, Inc., 1998, pg 3-66).

- DDT is a 3D discrete-heat-source, drift-scale, thermal submodel used to obtain temperatures and relative humidities for different waste package types along the drift. The DDT contains seven (i.e., six full packages and two ½ packages) representative waste packages of varying heat outputs. Only conductive heat transfer, plus radiant heat transfer within open drifts are included in the submodel. The DDT submodel accounts for variability in temperature and relative humidity among packages along the drifts. 1D vertical heat flow in the unsaturated zone is equivalent to that of the SDT and LDTH submodels (TRW Environmental Safety Systems, Inc., 1998, pg 3-68). Both point-load and line-load designs are evaluated. Similarly, with and without backfill is considered in the calculations. The circular cross-section of the drift and waste package are approximated using rectangular geometrical representations. Radiative heat transfer in the drift is included. Local topography, hydrostratigraphy, thermal properties, hydrological properties, boundary conditions, and initial temperature are consistent with the unsaturated zone site-scale model. Thermal and hydrological properties are homogeneous within hydrostratigraphic units. The SDT, LDTH, and DDT models all assume the same seven waste package types. An important role for the DDT model in the multiscale thermohydrologic modeling approach is to represent the drift-wall temperature differences that occur between specific waste package locations that are defined relative to the average drift-wall temperature along the drift. Another role is to determine the temperature between the waste package and the average drift-wall temperature. The DDT submodel inputs to the thermohydrologic multiscale modeling and abstraction method include the following: (i) waste package-location-specific temperature differences from the average drift-wall temperature along the drift and (ii) waste package-location-specific temperature differences between the waste package and the average drift-wall temperature along the drift. The DDT model predicts slightly higher absolute drift-wall and waste package temperatures than does the DDTH model, but the two models produce very similar temperature differences at each of the waste package locations (TRW Environmental Safety Systems, Inc., 1998, pg 3-70).

Major assumptions in the multiscale approach

- Perched water is omitted. Similarly, the effect of thermal-hydrological chemical (THC) processes on perching are omitted (TRW Environmental Safety Systems, Inc., 1998, pg 3-42).

- With the exception of isothermal drift-scale seepage models, small-scale and lateral heterogeneity is not included in thermohydrologic calculations.

- Because the thermal perturbation to the unsaturated zone flow field is generally short lived, it is not included in radionuclide transport through the unsaturated zone.

- Bulk permeabilities assigned to an open drift range from 10^{-12} to 10^{-18} m^2 (TRW Environmental Safety Systems, Inc., 1998, pg 3-45).

- It is assumed that if pressurization within the drift does not occur, which is the case for the selected range in bulk permeabilities, the total heat transfer rate from the waste package to the drift wall will be accurately approximated by the radiant heat transfer only (TRW Environmental Safety Systems, Inc., 1998, pg 3-46). (Note: this assumption is model dependent.)

- Thermal-hydrological-mechanical (THM) and THC alterations of hydrological properties can be neglected for the basecase. This assumption is tested by means of sensitivity studies at the scale of mountain and drift (TRW Environmental Safety Systems, Inc., 1998, pg 3-46).

- The average infiltration rate for the dry climate model was ~7.96 mm/yr. The average infiltration rate for the wet climate model was ~45.3 mm/yr (TRW Environmental Safety Systems, Inc., 1998, pg 3-53).

For a given drift-scale-model calculation (LDTH, SDT, DDT), there is only one mountain-scale submodel (SMT), but the LDTH is run for 35 different locations covering the entire block. SMT is run for 425 locations to get temperature and relative humidity (the 35 are a subset of the 425). The 35 LDTH results are interpolated for the 425 locations. Only six subregions are modeled in RIP. The six subregions are primarily based on the infiltration rate at the surface. The subregions represent the entire footprint (i.e., center and edges) and the variation of hydrogeological properties around the repository. The drift-scale analyses provide time-histories of waste package temperature and relative humidity, drift-wall temperature and liquid saturation, and invert-floor temperature and liquid saturation.

Additional model description

The NUFT computer program was used for all drift-scale thermohydrologic calculations (TRW Environmental Safety Systems, Inc., 1998, pg 3-13). All mountain-scale thermohydrologic models were completed with the TOUGH2 flow code. The thermohydrologic multiscale modeling and abstraction method provided temperature and relative humidity at the surface of the waste package, the drift-wall temperature, and liquid saturation in the invert. 1D and 2D thermohydrologic simulations are acceptable at the mountain scale, but 3D simulations are necessary to obtain the waste package variability in drift-scale results (TRW Environmental Safety Systems, Inc., 1998, pg 3-39). The vertical liquid flux through model elements below the elements that represented the center and edge of the repository was extracted from 2D thermohydrologic mountain-scale simulations (TRW Environmental Safety Systems, Inc., 1998, pg 3-85).

The net result of the thermohydrologic multiscale modeling and abstraction process is a discrete-heat source, mountain-scale, thermohydrologic model (DMTH). It is an abstracted process that accounts for waste package variability, fracture flow in a DKM conceptualization, and edge effects of a finite-sized repository. In its current formulation, the thermohydrologic multiscale modeling and abstraction method is unable to account for large-scale heat transfer processes occurring in the gas and liquid phases (TRW Environmental Safety Systems, Inc., 1998, pg 3-39).

The drift-scale thermohydrologic models that used the DKM conceptualization were employed to generate all base-case results as well as select sensitivity studies such as backfill repository design option. Drift-scale models making use of the generalized equivalent continuum model (G-ECM) were used in select sensitivity studies only. In the G-ECM, the matrix satiation saturation is reduced (to something less than fully saturated), which will permit fracture flow to occur. To achieve this flow, the capillary pressure in the matrix block approaches zero at the lower matrix satiation saturation value. The process of allowing fracture flow before the matrix is fully saturated is equivalent to saying that the matrix rock contains an irreducible gas-phase component within its pore space (TRW Environmental Safety Systems, Inc., 1998, pg 3-9).

2D mountain-scale models were used to develop base-case results as well as sensitivity studies. (TRW Environmental Safety Systems, Inc., 1998, pg 3-40). It is not clear if 2D, mountain-scale, thermohydrologic calculations provide the time-histories for gas-phase flow rates and air-mass fractions at repository center and edge locations. There is a conflict in the TBD as to whether the multiscale method is able to account for gas-phase advection that results from large-scale temperature and pressure gradients because only thermal conduction is included in its mountain-scale submodel (TRW Environmental Safety Systems, Inc., 1998, pg 3-12 and 3-13). It is also mentioned that a 3D G-ECM flow model is used to determine gas-phase flow through the mountain. The G-ECM mountain-scale model includes large-scale features such as the mountain's topography and spatial variability of the infiltration rate at the ground surface. It also includes repository-edge effects and the ability to develop large-scale fluid-flow processes such as buoyant convection (TRW Environmental Safety Systems, Inc., 1998, pg 3-12).

Verification of the thermal hydrological abstraction methodology (TRW Environmental Safety Systems, Inc., 1998, pg 3-12)

The independent model G-ECM was developed to provide an independent calculation for comparison with results from the multiscale models. The G-ECM approximation was 3D with fully coupled heat transfer and fluid flow but with less complicated coupling between mountain and drift scales. It uses abstracted information from mountain-scale thermohydrologic models to approximate edge effects. The DOE concludes, "that the combination of 1D or 2D models with reduced complexity in heat-transfer models suffices for determining near-field responses associated with waste package heating" (TRW Environmental Safety Systems, Inc., 1998, pg 3-12).

Property values and model input

Thermohydrologic analyses were run using a basecase set of thermal and hydrological properties. In all the thermohydrologic analyses, it is tacitly assumed that the van Genuchten representation applies to the fractures as well as to the matrix rock (TRW Environmental Safety Systems, Inc., 1998, pg 3-71). Properties identified with the potential to affect the thermohydrologic response only, include the rewetting characteristics of a dryout zone, bulk fracture permeability, and fracture van Genuchten α. The fracture permeability listed is the bulk fracture permeability. The bulk permeability is the product of the intrinsic fracture permeability and the fracture porosity (TRW Environmental Safety Systems, Inc., 1998, pg 3-72).

The DOE assumes that gravel-sized backfill has a thermal conductivity of 0.6 W/m-K (TRW Environmental Safety Systems, Inc., 1998, pg 3-6). This assumed value is significantly greater than a measured value of 0.26 W/m-K for a welded tuff gravel (Green, et al., 1997). A thermal conductivity, equivalent to radiation heat transfer, is used in the performance assessment testing models (TRW Environmental Safety Systems, Inc., 1998, pg 3-111). The equivalent thermal conductivity associated with the highest temperature range and including a contribution for the fluid motion (based on natural convection only, not forced convection) is about 3.2 W/m-K. This value is smaller than the 36 W/m-K associated with radiation heat transfer equivalent approximation for the same temperature range (TRW Environmental Safety Systems, Inc., 1998, pg 3-113).

Three TSPA-VA property sets were used to capture uncertainties in the hydrological properties. The preliminary basecase was calibrated to widely varying infiltration rates. The DKM/Weeps property set was developed to allow more fracture flow to occur in the unsaturated zone, particularly in the nonwelded geologic units (TRW Environmental Safety Systems, Inc., 1998, pg 3-116), for the purposes of examining the dryout zones around the emplacement drifts (TRW Environmental Safety Systems, Inc., 1998, pg 3-125). The thermohydrologic property set was used to represent rewetting uncertainty characterized by thermohydrologic processes (TRW Environmental Safety Systems, Inc., 1998, pg 3-70). The thermohydrologic property set was developed to provide a better match with the results of the SHT temperature data. This property set is similar to the basecase, with the major exceptions occurring in the rate of rewetting applied to the host-rock units and in the matrix diffusivity parameter of the lowermost Topopah Spring hydrogeological model units. The rewetting parameters include fracture van

Genuchten α and the matrix diffusivity parameters such as matrix permeability and matrix van Genuchten α (TRW Environmental Safety Systems, Inc., 1998, pg 3-71).

Drift-scale analyses

The multiscale process used in the drift-scale analyses is summarized in the TBD as follows:

Step 1

The first step is to conduct numerical-model calculations using the NUFT code, with the following submodels (TRW Environmental Safety Systems, Inc., 1998, pg 3-87):

- SMT model (1 model run)
- SDT model (105 model runs)
- LDTH model using DKM (105 model runs)
- DDT model (1 model run)

[This step is in conflict with pg 3-13 (TRW Environmental Safety Systems, Inc., 1998), which states all mountain-scale models are run using TOUGH2, not NUFT.]

Step 2

The second step is to construct the functional relations (represented by scanning curves) among the various model-output variables from complementary drift-scale models. The scanning curves relate the following interactions (TRW Environmental Safety Systems, Inc., 1998, pg 3-88 through 3-90):

- Drift-wall TH temperature vs. drift-scale, smeared-heat source, conduction-only temperature
- Drift-wall TH and relative humidity vs. drift-wall TH temperature
- Backfill TH RH (ratio) vs. backfill TH temperature difference
- Drift-wall TH matrix saturation vs. drift-wall TH temperature
- Invert TH liquid saturation vs. lower drift-wall TH temperature
- Drift-wall conduction-only axial temperature variation
- Waste package conduction-only axial temperature variation
- Waste package conduction-only, local temperature difference for backfill cases

Step 3

Interpolate the distribution of average drift-wall temperature. The result of this step is the distribution of average drift-wall temperatures as a function of location in the repository (TRW Environmental Safety Systems, Inc., 1998, pg 3-90).

Step 4

Interpolate the distribution of drift-wall and backfill temperature for each waste package type. In other words, step 4 = the result of step 3 + a result of step 2. Step 4 is calculated for cases with and without backfill.

Step 5

Interpolate the distribution of near-field and in-drift hydrological conditions. The relative humidity at the waste package, the drift-wall matrix saturation, and the invert liquid-phase saturation are calculated by interpolation for each waste package type, as a function of location in the repository (TRW Environmental Safety Systems, Inc., 1998, pg 3-91).

- Relative humidity at the drift wall
- Drift-wall matrix saturation
- Invert liquid-phase saturation

Step 6

Determine the distribution of waste package temperature for each waste package type. This step determines the distribution of waste package temperature as a function of waste package type and location in the repository (TRW Environmental Safety Systems, Inc., 1998, pg 3-93). In other words, Step 6 = the result of step 3 + a result of step 2.

Step 7

Determine the distribution of relative humidity on the waste package for each waste package type. The final step is to determine the distribution of relative humidity on waste packages throughout the repository area for each waste package type where
RH(wp) = RH(dw)[P(sat)(Tdw)/P(sat)(Twp)].

It should be noted that liquid water at the waste package is not determined in this analysis.

Constructing probability density functions of engineered-barrier system thermal-hydrologic conditions

Predictions from the thermohydrologic multiscale modeling and abstraction method are used by several modeling and analysis groups that support TSPA-VA (TRW Environmental Safety Systems, Inc., 1998, pg 3-94) for example:

- Waste package corrosion
- NFE geochemistry
- Waste-form dissolution
- Transport of radionuclides through the engineered barriers

For waste package analysis, the process of “binning” the waste package environments involves several steps.

Step (1): The repository area is subdivided into six major subdomains. For purposes of drift-seepage modeling, q(inf) is a major factor determining the tendency for water to seep into emplacement drifts.

Step (2): Group the five commercial spent nuclear fuel (CSNF) waste package types into a single CSNF waste package category and group the co-disposal HLW packages with the separate-disposal DOE spent nuclear fuel (SNF) waste packages into a single HLW-package category.

Steps (3)and (4): Involve developing probability density functions of temperature and relative humidity conditions for the CSNF waste package category and for the HLW-package category in each of the six q(inf) subdomains.

The environmental conditions on waste packages are binned according to the time required for the waste package environment to return to a relative humidity of 85 percent and the temperature on the waste package surface at 5000 years. A relative humidity of 85 percent was selected because it is typical of the critical relative humidity for atmospheric corrosion. Once RH > RH(crit), the corrosion rate for the outer corrosion-allowance material on the waste package also depends on temperature at the waste package surface. Because the relative humidity generally exceeds 85 percent within 5000 years (unless an engineered backfill is used), temperature at 5000 years is a good indicator of whether the waste package environment is relatively hot or relatively cool when relative humidity returns to 85 percent (TRW Environmental Safety Systems, Inc., 1998, pg 3-94).

<u>Base case analysis</u>

<u>Mountain-scale results</u>

The air-mass fraction and the gas-flow rates in the repository were generated using the 2D G-ECM mountain-scale, thermohydrologic model. [It is assumed that the DOE means that the air-mass fraction includes CO_2 and O_2.] The air-mass fraction and gas-flow rates were calculated at both the center and the edge of the repository. The gas-flow rate was averaged over all four sides of the repository elements. The air-mass fraction in the repository element will change as different mechanisms either drive air from the drift or permit air to return. Initially, the steam generated by the waste package drives water vapor and air from the repository, resulting in a drop in the air-mass fraction. As the rocks surrounding the element dryout, this water-vapor flux diminishes, allowing air to diffuse back into the repository. As the waste packages cool off, water that had been accumulating above the repository can imbibe into the rocks near the repository. Some of this water can then vaporize as it cools the hot rock. This vaporization results in the air-mass fraction dropping a second time. As the heat output from the waste packages drops to zero, the air-mass fraction around the repository will eventually return to the ambient value of 0.98. The air-mass fractions and the gas-flow rates are used in the near-field geochemistry models (TRW Environmental Safety Systems, Inc., 1998, pg 3-96).

Large-scale, gas-phase recirculation regions do not develop in the unsaturated zone because the vertical permeabilities are larger than the horizontal permeabilities, resulting in flows that are primarily in the vertical direction. The air-mass fraction field can be estimated by assuming that the air-mass fraction is inversely related to the temperature (TRW Environmental Safety Systems, Inc., 1998, pg 3-96). These results show that, for the range of simulations conducted, the air-mass fractions are more sensitive to the location in the repository than to the fracture van Genuchten α values or the variation in present-day infiltration rates that were contained in the base-case property sets (TRW Environmental Safety Systems, Inc., 1998, pg 3-97). The results also show, for the base-case parameter sets used to represent long-term average climate conditions, the air-mass fraction appears to be much more sensitive to the variability in infiltration rate than it is to the variability in fracture van Genuchten α (TRW Environmental Safety Systems, Inc., 1998, pg 3-97). Although it is clear that the infiltration rates seem to have a greater effect on air-mass fraction behavior than to changes in the fracture van Genuchten α, the differences between air-mass fraction time-histories at the center and at the edge of the mountain are still much more important than changes caused by spatial and temporal variations in the infiltration rate (TRW Environmental Safety Systems, Inc., 1998, pg 3-97) or any variation caused by using the different property sets (TRW Environmental Safety Systems, Inc., 1998, pg 3-98).

Drift-scale results

For regions in the lithophysal zones, in particular at low infiltration rates, the initial increase in temperature is more rapid than at other locations (TRW Environmental Safety Systems, Inc., 1998, pg 3-98). Edge response is not a factor at early times; however, during cooldown, preferential cooling for subregions close to the repository edge becomes increasingly noticeable with time (TRW Environmental Safety Systems, Inc., 1998, pg 3-99). Some of the hotter waste packages maintain boiling temperatures for 1000 to approximately 4000 years. Other waste packages proceed below the nominal boiling point in the first 100 to 1000 years after emplacement. The fact that the temperature predictions do not significantly flatten at the nominal boiling is a result of the DKM used in the thermohydrologic multiscale modeling and abstraction method. Model predictions using the thermohydrologic property set result in higher temperatures (and hence lower relative humidities) for approximately 10,000 years after waste emplacement (TRW Environmental Safety Systems, Inc., 1998, pg 3-100). These waste package temperature and relative humidity response curves are input into waste package corrosion models, such as WAPDEG, to predict the overall lifetime of a waste package in a repository drift. With the specification of a threshold temperature, a relative humidity threshold for humid-air corrosion, a relative humidity threshold for aqueous corrosion, and information related to dripping rate and fraction contracted, the corrosion processes related to humid air general corrosion, aqueous general corrosion, and aqueous corrosion can be quantified to describe the corrosion rates of the CAM.

The evolution of the thermodynamic environment in the emplacement drift is also applied to the in-drift gas model developed to describe the near-field geochemical environment. The air-mass fraction and the gas-flow rate evolutions are applied to the near-field gas composition models. Liquid saturation of the invert material is required to determine the diffusion coefficient used to transport radionuclides from the waste packages through and out of the EBS (TRW Environmental Safety Systems, Inc., 1998, pg 3-104).

For waste packages experiencing dripping at all times, higher temperatures have adverse effects on corrosion. For dry waste packages (no drips) low relative humidity is beneficial with respect to corrosion. For the waste packages experiencing drips at all times, the lower infiltration rate (and hence higher predicted temperatures) produced failed waste packages at earlier times. However, overall, the higher infiltration rate results in more waste packages encountering drips and hence more overall releases (TRW Environmental Safety Systems, Inc., 1998, pg 3-105).

The thermohydrologic property set produces a more extensive dryout zone by reducing the rewetting rates in the host units after cooldown begins. Response of the EBS is a function of waste package temperature as well as of the liquid saturation evolution of the concrete invert (TRW Environmental Safety Systems, Inc., 1998, pg 3-105). The concrete invert rewets from dried conditions extremely rapidly so that a diffusion coefficient based on a matrix saturation of nearly unity is a conservative result (TRW Environmental Safety Systems, Inc., 1998, pg 3-106). As seen in the results presented for the basecase, reduction of relative humidity is limited to about 1000 years or less for most waste packages (TRW Environmental Safety Systems, Inc., 1998, pg 107).

Sensitivity studies and model analysis

To instill greater confidence that the abstraction modeling approach represents the thermohydrologic processes expected to occur at Yucca Mountain, the staff developed independent testing models that included the highest model dimension (three) and fully coupled heat transfer and fluid flow at the scale of the drift. It uses abstracted data from mountain-scale thermohydrologic models to approximate edge effects, includes waste package-to-Waste package variability, and infiltration-rate variability (TRW Environmental Safety Systems, Inc., 1998, pg 3-111). The drift-scale model used for testing purposes is nearly identical to the DDT model, however, it includes the effects of thermohydrologic coupled processes. Good agreement was found when the independent approaches were compared at repository center and edge locations (TRW Environmental Safety Systems, Inc., 1998, pg 3-109).

For an open emplacement drift, the bulk permeability based on emplacement-drift dimensions was given by the cubic law. However, this large-bulk permeability (approximately on the order of square meters) causes numerical difficulties that do not allow the simulations to proceed at an acceptable time step. It was necessary to reduce the bulk permeability of the drift elements in the models. Selection of a bulk permeability in the range of 5×10^{-12} m^2 to 1×10^{-8} m^2 does not alter the results of the near-field temperatures predicted by the drift-scale (TRW Environmental Safety Systems, Inc., 1998, pg 3-114).

In general, the G-ECM approach produces much flatter temperature profiles at the nominal boiling point (approximately 96 $^\circ$C at the local pressure at the repository horizon) for longer periods of time than does the DKM approach of the LDTH model (TRW Environmental Safety Systems, Inc., 1998, pg 3-115).

For the DKM/Weeps property set at the center of the repository, the air-mass fractions vary considerably, depending on the fracture permeability. When the fracture permeability was high, the air-mass fractions never decreased below 10^{-3}. For the DKM/Weeps cases with a minimum fracture permeability and at both one third and three times the present day infiltration rates, the air-mass fraction dropped below 10^{-7} after 25 years and did not rise above 10^{-7} until after 1000 years (TRW Environmental Safety Systems, Inc., 1998, pg 3-118).

<u>Assessment of rock dryout surrounding drifts</u>

If the dryout zones of neighboring drifts merge together, then a complete repository-scale condensation cap may form. Some of the heat displaced water may drain through the fracture system between drifts by gravity. For the remaining water above the drifts, a repository-scale condensation cap can potentially divert large volumes of water to the edges of the repository, preventing water from dripping into the drifts, and keeping lower relative humidities in the drifts. It is noted, however, that this model scenario is based on a G-ECM conceptual flow model. While this flow model allows increased fracture flow at matrix saturations near ambient, condensate drainage through a zone of rock below ambient is governed by capillary pressure equilibrium such that fracture flow is redirected into the matrix. A nonequilibrium flow model between fractures and matrix rock may preclude this behavior and, with this, the development of a repository wide condensate zone above the drifts (TRW Environmental Safety Systems, Inc., 1998, pg 3-125). There is a critical nonconservative omission in this part of the analysis. There is no discussion of penetration of the boiling isotherm by water flow down a fracture leading to dripping into a drift during times when repository and waste package temperatures are predicted to be above boiling. This phenomenon has been theoretically predicted (Phillips, 1996; Pruess, 1997) and experimentally observed (Green and Prikryl, 1998, 1999; Wilder, et al., 1998).

There is a large range in the results for the cases evaluated. Increasing infiltration by a factor of three results in smaller dryout zones which collapse in a shorter period of time (i.e., for some cases, no coalescence is observed, breakthrough of condensation cap is observed in several hundred years, and all dryout gone within 1200 years). This assessment draws into question the statement on pg 3-84 of the TBD that liquid water contacting waste packages during the first 5000 years can be ignored.

Adjusting the modeled fracture permeability to bound the predicted response of the near-field environment shows the relatively low sensitivity of the system to that parameter. The dominant parameter controlling the extent of tuff dryout was the infiltration rate. The base-case analysis shows that a repository-scale, condensation cap is unlikely to form. The predicted formation of a substantial dryout zone should reduce the likelihood of drips into the drift for 1800 to 5000 years, depending on the proximity of the emplacement section to the edge of the repository. The conservative assumption of increasing the infiltration to the LTA reduces the predicted no drip period to a range of 1400 to 1800 years, again depending on the relative location to the edge of the repository (TRW Environmental Safety Systems, Inc., 1998, pg 3-129). These results again raise doubts regarding the assumption of no dripping into the drift during the first 5000 years after emplacement.

Effects of backfill

Note that in most cases, the average repository subregion relative humidity is maintained below 85 percent for approximately 3000 years or more. For the quartz sand, the relative humidity remains below 85 percent for 10,000 to 20,000 years. When compared to the reference repository design of no-backfill, this is a significant improvement while providing for much drier waste package surroundings (TRW Environmental Safety Systems, Inc., 1998, pg 3-131).

Comparison of drift segments

This sensitivity study is performed with the performance assessment (testing) drift-scale models; it is not a result of the thermohydrologic multiscale modeling and abstraction method (TRW Environmental Safety Systems, Inc., 1998, pg 3-139). The effect of variability in heat load is evaluated. Consequently, hot and cold drifts are predicted. After 1000 years, all waste packages in the cold drift segment have a relative humidity greater than 98 percent (TRW Environmental Safety Systems, Inc., 1998, pg 3-140). Again, there is a concern raised regarding the statement that water contacting the waste packages during the first 5000 years can be ignored (TRW Environmental Safety Systems, Inc., 1998, pg 3-84). It is recommended by the DOE that in future analyses, in particular for the license application, the drift segment study be performed using the thermohydrologic multiscale modeling and abstraction method that implements a DKM flow model (TRW Environmental Safety Systems, Inc., 1998, pg 3-141).

Nonisothermal seepage into drifts

According to Chapter 5 of the TSPA-VA TBD, less than 1 percent of the total waste packages will fail by a corrosion mechanism 10,000 years after waste emplacement. Consequently, perturbations in the unsaturated zone flow fields during the first 5000 years after waste emplacement in Yucca Mountain were assumed to be negligible. It should be noted that juvenile failures (presumably occurring in the first 100 years or so) were assumed to be small in number. The unsaturated zone flow fields used did not include any permanent alteration due to coupled THCM effects (TRW Environmental Safety Systems, Inc., 1998, pg 3-84).

One assumption in the seepage study was that the effects of temperature could be neglected. The DOE presented results of a simple abstraction to include thermohydrologic effects in the seepage calculation. This method could be used in future TSPAs if it were found necessary to include nonisothermal seepage effects. Two important caveats are (i) this method should be tested against more rigorous process modeling and (ii) only transient thermohydrologic effects are included; drift collapse caused by thermal stresses and permanent alteration of hydrological properties by THM or THC processes are not considered (TRW Environmental Safety Systems, Inc., 1998, pg 3-142).

In detailed drift-scale thermohydrologic calculations it was noted that no seepage occurred when the drift-wall temperature was above boiling. The DOE assumes for this sensitivity analysis that this effect is generally true, so no seepage is allowed into the drift when the drift is above boiling (TRW Environmental Safety Systems, Inc., 1998, pg 3-142). This critical caveat has not been satisfactorily demonstrated. Theoretical predictions (Phillips, 1996; Pruess, 1997) and experimental evidence (Green and Prikryl, 1998, 1999; Wilder, et al., 1998) suggest this assumption is not conservative.

Two quantities in the seepage abstraction are calculated as functions of the fracture percolation flux. The two quantities are seepage fraction, which is the fraction of waste packages contacted by water seeping into drifts and seep flow rate, which is the rate of flow of water dripping onto one of the waste packages that has seepage. To apply the seepage abstraction to a thermohydrologic calculation, the DOE uses results from the G-ECM model with mean infiltration and nominal fracture van Genuchten α, for the repository-center locations. The seepage is also reduced to zero when the drift-wall temperature is above boiling. The results show a pulse of enhanced seepage as a result of condensate drainage for a few thousand years. Also, a brief early pulse of condensate seepage right after emplacement is not shown in the figures because it occurs before 10 years (TRW Environmental Safety Systems, Inc., 1998, pg 3-143).

Thermohydrologic results of rockfall

The rockfall sensitivity study was performed using the 3D, drift-scale, thermohydrologic model which was designated as a testing model. The results of this study are not carried to dose-rate calculations. In the current study, the influence of convective heat transfer in the rubble zone showed little variation for the selected values of bulk permeability (TRW Environmental Safety Systems, Inc., 1998, pg 3-147).

It should be noted that the effect of rockfall on dripping was not considered in the TSPA-VA. Rockfall will alter both the hydraulic and thermal properties of the environment immediately next to the waste package in addition to changing the geometry of the drift ceiling asperities and the distance from the waste package to the altered ceiling.

Thermo-hydrological chemical and thermal-hydrological model coupled processes

Alterations in fracture properties (fracture porosity, bulk fracture permeability, and fracture van Genuchten α) predicted by a thermal mechanical (TM) code were coupled with thermohydrologic simulations for 700 years of simulation. While the overall temperature distributions were similar between the altered and unaltered simulations, the temperatures in the altered simulation were slightly higher near the repository and more symmetric above and below the repository, indicating reduced convection in the compressed zones (TRW Environmental Safety Systems, Inc., 1998, pg 3-156).

The DOE work on THC coupled processes focused on a fracture system in the unsaturated zone containing silica (TRW Environmental Safety Systems, Inc., 1998, pg 3-156). The waste package response curves, (such as temperature and relative humidity) are different for each case considered; however, the differences are not large enough to cause an appreciable response from the waste package corrosion models used to compute the degradation of the canister. Based on this result, THC effects are neglected for the base-case thermohydrologic calculations in support of TSPA-VA. Further study is required including consideration of different mineral types (TRW Environmental Safety Systems, Inc., 1998, pg 3-158). In addition, the influence of the precipitation cap on seepage into the drift requires further study. A precipitation cap can affect performance if the cap impedes or enhances seepage flow into emplacement drifts. This topic is one for further study leading into the license application (TRW Environmental Safety Systems, Inc., 1998, pg 3-158).

The expert elicitation panel for the DOE considers that for purposes of THC and THM processes, the change in fracture permeability in the vertical direction, depending on spatial location, can be 100 times less or 1000 times greater than its initial value. Fracture permeability in the horizontal direction may increase by as much as ~10 times. Based on the results of the elicitation, the potential for thermally driven alteration of fracture properties (e.g., permeability) falls within the range of natural variability of the natural heterogeneity of the system (TRW Environmental Safety Systems, Inc., 1998, pg 3-2). Based on this factor, the panel feels that thermally driven alteration of fracture properties falls within the natural bounds of variation.

Summary of sensitivity studies for thermal-hydrology

If rockfall occurs soon after waste emplacement, the increase in relative humidity in the rockfall zone surrounding the waste package may be very detrimental to performance of the waste package (TRW Environmental Safety Systems, Inc., 1998, pg 3-159). A sensitivity study using a thermohydrologic model to investigate the effects on an open drift indicated a substantial deviation from the basecase (i.e., an emplacement drift with a continual source of air during the heat decay process). This scenario is not unlike a ventilated repository. Air-mass fraction and gas-flow rate are quite sensitive to this feature. Drift-scale calculations did not consider this feature, so it is unclear how the waste packages would respond to such a process (open drifts with a continual source of air) (TRW Environmental Safety Systems, Inc., 1998, pg 3-160).

Summary and conclusions

Temperature and relative humidity vary appreciably for different design options, but not for different property sets for a given design. The appropriate characterization of thermal reflux is strongly dependent on conceptual flow model (TRW Environmental Safety Systems, Inc., 1998, pg 3-161).

The DST underway at the ESF will be the primary source of new information for improving the thermohydrologic models. The results of the heating period of this large-scale test will be available in time for the TSPA for the license application. This test is to provide information of drift-scale movement of heat through rock at Yucca Mountain and its impact on the flow system above and below an emplacement-sized drift. It is to include a detailed investigation of the heating period and movement of heat-driven water as well as the cooling period and subsequent rewetting analogous to the processes that would occur in the repository. Indirect measurements to detect water flow into the drift during heating are to provide crucial information related to thermal refluxing processes driven by large-scale heat-transfer processes. The data obtained from the DST will:

- Allow important verification of the conceptual flow models currently being used (or show the degree to which the current models are not adequate)
- Provide information on the effective hydrological properties during the various stages of heating and cooling
- Provide information of the spatial and temporal extent of mechanical and chemical changes to the fracture-flow system surrounding the heated drift.

Smaller scale tests include the already completed SHT at the ESF or any other future single- or multiple-element heater tests that may be planned for the East-West cross drift. The DOE indicates that more small-scale heater tests are to be conducted in repository specific units.

Early results from the single heater test (SHT) indicated that the DKM is most appropriate in governing heat transfer and fluid-flow processes and subsequent temperature field predictions (TRW Environmental Safety Systems, Inc., 1998 pg 3-162). Final analysis of the SHT confirmed that a DKM conceptualization provides better simulation of thermohydrologic processes than does an equivalent continuum model (ECM) conceptualization, however, the ECM appears to provide adequate representation if temperature only is used as the criterion to judge the appropriateness of a model (Tsang, et al., 1999). Similarly, preliminary analyses of the Drift-Scale Test (DST) suggested that a DKM conceptualization provides the most appropriate representation of both temperature and saturation distributions, but that an ECM conceptualization provides adequate representation of temperature-only observations (Civilian Radioactive Waste Management System, Management and Operating Contractor, 1998a) (note, this is the first DST progress report). An ECM-based model requires significantly less computational effort to solve than does a DKM-based model, however, the ECM-based models cannot effectively resolve changes in saturation distributions driven by a heat source.

The use of natural analogs for at least THC purposes is recognized by the DOE. Comparisons to natural analogs (the Papoose Lake Sill) also seem to indicate that the heating of fluids containing minerals may cause depositions of minerals that can alter the flow through the fracture system surrounding the heat source (TRW Environmental Safety Systems, Inc., 1998, pg 3-164).

Based on descriptions provided in the TBD, the DOE multiscale thermohydrologic model appears to be an acceptable systematic analysis of TEF at the proposed Yucca Mountain repository. Insufficient detail is included in the TBD to fully understand the complete TEF abstraction process, however, based on the TEF IRSR analysis, there are components to the multiscale thermohydrologic model that require modification or enhancement. The more important of these modifications or enhancements include:

- The inclusion of sufficient heterogeneity in media representation in models to avoid masking or omitting performance affecting heat and mass transfer mechanisms such as seepage and focused flow.

- The inclusion of thermohydrologic processes on seepage for the entire repository performance period. Thermohydrologic driven flow cannot be neglected for the initial 5,000 yrs after waste emplacement.

- The inclusion of penetration of the boiling isotherm by flow down a fracture. The assumption that water will not contact the waste package until the waste package temperature decreases below boiling is not conservative.

3.3.7.3 Technical Basis Document—Chapter 5: Waste Package Degradation Modeling and Abstraction

The principal factor leading to waste package degradation at the proposed geologic repository is corrosion. Corrosion rates in the absence of water (i.e., dry-air corrosion) can be considered insignificant. Appreciable corrosion requires the presence of water as either liquid or vapor. Liquid-phase water exposure to a waste package would most likely occur through dripping, and water vapor exposure would occur when the relative humidity is sufficiently high. If water is in the repository environment, then the quantity and chemistry of the water contacting the waste package and the temperature of the environment will determine the rate of corrosion. The chemistry is succinctly included in terms of pH (for aqueous corrosion only, TRW Environmental Safety Systems, Inc., 1998, pg 5-27) and chloride content. Factors not included in the DOE conceptual model that could potentially affect the rate of corrosion include corrosion accelerated by microbial activity and the exposure of the waste package to wet/dry cycles.

In the presence of water, the waste package surface undergoes either humid-air or aqueous corrosion. Although the specific values for relative humidity are adjustable, humid-air corrosion is expected at a relative humidity greater than about 70 but less than about 85 percent. Aqueous corrosion occurs at relative humidity greater than about 85 percent. Dripping is included only in terms of its effect on relative humidity, that is, aqueous corrosion is assumed active when relative humidity is in excess of 85 percent, irrespective of the presence or absence of liquid water by dripping or any other mechanism. The DOE considers the possibility that dripping can occur when relative humidity is low (i.e., less than 85 percent). This possibility recognizes those instances in which the waste package surface would experience humid-air corrosion even in the presence of dripping until the relative humidity is increased and aqueous corrosion is experienced. The DOE approach implies that the chemistry of dripping water is neglected if the dripping occurs for a humid-air corrosion regime (i.e., less than 85 percent relative humidity).

The DOE conceptual model does not account for dripping that may occur when the drift temperature is above boiling. However, water could enter the drift at high temperatures when the boiling isotherm is penetrated by rapid flow down fractures. Under this scenario, water refluxing toward the drift would be concentrated as water is evaporated. Therefore, any water that reaches the drift wall and drips into the drift and onto a waste package would be highly concentrated. Drips with very high mineral concentration were observed in laboratory-scale heater tests (Green and Prikryl, 1998, 1999). The highly concentrated sludge-like substance that dripped into the drift in these experiments behaved more like mud than water. Thereafter, even though the dripping water would potentially evaporate soon after falling on the waste package, the potentially corrosive salts from the drips would remain on the waste package surface after the water was removed. Neglecting the potential for dripping onto waste packages when drift-air temperatures exceed boiling and high mineral concentrations in drips when relative humidity is less than the threshold for aqueous corrosion is not a conservative assumption. The DOE acknowledges that salt deposition on a waste package surface could lead to higher rates of corrosion (TRW Environmental Safety Systems, Inc., 1998, pg 5-27); however, this mechanism is not included in the DOE conceptual model. The DOE claims its model is conservative because the corrosion factors exceed those from 1-year long tests of carbon steel by a factor of five to ten.

The two principal modes of corrosion include localized (pitting and crevice) corrosion and general corrosion. The particular susceptibility, in terms of corrosion mode of each potential waste package container material, is dependent on the environmental factors and the specific properties of the material. For example, in an aqueous corrosion environment, pitting corrosion of CAM (i.e., carbon steel) will be experienced when the dripping water has a pH greater than 10, whereas general corrosion can be expected for a pH less than 10. This observation highlights the importance of ascertaining the chemistry of water interacting with waste package surfaces. It also draws attention to the assumption that the chemistry of water is not included in dripping that occurs in a humid-air corrosion environment. In addition, neither an elevated pH (i.e., greater than 10) nor the presence of chloride ions is considered in the TSPA-VA basecase.

Corrosion of the CAM was separately assessed for humid-air and aqueous corrosion. The DOE states its conceptual model embeds all effects that may form on the surface of the corroding specimen from cyclic wetting and drying (TRW Environmental Safety Systems, Inc., 1998, pg 5-29). All data from marine environments containing chloride-induced corrosion were omitted. The DOE claims that the marine environments are much more corrosive than humid-air conditions expected in the potential environment.

Laboratory-scale heater experiments (Green and Prikryl, 1998, 1999) demonstrated that water with concentrated, dissolved chemical species can accumulate above a heat source and may contact the heat source with potentially corrosive consequences. The conceptual model formulated to explain the accumulation of highly concentrated liquid above a heat source placed in a geologic setting is the process of evaporation and condensation of water. Liquid that flows down a fracture evaporates as the liquid nears the heat source. Water vapor rises by buoyancy until the vapor encounters an environment (i.e., rock surface) sufficiently cool to condense. Continuous evaporation and condensation in the fracture results in higher concentrations of dissolved species in the liquid. In fact, mineral concentrations in the liquid can become sufficiently high that the liquid becomes sludge-like in consistency if sufficient water is boiled off. Sludge-like liquid is expected when the liquid is sampled near the point of maximum penetration of the fracture water beyond the boiling isotherm. The appearance of the depositional material in the laboratory-scale heater tests is interpreted to indicate that the liquid dripping into the heater drift was close to the maximum extent of penetration beyond the boiling isotherm and that the liquid was therefore highly concentrated and sludge-like because most of the water had been boiled off.

It should not be interpreted from this conceptual model that all water sampled from above the heat source would exhibit elevated mineral concentrations. Only water sampled from locations where water has penetrated beyond the boiling isotherm is likely to exhibit concentrations elevated relative to ambient water. The location of concentrated water relative to the heat source will be transient, consistent with the fact that the location of the boiling isotherm will vary with time.

Evidence supporting the assertion that this conceptual model could be valid for a HLW repository is found in results of the DST. Water sampled from hydrology borehole 59-4 on November 12, 1998 (first DST progress report) and resampled on January 26, 1999 (Civilian Radioactive Waste Management System, Management and Operating Contractor, 1998b) exhibited solute concentrations significantly greater than concentrations of water samples collected from other boreholes. Borehole 59 of the DST is placed above the wing heaters and the heater drift, whereas other water samples with much lower concentrations were collected from boreholes located below the heaters (i.e., boreholes 60, 77, and 186).

An alternative conceptual model to explain heat and mass movement above the heat source would be that the concentration of water in fractures located above the heat source is dilute because water vapor that condenses in the fractures is absent of mineralization. This conceptualization neglects the compounding effects of repetitive vaporization and condensation of water flowing down a fracture toward a heat source and the resulting concentrating effect experienced where water is evaporated. The presence of highly concentrated water from above the heat source at both the laboratory-scale and the DST heater tests raises questions about the validity of this alternative conceptual model.

Aqueous corrosion of the CAM also omitted using data collected from a marine environment (TRW Environmental Safety Systems, Inc., 1998, pg 5-41). In addition, pit stifling, which is potentially important in 10-cm thick CAM (TRW Environmental Safety Systems, Inc., 1998, pg 5-42), may not be important in thinner materials.

The Waste Package Degradation Expert Elicitation (WDPEE) panel estimated general corrosion rates of the CRM (C-22) in the absence of experimental results. The WAPDEG submodel does not consider localized corrosion of the inner CRM, even in the presence of dripping, unless the temperature is in the 80 °C to boiling temperature window (TRW Environmental Safety Systems, Inc., 1998, pg 5-59, pg 5-93). Boiling may exceed 100 °C due to water impurities. Simply stated, both dripping and a temperature between 80 °C and boiling are required for localized corrosion of the inner barrier CRM to occur. This restriction raises a critical concern. Numerical models used to predict temperature are predicated on relatively coarse spatial discretization of the drift environment. Localized variances in temperature may not be accurately predicted by the numerical models. This temperature smoothing could overlook small areas in which localized temperatures are within the window of corrosion. These small areas can be of critical importance because localized depressions in temperature could result from focused refluxing and dripping during the heating period. Although it is recognized that numerical models cannot include sufficient detail to represent all heterogeneity in a medium, allowances must be made in analyses to include the potentially consequences of focused dripping on corrosion rates and occurrences.

In the absence of dripping, the CRM undergoes only generalized corrosion (TRW Environmental Safety Systems, Inc., 1998, pg 5-43). The general corrosion rate for C-22 (the current CRM candidate material) in humid-air conditions is reported to be extremely slow; therefore, general corrosion of C-22 in a humid-air environment is essentially neglected (TRW Environmental Safety Systems, Inc., 1998, pg 5-43). There is no consideration of aqueous corrosion of C-22 in the absence of drips. From this lack of consideration it is inferred that the conceptual model of the DOE considers only aqueous conditions in the presence of drips.

The DOE states that salts deposited on waste packages during earlier hot and dry conditions would be washed away under sustained dripping conditions. The assumption was cited in the TSPA-VA analysis because of a lack of information on the evolution of the local chemistry on the waste package (TRW Environmental Safety Systems, Inc., 1998, pg 5-50). Although this conceptualization is reported to be conservative, a more supportable conservative assumption would be that predeposited salts do not get flushed and that dripping water under post-heating conditions is neither absent of nor depleted in mineralization. Even if the post-heating period dripping is with a less mineralized water, the dripping process may remove corrosion products, thereby exposing uncorroded material to conditions such as increases oxygen levels more prone to corrosion.

3.4 U.S. NUCLEAR REGULATORY COMMISSION/CENTER FOR NUCLEAR WASTE REGULATORY ANALYSES SENSITIVITY ANALYSES

Quantitative analyses were conducted to determine which physical properties and abstraction model input values have the greatest effect on the estimated performance of the proposed Yucca Mountain repository. Input factors used in the reflux submodules were selected for analysis. Thermohydrological process-level models at high, medium, and low infiltration were also evaluated.

The overall performance of the Yucca Mountain repository was evaluated by estimating total release and peak dose using TPA Version 3.1.1. Peak dose and total release were estimated to evaluate the sensitivity of dose to two reflux submodules after 20,000 years at a hypothesized 5 km critical group location and after 100,000 years at another hypothesized 20 km critical group location. TPA Version 3.1.1 includes two modules, REFLUX1 and REFLUX2, that abstract the refluxing mechanism using two alternative conceptual models. The importance of two input factors in the REFLUX1 submodule and the four input factors in the REFLUX2 submodule were evaluated during sensitivity analyses of the refluxing submodules. Peak dose and total release were also estimated to evaluate the sensitivity to the MULTIFLO Version 1.0 process-level model after 10,000 years at the hypothesized 5 km critical group location. Additionally, the amounts of water contacting the waste packages were calculated for a range of values assigned to the reflux parameters. The effect of infiltration was evaluated during sensitivity analyses of the process-level model.

3.4.1 Submodule Descriptions

REFLUX1 submodule

The REFLUX1 submodule provides an estimate for time-dependent water flux available for dripping onto the waste package. The REFLUX1 submodule is an option in the NFENV module of TPA Version 3.1.1.

NFENV uses time-dependent temperature profiles generated by either an internal to TPA conduction-only heat transfer model or an external process-level model. NFENV also uses values of time-dependent water flux (q_{infil}) taken from data input into REFLUX1 to calculate time-dependent water flux (q_{drip}) dripping onto a waste package. In the development of q_{drip}, NFENV considers: (i) the time-dependent amount of perching due to thermal pulsing; (ii) time-dependent refluxing of liquid and vapor; and (iii) drift-scale variability of hydraulic properties and fluxes.

The thermohydrologic conceptual model implemented in NFENV assumes that the flow system consists of matrix and fracture flow continua. It is assumed that refluxing water exists in fractures in the rock mass at a temperature above the boiling point T_{boil} isotherm. The thickness of the boiling zone with water in the fractures is dependent on q_{infil}. Below the T_{boil} isotherm is a reflux zone with thickness L_{reflux}. Above the T_{boil} isotherm, liquid is supplied to the fractures at a rate proportional to the thickness of the condensate zone layer. In the reflux zone, liquid from the condensate zone flows down through fractures and is vaporized (because $T > T_{boil}$). The vapor rises to the top of the boiling zone and condenses back to liquid in the condensate zone. The thickness of the reflux zone is dependent on q_{infil} and the local heat flux, that is, the temperature gradient. When the value of L_{reflux}, subtracted from the elevation of the T_{boil} isotherm, Z_{boil}, is below the elevation of the top of the drift, water begins to drip into the drift. Any liquid passing below the level of the repository is assumed to continue to the water table, and the thickness of the condensate zone decreases accordingly.

The near-field thermal response in REFLUX1 to the heat pulse is assumed to be dominated by conductive heat transfer and the near-field hydrology response is dominated by temperature distribution. It is also assumed that the near-field moisture distribution reaches equilibrium rapidly relative to changes in the temperature field.

The REFLUX1 submodule requires the following specific input:

- Thickness of the reflux zone above the repository horizon

- Maximum flux in the reflux zone

- Perched bucket volume in the subarea (the perched bucket volume is a hypothetical volume of water that must be exceeded for refluxing to occur)

The REFLUX1 submodule reports a time history of the quantity of water that leaves the reflux cycle and enters the repository horizon. The amount of water that interacts with a waste package is extracted from the time history of the reflux water and the flux of water from infiltration using three parameters: flow convergence/divergence factor, flow multiplication factor, and subarea wet fraction, that are specified input values in the EBSREL module.

REFLUX2 submodule

The second refluxing conceptual model included in TPA Version 3.1.1 considers the possibility that water can reflux through the boiling isotherm to the waste package. Conceptually, it is envisioned in REFLUX2 that the quantity of refluxing water can be sufficient to depress the boiling isotherm in fractures and reach the waste package during times the temperature of the waste package exceeds boiling. The mechanism on which REFLUX2 is predicated is the formation of a reflux cycle where water is vaporized by heat generated at the waste packages, the vapor flows away from the boiling zone, and then condenses where temperatures are below boiling. The condensate may then flow back to the boiling zone. This return of condensate to the boiling zone is called refluxing. A particular unit of water may participate in the reflux cycle many times. With every cycle, some portion of the refluxing water may escape and flow away from the heat source, possibly toward the water table. The refluxing cycle can gain water from two sources: (i) infiltration from ground surface; and (ii) water vaporized from the dry-out zone in rock surrounding the waste package. Water will continue to vaporize as long as temperatures remain above boiling and water is available for vaporization.

With the exception of the thickness of the dry-out zone, all input values into the REFLUX2 submodule are currently estimated by the NRC/Center for Nuclear Waste Regulatory Analyses (CNWRA) staff. These estimates will be refined using process-level model results. The thickness of the dry-out zone is estimated using results from process-level thermohydrologic numerical simulations. Inherent in the value assigned to the dry-out zone thickness are all the assumptions contained in the MULTIFLO Version 1.0 process-level model (i.e., the model medium is represented as an equivalent continuum, a constant infiltration rate of 1.0 mm/yr is specified, and material property values are taken from TSPA–93 and TSPA–95).

The REFLUX2 submodule requires the following specific input:

- Thickness of the dry-out zone
- Porosity of rock in the dry-out zone
- Initial water saturation in the dry-out zone
- Time period of the reflux cycle
- Fraction of infiltration-derived water that escapes each reflux cycle
- Fraction of dry-out derived water that escapes each reflux cycle

The REFLUX2 submodule reports a time history of the quantity of water that leaves the reflux cycle and enters the repository horizon. The amount of water that interacts with a waste package is extracted from the time history of the reflux water using three factors: (i) flow convergence/divergence; (ii) flow multiplication; and; (iii) the subarea wet fraction, which are specified input values in the EBSREL module.

Process-level model description

To model heat and mass transfer through bulk porous media, process-level analyses are being conducted in the TEF KTI using MULTIFLO, a multiphase, multidimensional, nonisothermal heat and mass transfer simulator (Lichtner and Seth, 1997, 1998).

A drift-scale model of heat and mass transfer was formulated to provide temperature, saturation, and relative humidity predictions at the canister surface for use in TPA Version 3.1.1. The model extended from land surface to the water table, a depth of 684 m (23 grid elements). Six hydrostratigraphic units were represented in the model as uniform layers. The model extended from the center of the drift (and waste package) to the mid-pillar point between drifts, a distance of 11 m (8 grid elements). The depth of the model from the mid-point of the waste package to the mid-point between waste packages is 9 m (6 grid elements). An assumption of two planes of symmetry required only one-half of the drift and one-quarter of the waste package to be modeled. The modeled half of the drift was 2.215 m wide and 4.43 m tall. Likewise, the modeled half of the waste package was 0.8 m wide and 1.6 m tall. The half-length of the waste package was 3.0 m and the in-drift half-distance between packages was 6.0 m.

Rates of 1.0, 5.5, and 10.0 mm/yr have been specified as constant, uniform infiltration sources at land surface. The base of the model was specified as the water table at full saturation. The vertical boundaries were no-flow. The initial heat load specified in the model was 83 metric tons per unit (MTU)/acre. Initial saturations and capillary pressures were generated by simulating flow until steady-state was approximated. Postwaste emplacement simulations were performed for 10,000 years. Property values assigned to the process-level model were taken from TSPA–93 (Wilson, et al., 1994) and TSPA–95 (TRW Environmental Safety Systems, Inc., 1995).

Initial MULTIFLO Version 1.0 process-level model runs were not successful due to numerical difficulties, when the complete TPA basecase property set was used. Therefore, several of the assigned property values used in these analyses differed from values contained in the TPA basecase property set. Process-level model runs at infiltration rates of 1.0, 5.5, and 10.0 mm/yr were only successful when several property values from TSPA–93 and TSPA–95 were used. Table 1 contains a listing of property values taken from TSPA–93 and TSPA–95, which differs from the TPA Version 3.1.1 basecase. Identification of which property values from the TPA basecase cause the modeling difficulties has not been completed. Subsequent model runs using the thermal-hydrological data set (TRW Environmental Safety Systems, Inc., 1998—Viability Assessment) and MULTIFLO Version 1.2 (Lichtner, et al., 2000) for the design specifications of EDA II with a thermal loading of 60 MTU/acre have not encountered numerical difficulties. Results from these analyses are being evaluated.

Temperature and relative humidity at the waste package surface are reported in tabular form from the process-level model. These data are taken as input into EBSFAIL. Temperature, relative humidity, and liquid water flux are provided as tabular input to EBSREL.

Table 1. Comparison of basecase parameter values from Total Performance Assessment Version 3.1.1 and Total System Performance Assessment–1993/Total System Performance Assessment–1995

Parameter TSw	TSPA–93/95*	TPA 3.1.1
van Genuchten λ–Matrix	0.444	0.333
van Genuchten λ–Fracture	0.7636	0.667
Matrix Porosity	0.139	0.12
Fracture Porosity	0.0018	0.001
Matrix Permeability (m^2)	2.131×10^{-18}	2.0×10^{-19}
Fracture Permeability (m^2)	3.9×10^{-12}	8.0×10^{-13}
CHnv		
van Genuchten	0.593	0.231
van Genuchten	0.7636	0.667
Matrix Porosity	0.331	0.33
Fracture Porosity	0.0018	0.001
Matrix Permeability (m^2)	1.118×10^{-16}	2.0×10^{-14}
Fracture Permeability (m^2)	3.9×10^{-13}	8.0×10^{-13}
CHnz		
van Genuchten λ–Matrix	0.414	0.565
van Genuchten λ–Fracture	0.7636	0.667
Matrix Porosity	0.306	0.32
Fracture Porosity	0.0018	0.001
Matrix Permeability (m^2)	1.617×10^{-18}	5.0×10^{-18}
Fracture Permeability (m^2)	3.9×10^{-12}	6.0×10^{-13}
* Used in sensitivity analysis		

3.4.2 Sensitivity Analyses Results

TPA Version 3.1.1 contains two reflux submodules: REFLUX1 and REFLUX2. Two simulations were performed for each submodule. Each simulation consisted of 100 realizations. In each realization the effects of changes in reflux parameters on predicted performance of the repository (as measured by peak dose and total release of radionuclides to groundwater) were estimated. The first simulation estimated the effects at the assumed 5 km critical group location, 20,000 years after emplacement of the wastes. The second simulation estimated the effects at the assumed 20 km critical group location, 100,000 years after emplacement.

For each realization, all parameters, except the reflux parameters and the three UZFLOW module parameters (mean annual infiltration at start, mean-average-precipitation multiplier at glacial maximum, and mean-average-temperature increase at glacial maximum), were held constant. In the REFLUX1 submodule, the thickness of the reflux zone and the perched bucket volume were allowed to vary. In the REFLUX2 submodule, the thickness of the dry-out zone, reflux cycle period, fraction of infiltration-derived water that escapes, and fraction of dry-out zone derived water that escapes were varied. In all cases, the sensitivity of repository performance to each parameter was estimated using linear regression analysis. The results were dominated by the three UZFLOW parameters. None of the reflux parameters in either submodule had a significant effect on predicted performance of the repository.

The effects of individual reflux parameters on the amount of water contacting the wastes were also simulated. Each simulation consisted of 100 realizations, and all parameters, except the one being evaluated, were held constant.

<u>REFLUX1 submodule</u>

Two REFLUX1 parameters were varied: length of the reflux zone and the perched bucket volume per subarea. As shown in Table 2, neither of the parameters had a significant effect on predicted repository performance. All correlation coefficients were zero.

Also, varying the values assigned to the REFLUX1 parameters had no effect on the amount of water contacting the waste packages (Table 3).

<u>REFLUX2 submodule</u>

Four REFLUX2 parameters were varied: (i) thickness of the dry-out zone; (ii) reflux cycle period; (iii) fraction of infiltration-derived water that escapes the reflux cycle each year; and (iv) fraction of dry-out derived water that escapes the reflux cycle each year. As shown in Table 4, none of these parameters had a significant effect on predicted repository performance. The largest correlation coefficient was 0.1.

Varying the values assigned to the REFLUX2 parameters affected the amount of water contacting the waste packages (Table 5).

Process-level model

Three MULTIFLO process-level simulations were performed at varying infiltration rates: (i) 1.0 mm/yr; (ii) 5.5 mm/yr; and (iii) 10.0 mm/yr. The look-up tables of time-variant temperature and relative humidity data produced by these simulations were used in TPA Version 3.1.1 to evaluate the effects of temperature and relative humidity on predicted repository performance. The highest temperatures were predicted for the lower infiltration rates and the highest relative humidities for the higher infiltration rates.

All the MULTIFLO process-level and TPA Version 3.1.1 simulations were run for 10,000 years. Only one TPA 3.1.1 realization was performed for each data set of temperature and relative humidity. The performance measures examined were peak total dose of radionuclides in groundwater at the assumed 5 km critical group location, time of first waste package failure due to corrosion, and number of waste package failures due to corrosion (Table 6).

3.4.3 Sensitivity Analyses Conclusions

Peak dose and total dose predictions made using TPA Version 3.1.1 proved to be insensitive to either of the refluxing submodules. Identifying the source of this insensitivity is of significant interest to the process of accurately assessing the performance of the repository. It is critical to examine if the TPA Version 3.1.1 captures all significant heat and mass transfer mechanisms that could impact the performance of the repository. Water refluxing onto canisters can potentially affect repository performance in two ways: degrading the integrity of the waste package and altering the transport of radionuclides once released from the waste package. The integrity of the waste package is addressed in the EBSFAIL module of TPA Version 3.1.1. Similarly, the transport of radionuclides subsequent to canister failure is represented in the EBSREL module. The integrity of waste packages, as modeled in TPA Version 3.1.1, is not affected by the presence of liquid water at the waste package surface, other than as an indication that aqueous corrosion conditions prevail for a relative humidity exceeding 75 percent. EBSFAIL (TPA Version 3.1.1) does not include the effect of episodic refluxing water and associated changes in chemical environment. EBSREL accounts for liquid water reflux in the calculation of radionuclide release from waste packages. TPA Version 3.1.1 sensitivity analyses, however, indicate no significant effect is realized from refluxing water interacting with the waste packages. This is explained, at least in part, by the potentially large volume of pore water mobilized during heating that would have already been transported away from the repository prior to waste package failure. If the lack of sensitivity of repository performance to refluxing can be confirmed, then models of TEF can be greatly simplified. In the future, EBSFAIL should be modified to account for corrosion rates accelerated by the effect of continuous or episodic wetting by liquid water and sensitivity analysis repeated to determine the importance of refluxing to repository performance.

Table 2. Sensitivity of predicted repository performance to REFLUX1 parameters

Parameter	5 km, 20,000 Years		20 km, 100,000 Years	
	Correlation Coefficient (r^2), Peak Dose	Correlation Coefficient (r^2), Total Release (EPA sum)	Correlation Coefficient (r^2), Peak Dose	Correlation Coefficient (r^2), Total Release (EPA sum)
Thickness of Reflux Zone (range = 10 m–200 m)	0.0	0.0	0.0	0.0
Perched Bucket Volume (range = 0.2–0.8 m^3/m^2)	0.0	0.0	0.0	0.0

Table 3. Effect of REFLUX1 parameters on amount of water contacting waste packages

Parameter	Minimum Amount of Water Contacting WPs (mm/10,000 Years)	Maximum Amount of Water Contacting WPs (mm/10,000 Years)
Thickness of Reflux Zone (range = 10 m–200 m)	2357	2357
Perched Bucket Volume (range = 0.2–0.8 m^3/m^2)	2353	2353

Table 4. Sensitivity of predicted repository performance to REFLUX2 parameters

Parameter	5 km, 20,000 Years		20 km, 100,000 Years	
	Correlation Coefficient (r^2), Peak Dose	Correlation Coefficient (r^2), Total Release ~~(EPA sum)~~	Correlation Coefficient (r^2), Peak Dose	Correlation Coefficient (r^2), Total Release ~~(EPA sum)~~
Thickness of Dry-Out Zone (range = 10–200 m)	0.0	0.0	0.0	0.0
Reflux Cycle Period (range = 1–3000 yr)	0.0	0.0	0.1	0.1
Fraction Infiltration-Derived Water Escaping (range = 0–1)	0.0	0.0	0.0	0.0
Fraction Dry-Out Zone-Derived Water Escaping (0–1)	0.0	0.0	0.0	0.0

Table 5. Effect of REFLUX2 parameters on amount of water contacting waste packages

Parameter	Minimum Amount of Water Contacting Waste Packages (mm/10,000 Years)	Maximum Amount of Water Contacting Waste Packages (mm/10,000 Years)
Thickness of Dry-out Zone (range = 10–200 m)	2403	3328
Reflux Cycle Period (range = 1–3000 yr)	2504	2844
Fraction Infiltration-Derived Water Escaping (range = 0–1)	2807	2842
Fraction Dry-out Zone Derived Water Escaping (range = 0–1)	2602	2844

Table 6. Effect of varying temperature and relative humidity on predicted repository performance

Infiltration Rate (mm/yr)	Peak Total Dose (rem/yr)	Time of Failure (yr)	Number of Failures
1.0	7.555	1487	6395
5.5	8.033	1219	6395
10.0	7.703	1075	6395

4.0 REVIEW METHODS AND ACCEPTANCE CRITERIA

The acceptance criteria and review methods for evaluating the DOE approach to include thermal effects on flow in their TSPA have been deleted from this section with this revision of the TEF IRSR (Revision 3). The detailed acceptance criteria and review methods previously identified in this section are being used to develop the YMRP. In developing the YMRP, the detailed acceptance criteria have undergone modifications. The general acceptance criteria used in Section 5.0 are consistent with and reflect, to the extent practicable, those modifications. The acceptance criteria in future versions of this IRSR will continue to be modified, as needed, to reflect the detailed acceptance criteria as developed in the YMRP.

As discussed in Section 3.0, the DOE needs to consider the thermal effects on flow both within and between key elements of the engineered and natural subsystems of the repository to adequately demonstrate and quantify the thermal effects on flow on repository performance. The review methods and acceptance criteria being developed for the YMRP focus on fourteen model abstractions. These fourteen abstractions are equivalent to the integrated subissues in the TSPAI IRSR (U.S. Nuclear Regulatory Commission, 1998b, 2000a). The integrated subissues are illustrated in Figure A-1 in Appendix A. Thermal effects on flow is a process relevant to four of these fourteen integrated subissues (abstractions). These four integrated subissue include: (i) degradation of engineered barriers, (ii) quantity and chemistry of water contacting waste packages and waste forms, (iii) radionuclide release rates and solubility limits; and (iv) flow paths in the unsaturated zone.

Section 5 provides a systematic approach to reviewing whether the DOE will adequately consider the process of thermal effects on flow (as defined in the two subissues identified in Section 2.0) in the four relevant abstractions within their performance assessment. This approach involves applying seven general criteria to the review. As discussed in Section 2.0, these seven criteria include: (i) identification of FEPs, (ii) screening of FEPs, (iii) model integration, (iv) data and model justification, (v) data uncertainty, (vi) model uncertainty, and (vii) model support. The status of resolution and resolution information needs are addressed for each subissue with respect to these seven general criteria. Because the acceptance criteria applied in Revision 2 of the TEF IRSR have been consolidated into the seven general acceptance criteria applied in Revision 3, a cross-walk between the acceptance criteria (and open items) of Revision 2 and Revision 3 is provided in Table B-1 of Appendix B.

5.0 STATUS OF SUBISSUE RESOLUTION AT THE STAFF LEVEL

We have reviewed and commented on the DOE site characterization and performance assessment programs in areas related to TEF. Reports other than this IRSR where the NRC concerns are documented include:

- *NRC Staff Site Characterization Analysis of DOE's SCP* (U.S. Nuclear Regulatory Commission, 1989)
- *NRC/CNWRA Audit Review of DOE's TSPA-95* (U.S. Nuclear Regulatory Commission, 1996a, 1996b)
- Letter from NRC to DOE with comments from the staff review of the *DOE Thermohydrology Testing and Modeling Program* (U.S. Nuclear Regulatory Commission, 1997)
- NRC staff review of the DOE's TSPA-VA (Secy-99-074) (Travers, 1999)

The NRC comments from these reports are summarized in Sections 5.4-5.7 of this IRSR. There are no open issues remaining with respect to TEF related comments in these past reports.

Table 7 provides a summary of the status of subissue resolution that reflects the NRC comments in this version of the TEF IRSR (Revision 3). 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 have 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 time of initial license application. 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.

Table 7. Status of issue resolution

Subissue	Status of Resolution
Features, events, and processes related to thermal effects on flow	Open
Thermal effects on temperature, humidity, saturation, and flux	Open

Table 8 provides a path to close open subissues. This includes a summary of the information the DOE needs to provide in order to close open subissues. The comments and status of resolution for each subissue reflect staff review of the DOE TSPA-VA. The status also reflects staff review of the RSS Revision 3, the TSPA-SR methods and assumptions, and available PMR's and AMR's. The staff recognizes the preliminary nature of the PMR's and AMR's;

Table 8. Path for Issue Resolution

Subissue	Path for Issue Resolution
Features, events and processes related to thermal effects on flow	To resolve this subissue, the DOE needs to: • Provide the final list of primary and secondary FEPs. • Provide the revised FEP screening analysis for thermohydrologic models. The screening analysis documentation should comprehensively address all primary FEPs. • Give greater visibility to secondary FEPs in the FEP screening documentation. • Provide a summary of the assumptions related to screening arguments for FEPs relevant to thermohydrologic models that need verification and the associated analyses planned to provide that verification. • Provide traceable references to previous analyses used as the technical basis for screening arguments for excluded FEPs.
Thermal effects on temperature, humidity, saturation, and flux	To resolve this subissue, the DOE needs to: • Complete thermohydrologic modeling for the current repository design. • Include the process (FEP) referred to as the "cold trap effect" in the MSTHM process models. Subsequently, provide model support for implementation of the MSTHM "cold trap effect" model by comparison with past observations such as condensation in the ECRB under a thermal gradient imposed by the TBM. • Provide traceable references to MSTHM model input and output to allow review of such aspects as boundary and initial conditions and to confirm the mass balance of model results. • Consider measuring losses of mass and energy through the bulkhead of the DST. • Address (i) the potential for unmonitored mass and energy flow through test boundaries of the CDTT and (ii) the effect of unmonitored mass and energy flow through test boundaries of the CDTT on the usefulness of test results before the test begins. Consider designing and conducting the CDTT so as to avoid unmonitored mass and energy flow through test boundaries. • Provide data support for the ventilation model by completing the ongoing ventilation test. Subsequently, provide model support for the ventilation model by comparisons to the test data. • Evaluate data uncertainty in (i) measurement error, bias, and scale-dependence in the saturation, water potential, and pneumatic pressure data used for model parameter calibration, (ii) heterogeneity and spatial variability in thermohydrologic properties, and (iii) variability in model results using the various property sets found to be valid for thermohydrologic modeling and propagate this uncertainty through the thermohydrologic model abstraction. • Evaluate model uncertainty as seen in results from various alternative conceptual models such as the ECM, DKM, and AFM, and propagate this uncertainty through the thermohydrologic model abstraction. • Provide model support by predicting thermohydrologic results of the CDTT to verify the thermohydrologic model abstraction adequately represents the potential thermohydrologic conditions expected in the proposed repository.

specifically, that they have not been accepted by the DOE. Because the preliminary PMR's and AMR's have not been accepted by the DOE, the staff have not used the information they contain to resolve any open subissues in this IRSR. To aid the issue resolution process, however, the staff may have reviewed and commented on the sufficiency of the information in the preliminary documents to address staff concerns. After receipt and review of the final PMR's or other documents that indicate the DOE acceptance of the information in the preliminary documents, we will consider whether it is appropriate to close any portion or all of the subissues.

5.1 INTEGRATED SUBISSUES (ABSTRACTIONS) AND GENERAL ACCEPTANCE CRITERIA RELEVANT TO THERMAL EFFECTS ON FLOW

Thermal effects on flow is currently considered an important process in repository performance. The consequences of thermal effects on flow may affect many aspects of repository performance. These are discussed in detail in Section 3.2 of this IRSR. The DOE needs to adequately demonstrate and quantify the consequences of thermal effects on flow on repository performance. This demonstration requires the DOE to consider the interactions of thermal effects on flow both within and among key elements of the natural and engineered subsystems of the repository.

Our strategy for reviewing the performance of the potential high-level waste repository at Yucca Mountain is described in the Total System Performance Assessment and Integration (TSPAI) IRSR (U.S. Nuclear Regulatory Commission, 1998a, 1998b, 2000a). The performance assessment IRSR provides the framework and context for other KTI IRSRs, and integrates the results of those IRSRs. Its overall goal is to delineate a systematic approach for determining compliance with an overall system performance objective. The TEF KTI supports the resolution of the TSPAI KTI by describing the information needed in key elements of the natural and engineered subsystems within the performance assessment and by pursuing issue resolution with respect to those key elements. Those key elements that are important to a postclosure performance assessment of a repository at the Yucca Mountain site are referred to as integrated subissues (ISIs). In Revision 2 of the TEF KTI, integrated subissues were referred to as Key Elements of System Abstraction (KESA). The approach that we will use to independently evaluate the DOE's postclosure performance assessment focuses on these integrated subissues. The integrated subissues are illustrated in Figure A-1 in Appendix A.

Acceptance criteria for the key elements of the DOE TSPA are under development and will be included in the YMRP. The review methods and acceptance criteria being developed for the YMRP focus on fourteen model abstractions. These fourteen "abstractions" are equivalent to the integrated subissues identified in the TSPAI IRSR and Figure A-1 in Appendix A. As highlighted in Figure A-1, thermal effects on flow is an important factor that the DOE need to consider in four key elements of the natural and engineered subsystems. The four key elements (integrated subissues or "abstractions") that thermal effects on flow influences include:

- Degradation of Engineered Barriers
- Quantity and Chemistry of Water Contacting Waste Packages and Waste Forms

- Radionuclide Release Rates and Solubility Limits
- Flow Paths in the Unsaturated Zone

The NRC comments in the following sections apply equally to these four integrated subissues.

An objective of the staff review of the DOE's program is to assess aspects of thermal effects on flow that may affect the performance of the repository. In this revision of the IRSR, the staff reviews whether the DOE assessment of thermal effects on flow on repository performance includes: (i) important FEPs and consistent and appropriate assumptions, (ii) sufficient data to adequately define relevant parameters and conceptual models, (iii) parameter values used in the performance assessment abstractions that are consistent with site characterization data, design data, laboratory experiments, field measurements, and natural analog data, (iv) consideration of alternative conceptual models, and (v) performance assessment abstractions that are justified by comparison with process-level models and empirical observations. To accomplish the review objective, the staff have used a systematic approach to determine whether the DOE will adequately consider the process of thermal effects on flow in the four relevant integrated subissues within their performance assessment. This approach involves applying seven general criteria to the review. These seven criteria include:

- Identifying an initial list of features, events, and processes related to thermal effects on flow
- Screening the initial list of features, events, and processes related to thermal effects on flow
- System description and model integration
- Data and model justification
- Data uncertainty
- Model uncertainty
- Model support

5.2 SUBISSUE 1: FEATURES, EVENTS, AND PROCESSES RELATED TO THERMAL EFFECTS ON FLOW

This subissue relates to whether the DOE has identified and considered FEPs related to thermal effects on flow in the assessment of repository performance. Two general criteria are used to conduct the review of this aspect of the DOE's program. These are: (i) adequacy of the DOE's identification of an initial list of FEPs related to thermal effects on flow, and (ii) adequacy of the DOE's screening of the initial list of FEPs related to thermal effects on flow to determine which FEPs are to be excluded from the performance assessment.

5.2.1 IDENTIFYING AN INITIAL LIST OF FEATURES, EVENTS, AND PROCESSES RELATED TO THERMAL EFFECTS ON FLOW

The scope of the NRC review under this criterion includes verifying the DOE's list of primary FEPs is complete in that the list includes all FEPs relevant to thermal effects on flow that have a potential to influence repository performance (i.e., those that should be screened to determine whether they should be included in thermohydrologic models).

U.S. Department of Energy Approach

The DOE has developed a draft set of FEPs to be considered for inclusion in the Yucca Mountain TSPA. The DOE has identified each FEP as being either a primary or secondary FEP (CRWMS, M&O, 2000b; page 12). Primary FEPs are those FEPs for which the project proposes to develop detailed screening arguments. Secondary FEPs are either FEPs that are completely redundant or that can be aggregated into a single primary FEP. A draft of the set of primary FEPs is provided in U.S. Department of Energy (1999), and a discussion of the DOE's FEPs identification and screening process is provided in Swift, et al., (1999).

The DOE created the draft set of FEPs by combining lists of FEPs previously identified as relevant to Yucca Mountain with a draft FEP list compiled by the Nuclear Energy Agency (NEA) of the Organization for Economic Co-Operation and Development (OECD) (CRWMS, M&O, 2000b; page 11). As of May, 2000, the DOE's FEPs list included 1786 entries organized under 151 categories. The DOE notes that considerable redundancy exists in the FEP list because similar FEPs have been identified by multiple sources. The DOE also indicates the redundancy helps ensure that a comprehensive review of FEPs will be performed. The DOE considers the FEPs list open and expects the list to grow as additional FEPs are identified.

U.S. Nuclear Regulatory Commission Staff Evaluation

The NRC staff have reviewed available information to determine whether the DOE's list of FEPs is complete in that the list includes all FEPs related to thermal effects on flow that have a potential to influence repository performance (i.e., those that should be screened to determine whether they should be included in thermohydrologic models). It is important to note that (i) information reviewed is preliminary and currently being revised by the DOE, and (ii) only the list of primary FEPs was available, secondary FEPs were not reviewed.

The DOE's draft list of primary FEPs appears reasonably complete in that we can not identify any particular feature, process, or event, related to thermal effects on flow, that could not be represented under one of the primary FEP categories. The DOE needs to provide a final version of the list of primary and secondary FEPs to the NRC staff before we can reach a final conclusion as to whether the DOE's list of FEPs is complete with respect to thermal effects on flow.

5.2.2 SCREENING THE INITIAL LIST OF FEATURES, EVENTS, AND PROCESSES RELATED TO THERMAL EFFECTS ON FLOW

The scope of the NRC review under this criterion includes examining the DOE's screening process and screening decisions for primary FEPs relevant to thermal effects on flow that have a potential to influence repository performance (i.e., those that should be screened to determine whether they should be included in thermohydrologic models). The review is focused on examining any screening decisions to exclude relevant FEPs from the TSPA and the technical bases for those screening decisions. The adequacy of the DOE's technical basis for excluding each FEP will be evaluated considering the description of the site, the repository design, and the waste characteristics. The exclusion of any particular FEP needs to be justified based on either probability of occurrence or expected consequence. We assume that all FEPs the DOE has not explicitly excluded will be included in the TSPA.

U.S. Department of Energy Approach

The DOE screens each FEP for inclusion or exclusion in the TSPA against three criteria (CRWMS M&O, 2000b; page 13). FEPs are excluded from the TSPA only if:

- They are specifically ruled out by regulation, are contrary to the stated regulatory assumptions, or are in conflict with statements made in background information regarding intent or directions of the regulations;
- They can be shown to have a probability of occurrence less than 10^{-4} in 10^{4} years; or
- Their occurrence can be shown to have no significant effect on the overall performance of the system

FEPs are screened by different DOE work groups (process modeling groups) consistent with the organization of the DOE's TSPA-SR. This process is discussed in the *EBS FEPs Degradation Modes Abstraction* AMR Revision 00 (CRWMS, M&O, 2000c; page 16) wherein it is stated:

> "To perform the screening and analysis, the FEPs have been assigned based on the PMR structure so that the analysis, screening decision, and TSPA disposition reside with the subject matter experts in the relevant disciplines. The TSPA recognizes the FEPs have the potential to affect multiple facets of the project, may be relevant to more than one PMR, or may not fit neatly within the PMR structure. For example, many FEPs affect waste form (WF), waste package (WP), and the EBS. Rather than create multiple separate FEPs, the FEPs have been assigned, as applicable, to one or more process modeling groups, which are responsible for the AMRs.
>
> At least two approaches have been used to resolve overlap and interface problems of multiple assigned FEPs. FEP owners from different process modeling groups may decide that only one PMR will address all aspects of the FEP, including those relevant to other PMRs. Alternatively, FEP owners may each address only those aspects of the FEP relevant to their area. In either case, the FEP AMR produced by each process modeling group lists the FEP and summarizes the screening result, citing the appropriate work in related AMRs as needed."

FEPs directly related to thermal processes are addressed in two areas of the DOE's TSPA-SR. These areas are (i) the near field environment (NFE), and (ii) the EBS. The near-field environment is treated as being equivalent to the thermohydrologic and coupled processes in the unsaturated zone repository host rock. The thermal environment inside of the drift is considered in the engineered barrier system (CRWMS, M&O, 2000b; page 9). The determination of seepage flow into the drift, including the impact of geophysical changes in this region of the rock, is a NFE issue while chemical processes involving rock bolts and the surrounding cement are considered EBS issues. All flow into the tunnel is provided as boundary conditions to the EBS from the NFE analyses (CRWMS, M&O, 2000b; page 20).

The DOE has identified 26 primary FEPs from the draft list of primary FEPs as being within the scope of the NFE (CRWMS, M&O, 2000b; page 9). These FEPs represent the key features, events, and processes of the NFE that influence other aspects of the repository. Table 9 provides the DOE's list of 26 FEPs to be screened by the NFE group. Table 9 also provides the DOE's screening basis and screening decision basis for each of the 26 FEPs (CRWMS, M&O, 2000b; page 60). Secondary FEPs were not included in this screening process.

The DOE has identified 84 primary FEPs from the draft list of primary FEPs as being within the scope of the EBS (CRWMS, M&O, 2000c; page 10). These FEPs represent the key features of the EBS, processes that result in degradation of these features, and processes that occur within the EBS that influence other aspects of the repository. Table 10 provides the DOE's list of 84 FEPs screened by the EBS group. Table 10 also provides the DOE's screening basis and screening decision basis for each of the 84 FEPs (CRWMS, M&O, 2000c; page 83). A separate, independent evaluation of EBS FEPs was performed by the EBS process modeling organization. An additional 37 FEPs were identified as relevant to the EBS. However, all but but two of the 37 newly identified FEPs were considered restatements of FEPs already in the primary FEPs database and thus were considered to be secondary FEPs. The two additional primary FEPs (ebs #23 and #27) are included in Table 10. Secondary FEPs were not screened.

<u>U.S. Nuclear Regulatory Commission Staff Evaluation</u>

The NRC staff have reviewed available information to determine whether primary FEPs that have a potential to influence repository performance are included in the DOE's thermohydrologic models. It is important to note that information reviewed is preliminary and currently being revised by the DOE.

The NRC staff review of the DOE's screening of thermal process related FEPs focused on two specific draft AMRs. These were (i) *Features, Events, and Processes in Thermal Hydrology and Coupled Processes* AMR Revision 00 (CRWMS, M&O, 2000b) and (ii) *EBS FEPs/Degradation Modes Abstraction* AMR Revision 00 (CRWMS, M&O, 2000c). The process-modeling areas covered by these two draft AMRs represent the thermally affected environments of interest to the TEF KTI (ie., repository host rock environment and in-drift environment). Based on this review, the staff have concluded the information presented in the two draft AMRs is not sufficient to allow the staff to broadly determine which FEPs will be included in thermohydrologic models. Having reviewed the DOE's primary FEPs database, the staff concludes there are other primary FEPs that should be screened for inclusion into thermohydrologic models which are not addressed in the two draft AMRs. Table 11 provides a list of the DOE primary FEPs that the staff believes merit screening for inclusion in thermohydrologic models. Table 11 indicates that 21 of the 53 primary FEPs identified are not addressed in either the NFE FEPs AMR or the EBS FEPs AMR. For example, the FEP named "rock properties of host and rock and other units" includes physical properties such as

Table 9. DOE Primary FEPs Screened in Draft Thermal-Hydrology and Coupled Processes AMR

FEP Number	FEP Name	Screening Decision	Screening Basis
1.1.02.00.00	**Excavation/Construction.** Excavation-related effects include changes to rock properties.	Fracture effects included/ Chemistry effects excluded	Meets all criteria/ Low consequence
1.1.02.02.00	**Effects of pre-closure ventilation.** Controls the extent of the boiling front. Condensation of moisture as a result of ventilation onto a waste package should not occur during the pre-closure period since the ventilation air is expected to be relatively dry and the air flow rate will be high.	Include	Meets all criteria
1.2.02.01.00	**Fractures.** Generation of new fractures and re-activation of preexisting fractures may significantly change the flow and transport paths. Newly formed and reactivated fractures typically result from thermal, seismic, or tectonic events.	Include seepage/ Exclude permanent effects	Meets criteria for seepage/ Low consequence
2.1.08.01.00	**Increased unsaturated water flux at the repository.** Extremely rapid influx could reduce temperatures below the boiling point during part or all of the thermal period.	Include climate change/ Exclude water quenching waste package	Meets all criteria/ Low consequence
2.1.08.02.00	**Enhanced influx (Philip's drips).** A mechanism for focusing unsaturated flow to an underground opening and producing local saturation.	Include	Meets all criteria
2.1.08.03.00	**Repository dry-out due to waste heat.** The zone of reduced saturation migrates outward during the heating phase (about the first 1000 years) and then migrates back to the containers as heat diffuses throughout the mountain and the radioactive sources decay.	Include	Meets all criteria
2.1.08.10.00	**Desaturation/dewatering of repository.** "Dewatering" of rock at Yucca Mountain occurs because of ventilation and because of repository heating. The UZ is unsaturated and "resaturation" (re-entry of water to an equilibrium partial saturation) has a meaning different from that for a repository beneath the water table.	Include	Meets all criteria

Table 9. DOE Primary FEPs Screened in Draft Thermal-Hydrology and Coupled Processes AMR (continued)

FEP Number	FEP Name	Screening Decision	Screening Basis
2.1.08.11.00	**Resaturation of the repository.** During the resaturation (and sealing) of the repository, flow directions are different and the hydraulic conductivity is different. The conceptual flow models used in the process level thermal-hydrologic models allowed rock matrix and fracture elements to resaturate as the repository cooled.	Include	Meets all criteria
2.1.09.01.00	**Properties of the potential carrier plume in the waste and EBS.** It is likely that the flow system re-establishes itself before radionuclides are mobile. This re-established flow system, which can be a locally saturated system (fracture flow) or a UZ flow system, carries the signature of the repository (e.g., pH, T, dissolved constituents, etc) and is termed the carrier plume.	Include	Meets all criteria
2.1.09.12.00	**Rind (altered zone) formation in waste, EBS, and adjacent rock.** Thermo-chemical processes alter the rock forming the drift walls mineralogically. These alterations have hydrologic, thermal and mineralogic properties different from the current country rock.	Included in THC models but excluded from TH models	Meets all criteria/ TM low consequence (TBV)
2.1.11.01.00	**Heat output/temperature in waste and EBS.** Decay heat is a major issue in design. High loading density is intended to be part of the waste isolation scheme. Temperatures in the waste and EBS will vary through time.	Include	Meets all criteria
2.1.11.02.00	**Nonuniform heat distribution/edge effects in repository.** Temperature inhomogeneities in the repository lead to localized accumulation of moisture. Uneven heating and cooling at repository edges lead to non-uniform thermal effects during both the thermal peak and the cool-down period.	Include/ Exclude TM effects	Meets all criteria/ TM low consequence
2.2.01.01.00	**Excavation and construction-related changes in the adjacent host rock.** Stress relief, leading to dilation of joints and fractures, is expected in an axial zone of up to one diameter width surrounding the tunnels.	Exclude	Low consequence (TBV)
2.2.01.02.00	**Thermal and other waste and EBS-related changes in the adjacent host rock.** Changes in host rock properties result from thermal effects or other factors related to emplacement of the waste and EBS, such as mechanical or chemical effects of backfill. Properties that may be affected include rock strength, fracture spacing and block size, and hydrologic properties such as permeability.	Exclude	Low consequence (TBV)

Table 9. DOE Primary FEPs Screened in Draft Thermal-Hydrology and Coupled Processes AMR (continued)

FEP Number	FEP Name	Screening Decision	Screening Basis
2.2.01.03.00	**Changes in fluid saturations in the excavation disturbed zone.** During repository construction and operation, the near field will partially desaturate, and the local hydrological regime may be disturbed. After backfilling, groundwater re-enters host rock zones which were partially desaturated during the operational phase.	Exclude	Low consequence
2.2.06.01.00	**Changes in stress (due to thermal, seismic, or tectonic effects) change porosity and permeability of rock.** Even small changes in the fracture openings cause large changes in permeability. The rock deforms according to the rock stress field. Changes in the groundwater flow and in the temperature field will change the stress acting on the rock which will in turn change the groundwater flow.	Exclude	Low consequence (TBV)
2.2.07.10.00	**Condensation zone forms around drifts.** Repository design will affect the scale at which condensation caps form (over waste packages, over panels, or over the entire repository), and to the extent to which "shedding" will occur as water flows from the region above one drift to the region above another drift or into the rock between drifts.	Include	Meets all criteria
2.2.07.11.00	**Return flow from condensation cap/resaturation of dry-out zone.** When the rocks have cooled enough, there is a return flow toward the drifts from the condensation cap as a plume of unsaturated flow.	Include	Included in process models used in TSPA
2.2.08.03.00	**Geochemical interactions in geosphere (dissolution, precipitation, weathering and effects on radionuclide transport).** Effects on hydrologic flow properties of the rock, radionuclide solubilities, sorption processes, and colloidal transport are relevant. Kinetics of chemical reactions should be considered in the context of the time scale of concern.	Include	Meets all crieria
2.2.08.04.00	**Redissolution of precipitates directs more corrosive fluids to container.** This FEP concerns chemical precipitation plugging pores during heating and dissolution of the plugs during cool-down. When the pores open, the corrosive water is released and drains into the drift.	Include	Meets all criteria
2.2.10.04.00	**Thermo-mechanical alteration of fractures near repository.** Heat from the waste causes thermal expansion of the surrounding rock, generating compressive stresses near the drifts and extensional stresses away from them. The zone of compression migrates with time.	Exclude	Low consequence (TBV)

Table 9. DOE Primary FEPs Screened in Draft Thermal-Hydrology and Coupled Processes AMR (continued)

FEP Number	FEP Name	Screening Decision	Screening Basis
2.2.10.05.00	**Thermo-mechanical alteration of rocks above and below the repository.** Thermal-mechanical compression at the repository produces tension-fracturing in the PTn and other units above the repository. These fractures alter unsaturated zone flow between the surface and the repository. Extreme fracturing may propagate to the surface, affecting infiltration. Thermal fracturing in rocks below the repository affects flow and radionuclide transport to the saturated zone.	Exclude	Low consequence (TBV)
2.2.10.06.00	**Thermo-chemical alteration (solubility speciation, phase changes, precipitation/dissolution).** Changes in the groundwater temperature in the far-field, if significant, may change the solubility and speciation of certain radionuclides. This would have the effect of altering radionuclide transport processes. Relevant processes include volume effects associated with silica phase changes, precipitation and dissolution of fracture-filling minerals (including silica and calcite), and alteration of zeolites and other minerals to clays.	Exclude except for THC input to some geochemical models	Low consequence (TBV)
2.2.10.10.00	**Two-phase buoyant flow/heatpipes.** A heat pipe consists of a system for transferring energy between a hot and a cold region using the heat of vaporization and movement of the vapor as the transfer mechanism. Two-phase circulation continues until the heat source is too weak to provide thermal gradients required to drive it.	Include	Meets all criteria
2.2.10.12.00	**Geosphere dry-out due to waste heat.** Repository heat evaporates water near the drifts. The zone of reduced saturation migrates outward during the heating phase (about the first 1000 years) and then migrates back to the containers as heat diffuses throughout the mountain and the radioactive sources decay. The exten and degree of dry-out depends on the design and on the loading strategy for emplacement.	Include	Meets all criteria
2.2.10.13.00	**Density-driven groundwater flow (thermal).** The distribution of temperature within the crystalline basement is expected to be correlated with a distribution of groundwater density. Variations in density provide a driving force for groundwater flow. Density driven flow is expected at Yucca Mountain, but with heat supplied by the repository. Based on the geothermal gradient and the depth to the basement rocks, there is not likely to be any significant thermal contribution from the deep rocks.	Include	Meets all criteria

Table 10. DOE Primary FEPs Screened in EBS FEPs/Degradation Modes Abstraction AMR

FEP Number	FEP Name	Screening Decision	Screening Basis
1.1.02.00.00	**Excavation/Construction**	Exclude	Low Consequences
1.1.02.01.00	**Site flooding (during construction and operation)**	Exclude	Regulatory
1.1.02.02.00	**Effects of preclosure ventilation**	Include	
1.1.02.03.00	**Undesirable materials left**	Exclude	Low Consequences
1.1.03.01.00	**Error in waste or backfill emplacement**	Exclude	Regulatory
1.1.07.00.00	**Repository design**	Include	(a)
1.1.08.00.00	**Quality control**	Include	(a)
1.1.12.01.00	**Accidents and unplanned events during operation**	Exclude	Regulatory
1.1.13.00.00	**Retrievability**	Include	(a)
1.2.04.03.00	**Igneous intrusion into repository**	Exclude (for EBS)	N/A - see DE PMR (b)
2.1.03.01.00	**Corrosion of waste containers**	Include	Also see WP PMR (c)
2.1.03.10.00	**Container healing**	Include	Also see WP PMR (c)
2.1.03.12.00	**Container failure (long-term)**	Include	Also see WP PMR (c)
2.1.04.01.00	**Preferential pathways in the backfill**	Include	
2.1.04.02.00	**Physical and chemical properties of backfill**	Include	
2.1.04.03.00	**Erosion or dissolution of backfill**	Exclude	Low Consequences

Table 10. DOE Primary FEPs Screened in EBS FEPs/Degradation Modes Abstraction AMR (continued)

FEP Number	FEP Name	Screening Decision	Screening Basis
2.1.04.04.00	**Mechanical effects of backfill**	Include	
2.1.04.05.00	**Backfill evolution**	Include	
2.1.04.06.00	**Properties of bentonite**	Exclude	Zero Probability (d)
2.1.04.07.00	**Buffer characteristics**	Exclude	Zero Probability (d)
2.1.04.08.00	**Diffusion in backfill**	Exclude	Low Consequences
2.1.04.09.00	**Radionuclide transport through backfill**	Exclude	Low Consequences
2.1.06.01.00	**Degradation of cementitious materials in drift**	Include	
2.1.06.02.00	**Effects of rock reinforcement material**	Include	
2.1.06.03.00	**Degradation of the liner**	Exclude	Zero Probability (d)
2.1.06.04.00	**Flow through the liner**	Exclude	Zero Probability (d)
2.1.06.05.00	**Degradation of invert and pedestal**	Include	
2.1.06.06.00	**Effects and degradation of drip shield**	Include	
2.1.06.07.00	**Effects at material interfaces**	Exclude	Low Consequences
2.1.07.01.00	**Rockfall (large block)**	Exclude	Low Consequences
2.1.07.02.00	**Mechanical degradation or collapse of drift**	Exclude	Low Consequences
2.1.07.03.00	**Movement of containers**	Include	

Table 10. DOE Primary FEPs Screened in EBS FEPs/Degradation Modes Abstraction AMR (continued)

FEP Number	FEP Name	Screening Decision	Screening Basis
2.1.07.04.00	**Hydrostatic pressure on container**	Exclude	Zero Probability (d)
2.1.07.05.00	**Creeping of metallic materials in the EBS**	Exclude	Low Consequences
2.1.07.06.00	**Floor buckling**	Exclude	Low Consequences
2.1.08.01.00	**Increased unsaturated water flux at the repository**	Include	
2.1.08.02.00	**Enhanced influx (Philip's drip)**	Exclude	Low Consequences
2.1.08.04.00	**Condensation forms on backs of drifts**	Include	
2.1.08.05.00	**Flow through invert**	Include	
2.1.08.06.00	**Wicking in waste and EBS**	Include	
2.1.08.07.00	**Pathways for unsaturated flow and transport in the waste and EBS**	Include	
2.1.08.08.00	**Induced hydrological changes in the waste and EBS**	Include	
2.1.08.09.00	**Saturated groundwater flow in waste and EBS**	Exclude	Low Consequences
2.1.08.11.00	**Resaturation of repository**	Include	
2.1.09.01.00	**Properties of the potential carrier plume in the waste and EBS**	Include	
2.1.09.02.00	**Interaction with corrosion products**	Include	
2.1.09.05.00	**In-drift sorption**	Exclude	Low Consequences
2.1.09.06.00	**Reduction-oxidation potential in waste and EBS**	Include	
2.1.09.07.00	**Reaction kinetics in waste and EBS**	Exclude	Low Consequences
2.1.09.08.00	**Chemical gradients/enhanced diffusion in waste and EBS**	Exclude	Low Consequences

Table 10. DOE Primary FEPs Screened in EBS FEPs/Degradation Modes Abstraction AMR (continued)

FEP Number	FEP Name	Screening Decision	Screening Basis
2.1.09.11.00	**Waste-rock contact**	Exclude	Low Consequences
2.1.09.12.00	**Rind (altered zone) formation in waste, EBS, and adjacent rock**	Include	
2.1.09.13.00	**Complexation by organics in waste and EBS**	Exclude	Low Consequences
2.1.09.14.00	**Colloid formation in waste and EBS**	Include	
2.1.09.15.00	**Formation of true colloids in waste and EBS**	Exclude	Low Consequences
2.1.09.16.00	**Formation of pseudo-colloids (natural) in waste and EBS**	Include	
2.1.09.17.00	**Formation of pseudo-colloids (corrosion products) in waste and EBS**	Include	
2.1.09.18.00	**Microbial colloid transport in waste and EBS**	Exclude	Low Consequences
2.1.09.19.00	**Colloid transport and sorption in waste and EBS**	Exclude	Low Consequences
2.1.09.20.00	**Colloid filtration in waste and EBS**	Exclude	Low Consequences
2.1.09.21.00	**Suspensions of particles larger than colloids**	Exclude	Low Consequences
2.1.10.01.00	**Biological activity in waste and EBS**	Include	
2.1.11.01.00	**Heat output/temperature in waste and EBS**	Include	
2.1.11.03.00	**Exothermic reactions in waste and EBS**	Exclude	Low Consequences
2.1.11.04.00	**Temperature effects/coupled processes in waste and EBS**	Include	
2.1.11.05.00	**Differing thermal expansion of repository components**	Exclude	Low Consequences
2.1.11.07.00	**Thermally-induced stress changes in waste and EBS**	Include	
2.1.11.08.00	**Thermal effects: chemical and microbiological changes in the waste and EBS**	Include	
2.1.11.09.00	**Thermal effects on liquid or two-phase fluid flow in the waste and EBS**	Include	

Table 10. DOE Primary FEPs Screened in EBS FEPs/Degradation Modes Abstraction AMR (continued)

FEP Number	FEP Name	Screening Decision	Screening Basis
2.1.11.10.00	**Thermal effects on diffusion (Soret effect) in waste and EBS**	Exclude	Low Consequences
2.1.12.01.00	**Gas generation**	Exclude	Low Consequences
2.1.12.02.00	**Gas generation (He) from fuel decay**	Exclude	Low Consequences
2.1.12.03.00	**Gas generation (H_2) from metal corrosion**	Exclude	Low Consequences
2.1.12.04.00	**Gas generation (CO_2,CH_4,H_2S) from microbial degradation**	Exclude	Low Consequences
2.1.12.05.00	**Gas generation from concrete**	Exclude	Low Consequences
2.1.12.06.00	**Gas transport in waste and EBS**	Exclude	Low Consequences
2.1.12.07.00	**Radioactive gases in waste and EBS**	Exclude (for EBS)	Low Consequences
2.1.12.08.00	**Gas explosions**	Exclude	Low Consequences
2.1.13.01.00	**Radiolysis**	Exclude (for EBS)	N/A - see WF PMR (b)
2.1.13.02.00	**Radiation damage in waste and EBS**	Exclude	Low Consequences
2.1.13.03.00	**Mutation**	Exclude	Low Consequences
2.2.07.06.00	**Episodic/pulse release from repository**	Include	(also see NFE PMR)
2.2.08.04.00	**Redissolution of precipitates directs more corrosive fluids to containers**	Include	
2.2.11.02.00	**Gas pressure effects**	Exclude	Low Consequences
New - EBS #23	**Drains**	Exclude	Zero Probability (d)
New - EBS #27	**Drainage with transport - sealing and plugging**	Exclude	Low Consequences

Table 10. DOE Primary FEPs Screened in EBS FEPs/Degradation Modes Abstraction AMR (continued)

(a) -Part of baseline design.
(b) -While the identified FEP may be important for TSPA, it is not important to modeling of the EBS.
(c) -These are primarily WP FEPs; the EBS analysis merely provides the appropriate boundary conditions.
(d) -This potential repository feature is not part of the baseline design.

Table 11. DOE Primary FEPs That Merit Screening for Inclusion in Thermohydrologic Models

FEP Number	FEP Name	Screened in FEPs in TH & Coupled Processes AMR	Screened in EBS FEPs Degradation Modes AMR
1.1.02.00.00	**Excavation/construction.** Excavation-related effects include changes to rock properties.	Yes Fracture effects included/Chemistry effect exclude	Yes Excluded
1.1.02.02.00	**Effects of pre-closure ventilation.** Controls the extent of the boiling front. Condensation of moisture as a result of ventilation onto a waste package should not occur during the pre-closure period since the ventilation air is expected to be relatively dry and the air flow rate will be high.	Yes Included	Yes Included
1.1.07.00.00	**Repository design.** Repository design refers to FEPs related to the design of the repository including both the design safety concept (i.e., the general features of the design) and the more detailed engineering specification for excavation, construction and operation.	No	Yes Included
1.2.02.01.00	**Fractures.** Generation of new fractures and re-activation of preexisting fractures may significantly change the flow and transport paths. Newly formed and reactivated fractures typically result from thermal, seismic, or tectonic events.	Yes Seepage affects included/permanent effects excluded	No
2.1.01.01.00	**Waste Inventory.** The expected inventory is considered part of the source term.	No	No
2.1.01.02.00	**Codisposal/colocation of waste.** Co-disposal and colocation refers to the disposal of CSNF, DSNF, DHLW, and possibly other wastes in close proximity within the repository. Co-disposal and colocation might affect thermal outputs.	No	No
2.1.01.03.00	**Heterogeneity of waste forms.** Containers of CSNF, DSNF, and DHLW shipped to the repository will contain quantities of radionuclides that will vary from container to container. There will be considerable variation in thermal output from a particular waste type and among waste types.	No	No

Table 11. DOE Primary FEPs That Merit Screening for Inclusion in Thermohydrologic Models (continued)

FEP Number	FEP Name	Screened in FEPs in TH & Coupled Processes AMR	Screened in EBS FEPs Degradation Modes AMR
2.1.08.01.00	**Increased unsaturated water flux at the repository.** Extremely rapid influx could reduce temperatures below the boiling point during part or all of the thermal period.	Yes Climate change included/water quenching wp excluded	Yes Included
2.1.08.02.00	**Enhanced influx (Philip's drips).** A mechanism for focusing unsaturated flow to an underground opening and producing local saturation.	Yes Included	Yes Excluded
2.1.08.03.00	**Repository dryout due to waste heat.** The zone of reduced saturation migrates outward during the heating phase (about the first 1000 years) and then migrates back to the containers as heat diffuses throughout the mountain and the radioactive sources decay.	Yes Included	No
2.1.08.04.00	**Condensation forms on backs of drifts.** Emplacement of waste in drifts creates a large thermal gradient across the drifts. Moisture condenses on the roof and flows downward and drips onto canisters, accelerating corrosion.	No	Yes Included
2.1.08.08.00	**Induced hydrological changes in the waste and EBS.** Thermal, chemical, and mechanical processes related to the construction of the repository and the emplacement of waste may induce changes in the hydrologic behavior of the system.	No	Yes Included
2.1.08.10.00	**Desaturation/dewatering of repository.** "Dewatering" of rock at Yucca Mountain occurs because of ventilation and because of repository heating. The UZ is unsaturated and "resaturation" (re-entry of water to an equilibrium partial saturation) has a meaning different from that for a repository beneath the water table.	Yes Included	No
2.1.08.11.00	**Resaturation of the repository.** During the resaturation (and sealing) of the repository, flow directions are different and the hydraulic conductivity is different. The conceptual flow models used in the process level thermal-hydrologic models allowed rock matrix and fracture elements to resaturate as the repository cooled.	Yes Included	Yes Included

Table 11. DOE Primary FEPs That Merit Screening for Inclusion in Thermohydrologic Models (continued)

FEP Number	FEP Name	Screened in FEPs in TH & Coupled Processes AMR	Screened in EBS FEPs Degradation Modes AMR
2.1.09.01.00	**Properties of the potential carrier plume in the waste and EBS.** It is likely that the flow system re-establishes itself before radionuclides are mobile. This re-established flow system, which can be a locally saturated system (fracture flow) or a UZ flow system, carries the signature of the repository (e.g., pH, T, dissolved constituents, etc) and is termed the carrier plume.	Yes Included	Yes Included
2.1.09.12.00	**Rind (altered zone) formation in waste, EBS, and adjacent rock.** Thermo-chemical processes alter the rock forming the drift walls mineralogically. These alterations have hydrologic, thermal and mineralogic properties different from the current country rock.	Yes Excluded from TH models/Included in THC models	Yes Included
2.1.11.01.00	**Heat output/temperature in waste and EBS.** Decay heat is a major issue in design. High loading density is intended to be part of the waste isolation scheme. Temperatures in the waste and EBS will vary through time.	Yes Included	Yes Included
2.1.11.02.00	**Nonuniform heat distribution/edge effects in repository.** Temperature inhomogeneities in the repository lead to localized accumulation of moisture. Uneven heating and cooling at repository edges lead to non-uniform thermal effects during both the thermal peak and the cool-down period.	Yes Included/TM effects excluded	No
2.1.11.04.00	**Temperature effects/coupled processes in waste and EBS.** This FEP broadly encompasses all coupled-processes effect of temperature changes within the waste and the EBS	No	Yes Included
2.1.11.07.00	**Thermally-induced stress changes in the waste and EBS.** Thermally induced stress changes in the waste and EBS may affect performance of the repository. Relevant processes include rockfall, drift stability, changes in physical properties of the disturbed rock zone around the repository and changes in physical properties of the surrounding rock.	No	Yes Included
2.1.11.09.00	**Thermal effects on liquid or two-phase flow in the waste and EBS.** Temperature differentials in the repository could initiate convection.	No	Yes Included
2.2.01.01.00	**Excavation and construction-related changes in the adjacent host rock.** Stress relief, leading to dilation of joints and fractures, is expected in an axial zone of up to one diameter width surrounding the tunnels.	Yes Excluded	No

Table 11. DOE Primary FEPs That Merit Screening for Inclusion in Thermohydrologic Models (continued)

FEP Number	FEP Name	Screened in FEPs in TH & Coupled Processes AMR	Screened in EBS FEPs Degradation Modes AMR
2.2.01.02.00	**Thermal and other waste and EBS-related changes in the adjacent host rock.** Changes in host rock properties result from thermal effects or other factors related to emplacement of the waste and EBS, such as mechanical or chemical effects of backfill. Properties that may be affected include rock strength, fracture spacing and block size, and hydrologic properties such as permeability.	Yes Excluded	No
2.2.01.03.00	**Changes in fluid saturations in the excavation disturbed zone.** During repository construction and operation, the near field will partially desaturate, and the local hydrological regime may be disturbed. After backfilling, groundwater re-enters host rock zones which were partially desaturated during the operational phase.	Yes Excluded	No
2.2.03.01.00	**Stratigraphy.** Stratigraphic information is necessary information for the performance assessment. This information should include identification of the relevant rock units, soils, and alluvium, and their thicknesses, lateral extents, and relationships to each other. Major discontinuities should be identified. Part of reference geologic database.	No	No
2.2.03.02.00	**Rock properties of host rock and other units.** Physical properties such as porosity and permeability of the relevant rock units, soils, and alluvium are necessary for the performance assessment. Possible heterogeneities in these properties should be considered.	No	No
2.2.06.01.00	**Changes in stress (due to thermal, seismic, or tectonic effects) change porosity and permeability of rock.** Even small changes in the fracture openings cause large changes in permeability. The rock deforms according to the rock stress field. Changes in the groundwater flow and in the temperature field will change the stress acting on the rock which will in turn change the groundwater flow.	Yes Excluded	No
2.2.06.02.00	**Changes in stress (due to thermal, seismic, or tectonic effects) produce change in permeability of faults.** Stress changes due to thermal, tectonic and seismic processes result in strains that alter the permeability along and across faults.	No	No

Table 11. DOE Primary FEPs That Merit Screening for Inclusion in Thermohydrologic Models (continued)

FEP Number	FEP Name	Screened in FEPs in TH & Coupled Processes AMR	Screened in EBS FEPs Degradation Modes AMR
2.2.07.02.00	**Unsaturated groundwater flow in geosphere.** Groundwater flow occurs in unsaturated rocks in most locations above the water table at Yucca Mountain, including the location of the repository.	No	No
2.2.07.04.00	**Focusing of unsaturated flow (fingers, weeps).** Unsaturated flow can differentiate into zones of greater and lower saturation (fingers) that may persist as preferential flow paths. Heterogeneities in rock properties, including fractures and faults, may contribute to focusing. Focused flow may become locally saturated.	No	No
2.2.07.05.00	**Flow and transport in the UZ from episodic infiltration.** Episodic flow occurs in the UZ as a result of episodic infiltration. An unsaturated flow plume forms during an episodic infiltration event and descends to interact with the repository, either with the vaporization isotherm and condensate during the thermal period or entering the drifts in the post-thermal period.	No	No
2.2.07.07.00	**Perched water develops.** Zones of perched water may develop above the water table. If these zones occur above the repository, they may affect UZ flow between the surface and the waste packages. If they develop below the repository, for example at the base of the Topopah Springs welded unit, they may affect flow pathways and radionuclide transport between the waste packages and the saturated zone.	No	No
2.2.07.08.00	**Fracture flow in the unsaturated zone.** Fractures or other analogous channels act as conduits for fluids to move into the subsurface to interact with the repository and as conduits for fluids to leave the vicinity of the repository and be conducted to the SZ.	No	No
2.2.07.10.00	**Condensation zone forms around drifts.** Repository design will affect the scale at which condensation caps form (over waste packages, over panels, or over the entire repository), and to the extent to which "shedding" will occur as water flows from the region above one drift to the region above another drift or into the rock between drifts.	Yes Included	No
2.2.07.11.00	**Return flow from condensation cap/resaturation of dry-out zone.** When the rocks have cooled enough, there is a return flow toward the drifts from the condensation cap as a plume of unsaturated flow.	Yes Included	No

Table 11. DOE Primary FEPs That Merit Screening for Inclusion in Thermohydrologic Models (continued)

FEP Number	FEP Name	Screened in FEPs in TH & Coupled Processes AMR	Screened in EBS FEPs Degradation Modes AMR
2.2.08.03.00	**Geochemical interactions in geosphere (dissolution, precipitation, weathering) and effects on radionuclide transport**. Effects on hydrologic flow properties of the rock, radionuclide solubilities, sorption processes, and colloidal transport are relevant. Kinetics of chemical reactions should be considered in the context of the time scale of concern.	Yes Included	No
2.2.08.04.00	**Redissolution of precipitates directs more corrosive fluid to container.** This FEP concerns chemical precipitation plugging pores during heating and dissolution of the plugs during cool-down. When the pores open, the corrosive water is released and drains into the drift.	Yes Included	No
2.2.10.01.00	**Repository-induced thermal effects in geosphere.** Heat generated by waste causes a thermo-chemo-mechano-hydraulic evolution of the mountain during the thermal period and produces durable changes to the mountain which persist in the post-thermal period.	No	No
2.2.10.02.00	**Thermal convection cell develops in SZ.** Thermal effects due to waste emplacement result in convective flow in the saturated zone beneath the repository.	No	No
2.2.10.03.00	**Natural geothermal effects.** The existing thermal gradient, and spatial or temporal variability in that gradient, may affect groundwater flow in the unsaturated and saturated zones.	No	No
2.2.10.04.00	**Thermo-mechanical alteration of fractures near repository.** Heat from the waste causes thermal expansion of the surrounding rock, generating compressive stresses near the drifts and extensional stresses away from them. The zone of compression migrates with time.	Yes Excluded	No
2.2.10.05.00	**Thermo-mechanical alteration of rocks above and below the repository.** Thermal-mechanical compression at the repository produces tension-fracturing in the PTn and other units above the repository. These fractures alter unsaturated zone flow between the surface and the repository. Extreme fracturing may propagate to the surface, affecting infiltration. Thermal fracturing in rocks below the repository affects flow and radionuclide transport to the saturated zone.	Yes Excluded	No

Table 11. DOE Primary FEPs That Merit Screening for Inclusion in Thermohydrologic Models (continued)

FEP Number	FEP Name	Screened in FEPs in TH & Coupled Processes AMR	Screened in EBS FEPs Degradation Modes AMR
2.2.10.06.00	**Thermo-chemical alteration (solubility, speciation, phase changes, precipitation/dissolution).** Changes in the groundwater temperature in the far-field, if significant, may change the solubility and speciation of certain radionuclides. This would have the effect of altering radionuclide transport processes. Relevant processes include volume effects associated with silica phase changes, precipitation and dissolution of fracture-filling minerals (including silica and calcite), and alteration of zeolites and other minerals to clays.	Yes Excluded except for THC input to some geochemical models	No
2.2.10.07.00	**Thermo-chemical alteration of the Calico Hills unit.** Fracture pathways in the Calico Hills are altered by the thermal and chemical properties of the water flowing out of the repository.	No	No
2.2.10.08.00	**Thermo-chemical alteration of the saturated zone.** Thermal and chemical processes related to the emplacement of waste in the repository may alter the hydrologic properties of the saturated zone.	No	No
2.2.10.09.00	**Thermo-chemical alteration of the Topopah Spring basal vitrophyre.** Heating the Topopah Spring basal vitrophyre with water available causes alteration of the glasses to clays and zeolites. Possible effects include volume increases that plug fractures, changes in flow paths, creation of perched water zones, and an increase in the sorptive properties of the unit.	No	No
2.2.10.10.00	**Two-phase bouyant flow/heat pipes.** A heat pipe consists of a system for transferring energy between a hot and a cold region using the heat of vaporization and movement of the vapor as the transfer mechanism. Two-phase circulation continues until the heat source is too weak to provide thermal gradients required to drive it.	Yes Included	No
2.2.10.11.00	**Natural air flow in the unsaturated zone.** Natural convective air circulation has been observed at a borehole at the top of the mountain. Repository heat is expected to increase this flow.	No	No
2.2.10.12.00	**Geosphere dry-out due to waste heat.** Repository heat evaporates water near the drifts. The zone of reduced saturation migrates outward during the heating phase (about the first 1000 years) and then migrates back to the containers as heat diffuses throughout the mountain and the radioactive sources decay. The exten and degree of dry-out depends on the design and on the loading strategy for emplacement.	Yes Included	No

Table 11. DOE Primary FEPs That Merit Screening for Inclusion in Thermohydrologic Models (continued)

FEP Number	FEP Name	Screened in FEPs in TH & Coupled Processes AMR	Screened in EBS FEPs Degradation Modes AMR
2.2.10.13.00	**Density-driven groundwater flow (thermal).** The distribution of temperature within the crystalline basement is expected to be correlated with a distribution of groundwater density. Variations in density provide a driving force for groundwater flow. Density driven flow is expected at Yucca Mountain, but with heat supplied by the repository. Based on the geothermal gradient and the depth to the basement rocks, there is not likely to be any significant thermal contribution from the deep rocks.	Yes Included	No
2.3.11.01.00	**Precipitation.** Precipitation is an important control on the amount of recharge	No	No
2.3.11.03.00	**Infiltration and recharge (hydrologic and chemical effects).** Infiltration into the subsurface provides a boundary condition for groundwater flow.	No	No
2.3.13.03.00	**Effects of repository heat on biosphere.** The heat released from radioactive decay of the waste will increase the temperatures at the surface above the repository.	No	No

permeability and porosity. Having reviewed DOE's thermohydrologic models, the staff is aware that this FEP is "included" in the models even though the FEP is not specifically addressed in thermally related process-model AMRs. It is not readily transparent or easily traceable whether other FEPs not addressed are appropriately included in the DOE's thermohydrologic models. The staff recognizes that all the primary FEPs are likely addressed by some area of the DOE's program. However, because the primary FEP screening results are presented across numerous AMRs, a clear and complete expression of all of the primary FEPs to be included in thermohydrologic models is not provided.

The DOE's screening process focuses on primary FEPs. Secondary FEPs are not screened. Screening primary FEPs often leads to some aspects of the FEP being included and some aspects of the primary FEP being excluded (refer to Table 9). The staff is concerned that the lack of visibility of secondary FEPs in the screening analysis documentation could result in some potentially important processes not being addressed, or implemented, in the thermohydrologic models. In some instances, secondary aspects of a primary FEP is discussed in the screening argument and TSPA disposition discussion. One example of this is the screening of the primary FEP "effects of pre-closure ventilation" (CRWMS M&O, 2000b; page 26). Ventilation will remove heat and moisture from the repository. Ventilation will be included in the TSPA but only in a limited way. The discussion indicates clearly that heat removal by conduction will be implemented in the thermohydrologic models but removal of heat via convective moisture movement will not be implemented. In other instances, secondary aspects of primary FEP is not addressed at all. One example of this is the screening of the primary FEP "Nonuniform heat distribution/edge effects in repository" (CRWMS M&O, 2000b; page 41). Although this primary FEP will be included in the TSPA, the screening argument and TSPA disposition discussion provides no mention of the "cold-trap effect" (see technical discussion of the "cold-trap effect" in section 5.3.1). The "cold-trap effect" can reasonably be considered a secondary FEP related to the primary FEP "Nonuniform heat distribution/edge effects in repository". The DOE should consider giving greater visibility to secondary FEPs in the FEP screening AMRs to assure no potentially important aspects of primary FEPs are overlooked. The NRC staff have not seen or reviewed the list of secondary FEPs.

In the *Features, Events, and Processes in Thermal Hydrology and Coupled Processes* AMR Revision 00 (CRWMS, M&O, 2000b), a screening decision has been made to exclude a number of primary FEPs from the TSPA. In a number of cases the DOE indicates that the screening basis is an assumption that needs to be verified (TBV in Table 9). There is some discussion in the AMR that implies there exist other assumptions to be verified, and that these assumptions are tracked by the Document Input Reference System (CRWMS, M&O, 2000b; page 22). The DOE needs to provide the staff with a summary of the assumptions related to screening arguments for FEPs relevant to thermohydrologic models that need verification and the associated analyses planned to provide that verification.

In some instances the screening argument for excluding a FEP is based on conclusions drawn from a previous analysis and a traceable reference to the analysis is not provided. For example, the FEP "Rind (altered zone) formation in waste, EBS, and adjacent rock" is excluded from thermohydrologic models because the "changes on the hydrologic properties were found to be small and so were excluded from the MSTHM and mountain scale TH models due to low consequence" (CRWMS, M&O, 2000b; page 38). No traceable reference is provided for the analysis where "the changes on the hydrologic properties were found to be small". The DOE needs to provide traceable references to previous analyses used as the technical basis for screening arguments for excluded FEPs.

Considering the above comments and because the DOE is currently revising FEP-related AMRs, the staff have not performed a detailed review of the DOE's FEP screening arguments at this time.

5.2.3 STATUS AND PATH TO RESOLVE SUBISSUE 1

Subissue 1 (Features, events, and processes related to thermal effects on flow) is open. To close this subissue, the DOE needs to address identified open items. Specifically, the DOE needs to:

- Provide the final list of primary and secondary FEPs.

- Provide the revised FEP screening analysis for thermohydrologic models. The screening analysis documentation should comprehensively address all primary FEPs.

- Give greater visibility to secondary FEPs in the FEP screening documentation.

- Provide a summary of the assumptions related to screening arguments for FEPs relevant to thermohydrologic models that need verification and the associated analyses planned to provide that verification.

- Provide traceable references to previous analyses used as the technical basis for screening arguments for excluded FEPs.

5.3 SUBISSUE 2: THERMAL EFFECTS ON TEMPERATURE, HUMIDITY, SATURATION, AND FLUX

This subissue relates to whether the DOE's approach to estimating subsurface environmental conditions and perturbations to flow paths in the unsaturated zone, as implemented in the performance assessment, is adequate. Key environmental conditions (parameters) influenced by thermal heat produced by waste include temperature, humidity, saturation, and flux. Five general criteria are used to conduct the review of this aspect of the DOE's program. These are: (i) system description and model integration, (ii) data and model justification, (iii) data uncertainty, (iv) model uncertainty, and (v) model support.

5.3.1 SYSTEM DESCRIPTION AND MODEL INTEGRATION WITH RESPECT TO THERMAL EFFECTS ON FLOW

The scope of the NRC review under this criterion includes evaluating the adequacy of the DOE's conceptual approach to incorporate the "included" FEPs related to thermal effects on flow into the performance assessment. The review primarily focuses on the DOE's approach to predict the thermal effects on temperature, humidity, saturation, flux and flow paths in the unsaturated zone in the context of the performance assessment. The review will consider whether DOE's approach is applied consistently, as appropriate, throughout relevant areas of the performance assessment (i.e., with respect to the four "abstractions" relevant to thermal effects on flow). If an approach is not yet described, then the DOE plans to develop an approach(s) will be evaluated. The review also includes evaluating whether the DOE's performance assessment will incorporate those design features that affect the thermal evolution of the repository environment, based on the currently available design. Review conclusions under this criterion will need to consider any comments or open items derived from the review provided in Section 5.3.2 (data and model justification with respect to thermal effects on flow).

U.S. Department of Energy Approach

This review of the DOE approach to system description and model integration with respect to thermal effects on flow is based on information in the *Multiscale Thermohydrologic Model* AMR Revision 00 (CRWMS M&O, 2000d) and the *Abstraction of Near-Field Environment Thermodynamic Environment and Percolation Flux* AMR Revision 00 (CRWMS M&O, 2000e). The *Multiscale Thermohydrologic Model* AMR Revision 00 (CRWMS M&O, 2000d) documents calculations of thermohydrologic variables for the in-drift, near-field, and far-field environments using the NUFT code (Nitao, 1995). This multiscale approach to calculating thermohydrologic variables in three-dimensions for the entire repository area, including in-drift design details and waste package to waste package variability, is similar to the multiscale approach used for TSPA-VA discussed in section 3.3.7.2 of this IRSR. Significant differences between the multiscale thermohydrologic model used for TSPA-VA and the *Multiscale Thermohydrologic Model* AMR Revision 00 (CRWMS M&O, 2000d) include the number of locations within the repository area where thermohydrologic variables are calculated, the locations within the repository of the submodels, and the AML used for thermal calculations. In light of these differences the *Multiscale Thermohydrologic Model* AMR Revision 00 (CRWMS M&O, 2000d) is summarized here.

The *Multiscale Thermohydrologic Model* (MSTHM) (CRWMS M&O, 2000d) used four submodel scales: (i) the Smeared-heat-source Drift-scale Thermal-conduction (SDT) submodel; (ii) the Line-average-heat-source Drift-scale Thermohydrologic (LDTH) submodel; (iii) the Discrete-heat-source Drift-scale Thermal-conduction (DDT) submodel; and (iv) the Smeared-heat-source Mountain-scale Thermal-conduction (SMT) submodel. In combining these four submodels, the MSTHM accounts for 3-D drift-scale and mountain-scale heat flow, repository-scale variability of stratigraphy and infiltration flux, and waste package to waste package variability in heat output from waste packages. All submodels are run using the NUFT simulation code. The repository EDA II design was modeled for 63,000 MTU of CSNF and 7000 MTU of DHLW and three infiltration-flux and property set scenarios of low, mean and high infiltration. These three infiltration flux scenarios and associated property sets, documented in the *Calibrated Properties Model* AMR Revision 00 (CRWMS M&O, 2000f), have three climate periods. Present climate is assumed for 600 yr, monsoonal climate is assumed from 600 to 2000 yr, and glacial climate is assumed from 2000 to one million yr. Ventilation in the MSTHM is modeled by reducing the heat source 70% for 50 yr as documented in the *Ventilation Model* AMR Revision 00 (CRWMS

M&O, 2000g). Ventilation is ceased, the dripshield is emplaced, and the drifts are backfilled with Overton sand at the end of the 50 yr preclosure period.

The LDTH submodel, the only submodel to explicitly incorporate coupled thermohydrologic processes, was implemented in 2-D using a line-averaged-heat-source and run at 31 locations in the repository for AMLs of 15, 25, 36, 50, and 60 MTU/acre to account for edge-cooling effects. The SMT was implemented in 3-D using a smeared-heat-source (all waste packages are represented as a planar, uniform heat-source) and includes the influence of thermal-property variations at the formation scale, lateral heat loss at the repository edges, and overburden-thickness variation with location. Relating 3-D thermal-conduction to the drift-scale was accomplished using the SDT which was implemented in 1-D (vertical) with a planar (smeared) heat-source and run at the same 31 repository locations as the LDTH submodel. The relationship between drift-wall temperature in the LDTH and SDT submodels was used to modify temperatures in the SMT submodel. This "corrects" the SMT submodel temperatures for the influences of thermohydrologic processes and 2-D drift-scale dimensionality. The DDT is a 3-D drift-scale conduction only submodel that incorporates the distinct heat-generation histories of 8 different waste package types and thermal radiation and thermal conduction between waste packages and drift surfaces. Drift-wall temperatures calculated using the combined LDTH, SMT, and SDT submodels are further refined to account for waste package specific deviations by using relationships between local temperatures at various points along the drift. The DDT was run at only one submodel repository location and was used only to calculate temperature difference between the waste package and drip shield and temperature variations along the length of the drift axis. The DDT was also the only submodel that explicitly included thermal radiation within the drift. Thermal radiation was modeled between waste package and drift-wall during the 50 yr preclosure period and between waste package and drip shield for the postclosure period.

The SMT model was run once for the preclosure period and once for the postclosure period for the base case, upper, and lower bound infiltration-flux scenarios. The preclosure period was run with a heat load reduced by 70% for 600 yr but only the first 50 yr were used. The postclosure period was run with heat reduced by 70% for 50 yr then with the full heat load for 1,000,000 yr, also only once for all three infiltration-flux scenarios. The 2-D LDTH submodels, using the dual-continuum formulation modified with the active fracture concept (Liu et al., 1998) were run at 31 repository locations for 5 AMLs and three infiltration-flux scenarios. This was done for the preclosure and again for the postclosure periods. The SDT was run parallel with the LDTH submodel at the same 31 repository locations for each of the 5 AMLs but not for different infiltration-flux scenarios because this submodel is for conduction only. Relationships between the LDTH and SDT submodels were used to create "scanning curves" for modifying SMT-predicted temperatures from the smeared to the line-averaged heat source. This intermediate result was termed the LMTH for Line-averaged-heat-source Mountain-scale Thermohydrologic model. The DDT model was run once for the preclosure period and once for the postclosure period to account for waste package-specific heat output and for thermal radiation between waste package and drift surfaces. The DDT submodel was then used to modify temperatures in the LMTH resulting in a Discrete-heat-source Mountain-scale Thermohydrologic model, or DMTH. In summary, the SMT was run once to get the mountain-scale temperature distribution and the LDTH and SDT submodels were run for 5 AMLs at 31 repository locations for each infiltration-flux scenario. Scanning curves were then created for the 31 repository locations from the LDTH and SDT submodel results. These scanning curves were then interpolated to 623 repository locations on the mountain-scale grid and used to calculate LMTH drift wall temperatures at the 623 repository locations. The final step was to adjust LMTH drift wall temperatures for waste package-specific heat sources and thermal radiation using the results of the DDT submodel. This calculation procedure was used to obtain temperatures at other locations besides the drift wall including the near-field host rock, in the backfill, on the drip shield, and in the invert.

The procedure for computing RH was similar to the procedure for calculating temperatures with the exception that the scanning curves were completely derived from the LDTH submodels. Specifically, the scanning curves related drift wall RH to drift wall temperature. The procedure used to calculate host rock RH was similar to the procedure used to calculate drift wall RH but computing drip shield RH required time-dependent scanning curves be created due to the sensitivity of RH in the drift to infiltration flux. Flux of the liquid phase also has time dependence. Scanning curves of liquid flux for each AML were created from the LDTH submodels as a function of time. Liquid fluxes were then adjusted based on relative position in the temperature history curves for each AML. A total of 38 themohydrologic variables, summarized in Table 12, were calculated using the MSTHM approach.

Abstraction of the thermohydrologic variables calculated by the MSTHM in the *Abstraction of Near-Field Environment Thermodynamic Environment and Percolation Flux* AMR Revision 00 (CRWMS M&O, 2000e) took a significantly different approach than that used in TSPA-VA as described in section 3.3.7.2 of this IRSR. Instead of binning thermohydrologic variables according to six repository subdivisions, results from the MSTHM were abstracted based on a subdivision of the repository footprint by glacial infiltration rate into five bins of 0-3, 3-10, 10-20, 20-60, and 60+ mm/yr. The same five bins were used for all three infiltration-flux scenarios. Output from the MSTHM was sorted such that each of the 623 repository locations went into one of the five glacial infiltration rate bins. Each of the 623 repository locations represents the environment that would be experienced by a waste package at that physical location. Averaged quantities for each bin were obtained by averaging the time histories of the locations within that bin multiplied by an area weighting factor to account for the different areas of the 623 repository locations in the MSTHM. In addition to the averaged time histories, the thermohydrologic variables at locations with the maximum and minimum peak temperature values were also abstracted in order to maintain variability. The abstraction process also reduced the number of time steps taken from the MSTHM to reduce runtimes in the TSPA. For waste package degradation calculations within TSPA, each waste package for which degradation is modeled has its own histories of temperature, RH, etc., drawn from the population of histories from the MSTHM. However for calculation of radionuclide release, waste packages were lumped into groups with common environmental histories.

All thermohydrologic variables used in TSPA are derived from the *Abstraction of Near-Field Environment Thermodynamic Environment and Percolation Flux* AMR Revision 00 (CRWMS M&O, 2000e).

Table 12. Thermohydrologic Variables Calculated from the MSTHM

TH Variable	Drift-Scale Location
Temperature	NFE host rock 5m above drift crown; NFE host rock mid-pillar; Maximum lateral extent of boiling; Upper drift wall at the crown; Lower drift wall below invert; Drift wall perimeter average; Backfill crown; Drip shield perimeter average; Waste package surface average; Invert average
Relative humidity	Drift wall perimeter average; Backfill crown; Drip shield perimeter average; Invert average
Liquid-phase saturation in the matrix	Drift wall perimeter average; Drip shield perimeter average; Invert average
Liquid-phase flux in the fractures	NFE host rock 5m above drift crown; NFE host rock 3m above drift crown; NFE host rock 0.2m above drift crown; Drip shield crown; Drip shield upper surface average; Drip shield lower side at base; Invert average
Gas-phase air-mass fraction	Drip shield perimeter average
Gas-phase air pressure	Drip shield perimeter average

Table 12. Thermohydrologic Variables Calculated from the MSTHM (continued)

TH Variable	Drift-Scale Location
Capillary pressure	Drip shield perimeter average; Invert average; Drift wall crown in the matrix; Drift wall crown in the fractures
Gas-phase water vapor flux	Drift wall perimeter average
Gas-phase air flux	Drift wall perimeter average
Evaporation rate	Backfill crown' Drip shield crown; Drip shield perimeter total; Invert total

U.S. Nuclear Regulatory Commission Staff Evaluation

Thermohydrologic variables for evaluating thermal effects on flow for the four integrated subissues appear to be consistently used throughout the abstractions for TSPA. However, the current repository design does not include backfill. The presence of backfill in drifts affects the near-field thermodynamic environment, particularly by capillary wicking of water from drift walls into the backfill. Staff are aware that MSTHM calculations for drifts with no backfill will be presented in upcoming revisions of these AMRs.

An apparent inadequacy in the present MSTHM approach is its inability to represent what may be called the cold-trap effect. That is mass movement along the length of drift, resulting from thermal gradients, causing condensation in the cooler regions. This process was observed to occur in the Enhanced Characterization of the Repository Block (ECRB) drift when it was isolated from the ventilation system by a bulkhead to allow re-equilibration to unventilated conditions. Shortly after the ECRB was closed off with a bulkhead, condensation formed and dripped in cooler portions of the drift (A. Flint, personal communication). Subsequently it was determined that heat given off by the Tunnel Boring Machine (TBM) parked at the end of the ECRB created a thermal gradient in the drift causing water vapor to move toward the cooler end where it condensed and dripped. Such a process may occur in a closed repository where some waste packages, perhaps near the repository edge, are cooler than other waste packages. The resultant temperature gradient could cause vapor flow, condensation, and perhaps dripping onto the cooler waste packages. The SMT submodel of the MSTHM shows that the repository edge may be much cooler than the central regions. The MSTHM indicates condensation as a negative evaporation rate but there is no MSTHM submodel that incorporates the repository-scale thermal gradients along drifts from the center of the repository to the edges. In the nomenclature of the MSTHM submodels, a submodel that may be able to capture the potential cold-trap effect would be a Line-average-heat-source Mountain-scale Thermohydrologic (LMTH) submodel. The intermediate LMTH combination of the LDTH and SMT submodels as discussed above in the DOE Approach is not capable of modeling mass flow along the length of the drift because the LDTH submodel is a cross-section perpendicular to the long axis of the drift. It may be possible to model explicitly only one drift using symmetry boundary conditions to avoid the computational intractability of a fully three-dimensional mountain-scale thermohydrologic model. The LMTH submodel may possibly be validated, and confidence in the MSTHM increased, if it were to reproduce the condensation that occurred in the ECRB as a result of the thermal gradient created by the TBM. The cold-trap effect could potentially occur in drifts that are partially above boiling as well as drifts that are entirely below boiling.

The MSTHM is a large and complex computational tool involving numerous inputs, several interlinked sub-scale models, and voluminous outputs of data that are subsequently processed into the thermohydrologic abstraction for performance assessments. Consequently, it is very difficult to thoroughly evaluate all of the model assumptions and procedures, such as the scanning curves linking the sub-scale models, based solely upon the graphical interpretation of modeling results. A complete review of the MSTHM will likely require access to the model input and output files, and underlying codes, in order to assess aspects such as boundary and initial conditions and to confirm mass balance of model results.

5.3.2 DATA AND MODEL JUSTIFICATION WITH RESPECT TO THERMAL EFFECTS ON FLOW

The scope of the NRC review under this criterion includes evaluating the data and analyses the DOE references as justifying their planned approach (i.e., models) to incorporate FEPs related to thermal effects on flow into the performance assessment. The review will evaluate how specific data and analyses were used, interpreted, and synthesized into parameters to be included in the performance assessment. The review includes evaluating any DOE plans to collect additional information or perform additional analyses to provide justification for their planned modeling approach as well as identifying any additional information or analyses needed.

U.S. Department of Energy Approach

Data and analyses supporting thermohydrologic models are primarily derived from the thermal testing program at Yucca Mountain. A 1997 review of the DOE thermal testing and modeling program is included in section 5.6 of this IRSR. So far two tests (the Large Block Test (LBT) and the Single Heater Test (SHT)) have been completed, one test (the Drift-Scale heater Test (DST)) is in its third year of heating in a test with a total duration of 8 yrs, and one test (the Cross-Drift Thermal Test (CDTT)) is still in the planning stages. Revision 02 of the TEF IRSR (NRC, 1999) reviewed the goals and objectives of the thermal testing program stated in DOE planning documents. These goals and objectives are still considered valid and important but will not be repeated here. This summary focuses on the DST because this test has the largest spatial and temporal extent and provides the most recent and extensive data for verifying thermohydrologic process models.

The series of thermal tests conducted by DOE started with the LBT on Fran Ridge followed by the SHT and the ongoing DST in Alcove 5 of the ESF. These three tests were all conducted in the Middle Nonlithophysal unit of the Topopah Spring tuff. Plans have been prepared for a thermal test (CDTT) in the Lower Lithophysal unit of the Topopah Spring tuff, which comprises the majority of the repository host block, but this test has so far not been initiated. Conceptual models of thermohydrologic processes have evolved from the equivalent continuum approach through dual continuum models (DKM) using a constant continua interaction factor to the current so-called Active Fracture Model (AFM) that adjusts continua interactions according to fracture saturations using a fitting parameter.

Alcove 5 in the ESF is the site of two thermal tests. The SHT, conducted in a single borehole has been completed. The DST presently underway in the ESF is now the primary source of new information for improving and verifying thermohydrologic models. The test objectives of the DST specific to thermohydrologic processes were stated as (U.S. Department of Energy, 1995)

- Thermal
  - — Measure the temporal and spatial distributions of temperature
  - — Evaluate the influence of heat transfer modes

— Investigate possible formation of heat pipes
— Determine rock mass thermal properties

- Hydrological
  — Measure changes in rock saturation, particularly in the drying zone
  — Monitor the propagation of drying and subsequent rewetting regions, if any, including potential condensate cap and drainage.
  — Measure changes in bulk permeability (pneumatic)
  — Measure drift-air humidity, temperature, and pressure

The DST began heating a 47.5 m long, 5 m diameter drift in December 1997 (TRW Environmental Safety Systems, Inc., 1997a). The maximum planned drift wall temperature for the DST is 200 °C. Drift wall temperatures in the DST have been rising steadily since the onset of heating, with the exception of a few anomalies caused by power outages, and drift wall temperatures ranging from 185 to 204°C were observed on day 884 (CRWMS M&O, 2000h). This target drift wall temperature is consistent with expected conditions for an 85 MTU per acre thermal load. However, current EDA II design specifies a lower repository heat loading of 60 MTU per acre (CRWMS M&O, 1999a). The relevance of the DST planned maximum temperature to the lower thermal load is reassessed in Thermal Test Progress Report #4 (CRWMS M&O, 1999b). This reassessment states in part that the

> "goal of understanding heat-driven coupled processes is not directly tied to a specific repository design and does not require the replication of potential repository conditions, geometries, and heating rates, nor is such replication practical in the DST. The fundamental nature of the DST is to test conceptual process models in the system and the ability to model quantitatively the systems response to those processes. Once confidence is developed in the coupled process models, they can be applied to any repository design."

The DST is instrumented with a variety of sensors to monitor the progress of the test. In addition, the DST is actively monitored on a periodic basis with air permeability borehole testing and geophysical measurements over three scales [borehole neutron probe, cross-hole ground penetrating radar (GPR) tomography, and cross-hole electrical resistivity tomography (ERT)] to provide information on changes in saturation associated with thermohydrologic coupled processes. Acoustic emissions are continuously monitored to detect microfracturing related to thermal-mechanical-coupled processes. Limited additional instrumentation was installed after heating started in the DST. Heat dissipation probes and time domain reflectometers were installed in the ceiling on the cool side of the thermal bulkhead approximately 5 months after the onset of heating to track the movement of heat and moisture in the rock mass near the thermal bulkhead of the heated drift. These instruments were installed after water condensation on the drift walls immediately outside of the bulkhead was observed after about 40 days of heating.

The DST test block was characterized prior to the onset of heating. On-site characterization of the local geology, *in situ* hydrology, and local rock mass quality was supplemented with laboratory tests of Thermal-Mechanical-Hydrologic-Chemical (TMHC) properties. Characterization data collected from the SHT block (TRW Environmental Safety Systems, Inc., 1997b) were also incorporated. The ensemble of these data provides the characterization of the DST block and model parameters. These data are consistent with results from previous nonthermal test studies by Brechtel et al. (1995) and TRW Environmental Safety Systems, Inc. (1997b). The data are also consistent with parameter values cited in the TSPA-VA (TRW Environmental Safety Systems, Inc., 1998).

A specific objective of the *Thermal Hydrology Thermal Testing* AMR Revision 00 (CRWMS M&O, 2000i) was to compare calibrated property sets to data from the DST in order to determine the optimal property set to be used for thermohydrologic abstractions (CRWMS M&O, 2000j) in the TSPA. Computations reported in this AMR included sensitivity analyses and objective comparisons to DST data, primarily temperature. A conclusion of this AMR was that, based on comparisons to measured temperatures, all of the property sets tested could be considered valid. However, a QA audit conducted by the OQA of the DOE (Carter et al, 2000) noted that the AMR had not achieved its intended purpose in determining the best property set for thermal hydrology because all quantitative comparisons were to temperature data. Model-predicted saturations were compared only qualitatively and, in the fracture continua, varied significantly between the various property sets evaluated.

U.S. Nuclear Regulatory Commission Staff Evaluation

An aspect of the DST that may be of importance to repository performance is its ability to evaluate the development of thermal refluxing and to determine the potential for liquid water from refluxing to enter emplacement drifts during the thermal period, potentially contacting the EBS. The DST was designed and constructed to permit viewing the interior of the heated drift. Visual observations and camera shots through a window in the thermal bulkhead allow detecting the occurrence of refluxing water that may enter the drift. Temperature measurements within the rock mass also may indicate areas where refluxing water decreases the temperature of the drift wall to sub-boiling. This thermal bulkhead was never intended to prevent gas flow between the heated drift and the connecting drift. It was designed only to restrict the flow of heat out of the heated drift. During the design phase of the DST there were concerns that excessive pressure could build up in the heated drift, potentially creating a hazard. Therefore, the bulkhead was neither designed nor constructed to restrict gas flow from the heated drift and, in fact, it's doubtful whether a bulkhead could be constructed that would restrict gas flow from the heated drift because of the high permeability fracture system. The direction of gas flow through the bulkhead changes in response to changes in atmospheric pressure, although the predominate direction of water vapor flow has been out of the heated portion of the heated drift toward the connecting drift and ultimately into the ESF main drift (Chestnut, et al., 1998). This flow of air is driven by the heat source in the heated drift and is accentuated by the presence of ventilation ducts near the bulkhead.

Pretest analyses of the DST indicated that allowing gas pressure venting through the bulkhead would have a negligible effect on gas pressure, temperature, and dryout in the heated drift (Buscheck, et al., 1997). But monitoring gas pressure through a release valve in the bulkhead would be necessary in order to determine if buoyant advective dryout would occur (Buscheck and Nitao, 1995). This interpretation was based on an ECM conceptualization and is sensitive to the property values assigned to the air space of the heated drift and the manner in which air flow through the heated drift is represented. The DOE has estimated 5–7 kW of conductive heat loss and from 4 to 30 kW of convective heat loss (CRWMS M&O, 1999b) based on comparisons of temperature from thermohydrologic models to DST temperature data and heat flux measurements at the bulkhead. This, the DOE estimates, corresponds to approximately 35 L/hr of water vapor. NRC staff have expressed concern that unmeasured loss of mass from the heated drift complicates analysis of the DST results and may ultimately compromise the utility of the DST for evaluating refluxing during the thermal phase of the proposed repository design. The DOE has maintained that "more accurate characterization of the heat loss through the bulkhead" is "difficult, problematic, and unnecessary" (CRWMS M&O, 1999b). Because of concerns regarding these uncertainties, however, it was decided after extensive discussions among the thermal testing team to take a dual approach to quantifying mass and energy losses through the bulkhead (CRWMS M&O, 2000h). First, a proposal by the University of Nevada to measure losses in a manner requiring the sealing of cable bundles and other leakage through the bulkhead would be pursued. Second, the thermal test team would deploy a series of humidity and temperature sensors along the drift immediately outside the bulkhead. Muffin fans would be used to ensure proper air movement to prevent condensation. Both approaches would be implemented in FY01 if funding is approved (CRWMS M&O, 2000h).

Heat and mass losses from the heated drift through this bulkhead may have the effect of reducing the extent of refluxing above the drift. Modeling studies of the DST were performed at the CNWRA using the two-phase, multidimensional, nonisothermal heat and mass transfer simulator, MULTIFLO Version 1.2 (Lichtner et al., 2000) using a dual-continuum conceptual model. Effects from the boundary condition represented by the thermal bulkhead were indirectly incorporated into the 2D model by placing mass sink terms uniformly in the elements at the drift wall boundary totaling 0.08 kg/hr. These simulations indicated that, for a mass removal of 0.08 kg/hr from the drift wall elements, the predicted saturation in the heater drift crown is decreased, the zone of dryout in the fracture continuum is depressed slightly deeper into the rock unit, and the maximum fracture saturation observed in the fractures in the condensation zone above the heater drift is decreased. The total mass of water in the condensation zone in the fracture continuum is reduced slightly by the mass removal, however, the condensation zone in the matrix continuum is similar for the cases with and without mass removal. Different assumptions about parameters produced other results. In some test cases the differences with or without this mass loss were small.

Variations in temperatures and saturations as in the CNWRA models with and without mass loss also appear in DOE models using the various property sets and the ECM, DKM and AFM conceptual models. Comparisons between the DKM and AFM conceptualizations at 21 months of heating show similar good matches to temperature data but differences in distribution of fracture saturations. Heat pipe signatures seen in temperature data are reasonably well represented by the DKM model but are diminished or absent in the AFM model (CRWMS M&O, 1999b). In addition, ambient fracture saturations using the DKM are about 12 percent, whereas with the AFM, they are closer to 2 percent. Using the DKM, fracture saturations increase up to 50 percent during heating, while with the AFM, increases in fracture saturation are around 10 percent (CRWMS M&O, 1999b). While these different conceptualizations reproduce temperatures from the DST reasonably well, there are significant differences in their representations of fracture saturation. Qualitatively the results of these conceptualizations are similar, showing a dryout zone around the heaters and formation of condensate. However, the models differ in predicting the extent of dryout, the extent of two-phase or reflux zones, and the vertical symmetry of dryout.

The DOE is using Electrical Resistivity Tomography (ERT), Ground Penetrating Radar (GPR), neutron probes, and air-injection permeability tests to monitor changes in saturation in the rock mass surrounding the thermal tests. Of greatest relevance is instrumentation used to measure saturation at the DST. There is significant uncertainty in the interpretation of these data. Estimates of changes in saturation based on changes in electrical resistivity depend not only on saturation but also on temperature, ionic strength of the water, and the model used to relate these factors. The two models used to estimate saturation from resistivity (Blair, et al., 1998) produce significantly different saturation distributions. Temperature also affects radar wave velocity, and thus estimates of saturation based on GPR data. Neutron probes measure bulk water content in the rock, both in matrix and fractures, and thus are of limited use in determining changes in fracture saturation important to evaluating condensate drainage through fractures. Changes in air permeability, on the other hand, are inferred to directly result from changes in fracture saturation. However, these changes in air permeability can only be related qualitatively to changes in fracture saturation. A decrease in air permeability is inferred to correspond to an increase in fracture saturation, but quantitative determination of the fracture saturation is not yet possible by this method.

It appears that, at the present time, there is significant uncertainty in both the measurement and modeling of fracture saturations, extent of dryout, formation of heat pipes, liquid fluxes in heat pipes, and ultimately the fate of thermally mobilized water. A key aspect of the EDA II design is the intention for thermally mobilized water to condense and shed through the pillars between drifts. Given uncertainties in the losses of moisture through the bulkhead of the DST and the lack of quantitative measurements of condensation and drainage in fractures it is not clear that the DST can be used to determine the fate of thermally mobilized water. Measurements of losses through the bulkhead after 3 yr of heating may help to reduce this uncertainty somewhat but, if significant losses have occurred through the bulkhead, measurements now may not be sufficient to assess those losses. The test planned for the cross-drift, however, may be designed and conducted such that thermally mobilized water is not affected by unmonitored losses through a bulkhead, ventilation system, or test boundaries. This test may reduce uncertainty in the fate of mobilized water for the main repository block.

The design objective of maintaining pillar temperatures below boiling to allow for condensate drainage between emplacement drifts depends upon the efficacy of the ventilation system. The *Ventilation Model* AMR Revision 00 (CRWMS M&O, 2000g) shows 70% heat removal by ventilation flow rates between 10 and 15 m^3/s. However this model involves simplifying assumptions and is not supported by experimental data. Plans have been developed for a quarter-scale ventilation test to be conducted at the Engineered Barrier System Test Facility in North Las Vegas, Nevada (CRWMS M&O, 2000k). The NRC staff have not reviewed the plans for the ventilation test. This test needs to be completed to provide data for support and verification of the ventilation model.

5.3.3 DATA UNCERTAINTY WITH RESPECT TO THERMAL EFFECTS ON FLOW

The scope of the NRC review under this criterion includes evaluating the DOE approach to account for data uncertainty (including spatial variability and heterogeneity) in predictions of thermal effects on temperature, humidity, saturation, flux, and flow paths in the unsaturated zone. This includes reviewing the values, assumed ranges of values, probability distributions and assumptions for parameters (i.e., coefficients, variables, etc) used in non-isothermal process-level and abstracted models. The review includes evaluating any DOE plans to collect additional data or perform additional analyses to better characterize or constrain uncertainty with respect to non-isothermal affects as well as identifying any additional data or analysis needed.

U.S. Department of Energy Approach

Property sets for the matrix and fracture continua of the hydrostratigraphic units used in the MSTHM were taken from the *Calibrated Properties Model* AMR Revision 00 (CRWMS M&O, 2000f). The *Calibrated Properties Model* AMR Revision 00 (CRWMS M&O, 2000f) documents hydrologic property determination by an inverse methodology using the code ITOUGH2 (Finsterle, 1999). Basically, ITOUGH2 uses an iterative weighted-least-squares minimization of model results compared to measured data such as matrix saturation from borehole cores, *in situ* water potential measured in boreholes, and *in situ* pneumatic pressure data measured in boreholes. Properties were calibrated on two different scales, the mountain-scale and the drift-scale. Calibration of the mountain-scale properties used pneumatic pressure data which reflect the mountain-scale process of barometric pumping whereas calibration of the drift-scale properties did not consider pneumatic pressure data. Calibration of the mountain-scale properties using the pneumatic pressure data resulted in fracture permeabilities almost two orders of magnitude greater than fracture permeabilities determined from air-injection tests. This was explained as scale-dependence of the larger-scale pneumatic pressure data versus the smaller-scale air permeability data. Only fracture permeabilities were recalibrated for the drift-scale property sets while all other properties remained the same as the mountain-scale property sets. The *Multiscale Thermohydrologic Model* AMR Revision 00 (CRWMS M&O, 2000d) used the drift-scale property sets calibrated for the base case, lower bound, and upper bound infiltration maps. These infiltration maps are identified by the Data Tracking Number (DTN) GS000399991221.002. The development of these infiltration estimates are documented in the *Simulation of Net Infiltration for Modern and Potential Future Climates* AMR Revision 00 AMR (CRWMS M&O, 2000l). Drift-scale property sets for the base case infiltration map are identified as LB990861233129.001, for the upper bound infiltration map as LB990861233129.002, and for the lower bound infiltration map as LB990861233129.003.

Hydrologic model properties calibrated by the inverse method were permeability k, van Genuchten parameters α and m for both the fracture and matrix continua, and the active fracture model parameter β. Hydrologic parameters that were not calibrated by the inverse method were fracture and matrix porosity and residual and satiated saturation. The inversion was carried out in steps for the mountain-scale property sets using one-dimensional submodels corresponding to the locations of 11 surface-based boreholes for which matrix saturations, water potentials, and pneumatic pressure data have been measured. First, properties were calibrated by inversion on saturation and water potential data. Second, properties from the first step were used as initial estimates for further calibration against pneumatic pressure data. Third, the calibrated property set was checked against the saturation and water potential data and calibrated further if necessary. If further calibration was done at step three, the property set was checked against the pneumatic pressure data again. In the calibration against saturation and water potential in steps 1 and 3, fracture permeabilities for layers tcw11 through tsw37 were not included as calibration parameters but were set at fixed values. In the inversion against pneumatic data, these fracture permeabilities were the only parameters calibrated. For the drift-scale property sets, only fracture permeabilities of model layers tsw32-tsw37 were recalibrated with a single value of fracture permeability estimated for layers tsw36 and tsw37. Data used for calibration of the drift-scale property set were the same as for the mountain-scale property set with the exception that the pneumatic pressure data were excluded. The *Multiscale Thermohydrologic Model* AMR Revision 00 (CRWMS M&O, 2000d) used the drift-scale property sets for the base case, lower, and upper bound infiltration maps to calculate the variables listed in Table 12. Thermal properties used in the MSTHM were the same as those used for TSPA-VA (CRWMS M&O, 2000m). The *Abstraction of Near-Field Environment Thermodynamic Environment and Percolation Flux* AMR Revision 00 (CRWMS M&O, 2000e) then binned and averaged the variables listed in Table 12 according to glacial infiltration rates and stated "[t]he bin-averaged values preserve and highlight the overall variability and uncertainty in the variables used to describe the thermohydrologic performance of a geological repository."

U.S. Nuclear Regulatory Commission Staff Evaluation

Regarding uncertainties in the calibrated property sets used in the MSTHM, The *Calibrated Properties Model* AMR Revision 00 (CRWMS M&O, 2000f) states, "[q]uantifiable uncertainties are difficult if not impossible to establish for the estimated parameter sets." While this statement is very likely true, it is less difficult to show by the following three arguments that the full range of uncertainties in the property sets, and thus the variables calculated from them, are significantly under-represented.

First, measurement error, bias, and scale dependence in the saturation, water potential, and pneumatic pressure data were not adequately accounted for. Standard deviation of saturation data from cores was used to estimate weights for the weighted-least-squares inverse algorithm (CRWMS M&O, 2000f), but the effect of measurement errors on the resulting calibrated properties was not evaluated. Drying of the core during drilling and handling may have resulted in systematic bias in the matrix saturation data. A simplified model of core drying by evaporative loss was used to adjust the matrix saturation data for the inverse procedure (CRWMS M&O, 2000f). However, core drying during drilling was not included in the evaporative loss model and no attempt was made to correlate matrix saturations measured on core data with other data such as *in situ* measurements made using heat-dissipation probes. Measurements of *in situ* water potential were made in open boreholes and rock in the immediate vicinity around the boreholes may have dried out which would have systematically biased these data.

These three types of data (matrix saturation from cores, water potential from boreholes, and pneumatic pressures) were measured on different scales ranging from a few cm for cores to several 10's of m or more for pneumatic pressures. Matrix saturations from core data were upscaled by arithmetic averaging, a process that may tend to smooth out variability, but it is not clear how the scale dependence of the water potentials and pneumatic pressure data was treated. Pneumatic pressure data are known to be scale dependant because fracture permeabilities from barometric pumping response tend to be about two orders of magnitude greater than fracture permeabilities determined from air-injection testing (CRWMS M&O, 2000f).

The nonlinear least-squares maximum likelihood inverse method implemented in ITOUGH2 is essentially deterministic in that the only source of randomness or uncertainty is in the measurement error. Thus the measurement error must be generalized to include such things as scale dependence and modeling errors because there is no other way to account for uncertainty in the least-squares inverse approach (McLaughlin and Townley, 1996).

Second, in a discussion of the conceptual model used to develop the calibrated property sets the *Calibrated Properties Model* AMR Revision 00 (CRWMS M&O, 2000f) states that, "[h]eterogeneity of hydrologic properties is predominantly a function of geological layering" and treats each geological layer in the model as homogeneous. The resulting average layer-calibrated drift-scale property sets for the base case show fracture permeability in the Tsw34 unit to be 2.76E-13 m^2 and in the Tsw35 unit to be 1.29E-12 m^2. For the upper bound infiltration map these change to 4.63E-13 m^2 and 5.09E-12 m^2 and for the lower bound to 4.99E-13 m^2 and 1.82E-12 m^2 for the Tsw34 and Tsw35 units respectively. Thus all of the variability and uncertainty in model layer fracture permeability for these two units ranges within about one order of magnitude. A statistical analysis of air-injection data collected from the niches in the ESF, however, found fracture permeabilities ranging from 1.53E-15 m^2 to 7.15E-10 m^2. These data, all collected in the Tsw34 unit, indicate that heterogeneity of fracture permeability can range over at least four orders of magnitude within a single geological layer. It is not clear how using homogeneous layer properties in a model, with variability ranging over one order of magnitude, can adequately represent variability and uncertainty that may range over several orders of magnitude within a single geological layer.

Third, the *Thermal Tests Thermal-Hydrological* AMR Revision 00 (CRWMS M&O, 2000i) was conducted for the purpose of evaluating "the drift scale thermohydrologic (DS) property set derived from the unsaturated (UZ) flow and transport analyses for thermally-perturbed conditions." That is, it had as a purpose to evaluate the use of the drift-scale property sets from the *Calibrated Properties Model* AMR Revision 00 (CRWMS M&O, 2000f) for modeling thermohydrologic processes. "Also, the secondary purpose [was] to conduct sensitivity studies of other TH property sets, including the mountain scale thermohydrologic (MS) property set, and to investigate modifications that would result in adequate agreement between simulated and measured TH data." To this end the AMR compared eight property sets against thermal test results from the Single Heater Test, the Large Block Test, and the Drift Scale Test. The property sets evaluated in this AMR included the DS, the MS, the TSPA-VA property set, the Alcove #5 property set (DKM-TT99), the SHT median bulk permeability (Median kb), the Mountain Scale Local Thermal Conductivity (MSLK), the Mountain Scale Higher Fracture

Permeability (MSFP), and the Conduction Only (CON) data. In conclusion this AMR found that, of “the numerous combinations of property sets and thermal tests considered in the analyses, no one property set is distinctly superior in simulating thermal response” and that, based on comparisons of measured with modeled temperatures, all the models and property sets “considered were sufficiently valid for the purposes of these analyses” (CRWMS M&O, 2000i). But comparison of model results for fracture saturations shows the DS property set predicting maximum fracture saturations of around 0.15 and the DKM-TT99 property set predicting maximum fracture saturations of around 0.5. These differences in predicted fracture saturations translate to between one and two orders of magnitude difference in predicted capillary pressures. While the reasonably good comparisons between measured and modeled temperatures indicate that heat transfer is predominantly by conduction and fairly well-understood, predictions of hydrologic variables such as fracture saturations, capillary pressures, and fracture fluxes can vary significantly between property sets and thus the distribution of mass predicted by the models is highly uncertain. The *Multiscale Thermohydrologic Model* AMR Revision 00 (CRWMS M&O, 2000d) uses only the drift-scale property sets to calculate thermohydrologic variables and it is not clear how this captures the variability and uncertainty seen in predictions using other property sets or the uncertainty in comparisons to actual test results. Note that all thermal tests at Yucca Mountain to date have been conducted in the Tsw34 unit so all of the conclusions of the *Thermal Tests Thermal-Hydrological* AMR Revision 00 (CRWMS M&O, 2000i) apply only to that unit. Thus it seems reasonable that, if the analyses were done on the remaining geological units, the predicted variability and uncertainty would be greater.

The *Calibrated Properties Model* AMR Revision 00 (CRWMS M&O, 2000f) concludes by recommending that future studies “should consider the use of Monte Carlo simulations to evaluate the appropriateness of using the prior information uncertainty for the calibrated properties.” Such exercises would be useful for evaluating the propagation of uncertainty through the least-squares inverse approach as discussed in the first point above. However this would not address the uncertainty inherent in spatial heterogeneity as discussed in the second point nor would it adequately address the uncertainty in the equally valid but significantly different models and property sets of the *Thermal Tests Thermal-Hydrological* AMR Revision 00 (CRWMS M&O, 2000i) as discussed in the third point above. Additional studies applying generally accepted methods of stochastic subsurface hydrology, sensitivity, and bounding analyses would be required to address the uncertainty raised in the second and third points above.

5.3.4 MODEL UNCERTAINTY WITH RESPECT TO THERMAL EFFECTS ON FLOW

The scope of the NRC review under this criterion includes evaluating whether the DOE has considered alternative modeling approaches to make predictions of thermal effects on temperature, humidity, saturation, flux, and flow paths in the unsaturated zone. The review should evaluate whether alternative models are consistent with available data and analyses. Assuming the DOE has considered alternative conceptual models, the review should evaluate the approach the DOE has taken to use the alternative models to address model uncertainty to determine whether there is an adequate technical basis for DOE’s approach. The review includes evaluating any DOE plans to conduct additional analyses related to alternative modeling approaches as well as identifying any additional analyses needed.

U.S. Department of Energy Approach

The *Multiscale Thermohydrologic Model* AMR Revision 00 (CRWMS M&O, 2000d) includes a section titled “Comparison of MSTHM against an Alternative Conceptual Model. The alternative conceptual model referenced is by Haukwa et al. (1998) which is also documented in the *Mountain-Scale Coupled Processes (TH) Models* AMR Revision 00 (CRWMS M&O, 2000m). The MSTHM was implemented using the NUFT code and the mountain-scale coupled process model was implemented using the TOUGH2 code. Both models use the DKM formulation modified by the AFM and the property sets derived from the *Calibrated Properties Model* AMR Revision 00 (CRWMS M&O, 2000f). The major differences between the two models are the dimensionality, the MSTHM is a 3-D representation while the mountain-scale coupled process model is an east-west 2-D cross-section, and the areal power loading representing waste package heat. The MSTHM model has an areal power loading of 92.3 kW/acre while the mountain-scale coupled processes model has an areal power loading of 99.4 kW/acre. Other minor differences between the two models are in the representation of the drift, grid discretization, and averaging of waste package thermal output along the drift axes. Not surprisingly, the two models get fairly similar results.

An alternative conceptual model for incorporating the possibility of preferential liquid flow through rock heated above the boiling point of water was implemented in the *Abstraction of Near-Field Environment Thermodynamic Environment and Percolation Flux* AMR Revision 00 (CRWMS M&O, 2000e). This alternative conceptual model is mentioned in the *Features, Events, and Processes in Thermal Hydrology* AMR Revision 00 (CRWMS M&O, 2000b) and recommended in the *Abstraction of Drift Seepage* AMR Revision 00 (CRWMS M&O, 2000n) which states:

> “An approximate method for including thermal effects on seepage is to use percolation flux above the emplacement drifts from a thermal-hydrology model as input to the seepage abstraction, rather than percolation flux from the isothermal UZ flow model. That way, if the thermal-hydrology model indicates a period of increased liquid flow because of condensate drainage, it will automatically be translated to an increase in seepage during that period. However, in order to be conservative, if the thermal-hydrology model indicates a period of reduced liquid flow because of dryout of the rock around a drift, seepage should instead be continued at its ambient (pre-heating) level through that period, in recognition that it may be possible for rapid fracture flow in discrete flow paths to penetrate the hot rock and reach the drift.”

The *Abstraction of Near-Field Environment Thermodynamic Environment and Percolation Flux* AMR Revision 00 (CRWMS M&O, 2000e) implements this recommendation by taking flux calculated in the MSTHM at a location 5 m above the crown of the drift and inputting this into the seepage abstraction model. The seepage abstraction (CRWMS M&O, 2000n) used data from the *Seepage Model for PA Including Drift Collapse* AMR Revision 00 (CRWMS M&O, 2000o) to develop a probabilistic relationship between deep percolation flux rate and the fraction of waste packages contacted by seepage and flow rates onto those wetted waste packages. The *Seepage Model for PA Including Drift Collapse* AMR Revision 00 (CRWMS M&O, 2000o) used a process model of flow through the fractures represented by a heterogeneous porous media continuum with the TOUGH2 code. Fracture permeability was treated stochastically as a heterogeneous random field and data of flow rates and wetted area were developed by Monte Carlo simulations. The alternative conceptual model for seepage into above-boiling drifts in the *Abstraction of Near-Field Environment Thermodynamic Environment and Percolation Flux* AMR Revision 00 (CRWMS M&O, 2000e) takes liquid velocities 5 m above the drift out of the thermohydrology model and uses the abstraction of the seepage model for ambient conditions to distribute this liquid water onto above boiling waste packages.

U.S. Nuclear Regulatory Commission Staff Evaluation

The mountain-scale coupled processes alternative conceptual model referenced in the *Multiscale Thermohydrologic Model* AMR Revision 00 (CRWMS M&O, 2000d) and used for comparisons is actually not an alternative conceptual model but instead is nearly identical to the MSTHM conceptual model, differing only in a few details of implementation. If these two models failed to give very similar results it would be a matter of concern.

The development of models for simulating coupled thermohydrologic processes has gone through a number of stages that could be considered alternative conceptual models. This continuing development indicates that conceptual models of thermohydrology in unsaturated fractured rock environments are not sufficiently refined and that additional improvements are not only possible but are needed. For instance, if a single continuum representation were adequate then there would have been no need to develop the dual-continuum approach. If the matrix were in constant equilibrium with the fractures then there would have been no need for a matrix-fracture restriction factor and no need for the AFM conceptual model. It is very likely that the thermohydrologic models in use a few years from now will be modified and different in some key aspects from the AFM adjusted DKM currently in use. Uncertainty in model parameters (e.g. permeability) can be treated by methods such as Monte Carlo simulations and sensitivity analyses. Uncertainty in the models themselves, however, is much more difficult to estimate and that is the purpose of looking at alternative conceptual models. Uncertainty inherent in conceptual models may be evaluated from the range of results predicted by alternative conceptual models. It appears that alternative conceptual models have been used for just this purpose. It may be that the *Thermal Tests Thermal-Hydrological* AMR Revision 00 (CRWMS M&O, 2000i) is, in part, such an exercise in evaluating alternative conceptual models by comparison with data from thermal tests. Previously, comparisons of the equivalent continuum model (ECM) with the DKM have indicated that data from the thermal tests are not sufficient to discern which of these alternative conceptual models gives the more accurate representation of thermohydrologic behavior (Tsang et al, 1999). In fact, the *Thermal Tests Thermal-Hydrological* AMR Revision 00 (CRWMS M&O, 2000i) found that, based on temperature comparisons, all of the conceptual models and property sets evaluated were essentially valid. Even though the various property sets and conceptual models gave different results for thermohydrologic variables such as fracture saturations, the techniques for measuring fracture saturations were not sufficiently accurate to allow determination of the most appropriate conceptual model and property set.

Because the data from the thermal testing program are not sufficient to unequivocally determine the most realistic conceptual model and the most representative property set for modeling thermohydrologic processes at Yucca Mountain, then the range of results from all of the alternative models may perhaps give an estimate of the conceptual model uncertainty. While conceptual models and property sets are inextricably linked, conceptual model uncertainty exists in addition to parameter uncertainty and variability. That is the actual uncertainty in thermohydrologic process models is a combination of parameter uncertainty, spatial variability, and conceptual model uncertainty. Ignoring any of these may lead to false confidence in the model predictions.

Combining thermal flux of water at 5 m above the drift crown with an isothermal seepage abstraction at the drift wall boundary is an innovative, although not entirely plausible, alternative conceptual model of a process that may result in preferential flow through above-boiling fractures. It has been recognized in development of geothermal fields that instability of a liquid front can cause liquid fingers to advance ahead of the front and breakthrough superheated rock to steam extraction wells (e.g. Woods and Fitzgerald, 1993; Fitzgerald and Woods, 1994). This process of liquid flow through above boiling rock as fingers, rivulets, and preferential flow channels has been investigated specifically for the proposed Yucca Mountain repository both analytically (Phillips, 1996) and numerically (Pruess, 1997). The physical process of fingering liquid flow by gravity drainage along a subvertical fracture infiltrating rock at temperatures above boiling has recently been visualized in a Hele-Shaw cell laboratory experiment (Hughson et al. 2000). Clearly, liquid water flow through rock at above-boiling temperatures is a real phenomenon that should be considered in performance assessments of the proposed repository. However, while staff support the use of alternative conceptual models in performance assessment abstractions and prudent conservative assumptions as in the paragraph quoted above, the conceptual model of distributing flux from 5 m above the drift crown into the drift during the above boiling period through the isothermal seepage abstraction may not be entirely defensible.

The location, extent, and magnitude of the zone of thermal refluxing vary according to the thermal loading and duration of heating. As the dryout zone around the heated drifts expands, the boiling isotherm moves farther away from the drift. The zone of thermal refluxing exists beyond the boiling isotherm and its extent and the magnitude of liquid flux by gravity drainage depend on several hydrologic properties such as fracture permeability and fracture – matrix interaction and the available amount of water. Observation of liquid flux at a fixed location above a heated drift through time would initially see percolation flux at the ambient background rate. As the above-boiling zone developed, flux magnitudes at the fixed observation point would sharply increase as the refluxing zone moved upwards then drop to zero as the refluxing zone passed and the dryout zone enveloped the point of observation. Liquid flux would remain at zero until the heat dissipated and then spike upwards again as the refluxing zone collapsed back to the drift. Finally fluxes would return to the ambient background rate as the repository cooled. The phenomenon of liquid flow through the above boiling region, as described theoretically by Phillips (1996), is a small-scale process that is not captured by volume-averaged continuum models with grid block sizes on the order of a meter, even including heterogeneity ranging over several orders of magnitude. Using a spatial grid resolution on the order of 0.2 m and flow rates of approximately 274 l/day, Pruess (1997) found seeps may advance downward through fractures at above-boiling temperatures at rates on the order of 1 m/hr. Fine grid resolution simulations may be computational intractable for drift- and mountain-scale domains modeled in the MSTHM. However, the MSTHM has approached the problem of scale and computational intractability using an innovative multi-scale technique whereby processes are modeled at the appropriate scale, whether mountain-scale thermal conduction or drift-scale thermohydrology, and the results combined into a fully 3-D model of the entire repository block and surrounding region. It may be possible to extend this multi-scale methodology to include process-level models of preferential liquid flow through above-boiling regions as demonstrated by Pruess (1997). Physically based process models of the potential for liquid flow into above-boiling rock would be much more defensible than forcing water into above-boiling drifts via the isothermal seepage abstraction.

5.3.5 MODEL SUPPORT WITH RESPECT TO THERMAL EFFECTS ON FLOW

The scope of the NRC review under this criterion includes evaluating whether the DOE's approach to predict the thermal effects on temperature, humidity, saturation, flux and flow paths in the unsaturated zone, in the context of the performance assessment, is additionally supported by comparisons with output of sensitivity studies, natural analogs, or empirical observations. Note that for those instances where the output of process-level models is directly incorporated ("abstracted") into the performance assessment analysis, objective comparisons of process-level and abstracted model "outputs" is not a meaningful objective measure of support.

U.S. Department of Energy Approach

As discussed under the previous four review criteria, computation of thermohydrologic variables was accomplished using the MSTHM as documented in the *Multiscale Thermohydrologic Model* AMR Revision 00 (CRWMS M&O, 2000d). Comparisons of the NUFT thermohydrologic model predictions with thermal tests results from the LBT and DST and sensitivity studies of the various models and property sets are documented in the *Thermal Tests Thermal-Hydrological* AMR Revision 00 (CRWMS M&O, 2000i). In preparing results from the MSTHM for use in performance assessments, the *Abstraction of Near-Field Environment Thermodynamic Environment and Percolation Flux* AMR Revision 00 (CRWMS M&O, 2000e) binned variables according to five ranges of glacial percolation flux, averaged the results, and included the extreme high and low ranges. The abstracted thermohydrologic variables were not compared to the sensitivity studies, natural analogs, data from the thermal tests, or output from the process-level models. Because the results from the MSTHM were incorporated directly into the abstraction it seems reasonable to expect that thermohydrologic conditions drawn from any realization of the abstraction could be found somewhere in the 3-D domain of the MSTHM.

U.S. Nuclear Regulatory Commission Staff Evaluation

Heating of large volumes of unsaturated fractured rock, accessible to instrumentation, to above-boiling temperatures is likely restricted to geological repositories and thus it is unlikely that meaningful comparisons can be made to natural analogs or other observations outside of thermal tests at the proposed Yucca Mountain repository. Therefore, that aspect of the scope related to supporting models by comparing results to natural analogs or off-site observations is not meaningful or applicable. However, one thermal test (the CDTT) remains to be conducted and this offers an opportunity for building confidence in the thermohydrologic abstraction. Pre-test process-level model predictions could be compared with the actual test results to verify that the thermohydrologic models do actually represent the important processes in thermal effects on flow. The distribution of abstracted model results should encompass the variability of both the pre-test model predictions and the actual thermal test results. In addition, the abstracted model should represent the CDTT more than the previous thermal test results because the lower lithophysal unit of the Topopah Spring Tuff in which the CDTT will be conducted is the predominant host formation of the proposed repository.

5.3.6 STATUS AND PATH TO RESOLVE SUBISSUE 2

Subissue 2 (Thermal effects on temperature, humidity, saturation, and flux) is open. To close this subissue, the DOE needs to address identified open items. Specifically, the DOE needs to:

- Complete thermohydrologic modeling for the current repository design.

- Include the process (FEP) referred to as the “cold-trap effect” in the MSTHM process models. Subsequently, provide model support for implementation of the MSTHM “cold-trap effect” model by comparison with past observations such as condensation in the ECRB under a thermal gradient imposed by the TBM.

- Provide traceable references to MSTHM model input and output to allow review of such aspects as boundary and initial conditions and to confirm the mass balance of model results.

- Consider measuring losses of mass and energy through the bulkhead of the DST. This would improve understanding of the fate of thermally mobilized water in the DST, and improve predictive modeling of the distribution of thermally mobilized water in the proposed repository.

- Address (i) the potential for unmonitored mass and energy flow through test boundaries of the CDTT and (ii) the effect of unmonitored mass and energy flow through test boundaries of the CDTT on the usefulness of test results before the test begins. Consider designing and conducting the CDTT so as to avoid unmonitored mass and energy flow through test boundaries.

- Provide data support for the ventilation model by completing the ongoing ventilation test. Subsequently, provide model support for the ventilation model by comparisons to the test data.

- Evaluate data uncertainty in (i) measurement error, bias, and scale-dependence in the saturation, water potential, and pneumatic pressure data used for model parameter calibration, (ii) heterogeneity and spatial variability in thermohydrologic properties, and (iii) variability in model results using the various property sets found to be valid for thermohydrologic modeling and propagate this uncertainty through the thermohydrologic model abstraction.

- Evaluate model uncertainty as seen in results from various alternative conceptual models such as the ECM, DKM, AFM and propagate this uncertainty through the thermohydrologic model abstraction.

- Provide model support by predicting thermohydrologic results of the CDTT to verify the thermohydrologic model abstraction adequately represents the potential thermohydrologic conditions expected in the proposed repository.

5.4 U.S. NUCLEAR REGULATORY COMMISSION REVIEW OF THE U.S. DEPARTMENT OF ENERGY SITE CHARACTERIZATION PLAN

The NRC review of the DOE's SCP (U.S. Nuclear Regulatory Commission, 1989) resulted in two comments and one question within the scope of the TEF KTI:

- Comment 11 (U.S. Nuclear Regulatory Commission, 1989): There are no hypotheses presented about thermal effects on the hydrologic system caused by emplaced waste. As a result, it is unclear if the limited testing program will be adequate to understand the response of the hydrologic system to the thermal load. Further, some information from the geohydrology program expected by other program areas cannot be provided.

- Comment 73 (U.S. Nuclear Regulatory Commission, 1989): Conservative design approach has not been used to determine required backfill hydraulic conductivity.

- Question 33 (U.S. Nuclear Regulatory Commission, 1989): It is stated that the accumulation of standing water in boreholes would lead to deleterious effects on the waste package performance. For that reason, as part of the performance allocation process, a design goal for drainage from boreholes is to allow no more than 5 L of standing water per package to accumulate in the emplacement hole for the first 1000 years following repository closure. How can the presence of standing water during the first 1000 years be justified? What is the acceptance basis for 5 L of standing water per canister?

Comment 11 relates to Subissue 1, sufficiency of the DOE's thermohydrologic testing program. Since the time of Comment 11 (U.S. Nuclear Regulatory Commission,1989), the DOE has developed a number of hypotheses about attributes of the disposal system deemed important to containment and isolation as part of the DOE's WCIS. As noted in Section 3.1 of this report, a number of these hypotheses can be related to TEF. Also, since 1989, staff have engaged in numerous interactions with the DOE and commented directly on the sufficiency of the DOE's thermohydrologic testing and modeling programs, as discussed in Section 5.3 of this report. Given the evolution of the DOE's WCIS and the DOE's thermohydrologic testing program since 1989, Comment 11 has been superseded by the focused review of the evolving DOE program by the NRC. Hence, Comment 11 is considered resolved.

Comment 73 relates to Subissue 2, sufficiency of the DOE's thermohydrologic modeling approach and Subissue 3, adequacy of treatment of TEF in the DOE's TSPA. At the time, Comment 73 was prepared, repository design was considerably different than the DOE reference design. Currently, backfill is considered a design option and is not part of the reference design. The staff concludes that the analysis underlying the DOE's determination of design backfill requirements presented in the DOE's SCP is outdated and, in that sense, Comment 73 is considered resolved. The staff notes that in the TSPA-VA plan, however, the DOE identified questions about backfill (backfill or no backfill options, including type of material and method of backfilling) as key uncertainties related to the EBS in current thermohydrologic analyses (TRW Environmental Safety Systems, Inc., 1996). Clearly, thermal modeling requires sufficient data (or design requirements) to adequately define relevant parameters, parameter values, and conceptual models. Although Comment 73 is considered closed, staff will continue to review the bases underlying the parameter values used in thermohydrologic analyses supporting the DOE's TSPA-VA and new questions that could arise regarding the process for determining the design requirements for backfill hydraulic conductivity or other parameters.

Question 33 relates to Subissue 3, adequacy of treatment of TEF in the DOE's TSPA. Since the time of question 33, there has been considerable change in the DOE's reference repository design. The waste packages will no longer be placed in vertical boreholes, hence, the question about design goals for, or estimates of, the amount of standing water in waste package emplacement holes is moot. Therefore, Question 33 is considered resolved. As noted throughout this report, the question of the amount, timing, and duration of water contacting the waste packages as liquid or vapor is a significant question that will continue to be tracked by the staff.

5.5 U.S. NUCLEAR REGULATORY COMMISSION AUDIT REVIEW OF THE U.S. DEPARTMENT OF ENERGY TOTAL SYSTEM PERFORMANCE ASSESSMENT–1995

The NRC/CNWRA audit review of the DOE's TSPA–95 identified two areas of concern related to Subissue 3, adequacy of treatment of TEF in the DOE's TSPA:

- Heat transfer calculations are not transparent and inconsistencies with previous estimates are not adequately explored (U.S. Nuclear Regulatory Commission, 1996a).

- Assumptions and limitations inherent in the ECM formulation were neither assessed nor comparisons made with alternative models.

The NRC staff considers these two areas of concern with the DOE's TSPA-95 rendered moot by the DOE's completion of TSPA-VA. Nevertheless, the following discussion is retained in this revision of the IRSR for completeness.

The CNWRA performed independent heat transfer calculations at drift scale to determine the time varying temperature and relative humidity at the surface of a typical waste package. The staff used both a heat-conduction-only model and a multiphase-flow model, simulating heat and mass transfer. The staff concluded that the DOE's assumptions regarding backfill conductivity and prebackfill radiative heat transfer do not appear to be consistent with previous work and may not be realistic. The staff also concluded that the DOE's calculation of backfill conductivity and prebackfill radiative heat transfer are not sufficiently documented to allow a proper examination of differences in results (for the prebackfill period).

In addition to calculations of temperature in TSPA–95, the staff raised a concern regarding the conceptual models used in the thermohydrologic calculations. Three sets of analyses in TSPA–95 (Chapter 4) relate to thermohydrology: (i) a primary set of drift-scale analyses, (ii) an alternative drift-scale model (Buscheck, et al., 1995), and (iii) a set of repository-edge calculations. All analyses were predicated on an ECM (Pruess, et al., 1985) in which hydraulic equilibrium between fractures and the matrix is assumed. Justification for invoking an ECM was cited as a paucity of data on geometric/hydraulic characteristics of fractures at Yucca Mountain and the computational complexity associated with modeling hydrothermal behavior in a discrete fracture network. ECM models have not been shown to provide conservative estimates of groundwater flow through heterogeneous media because the ECM formulation is incapable of accommodating episodic fracture flow, a mechanism that could lead to rapid transport pathways.

The assumption of hydraulic equilibrium between fractures and the matrix inherent in the ECM formulation precludes episodic fracture flow back to waste packages in the presence of less than a fully-saturated matrix. This or other fluid transport mechanisms not included in the ECM formulation could result in significantly different water contents or fluxes in the waste package environment than those suggested by the thermohydrologic analyses. The presence of water, as bulk liquid or as a thin film on the canister surface, can enhance the onset and rate of corrosion of the waste package. Water transport models are required, that accurately incorporate the mechanisms that dictate the saturation, flux of water through the matrix or fractures, and time at which water re-enters the near-field environment of the waste package subsequent to the onset of heating. The omission of a mechanism, such as episodic fracture flow from an ECM, suggests that results drawn from the analyses are not conservative (Pruess and Tsang, 1993, 1994; Wittwer, et al., 1995).

The lack of conservatism in the thermohydrologic modeling can be assessed, at least in part, by comparing the ECM formulation results with those derived from alternative conceptual models. For example, one possible alternative conceptual model could be formulated from dual-porosity, dual-permeability, or both representations. Additional alternative conceptualizations could be taken from a discrete fracture flow model or from an ECM model in which the hydraulic equilibrium requirement is relaxed. These flow models could be used to investigate the relative importance of episodic fracture flow and provide evidence to test if the ECM formulation adequately incorporates the important fluid transport mechanisms expected at the proposed repository.

In its TSPA-VA plan, the DOE noted staff concerns about the transparency (and reproducibility) of its heat transfer calculations and the use of 2D versus models (TRW Environmental Safety Systems, Inc., 1996). Further, the DOE noted that preliminary modeling results, using both DKM and ECM models, demonstrate that the results can be affected by the assumed conceptual flow model (TRW Environmental Safety Systems, Inc., 1996). The concerns expressed by the staff about the dimensionality of models and assumed conceptual flow models have been included as key issues in the DOE's thermal-hydrology abstraction/testing workshop (Francis, et al., 1997; Table 1-1, Key Issues List). The DOE has developed a number of task plans to specifically resolve the key thermohydrologic modeling and TSPA issues (Francis, et al., 1997). Based on information provided by the DOE at the DOE/NRC Technical Exchange on TSPA, July 21–22, 1997, San Antonio, Texas, it appears the DOE has made progress in implementing specific task plans related to thermohydrologic modeling for its TSPA-VA. Staff feels it is necessary, however, to be able to review in more detail the thermohydrologic modeling methodology employed by the DOE for its TSPA-VA prior to resolving the noted open items. Staff may propose an additional Appendix 7 interaction focusing solely on thermohydrologic modeling for TSPA-VA.

As stated previously, the NRC staff considers the two areas of concern related to the DOE's TSPA-95 to be resolved based on review of the DOE's TSPA-VA.

5.6 U.S. NUCLEAR REGULATORY COMMISSION REVIEW OF THE U.S. DEPARTMENT OF ENERGY THERMAL TESTING AND MODELING PROGRAM–1997

Staff reviewed information on the DOE's thermohydrology testing and modeling program and submitted comments to the DOE (U.S. Nuclear Regulatory Commission, 1997). The objective of this review was to evaluate if the program will provide information necessary for the license application.

For this review, staff depended mainly on the January 1996 report by the peer review team (PRT) (U.S. Department of Energy, 1996b) established by the DOE to review its thermohydrology program and associated DOE responses and PRT counter responses. In addition, staff factored in information from previous DOE documents as well as information gathered during an Appendix 7 meeting (July 1996) and the DOE/NRC ESF Video Conference (September 1996).

This review identified no objections related to the DOE's program; however, several comments related to Subissue 1, sufficiency of the DOE's thermohydrologic testing program and Subissue 2, sufficiency of the DOE's thermohydrologic modeling approach, were generated. First, there was a concern that an accelerated DST at thermal loads much higher than those expected at the repository would pose a risk of masking potentially important heat and mass transfer phenomena that might be present during operation of a HLW repository. If these phenomena were masked in the DST, test results would not provide the information necessary to differentiate among alternative heat and mass transfer conceptual models. Second, the applicability of the ECM approach or alternative approaches to bound predictions of liquid flow to waste packages has not been demonstrated. Finally, it is not clear that the testing and modeling strategy will observe and evaluate phenomena to determine the importance of THC coupling. These comments are discussed in more detail:

- Thermal Testing Strategy: The staff supports the DOE's approach of phased thermal testing at various scales from laboratory-scale testing to the Fran Ridge LBT to the alcove-scale single heater test to the drift-scale heater test. It is the understanding of the staff that evaporation of water close to the heat source, condensation in cooler regions at some distance from the source, and potential gravity influenced liquid water flow (mostly through fractures) toward the heat source are possible phenomena of significant interest, because they may determine the time and rate of wetting of the waste packages and hence, effectiveness in waste containment and subsequent radionuclide transport. Of the thermal tests to be conducted at various scales, the DST at the ESF testing will probably provide the best source of data for differentiating among conceptual models. Using knowledge of the location and kinds of sensors used in the test, analyses should be conducted to check that the significantly higher heat load of the planned DST compared to the expected repository heat load will not mask potentially important phenomena.

- Adequacy of Conceptual Model: The influence of fractures on rates of water flow toward waste packages is a central question in estimating the life of waste packages. The proposed DOE thermal-hydrology tests should distinguish among alternative conceptual models, including those that incorporate fractures and those that do not. Specifically, the proposed tests should be designed to discriminate among various conceptual models, such as the ECMs in which the fractures and porous rock are conceptualized as a single continuum, in contrast to discrete fracture models or models that use the concept of multiple interacting continua. The DOE needs to demonstrate that the model selected for performance analyses will include the important processes that affect water flow and to provide conservative bounds on water flow rates and subsequent effects on EBS performance.

- Effects of THC Coupling: the DOE's testing and modeling strategies should include means for bounding the effects of THC coupled processes on repository performance. Some NRC/CNWRA and DOE-sponsored work indicates that this three-process coupling may lead to significant changes in the near-field environment, and thus, influence waste package performance. A suitable DOE THC modeling strategy needs to be developed. The staff supports a phased approach in which a scoping analysis is first performed to demonstrate that THC bounding assumptions and analyses are conservative. If the THC bounding assumptions and analyses cannot be shown to be conservative by the DOE, then THC coupled effects need to be evaluated using more robust THC models.

The DOE sent a response to the NRC letter review of the DOE's thermal testing and modeling program (U.S. Department of Energy, 1997a, b, or c). In the letter, the three areas of concern were individually addressed. The DOE cited recent analyses and thermal-hydrology test design modifications made subsequent to the NRC review. Of greatest relevance in these test design modifications is an incorporation of variable thermal load instrumentation in the DST—a modification that will allow the DOE to adjust the thermal load during the conduct of the DST. Although not identified as a firm test limitation, the DOE's letter states the design drift wall temperature is to be a maximum of 200 °C. Of continuing concern, however, is an apparent lack of appreciation for the possibility for condensate drainage, or refluxing, into emplacement drifts at times prior to the postboiling period. The DOE cites analyses that indicate the dry-out zone may extend more than 300 m vertically, which would suggest refluxing will not be a concern until the postboiling period. A peer review of the DOE TSPA interim report (U.S. Department of Energy, 1997c), however, cites numerical predictions by Haukwa, et al. (1996) and Ho, et al. (1997) in which the temperature of the repository horizon never exceeds boiling for a thermal load of 83 MTU/acre and infiltration rates of 4.4 and 10 mm/yr, respectively. This observation by the PRT supports the concern for the possibility of condensate drainage into emplacement drifts prior to the postboiling period.

Following are summaries of the original NRC comments on the thermal testing and modeling strategies, staff understandings of the DOE's responses, and staff evaluations of those responses:

Comment 1: A field-scale heater test, at thermal loads much higher than those expected at the repository, poses a risk of masking the phenomenon of gravity-driven liquid water flow toward the heaters that might occur at the lower temperatures expected at the repository.

The DOE Response: Hardware for the DST has been modified to insure peak temperatures at the drift wall of the heated drift will not exceed 200 °C. This maximum temperature is expected along the spring line at the center of the heated drift. The thermal load will be reduced when the maximum drift wall temperature approaches 200 °C to ensure the temperature at the drift wall does not exceed this allowable maximum. The thermal load along the axis of the drift (for both the wing heaters and the canister heaters) will be constant with the result that temperatures at the ends of the drift will be less than temperatures at the center of the drift due to end effects.

The NRC Evaluation: Staff considers the DOE's modifications to the thermal testing program, ensuring peak drift wall temperatures will not exceed 200 °C, adequately reduce the risk of masking important phenomena during the DST. Although limited in its capability, the incorporation of cameras into the heater drift allows inspection for liquid water dripping into the heater drift during the test. Staff determined that the DOE's response adequately addresses the original comment and considers the comment closed.

Comment 2: The applicability of the ECM approach, or alternative approaches to bound predictions of liquid flow to containers, has not been demonstrated. The planned laboratory-scale studies, field-scale heater test, and related analyses may not provide information to discriminate among alternative conceptual models or provide the basis for selection of a bounding model.

The DOE Response: Current and future analyses are and will be conducted using the DKM in addition to the ECM approach. The currently planned tests and analyses are sufficient to provide a reasonable understanding of coupled processes for use in the licensing process. The DOE recognizes the thermal testing data that will be available for the license application will be limited and will need to be confirmed by additional data collected during performance confirmation.

The NRC Evaluation: Staff determined that the current DOE thermohydrologic modeling and testing program recognizes and appreciates the limitations of basing analyses on the ECM approach. Staff considers that the DOE's response adequately addresses the original comment and considers the comment closed.

Comment 3: An approach for obtaining conservative bounds for the effects of THC coupled processes has not been demonstrated.

The DOE Response: The DOE agrees that interaction between THC processes can have a significant effect on the near-field environment and conservative bounds on the effects of THC processes can only be made by considering a synergistic analysis of the results of laboratory experiments, modeling calculations, and natural analog studies. The DOE will provide documentation to ensure staff are aware that THC phenomena are observed, monitored, and sampled in the DOE's program. THC processes will be modeled using a variety of codes; however, currently there is not an adequate computation platform or numerical modeling capability to adequately model all THC coupled processes. Different codes will be used to provide some measure of conservatism to establish bounds to the processes.

The NRC Evaluation: The evaluation of the DOE's response to Comment 3 is provided in Revision 1 of the NRC's IRSR on *Evolution of the Near-Field Environment* (U.S. Nuclear Regulatory Commission, 1998c). As noted in that document, staff considers that the DOE's response adequately addresses Comment 3 and considers the comment closed.

5.7 U.S. NUCLEAR REGULATORY COMMISSION REVIEW OF THE U.S. DEPARTMENT OF ENERGY TOTAL SYSTEM PERFORMANCE ASSESSMENT—VIABILITY ASSESSMENT

The following comment was extracted from a letter report documenting a high-order review of the TSPA-VA (Travers, 1999). This comment addresses an issue that transcends several KTIs (i.e., TEF, Evolution of Near-Field Environment, Unsaturated/Saturated Flow of Isothermal Conditions) and is included here because of the importance of seepage to the TEF KTI.

Comment:

The data and models used in the TSPA-VA to calculate the quantity and chemistry of water dripping on waste packages are inadequate to describe the process and extent of potential dripping under ambient and thermally altered conditions. This concern is an issue because both the DOE and NRC performance assessment analyses indicate that the fraction of waste packages contacted by water is the most important factor affecting dose along the groundwater pathway. Further, the NRC staff view the current DOE testing and modeling plans as insufficient to resolve this issue prior to the license application. There are activities that the DOE could complete prior to the license application that would provide additional support for addressing this issue.

Importance:

The quantity and chemistry of water contacting the waste package are the major factors in determining the lifetime of the waste package. Radionuclide release rates from breached waste packages are also dependent on the quantity and chemistry of water contacting the waste packages and, subsequently, the waste forms. Degradation of waste packages by corrosion and alteration of waste forms is accelerated in the presence of water and certain dissolved aqueous species. Differences in the amount of seepage into the emplacement drifts and onto waste packages lead to calculated radionuclide releases that vary by several orders of magnitude.

Status of Resolution:

The DOE recognizes that there is inadequate information regarding seepage into drifts, the effects of heat and excavation on flow at the drift scale dripping onto waste packages, and the chemistry of water on waste packages. In addition, the DOE has recognized that its current performance assessment models do not adequately capture the effects of coupled processes on the quantity and chemistry of water contacting waste packages. The DOE has assigned a high priority to both the data collection and modeling efforts and is conducting a peer review on drift seepage to guide its prelicensing scientific activities. The range of activities outlined in the license application plan are unlikely to provide an adequate licensing basis for assessing the quantity and chemistry of water contacting waste packages and waste forms. For instance, it was noted at the Drift Seepage Peer Review Meeting on January 11–13, 1999, that the niche studies conducted and proposed to be completed prior to the license application do not provide an adequate basis to support the seepage abstraction (Hughson, 1999b). Two activities were suggested by members of the peer review panel (Hughson, 1999b), that could be completed prior to the license application and would lead to a more defensible approach for addressing the quantity and chemistry of water contacting the waste packages and waste forms. First, systematic air permeability measurements conducted in horizontal boreholes in the three repository host rock units could provide data on the scales of variability and heterogeneity in rock properties that are necessary to describe seepage. Second, additional model development efforts should focus on explaining the observed patterns of seepage in the niche experiments. This comment has been rephrased and is included in Section 5.

Additional Background:

The data and processes necessary to describe the quantity and chemistry of water contacting waste packages and waste forms through abstraction in a performance assessment have been addressed in several IRSRs (U.S. Nuclear Regulatory Commission, 1998a,b,c,e). In addition, the importance of characterizing thermal perturbations to unsaturated zone flow fields during the heating phase and considering coupled THMC processes in performance assessment was discussed in letters to the DOE (U.S. Nuclear Regulatory Commission, 1997, 1998f).

Basis:

An ongoing peer review of the DOE drift seepage approach has identified inadequacies in the data, experiments used to collect the data, the models used to describe the seepage process, and the methods used to abstract seepage into performance assessments (Hughson, 1999b). Both laboratory-scale heater tests and analog site heater tests have indicated the potential for liquid water to contact a heat source under heterogeneous or transient boiling conditions. The potential for gravity-driven refluxing during the thermal period and other coupled processes and the importance of these processes for adequately describing waste package performance have been presented to the DOE (U.S. Nuclear Regulatory Commission, 1997, 1998d). Drift collapse may also significantly alter effective parameters describing moisture retention characteristics of the fracture continuum, and thus result in more seepage for a given percolation flux. On the small scale of a drift wall, the presence of surface irregularities and conducting fractures that dead-end at the drift crown will result in less capillarity and thus less diversion of percolation flux around the drift (Hughson and Dodge, 2000). Many alteration products of tuff and engineered materials are likely to affect the chemistry and water contacting waste packages, which in turn can affect corrosion rates, waste form altering rates, and radionuclide solubility and specification (U.S. Nuclear Regulatory Commission, 1998e). Although an effort was made to address this subject, there are many limitations in the data used and the extent of phases considered. Additional data and analysis of seepage under both isothermal and thermal conditions are required for a complete license application. The amount of data required for the license application, and the need to confirm expected performance of the evolving repository system, will depend on the importance of the quantity and chemistry of water contacting the waste packages and waste forms to the DOE safety case.

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APPENDIX A

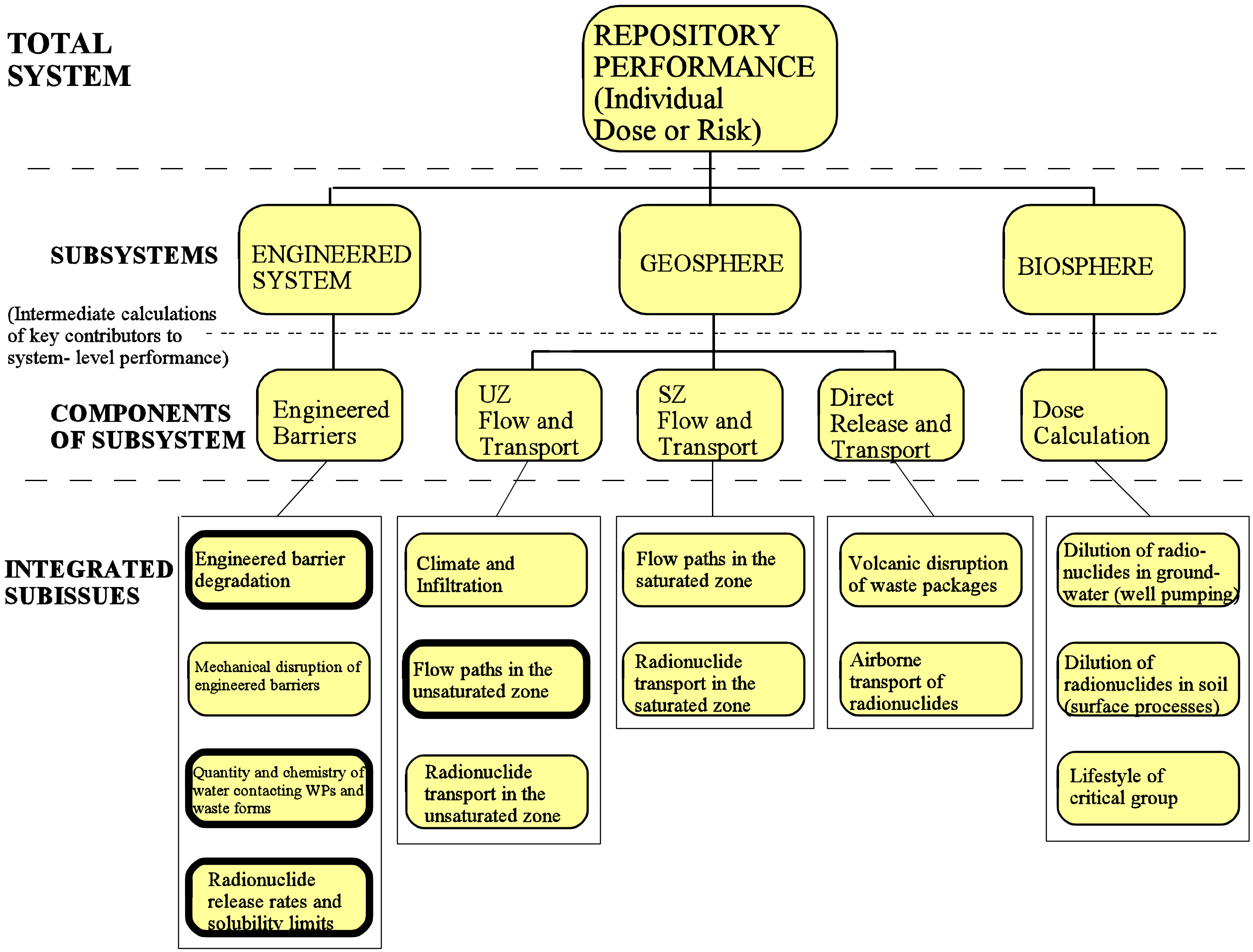

Figure A-1.
Flowdown diagram for Total System Performance Assessment

APPENDIX B

TABLE B-1. ACCEPTANCE CRITERIA CROSS-WALK BETWEEN TEF IRSR REV. 2 & 3

TEF IRSR REVISION 2	TEF IRSR REVISION 3
Subissue 1 Programmatic Criterion 1: DOE's thermohydrologic testing program was developed, and data collected and documented, under acceptable QA procedures. No TEF specific concerns raised in Rev. 2.	Not addressed in Rev. 3. DOE's QA program will not be reviewed "piece-meal" under individual KTI IRSRs. Yucca Mountain Review Plan (YMRP) will provide acceptance criteria for the DOE's QA program in a specific chapter covering administrative and programmatic requirements. No TEF specific open items related to QA identified in Rev. 2 of TEF IRSR to carry forward to Rev. 3.
Subissue 1 Programmatic Criterion 2: Expert elicitation may be used for, but not necessarily limited to, assessing if conceptual models bound the range of thermally driven refluxing expected at YM, in addition to thermohydrologic testing to provide conservative bounds to estimates. All expert elicitation are conducted and documented in accordance with NUREG-1563 (Kotra, et al., 1996) or other acceptable approaches. No TEF specific concerns raised in Rev. 2.	Not addressed in Rev. 3. DOE's use of expert elicitation will not be reviewed "piece-meal" under individual KTI IRSRs. YMRP will provide acceptance criteria for the DOE's use of "expert elicitation" in a specific chapter covering administrative and programmatic requirements. No TEF specific open items related to expert elicitation identified in Rev. 2 of TEF IRSR to carry forward to Rev. 3.
Subissue 1 Technical Acceptance Criterion 1: Thermohydrologic tests are designed and conducted: 1.1 With the explicit objective of tesing conceptual and numerical models so that critical thermohydrologic processes can be observed and measured. No specific concerns raised in Rev. 2.	Subissue 2 **General acceptance criterion**: Data and model justification with respect to thermal effects on flow. DOE's thermal testing program reviewed under this criterion. In addition, any concerns about the usefulness of thermal test results to provide "model support", another general criterion, for the DOE thermohydrologic modeling approach would likely be first introduced here with follow-up discussion under "model support" as needed. No specific open items related to old criterion 1.1 identified in Rev. 2 of TEF IRSR to carry forward to Rev. 3 (closed in Rev. 2).

TABLE B-1. ACCEPTANCE CRITERIA CROSS-WALK BETWEEN TEF IRSR REV. 2 & 3

TEF IRSR REVISION 2	TEF IRSR REVISION 3
Subissue 1 Technical Acceptance Criterion 1: Thermohydrologic tests are designed and conducted: 1.2 With explicit consideration of TH, thermal-chemical, and hydrologic-chemical couplings No specific concerns raised in Rev. 2.	Subissue 2 **General acceptance criterion**: Data and model justification with respect to thermal effects on flow. DOE's thermal testing program reviewed under this criterion. No specific open items related to old criterion 1.2 identified in Rev. 2 of TEF IRSR to carry forward to Rev. 3 (closed in Rev. 2).
Subissue 1 Technical Acceptance Criterion 1: Thermohydrologic tests are designed and conducted: 1.3 At different scales to discern scale effects on observed phenomena No specific concerns raised in Rev. 2.	Subissue 2 **General acceptance criterion**: Data and model justification with respect to thermal effects on flow. DOE's thermal testing program reviewed under this criterion. No specific open items related to old criterion 1.3 identified in Rev. 2 of the TEF IRSR to carry forward to Rev. 3 (closed in Rev. 2).
Subissue 1 Technical Acceptance Criterion 1: Thermohydrologic tests are designed and conducted: 1.4 For temperature ranges expected for repository operating conditions No specific concerns raised in Rev. 2.	Subissue 2 **General acceptance criterion**: Data and model justification with respect to thermal effects on flow. DOE's thermal testing program reviewed under this criterion. No specific open items related to old criterion 1.4 identified in Rev. 2 of TEF IRSR to carry forward to Rev. 3 (closed in Rev. 2).
Subissue 1 Technical Acceptance Criterion 1: Thermohydrologic tests are designed and conducted: 1.5 To determine if water refluxes back to the heaters during the heating or cool-down phases of the tests No specific concerns raised in Rev. 2.	Subissue 2 **General acceptance criterion**: Data and model justification with respect to thermal effects on flow. DOE's thermal testing program reviewed under this criterion. No specific open items related to old criterion 1.5 identified in Rev. 2 of TEF IRSR to carry forward to Rev. 3 (closed in Rev. 2).

TABLE B-1. ACCEPTANCE CRITERIA CROSS-WALK BETWEEN TEF IRSR REV. 2 & 3

TEF IRSR REVISION 2	TEF IRSR REVISION 3
Subissue 1 Technical Acceptance Criterion 1: Thermohydrologic tests are designed and conducted: 1.6 To evaluate the possibility for occurrence of cyclic wetting/drying on WP surfaces No specific concerns raised in Rev. 2.	Subissue 2 **General acceptance criterion**: Data and model justification with respect to thermal effects on flow. DOE's thermal testing program reviewed under this criterion. No specific open items related to old criterion 1.6 identified in Rev. 2 of TEF IRSR to carry forward to Rev. 3 (closed in Rev. 2).
Subissue 1 Technical Acceptance Criterion 1: Thermohydrologic tests are designed and conducted: 1.7 To account for all mass and energy losses/gains in the thermal test system Concern raised about losses through DST bulkhead.	Subissue 2 **General acceptance criterion**: Data and model justification with respect to thermal effects on flow. DOE's thermal testing program reviewed under this criterion. Previous open item about mass and energy losses related to the DST in Rev. 2 of TEF IRSR is carried forward to Rev. 3 (see related discussion in section 5.3.2 and section 5.3.6, fourth and fifth bullets, of Rev. 3).
Subissue 1 Technical Acceptance Criterion 1: Thermohydrologic tests are designed and conducted: 1.8 Such that the thermal test environment is sufficiently characterized so that uncertainty in property values does not result in unacceptable uncertainty in thermal test results interpretation No specific concerns raised in Rev. 2.	Subissue 2 **General acceptance criterion**: Data and model justification with respect to thermal effects on flow. DOE's thermal testing program reviewed under this criterion. No specific open items related to old criterion 1.8 identified in Rev. 2 of TEF IRSR to carry forward to Rev. 3 (closed in Rev. 2).

TABLE B-1. ACCEPTANCE CRITERIA CROSS-WALK BETWEEN TEF IRSR REV. 2 & 3

TEF IRSR REVISION 2	TEF IRSR REVISION 3
Subissue 1 Technical Acceptance Criterion 1: Thermohydrologic tests are designed and conducted: 1.9 Such that the accuracy in the measurement of the test environment saturation is sufficient to discern the relative ability of different conceptual models to represent TH processes in heated partially saturated fractured porous media No specific concerns raised in Rev. 2.	Subissue 2 **General acceptance criterion**: Data and model justification with respect to thermal effects on flow. DOE's thermal testing program reviewed under this criterion. No specific open items related to old criterion 1.9 identified in Rev. 2 of TEF IRSR to carry forward to Rev. 3 (closed in Rev. 2).
Subissue 1 Technical Acceptance Criterion 2: Thermohydrologic test results from other sites and programs have been analyzed and applied, as appropriate, to the YM site. No specific concerns raised in Rev. 2.	Subissue 2 **General acceptance criterion**: Model support with respect to thermal effects on flow. Verifying conceptual models by comparison with test or experimental data addressed under this criterion. Some aspects of scope of general acceptance criterion not applicable as comparisons with "natural analogs" not meaningful in this case. No specific open items related to old technical acceptance criterion 2 identified in Rev. 2 of TEF IRSR to carry forward to Rev. 3 (closed in Rev. 2).
Subissue 1 Technical Acceptance Criterion 3: If the thermohydrologic testing program is not complete at the time of LA submittal, DOE has explained why the testing program does not need to be completed for the LA and identified specific plans for completion of the testing program as part of the performance confirmation program. No specific concerns raised in Rev. 2.	Not addressed in Rev. 3. DOE's performance confirmation plan will not be reviewed "piece-meal" under individual KTI IRSRs. In a specific chapter, the YMRP will provide acceptance criteria for the review of the entire DOE performance confirmation plan. No specific open items related to performance confirmation identified in Rev. 2 of the TEF IRSR to carry forward to Rev. 3 (closed in Rev. 2).

TABLE B-1. ACCEPTANCE CRITERIA CROSS-WALK BETWEEN TEF IRSR REV. 2 & 3

TEF IRSR REVISION 2	TEF IRSR REVISION 3
Subissue 2 Programmatic Acceptance Criterion 1: DOE's thermohydrologic modeling analyses were developed and documented under acceptable QA procedures. No TEF specific concerns raised in Rev. 2.	Not addressed in Rev. 3. DOE's QA program will not be reviewed "piece-meal" under individual KTI IRSRs. Yucca Mountain Review Plan (YMRP) will provide acceptance criteria for the DOE's QA program in a specific chapter covering administrative and programmatic requirements. No TEF specific open items related to QA identified in Rev. 2 of TEF IRSR to carry forward to Rev. 3.
Subissue 2 Programmatic Acceptance Criterion 2: Expert elicitation may be used for, but not necessarily limited to, selecting a conceptual model and its parameters. All expert elicitation are conducted and documented in accordance with NUREG-1563 (Kotra, et al., 1996) or other acceptable approaches. No TEF specific concerns raised in Rev. 2.	Not addressed in Rev. 3. DOE's use of expert elicitation will not be reviewed "piece-meal" under individual KTI IRSRs. YMRP will provide acceptance criteria for the DOE's use of "expert elicitation" in a specific chapter covering administrative and programmatic requirements. No TEF specific open items related to expert elicitation identified in Rev. 2 of TEF IRSR to carry forward to Rev. 3.
Subissue 2 Technical Acceptance Criterion 1 Sufficient data are available to adequately define relevant parameters, parameter values, and conceptual models: 1.1 Uncertainties and variabilities in parameter values are accounted for using defensible methods. The technical bases for parameter ranges, probability distributions or bounding values used are provided. Parameter values (single values, ranges, probability distributions, or bounding values) are derived from site-specific data or an analysis is included to show the assumed parameter values lead to a conservative effect on performance. No specific concerns raised in Rev. 2.	Subissue 2 **General acceptance criterion**: Data uncertainty with respect to thermal effects on flow. DOE's approach to evaluating data (parameter) uncertainty addressed under this criterion. Adequacy of parameter sets also addressed under this criterion. Refer to discussion in Section 5.3.3 of Rev. 3. Also refer to new open items in Section 5.3.6 (seventh bullet, items (i) through (iii)). No specific open items related to old criteria 1.1 identified in Rev. 2 of TEF IRSR to carry forward to Rev. 3 (closed in Rev. 2).

TABLE B-1. ACCEPTANCE CRITERIA CROSS-WALK BETWEEN TEF IRSR REV. 2 & 3

TEF IRSR REVISION 2	TEF IRSR REVISION 3
Subissue 2 Technical Acceptance Criterion 1 Sufficient data are available to adequately define relevant parameters, parameter values, and conceptual models: 1.2 Analyses are consistent with site characteristics in establishing initial conditions, boundary conditions, and computational domains for conceptual models evaluated. No specific concerns raised in Rev. 2.	Subissue 2 **General acceptance criterion**: System description and model integration with respect to thermal effects on flow. Refer to the discussion in Section 5.3.1 of Rev. 3. No specific open items related to old criterion 1.2 identified in Rev. 2 of TEF IRSR to carry forward to Rev. 3 (closed in Rev. 2).
Subissue 2 Technical Acceptance Criterion 2 Descriptions of process-level conceptual and mathematical models used in the analyses are reasonably complete. See 2.1 through 2.16 below.	Subissue 2 **General acceptance criterion**: System description and model integration with respect to thermal effects on flow. Overall completeness of model descriptions addressed under this criterion, primarily in the context of describing how “included” FEPs have been incorporated into the models. No equivalent to this “broader” perspective in Rev. 2 of TEF IRSR in that the “sum” of open items related to old criteria 2.1 through 2.16 did not result in any “higher level “ concerns to carry forward to Rev. 3. There was no systematic review of FEP identification and screening in Rev. 2 of the TEF IRSR.
Subissue 2 Technical Acceptance Criterion 2 Descriptions of process-level conceptual and mathematical models used in the analyses are reasonably complete. Further, DOE should demonstrate that: 2.1 Models are based on well-accepted principles of heat and mass transfer applicable to unsaturated geologic media. No specific concerns raised in Rev. 2.	Subissue 2 **General acceptance criterion**: Data and model justification with respect to thermal effects on flow. Any concerns regarding the physical basis of conceptual models would be addressed under this criterion. No specific open items related to old criterion 2.1 identified in Rev. 2 of TEF IRSR to carry forward to Rev. 3 (closed in Rev. 2).

TABLE B-1. ACCEPTANCE CRITERIA CROSS-WALK BETWEEN TEF IRSR REV. 2 & 3

TEF IRSR REVISION 2	TEF IRSR REVISION 3
Subissue 2 Technical Acceptance Criterion 2 <u>Descriptions of process-level conceptual and mathematical models used in the analyses are reasonably complete. Further, DOE should demonstrate that:</u> <u>2.2 Models include, at a minimum, the processes of evaporation and condensation and the effects of discrete geologic features.</u> Concern raised about incorporating the effects of discrete geologic features.	Subissue 1 **General acceptance criterion**: <u>Screening the initial list of FEPs related to TEF</u>. Refer to discussion in Section 5.2.2 of Rev. 3 for broader review of FEPs screening process. Refer to new FEP related open items in Section 5.2.3 of Rev. 3 (bullets one through five) that supercede some FEP related aspects of old criterion 2.2 of Rev. 2. Subissue 2 **General acceptance criterion**: <u>System description and model integration with respect to thermal effects on flow</u>. Refer to discussion of condensation in Section 5.3.1 of Rev. 3. **General acceptance criterion**: <u>Model uncertainty with respect to thermal effects on flow</u>. Refer to the discussion of seepage into drifts during the thermal period in Section 5.3.4 of Rev. 3 regarding the effects of discrete geologic features. See also Section 5.3.6 for new open items (bullet two and bullet seven, item ii) that supercede aspects of old criterion 2.2 of Rev. 2.

TABLE B-1. ACCEPTANCE CRITERIA CROSS-WALK BETWEEN TEF IRSR REV. 2 & 3

TEF IRSR REVISION 2	TEF IRSR REVISION 3
Subissue 2 Technical Acceptance Criterion 2 Descriptions of process-level conceptual and mathematical models used in the analyses are reasonably complete. Further, DOE should demonstrate that: 2.3 Models include, at a minimum, an evaluation of important thermhydrological phenomena, such as: (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. Concern raised about the need to incorporate the effects of radiative heat transfer and ventilation into the models used to predict formation of cold traps. Concern raised about the need to incorporate the effects of discrete geologic features into the models. Concern raised about the need to support the DKM model with results from a longer duration of the DST than currently available.	Subissue 1 **General acceptance criterion**: Screening the initial list of FEPs related to TEF. Refer to discussion in Section 5.2.2 of Rev. 3 for broader review of FEPs screening process. Refer to new FEP related open items in Section 5.2.3 of Rev. 3 (bullets one through five) that supercede some FEP related aspects of old criterion 2.3 of Rev. 2. Subissue 2 **General acceptance criterion**: System description and model integration with respect to thermal effects on flow. Refer to discussion of condensation and cold trap effect in Section 5.3.1 of Rev. 3. Also refer to Section 5.3.6 for related open item (bullet 2) that supercedes aspects of old criterion 2.3 of Rev. 2. **General acceptance criterion**: Model uncertainty with respect to thermal effects on flow. Refer to the discussion of seepage into drifts during the thermal period in Section 5.3.4 of Rev. 3 regarding condensate drainage through fractures. See also Section 5.3.6 for new open item (bullet seven, item ii) that supercede aspects of old criterion 2.3 of Rev. 2. **General acceptance criterion**: Model support with respect to thermal effects on flow. Refer to the discussion in Section 5.3.5 of Rev. 3. Also refer to Section 5.3.6, bullets six and nine, for new open items related to model support.

TABLE B-1. ACCEPTANCE CRITERIA CROSS-WALK BETWEEN TEF IRSR REV. 2 & 3

TEF IRSR REVISION 2	TEF IRSR REVISION 3
Subissue 2 Technical Acceptance Criterion 2 <u>Descriptions of process-level conceptual and mathematical models used in the analyses are reasonably complete. Further, DOE should demonstrate that:</u> <u>2.4 Models include all significant repository design features</u>. Concern raised about incorporating features of the revised repository design into the models.	Subissue 1 **General acceptance criterion**: <u>Screening the initial list of FEPs related to TEF</u>. Refer to discussion in Section 5.2.2 of Rev. 3 for broader review of FEPs screening process. Refer to new FEP related open items in Section 5.2.3 of Rev. 3 (bullets one through five) that supercede some FEP related aspects of old criterion 2.4 of Rev. 2. Subissue 2 **General acceptance criterion**: <u>System description and model integration with respect to thermal effects on flow</u>. Refer to discussion of backfill in Section 5.3.1 of Rev. 3. Refer to Section 5.3.6 for related open item (bullet one) that supercedes aspects of old criterion 2.4 of Rev. 2 of the TEF IRSR.
Subissue 2 Technical Acceptance Criterion 2 <u>Descriptions of process-level conceptual and mathematical models used in the analyses are reasonably complete. Further, DOE should demonstrate that:</u> <u>2.5 Models are capable of accommodating variation in infiltration</u>. Concern raised about the need to include the effects of spatially variable infiltration into the models.	Subissue 1 **General acceptance criterion**: <u>Screening the initial list of FEPs related to TEF</u>. Refer to discussion in Section 5.2.2 of Rev. 3 for broader review of FEPs screening process. Refer to new FEP related open items in Section 5.2.3 of Rev. 3 (bullets one through five) that supercede some FEP related aspects of old criterion 2.5 of Rev. 2 of the TEF IRSR. Subissue 2 **General acceptance criterion**: <u>System description and model integration with respect to thermal effects on flow</u>. Models as described in the draft *Multiscale Thermohydrologic Model* AMR (Rev. 00) include variable infiltration. Therefore, the open item related to old criterion 2.5 has not been carried forward to technical discussions in Rev. 3. However, the DOE should consider the previous open item as remaining open until the DOE "formally" accepts the draft contractor report *Multiscale Thermohydrologic Model* AMR (Rev. 00).

TABLE B-1. ACCEPTANCE CRITERIA CROSS-WALK BETWEEN TEF IRSR REV. 2 & 3

TEF IRSR REVISION 2	TEF IRSR REVISION 3
Subissue 2 Technical Acceptance Criterion 2 Descriptions of process-level conceptual and mathematical models used in the analyses are reasonably complete. Further, DOE should demonstrate that: 2.6 Conceptual model uncertainties have been defined and documented and effects on conclusions regarding performance assessed. Concern raised about the need to define and document conceptual model uncertainty. Concern raised about the need to demonstrate that the models are consistent with physical observations of the DST or some other appropriate heater test or analog site.	Subissue 2 **General acceptance criterion**: Model uncertainty with respect to thermal effects on flow. Refer to the discussion of alternative conceptual models in Section 5.3.4 of Rev. 3. Also refer to Section 5.3.6, bullet eight, that supercedes (incorporates) the previous open item under old criterion 2.6 in Rev. 2 of the TEF IRSR. **General acceptance criterion**: Model support with respect to thermal effects on flow. Refer to the discussion in Section 5.3.5 of Rev. 3. Also refer to Section 5.3.6, bullets six and nine, for new open items related to model support.
Subissue 2 Technical Acceptance Criterion 2 Descriptions of process-level conceptual and mathematical models used in the analyses are reasonably complete. Further, DOE should demonstrate that: 2.7 Mathematical models are consistent with conceptual models, based on consideration of site characteristics. No specific concerns raised in Rev. 2.	Subissue 2 **General acceptance criterion**: System description and model integration with respect to thermal effects on flow. No specific open items related to old criterion 2.7 identified in Rev. 2 of TEF IRSR to carry forward to Rev. 3 (closed in Rev. 2).

TABLE B-1. ACCEPTANCE CRITERIA CROSS-WALK BETWEEN TEF IRSR REV. 2 & 3

TEF IRSR REVISION 2	TEF IRSR REVISION 3
Subissue 2 Technical Acceptance Criterion 2 <u>Descriptions of process-level conceptual and mathematical models used in the analyses are reasonably complete. Further, DOE should demonstrate that:</u> <u>2.8 Alternative models and modeling approaches, which are consistent with available data and current scientific understanding, have been investigated, limitations defined, and results appropriately considered</u>. Concern raised about the need to provide and evaluate alternative conceptual models for critical process-level heat and mass transfer mechanisms, such as refluxing into the drift during the thermal period.	Subissue 2 **General acceptance criterion**: <u>Model uncertainty with respect to thermal effects on flow</u>. Refer to discussion of alternative models in Section 5.3.4 of Rev. 3. Also refer to Section 5.3.6 for new open item (bullet eight) that supercedes (incorporates) open item of old criterion 2.8 of Rev. 2 of the TEF IRSR.
Subissue 2 Technical Acceptance Criterion 2 <u>Descriptions of process-level conceptual and mathematical models used in the analyses are reasonably complete. Further, DOE should demonstrate that:</u> <u>2.9 Results from different mathematical models have been compared to judge robustness of models</u>. Concern raised about the need to compare models using field-scale measurements taken over sufficiently long durations and large spatial distances (thermal tests).	Subissue 2 **General acceptance criterion**: <u>Model uncertainty with respect to thermal effects on flow</u>. Refer to discussion of alternative models in Section 5.3.4 of Rev. 3. Also refer to Section 5.3.6 for new open item (bullet eight) that supercedes (incorporates) open item of old criterion 2.9 of Rev. 2 of the TEF IRSR. **General acceptance criterion**: <u>Model support with respect to thermal effects on flow</u>. Refer to the discussion in Section 5.3.5 of Rev. 3. Also refer to Section 5.3.6, bullets six and nine, for new open items related to model support.

TABLE B-1. ACCEPTANCE CRITERIA CROSS-WALK BETWEEN TEF IRSR REV. 2 & 3

TEF IRSR REVISION 2	TEF IRSR REVISION 3
Subissue 2 Technical Acceptance Criterion 2 <u>Descriptions of process-level conceptual and mathematical models used in the analyses are reasonably complete. Further, DOE should demonstrate that:</u> <u>2.10 Models used to predict shedding around emplacement drifts are shown to contain an adequate level of heterogeneity in media properties</u>. Concern raised about the ability of seepage models to predict penetration of the boiling isotherm by water flowing down a fracture (resulting from heterogeneity).	Subissue 2 **General acceptance criterion**: <u>Data uncertainty with respect to thermal effects on flow</u>. Refer to discussion of data uncertainty, including variability and heterogeneity, in Section 5.3.3 of Rev. 3. Also refer to Section 5.3.6 for new open item (bullet seven, item ii) that supercedes (incorporates) open item of old criterion 2.10 of Rev. 2 of the TEF IRSR. **General acceptance criterion**: <u>Model uncertainty with respect to thermal effects on flow</u>. Refer to the discussion of seepage into drifts during the thermal period in Section 5.3.4 of Rev. 3 regarding condensate drainage through fractures. See also Section 5.3.6 for new open items (bullet two and bullet seven, item ii) that supercede aspects of old criterion 2.10 of Rev. 2.

TABLE B-1. ACCEPTANCE CRITERIA CROSS-WALK BETWEEN TEF IRSR REV. 2 & 3

TEF IRSR REVISION 2	TEF IRSR REVISION 3
Subissue 2 Technical Acceptance Criterion 2 <u>Descriptions of process-level conceptual and mathematical models used in the analyses are reasonably complete. Further, DOE should demonstrate that:</u> <u>2.11 TH models have been demonstrated to be appropriate for the temperature regime expected at the repository.</u> Concern raised about the uncertainty in repository design, including the heat load, and the need to demonstrate that thermal test results are meaningful with respect to the intended repository thermal regime so that test results can be justifiably used to provide model support.	Subissue 1 **General acceptance criterion**: <u>Screening the initial list of FEPs related to TEF</u>. Refer to discussion in Section 5.2.2 of Rev. 3 for broader review of FEPs screening process. Refer to new FEP related open items in Section 5.2.3 of Rev. 3 (bullets one through five) that supercede FEP related aspects of old criterion 2.11 of Rev. 2 of TEF IRSR. Subissue 2 **General acceptance criterion**: <u>System description and model integration with respect to thermal effects on flow</u>. Refer to discussion of completing modeling based on current repository design in Section 5.3.1 of Rev. 3. Refer to Section 5.3.6 for related open item (bullet one) that supercedes (incorporates) current design aspects of old criterion 2.11 of Rev. 2 of TEF IRSR. **General acceptance criterion**: <u>Data and model justification with respect to thermal effects on flow</u>. DOE's thermal testing program reviewed under this criterion. Previous open item about mass and energy losses related to the DST in Rev. 2 of TEF IRSR is carried forward to Rev. 3 (see related discussion in section 5.3.2 and section 5.3.6, fourth and fifth bullets, of Rev. 3).

TABLE B-1. ACCEPTANCE CRITERIA CROSS-WALK BETWEEN TEF IRSR REV. 2 & 3

TEF IRSR REVISION 2	TEF IRSR REVISION 3
Subissue 2 Technical Acceptance Criterion 2 Descriptions of process-level conceptual and mathematical models used in the analyses are reasonably complete. Further, DOE should demonstrate that: 2.12 Models include radiative heat transport unless it is shown that radiative heat loss by a WP is not significant. No specific concerns raised in Rev. 2.	Subissue 1 **General acceptance criterion**: Screening the initial list of FEPs related to TEF. Refer to discussion in Section 5.2.2 of Rev. 3 for broader review of FEPs screening process. Refer to new FEP related open items in Section 5.2.3 of Rev. 3 (bullets one through five). Subissue 2 **General acceptance criterion**: System description and model integration with respect to thermal effects on flow. Refer to discussion in Section 5.3.1 of Rev. 3. No specific open items related to old criterion 2.12 identified in Rev. 2 of TEF IRSR to carry forward to Rev. 3 (closed in Rev. 2).
Subissue 2 Technical Acceptance Criterion 2 Descriptions of process-level conceptual and mathematical models used in the analyses are reasonably complete. Further, DOE should demonstrate that: 2.13 Models include the effect of ventilation particularly if ventilation could result in deposition or condensation of moisture on a WP surface. Concern raised that models do not include the effects of ventilation.	Subissue 1 **General acceptance criterion**: Screening the initial list of FEPs related to TEF. Ventilation to be included in TSPA as indicated in draft AMRS. However, refer to discussion in Section 5.2.2 of Rev. 3 for broader review of FEPs screening process. Refer to new FEP related open items in Section 5.2.3 of Rev. 3 (bullets one through five). Subissue 2 **General acceptance criterion**: System description and model integration with respect to thermal effects on flow. DOE has described technical approach to incorporate effects of ventilation in models in draft AMRs. No questions regarding that approach at this time pending resolution of new open item (sixth bullet; Sec 5.3.6 in Rev. 3). **General acceptance criterion**: Data uncertainty and model justification. Refer to discussion in Section 5.3.3. Also refer to new open item in Section 5.3.6 (bullet six) that supercedes the previous open item under old criterion 2.13 in Rev. 2 of the TEF IRSR.

TABLE B-1. ACCEPTANCE CRITERIA CROSS-WALK BETWEEN TEF IRSR REV. 2 & 3

TEF IRSR REVISION 2	TEF IRSR REVISION 3
Subissue 2 Technical Acceptance Criterion 2 Descriptions of process-level conceptual and mathematical models used in the analyses are reasonably complete. Further, DOE should demonstrate that: 2.14 The media properties of a model contain an adequate level of heterogeneity so that mechanisms such as dripping are not neglected or misrepresented. Concern raised that models do not contain an adequate level of heterogeneity so that mechanisms such as dripping from refluxing during the thermal period or from seepage under isothermal conditions are adequately and appropriately represented.	Subissue 2 **General acceptance criterion**: Data uncertainty with respect to thermal effects on flow. Refer to discussion of data uncertainty, including variability and heterogeneity, in Section 5.3.3 of Rev. 3. Also refer to Section 5.3.6 for new open item (bullet seven, item ii) that supercedes (incorporates) open item of old criterion 2.14 of Rev. 2 of the TEF IRSR. **General acceptance criterion**: Model uncertainty with respect to thermal effects on flow. Refer to the discussion of seepage into drifts during the thermal period in Section 5.3.4 of Rev. 3 regarding condensate drainage through fractures. See also Section 5.3.6 for new open items (bullet two and bullet seven, item ii) that supercede aspects of old criterion 2.10 of Rev. 2.
Subissue 2 Technical Acceptance Criterion 2 Descriptions of process-level conceptual and mathematical models used in the analyses are reasonably complete. Further, DOE should demonstrate that 2.15 Drift wall representations in models must contain sufficient physical detail so that processes predicted using a continuum model, such as capillary diversion, are appropriate for the geologic media at the proposed repository location. Concern raised that capillary diversion around drift openings is an assumption that may not be demonstrated by models that include the effects of drift wall irregularities.	Subissue 2 **General acceptance criterion**: Model uncertainty with respect to thermal effects on flow. General applicability of the DOE's seepage abstraction is discussed in Section 5.3.4 of Rev. 2. However, the specific open item of old criterion 2.15 of Rev. 2 of the TEF IRSR is no longer addressed under the TEF KTI, and is considered closed with respect to the TEF KTI, because a similar open item is being tracked under the USFIC KTI (USFIC Subissue 4, Deep Percolation, Item 3 on smaller scale tunnel irregularities, identified as closed-pending); refer to enclosure of 9/8/00 letter from J. R. Schlueter, NRC to S. Brocoum, DOE on the NRC/DOE 8/16-17, 2000 Technical Exchange on Unsaturated and Saturated Flow under Isothermal Conditions.

TABLE B-1. ACCEPTANCE CRITERIA CROSS-WALK BETWEEN TEF IRSR REV. 2 & 3

TEF IRSR REVISION 2	TEF IRSR REVISION 3
Subissue 2 Technical Acceptance Criterion 2 Descriptions of process-level conceptual and mathematical models used in the analyses are reasonably complete. Further, DOE should demonstrate that: 2.16 Physical mechanisms such as pentration of the boiling isotherm by flow down a fracture are not omitted due to over-simplification of the physical medium or the conceptual model. Concern raised that models do not include all necessary mechanisms to ensure that all processes that could lead to water introduction into the drift (seepage, dripping) under isothermal and non-isothermal conditions are included.	Subissue 1 **General acceptance criterion**: Screening the initial list of FEPs related to TEF. Refer to discussion in Section 5.2.2 of Rev. 3 for broader review of FEPs screening process. Refer to new FEP related open items in Section 5.2.3 of Rev. 3 (bullets one through five). Subissue 2 **General acceptance criterion**: Data uncertainty with respect to thermal effects on flow. Refer to discussion of data uncertainty, including variability and heterogeneity, in Section 5.3.3 of Rev. 3. Also refer to Section 5.3.6 for new open item (bullet seven, item ii) that supercedes (incorporates) open item of old criterion 2.16 of Rev. 2 of the TEF IRSR. **General acceptance criterion**: Model uncertainty with respect to thermal effects on flow. Refer to the discussion of seepage into drifts during the thermal period in Section 5.3.4 of Rev. 3 regarding condensate drainage through fractures. See also Section 5.3.6 for new open items (bullet two and bullet seven, item ii) that supercede aspects of old criterion 2.16 of Rev. 2.

TABLE B-1. ACCEPTANCE CRITERIA CROSS-WALK BETWEEN TEF IRSR REV. 2 & 3

TEF IRSR REVISION 2	TEF IRSR REVISION 3
Subissue 2 Technical Acceptance Criterion 3: Coupling of processes has been evaluated using a methodology in accordance with NUREG-1466 (Nataraja and Brandshaug, 1992) or other acceptable methodology. Coupled processes may be uncoupled, if it is shown that the uncoupled model results bound the predictions of the fully-coupled model results. No specific concerns raised in Rev. 2.	Subissue 1 **General acceptance criterion**: Screening the initial list of FEPs related to thermal effects on flow. The DOE is evaluating the need to incorporate TM and TC effects in thermohydrologic models as part of the FEP screening process. Refer to discussion in Section 5.2.2 of Rev. 3. Also refer to new open items regarding FEPs in Section 5.2.3 of Rev. 3. The potential direction and magnitude of TM or TC induced changes in rock properties (fracture aperture, fracture permeability) is a topic addressed under the NRC's RDTME and ENFE KTIs, respectively. As stated in Section 5.2.2 of Rev. 3, because of the broad level comments about the DOE's FEPs screening process and documentation and the fact that the DOE is currently revising FEP related AMRs, the NRC staff have not performed a detailed review of the DOE's FEP screening arguments at this time. When revised AMRs are available, the NRC staff evaluations will focus on the technical basis for excluding individual FEPs. Finally, no specific concern related to old criterion 3 is identified in Rev. 2 of the TEF IRSR to carry forward to Rev. 3 as the topic was essentially unreviewed at that time. For tracking purposes, the DOE can consider the old criterion 3 of Rev. 2 to be closed. New concerns regarding coupling of processes could arise in future reviews of FEP exclusion arguments.

TABLE B-1. ACCEPTANCE CRITERIA CROSS-WALK BETWEEN TEF IRSR REV. 2 & 3

TEF IRSR REVISION 2	TEF IRSR REVISION 3
Subissue 2 Technical Acceptance Criterion 4: <u>The dimensionality of models, which include heterogeneity at appropriate scales and significant process couplings, may be reduced, if shown that the reduced dimension model bounds the predictions of the full dimension model</u>. Concern raised as to whether the 2-D, mountain-scale TH calculations provide the time histories for gas-phase flow rates and air-mass fractions at repository center and edge locations because only thermal conduction is included in the DOE's mountain-scale submodel.	Subissue 2 **General acceptance criterion**: <u>System description and model integration with respect to thermal effects on flow</u>. Refer to discussion of condensation and cold trap effect in Section 5.3.1 of Rev. 3. Also refer to Section 5.3.6 for related open item (second bullet).
Subissue 2 Technical Acceptance Criterion 5: <u>Equivalent continuum models are acceptable for the rock matrix and small discrete features, if it can be demonstrated that water in small discrete features is in continuous hydraulic equilibrium with matrix water. Significant discrete features, such as fault zones, should be represented separately unless it can be shown that inclusion in the equivalent continuum model (ECM) produces a conservative effect on calculated overall performance</u>. Concern raised that the DOE has not demonstrated which discrete features (i.e., faults or fracture zones) need to be modeled discretely to conservatively bound heat and mass transfer.	Subissue 1 **General acceptance criterion**: <u>Screening the initial list of FEPs related to TEF</u>. Refer to discussion in Section 5.2.2 of Rev. 3 for broader review of FEPs screening process. Refer to new FEP related open items in Section 5.2.3 of Rev. 3 (bullets one through five). Subissue 2 **General acceptance criterion**: <u>System description and model integration with respect to thermal effects on flow</u>. Refer to discussion of condensation in Section 5.3.1 of Rev. 3. **General acceptance criterion**: <u>Data uncertainty with respect to thermal effects on flow</u>. Refer to the discussion in Section 5.3.3 of Rev. 3 related to variability and heterogeneity. Also refer to Section 5.3.6 for related open item (bullet seven, item ii) that supercedes aspects of old criterion 5 of Rev. 2. **General acceptance criterion**: <u>Model uncertainty with respect to thermal effects on flow</u>. Refer to the discussion of seepage into drifts during the thermal period in Section 5.3.4 of Rev. 3 regarding the effects of discrete geologic features.

TABLE B-1. ACCEPTANCE CRITERIA CROSS-WALK BETWEEN TEF IRSR REV. 2 & 3

TEF IRSR REVISION 2	TEF IRSR REVISION 3
Subissue 2 Technical Acceptance Criterion 6: Accepted and well-documented procedures have been adopted to construct and calibrate numerical models used. No specific concerns raised in Rev. 2.	Subissue 2 **General acceptance criterion**: System description and model integration with respect to thermal effects on flow. Refer to discussion in Section 5.3.1 of Rev. 3. No specific open items related to old criterion 2.7 identified in Rev. 2 of TEF IRSR to carry forward to Rev. 3 (closed in Rev. 2).
Subissue 2 Technical Acceptance Criterion 7: Results of process-level models have been verified by demonstrating consistency with results/observations from field-scale, thermohydrologic tests. In particular, sufficient physical evidence should exist to support the conceptual models used to predict thermally driven flow in the near field. No specific concerns raised in Rev. 2.	Subissue 2 **General acceptance criterion**: Data and model justification with respect to thermal effects on flow. DOE's thermal testing program reviewed under this criterion (collecting physical evidence to support conceptual models). Any concerns about the usefulness of thermal test results to provide "model support", another general criterion, for the DOE thermohydrologic modeling approach would be first introduced here with follow-up discussion under "model support" as needed. Refer to new open items in Section 5.3.6 (bullets four and five). No specific open items related to old criterion 7 identified in Rev. 2 of TEF IRSR to carry forward to Rev. 3 (closed in Rev. 2). **General acceptance criterion**: Model support with respect to thermal effects on flow. Refer to the discussion in Section 5.3.5 of Rev. 3. Also refer to Section 5.3.6, bullets six and nine, for new open item related to model support. No specific open items related to old criterion 7 identified in Rev. 2 of TEF IRSR to carry forward to Rev. 3 (closed in Rev. 2).
Subissue 3 Programmatic Acceptance Criterion 1: DOE's analyses were developed and documented under acceptable QA procedures. No TEF specific concerns raised in Rev. 2.	Not addressed in Rev. 3. DOE's QA program will not be reviewed "piece-meal" under individual KTI IRSRs. Yucca Mountain Review Plan (YMRP) will provide acceptance criteria for the DOE's QA program in a specific chapter covering administrative and programmatic requirements. No TEF specific open items related to QA identified in Rev. 2 of TEF IRSR to carry forward to Rev. 3.

TABLE B-1. ACCEPTANCE CRITERIA CROSS-WALK BETWEEN TEF IRSR REV. 2 & 3

TEF IRSR REVISION 2	**TEF IRSR REVISION 3**
Subissue 3 Programmatic Acceptance Criterion 2: <u>Expert elicitation may be used for, but not necessarily limited to, justifying the use of abstracted models in DOE's TSPA. All expert elicitation are conducted and documented in accordance with NUREG-1563 (Kotra, et al., 1996) or other acceptable procedures.</u> No TEF specific concerns raised in Rev. 2.	Not addressed in Rev. 3. DOE's use of expert elicitation will not be reviewed "piece-meal" under individual KTI IRSRs. YMRP will provide acceptance criteria for the DOE's use of "expert elicitation" in a specific chapter covering administrative and programmatic requirements. No TEF specific open items related to expert elicitation identified in Rev. 2 of TEF IRSR to carry forward to Rev. 3.
Subissue 3 Technical Acceptance Criterion 1: <u>Abstractions of process-level models may be used if predictions from the abstracted model are shown to conservatively bound process-level predictions. In particular, DOE may use an abstracted model to predict water influx into an emplacement drift if the abstracted model is shown to bound process-level predictions of the influx of water as liquid or vapor into an emplacement drift</u>. A concern was raised that the DOE cannot demonstrate that abstracted models bound process-level models until concerns about whether process-levels adequately incorporate seepage (under isothermal conditions) and refluxing mechanisms are addressed.	Subissue 2 **General acceptance criterion**: <u>Model uncertainty</u>. Refer to discussion of seepage into drifts during the thermal period in Section 5.3.4. Also refer to related open item in Section 5.3.6 (bullet seven, item ii). **General acceptance criterion**: <u>Model support with respect to thermal effects on flow</u>. Refer to discussion in Section 5.3.5 of Rev. 3. Also refer to related open item in Section 5.3.6 (bullet nine).

TABLE B-1. ACCEPTANCE CRITERIA CROSS-WALK BETWEEN TEF IRSR REV. 2 & 3

TEF IRSR REVISION 2	TEF IRSR REVISION 3
Subissue 3 Technical Acceptance Criterion 2: Sufficient data are available to adequately define relevant parameters, parameter values and conceptual models: 2.1 Uncertainties and variabilities in parameter values are accounted for using defensible methods. The technical bases for parameter ranges, probability distributions or bounding values used are provided. Parameter values (single values, ranges, probability distributions, or bounding values) are derived from site-specific data or an analysis is included to show the assumed parameter values lead to a conservative effect on performance. No specific concerns raised in Rev. 2.	Subissue 2 **General acceptance criterion**: Data uncertainty with respect to thermal effects on flow. DOE's approach to evaluating data (parameter) uncertainty addressed under this criterion. Adequacy of parameter sets also addressed under this criterion. Refer to discussion in Section 5.3.3 of Rev. 3. Also refer to new open item in Section 5.3.6 (seventh bullet, items (i) through (iii)). No specific open items related to old criteria 2.1 identified in Rev. 2 of TEF IRSR to carry forward to Rev. 3 (closed in Rev. 2).
Subissue 3 Technical Acceptance Criterion 2: Sufficient data are available to adequately define relevant parameters, parameter values and conceptual models: 2.2 Analyses are consistent with site characteristics in establishing initial conditions, boundary conditions, and computational domains for conceptual models evaluated. No specific concerns raised in Rev. 2.	Subissue 2 **General acceptance criterion**: System description and model integration with respect to thermal effects on flow. Refer to the discussion in Section 5.3.1 of Rev. 3. No specific open items related to old criterion 2.2 identified in Rev. 2 of TEF IRSR to carry forward to Rev. 3 (closed in Rev. 2).

TABLE B-1. ACCEPTANCE CRITERIA CROSS-WALK BETWEEN TEF IRSR REV. 2 & 3

TEF IRSR REVISION 2	TEF IRSR REVISION 3
Subissue 3 Technical Acceptance Criterion 3: <u>Descriptions of the conceptual and mathematical models used in DOE's TSPA are reasonably complete.</u> See 3.1 through 3.6 below.	Subissue 2 **General acceptance criterion**: <u>System description and model integration with respect to thermal effects on flow</u>. Overall completeness of model descriptions addressed under this criterion, primarily in the context of describing how "included" FEPs have been incorporated into the models. No equivalent to this "broader" perspective in Rev. 2 of TEF IRSR in that the "sum" of open items related to old criteria 3.1 through 3.6 did not result in any "higher level " concerns to carry forward to Rev. 3. There was no systematic review of FEP identification and screening in Rev. 2 of the TEF IRSR.

TABLE B-1. ACCEPTANCE CRITERIA CROSS-WALK BETWEEN TEF IRSR REV. 2 & 3

TEF IRSR REVISION 2	TEF IRSR REVISION 3
Subissue 3 Technical Acceptance Criterion 3: Descriptions of the conceptual and mathematical models used in DOE's TSPA are reasonably complete. Further, DOE should demonstrate that: 3.1 Performance affecting heat and mass transfer mechanisms, including processes observed in available thermohydrologic tests and experiments, have been identified and incorporated into the TSPA. Specifically, it is necessary to either demonstrate that liquid water will not reflux into the underground facility or incorporate refluxing water into the TSPA and bound the potential adverse effects of: (i) corrosion of the WP; (ii) accelerated transport of radionuclides; and (iii) alteration of hydraulic and transport pathways that result from refluxing water. Concern raised that models do not include, either directly or as an abstraction, heat and mass transport mechanisms that could lead to water refluxing into the drift, particularly during the thermal period. TSPA-VA models assume no water can enter the drift at all times when drift wall temperatures exceed boiling. TSPA-VA models assume no dripping into the drift during the first 5,000 years of heating. Concern raised about the need to incorporate sufficient heterogeneity in the models so as to not mask critical heat and mass transfer mechanisms. Concern raised that alternative models of seepage evaluated resulted in seepage predictions that significantly exceeded the "standard" model predictions used in the TSPA-VA.	Subissue 2 **General acceptance criterion**: Data and model justification with respect to thermal effects on flow. DOE's thermal testing program reviewed under this criterion. Refer to discussion of condensate buildup and losses through the bulkhead of the DST in Section 5.3.2 of Rev. 3. Also refer to related open items in Section 5.3.6 (fourth and fifth bullets) of Rev. 3. **General acceptance criterion**: Data uncertainty with respect to thermal effects on flow. Refer to discussion of data uncertainty, including heterogeneity, in Section 5.3.3 of Rev. 3. Also refer to Section 5.3.6 for new open item (bullet seven, item ii) that supercedes (incorporates) open item of old criterion 3.1 of Rev. 2 of the TEF IRSR. **General acceptance criterion**: Model uncertainty. Refer to discussion of alternative conceptual models in Section 5.3.4. Also refer to related open item in Section 5.3.6 (bullet eight). **General acceptance criterion**: Model support with respect to thermal effects on flow. Refer to discussion in Section 5.3.5 of Rev. 3. Also refer to related open item in Section 5.3.6 (bullet nine).

TABLE B-1. ACCEPTANCE CRITERIA CROSS-WALK BETWEEN TEF IRSR REV. 2 & 3

TEF IRSR REVISION 2	TEF IRSR REVISION 3
Subissue 3 Technical Acceptance Criterion 3: Descriptions of the conceptual and mathematical models used in DOE's TSPA are reasonably complete. Further, DOE should demonstrate that: 3.2 Significant Geologic Repository Operations Area (GROA) underground facility design features, such as the addition of backfill or drip shields, that can result in changes in TSP have been identified and incorporated into the TSPA. No specific concerns raised in Rev. 2.	Subissue 1 **General acceptance criterion**: Screening the initial list of FEPs related to TEF. Refer to discussion in Section 5.2.2 of Rev. 3 for broader review of FEPs screening process. Refer to new FEP related open items in Section 5.2.3 of Rev. 3 (bullets one through five). Subissue 2 **General acceptance criterion**: System description and model integration with respect to thermal effects on flow. Refer to discussion of backfill in Section 5.3.1 of Rev. 3. Also refer to Section 5.3.6 of Rev. 3 for new open item (bullet one).

TABLE B-1. ACCEPTANCE CRITERIA CROSS-WALK BETWEEN TEF IRSR REV. 2 & 3

TEF IRSR REVISION 2	TEF IRSR REVISION 3
Subissue 3 Technical Acceptance Criterion 3: Descriptions of the conceptual and mathematical models used in DOE's TSPA are reasonably complete. Further, DOE should demonstrate that: 3.3 Conceptual model uncertainties have been defined and documented, and their effects on conclusions regarding TSP have been assessed. Concern raised that current models do not incorporate heat and mass transport mechanisms that could indicate water reflux into the drift during and after the heating period and that the effects of refluxing water need to be incorporated into the TSPA.	Subissue 1 **General acceptance criterion**: Screening the initial list of FEPs related to TEF. Refer to discussion in Section 5.2.2 of Rev. 3 for broader review of FEPs screening process. Refer to new FEP related open items in Section 5.2.3 of Rev. 3 (bullets one through five) that supercede some FEP related aspects of old criterion 3.3 of Rev. 2. Subissue 2 **General acceptance criterion**: System description and model integration with respect to thermal effects on flow. Refer to discussion of condensation and cold trap effect in Section 5.3.1 of Rev. 3. Also refer to Section 5.3.6 for related open item (bullet 2) that supercedes aspects of old criterion 3.3 of Rev. 2. **General acceptance criterion**: Data uncertainty with respect to thermal effects on flow. Refer to discussion of data uncertainty, including variability and heterogeneity, in Section 5.3.3 of Rev. 3. Also refer to Section 5.3.6 for new open item (bullet seven, item ii) that incorporates aspects of open item of old criterion 3.3 of Rev. 2 of the TEF IRSR. **General acceptance criterion**: Model uncertainty with respect to thermal effects on flow. Refer to the discussion of alternative models, and seepage into drifts during the thermal period, in Section 5.3.4 of Rev. 3. See also Section 5.3.6 for new open item (bullet eight) that supercedes aspects of old criterion 3.3 of Rev. 2.

TABLE B-1. ACCEPTANCE CRITERIA CROSS-WALK BETWEEN TEF IRSR REV. 2 & 3

TEF IRSR REVISION 2	TEF IRSR REVISION 3
Subissue 3 Technical Acceptance Criterion 3: Descriptions of the conceptual and mathematical models used in DOE's TSPA are reasonably complete. Further, DOE should demonstrate that: 3.4 Mathematical models are consistent with conceptual models, based on consideration of site characteristics. Concern raised that the mass balance of models needs to be confirmed.	Subissue 2 **General acceptance criterion**: System description and model integration with respect to thermal effects on flow. Refer to the discussion in Section 5.3.1 of Rev. 3. Also refer to related open item in Section 5.3.6 (third bullet).
Subissue 3 Technical Acceptance Criterion 3: Descriptions of the conceptual and mathematical models used in DOE's TSPA are reasonably complete. Further, DOE should demonstrate that: 3.5 Alternative models and modeling approaches, consistent with available data and current scientific understanding, are investigated; limitations defined; and results appropriately considered. Concern raised that alternative process-level models are not provided for critical heat and mass transfer mechanism (such as refluxing). Concern raised that an alternative DOE model for seepage into a drift that indicates significantly higher levels of seepage rates should be considered in the TSPA to ensure the TSPA is conservative.	Subissue 2 **General acceptance criterion**: Model uncertainty with respect to thermal effects on flow. Refer to discussion of alternative models in Section 5.3.4 of Rev. 3. Also refer to Section 5.3.6 for new open item (bullet eight) that supercedes (incorporates) open item of old criterion 3.5 of Rev. 2 of the TEF IRSR.

TABLE B-1. ACCEPTANCE CRITERIA CROSS-WALK BETWEEN TEF IRSR REV. 2 & 3

TEF IRSR REVISION 2	TEF IRSR REVISION 3
Subissue 3 Technical Acceptance Criterion 3: Descriptions of the conceptual and mathematical models used in DOE's TSPA are reasonably complete. Further, DOE should demonstrate that: 3.6 Results from different mathematical models have been compared to judge robustness of models. No specific concern raised in Rev. 2.	Subissue 2 **General acceptance criterion**: Model uncertainty with respect to thermal effects on flow. Refer to discussion of alternative models in Section 5.3.4 of Rev. 3. Also refer to Section 5.3.6 for new open item (bullet eight) that supercedes (incorporates) open item of old criterion 3.6 of Rev. 2 of the TEF IRSR.
Subissue 3 Technical Acceptance Criterion 4 Coupling of thermal processes has been evaluated using a methodology in accordance with NUREG-1466 (Nataraja and Brandshaug, 1992) or other acceptable methodology. Coupled processes may be uncoupled, if it is shown that the uncoupled model results bound the predictions of the fully-coupled model results. No specific concern raised in Rev. 2.	Subissue 1 **General acceptance criterion**: Screening the initial list of FEPs related to thermal effects on flow. The DOE is evaluating the need to incorporate TM and TC effects in thermohydrologic models as part of the FEP screening process. Refer to discussion in Section 5.2.2 of Rev. 3. Also refer to new open items regarding FEPs in Section 5.2.3 of Rev. 3. The potential direction and magnitude of TM or TC induced changes in rock properties (fracture aperture, fracture permeability) is a topic addressed under the NRC's RDTME and ENFE KTIs, respectively. As stated in Section 5.2.2 of Rev. 3, because of the broad level comments about the DOE's FEPs screening process and documentation and the fact that the DOE is currently revising FEP related AMRs, the NRC staff have not performed a detailed review of the DOE's FEP screening arguments at this time. When revised AMRs are available, the NRC staff evaluations will focus on the technical basis for excluding individual FEPs. Finally, no specific concern related to old criterion 4 is identified in Rev. 2 of the TEF IRSR to carry forward to Rev. 3 as the topic was essentially unreviewed at that time. For tracking purposes, the DOE can consider the old criterion 4 of Rev. 2 to be closed. New concerns regarding coupling of processes could arise in future reviews of FEP exclusion arguments.

TABLE B-1. ACCEPTANCE CRITERIA CROSS-WALK BETWEEN TEF IRSR REV. 2 & 3

TEF IRSR REVISION 2	TEF IRSR REVISION 3
Subissue 3 Technical Acceptance Criterion 5 The dimensionality of models used to assess the importance of refluxing water on repository performance may be reduced if it is shown that the reduced dimension model bounds the predictions of the full dimension model in performance. Concern raised as to whether the 2-D, mountain-scale TH calculations provide the time histories for gas-phase flow rates and air-mass fractions at repository center and edge locations because only thermal conduction is included in the DOE's mountain-scale submodel.	Subissue 2 **General acceptance criterion**: System description and model integration with respect to thermal effects on flow. Refer to discussion of condensation and cold trap effect in Section 5.3.1 of Rev. 3. Also refer to Section 5.3.6 for related open item (second bullet).

TABLE B-1. ACCEPTANCE CRITERIA CROSS-WALK BETWEEN TEF IRSR REV. 2 & 3

TEF IRSR REVISION 2	TEF IRSR REVISION 3
Subissue 3 Technical Acceptance Criterion 6 Results of the TSPA related to TEF have been verified by demonstrating consistency with results of process-level models. Concern raised that the DOE process-level models do not yet incorporate all potentially important heat and mass transfer mechanisms. Seepage into the drift under isothermal conditions, and refluxing into the drift during and after the heating period, are two mechanisms not adequately incorporated into the DOE process-level models. In the absence of process-level models that represent these mechanisms, results from the TSPA analyses cannot be verified as consistent with the process-level models.	Subissue 1 **General acceptance criterion**: Screening the initial list of FEPs related to TEF. Refer to discussion in Section 5.2.2 of Rev. 3 for broader review of FEPs screening process. Refer to new FEP related open items in Section 5.2.3 of Rev. 3 (bullets one through five). Subissue 2 **General acceptance criterion**: Data uncertainty with respect to thermal effects on flow. Refer to discussion of data uncertainty, including variability and heterogeneity, in Section 5.3.3 of Rev. 3. Also refer to Section 5.3.6 for new open item (bullet seven, item ii) that supercedes (incorporates) open item of old criterion 6 of Rev. 2 of the TEF IRSR. **General acceptance criterion**: Model uncertainty with respect to thermal effects on flow. Refer to the discussion of seepage into drifts during the thermal period in Section 5.3.4 of Rev. 3 regarding condensate drainage through fractures. See also Section 5.3.6 for new open items (bullet two and bullet seven, item ii) that supercede aspects of old criterion 6 of Rev. 2. **General acceptance criterion**: Model support with respect to thermal effects on flow. Refer to discussion in Section 5.3.5 of Rev. 3. Also refer to related open items in Section 5.3.6 (bullets six and nine).

TABLE B-1. ACCEPTANCE CRITERIA CROSS-WALK BETWEEN TEF IRSR REV. 2 & 3

TEF IRSR REVISION 2	TEF IRSR REVISION 3
Subissue 3 Technical Acceptance Criterion 7 Sensitivity and importance analyses were conducted to assess the need for additional data or information with respect to TEF. No specific concerns raised in Rev. 2.	Subissue 1 **General acceptance criterion**: Screening the initial list of FEPs related to thermal effects on flow. Part of the basis for excluding a FEP from the TSPA is consequence. To the degree that sensitivity and importance analyses are used to provide the technical basis for FEP exclusion arguments, they would be reviewed under this criterion. As stated in Section 5.2.2 of Rev. 3, because of the broad level comments about the DOE's FEPs screening process and documentation and the fact that the DOE is currently revising FEP related AMRs, the NRC staff have not performed a detailed review of the DOE's FEP screening arguments at this time. When revised AMRs are available, the NRC staff evaluations will focus on the technical basis for excluding individual FEPs. System level sensitivity and importance analyses in the context of specific barrier degradation analyses, or multiple barriers, is a topic addressed under the NRC TSPAI KTI (Total System Performance Assessment and Integration). No specific concern related to old criterion 7 is identified in Rev. 2 of the TEF IRSR to carry forward to Rev. 3 (closed in Rev. 2).