Transmitted with letter dated 9/15/99 T5C3
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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 2

AUGUST 1999

9909280158 990915
PDR WASTE
WM-11 PDR
102

Change pages 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 PA Technical Exchanges
1	3.3.5/all	Sept 1998	Discussion of TSPA-VA added
1	3.3.6/all	Sept 1998	Discussion of PA 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
1	4.3.3/1	Sept 1998	Additional references added to review method

Change pages (cont'd)

Revision #	Section/ Paragraph	Date	Modification
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 DOE response to three comments on thermohydrological testing sent by NRC to 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.
2	5.1.2	Aug 1999	Updated evaluation of PAC 2. Status summary added.

Change pages (cont'd)

Revision #	Section/ Paragraph	Date	Modification
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 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

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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).

The authors thank N. Sridhar and G. Cragnolino for assistance in understanding waste package corrosion mechanisms and the incorporation of corrosion processes into the performance assessment of the high-level radioactive waste repository. The authors thank A. Armstrong and B. Sagar for reviews of this report. The authors are also grateful to J. Wike for skillful typing and preparation of the final document and to B. Long, who provided a full range of expert editorial services.

Revision 2

The authors thank D. Farrell and B. Sagar for reviews of this report. The authors are also grateful to J. Wike for skillful typing and preparation of the final document and to B. Long, who provided editorial services.

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

One of the primary objectives of the U.S. Nuclear Regulatory Commission (NRC) refocused prelicensing high-level radioactive waste (HLW) program is to focus all its activities on resolving the 10 key technical issues (KTIs) considered most important to repository performance. 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). Other chapters of the Annual Progress Report address each of the 10 KTIs by describing the scope of the issue and subissues, path to resolution, and progress achieved during fiscal year (FY) 1996.

Consistent with Title 10 Code of Federal Regulations (CFR) Part 60 and a 1992 agreement with the U.S. Department of Energy (DOE), staff-level issue resolution can be achieved during the prelicensing consultation period, however; such resolution would not preclude the issue being raised and considered during the licensing proceedings. Issue resolution at the staff level during prelicensing is achieved when the staff has no further questions or comments (i.e., open items), at a point in time, regarding how DOE's program is addressing an issue. There may be some cases where resolution at the staff level may be limited to documenting a common understanding regarding differences in NRC and DOE points of view. Furthermore, pertinent additional information could raise new questions or comments regarding a previously resolved issue.

An important step in the staffs approach to issue resolution is to provide DOE with feedback regarding issue resolution before the viability assessment (VA). Issue Resolution Status Reports (IRSRs) are the primary mechanisms that the staff will use to provide DOE feedback on the progress toward resolving the subissues comprising the KTIs. This report is the first revision of the IRSR on Thermal Effects on Flow (TEF). Revision 1 of this IRSR completely supersedes Revision 0, which becomes obsolete. IRSRs include: (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. Additional information is also contained in the staff Annual Progress Report that summarizes the significant technical work toward resolution of all KTIs during the preceding FY. Finally, open meetings and technical exchanges with DOE provide opportunities to discuss issue resolution, identify areas of agreement and disagreement, and develop plans to resolve such disagreements.

In addition to providing feedback, the IRSRs will serve as guidance for the staffs review of information in DOE's VA. The staff also plans to use the IRSRs in the future to develop the Yucca Mountain Review Plan (YMRP) for the repository license application (LA).

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 a total system performance (TSP) flowdown diagram (U.S. Nuclear Regulatory Commission, 1998a); (iii) results of available sensitivity analyses; and (iv) relationship to DOE Repository Safety Strategy (RSS) (U.S. Department of Energy, 1998), which supersedes the DOE Waste Containment and Isolation Strategy (WCIS) (U.S. Department of Energy, 1996a). Section 4.0 provides staff

review methods and acceptance criteria, which indicate the basis for resolution of the subissues and will be used by the staff in subsequent reviews of DOE submittals. These acceptance criteria are guidance for the staff and indirectly for DOE as well. The staff technical bases for the acceptance criteria are also included to further document the rationale for their decisions. Section 5.0 concludes the revision with the status of resolutions indicating those items resolved at the staff level or those items remaining open. These open items will be tracked by staff, and resolution will be documented in future IRSRs. Finally, Section 6.0 includes a list of pertinent references.

2.0 KEY TECHNICAL ISSUE AND SUBISSUES

The primary technical aspects of the TEF KTI is the estimation of temperature, moisture content, and humidity at the waste package (WP) surface and estimation of temperature and thermally driven water flux with respect to the transport of radionuclides from failed WPs. Redistribution of moisture driven by heat may result in extended periods of dryness in the proposed repository. Redistribution of moisture driven by heat could result in channeling moisture toward the WP—a phenomenon referred to as "thermal reflux" in this report. As explained in Section 3, it is necessary to understand the spatial and temporal effects of the thermal load on liquid phase and gas phase fluxes, and resultant effects on temperature and relative humidity (RH) of the WP environment at the proposed repository to have confidence in predictions of containment and long-term waste isolation. Because the focus of the staff review of DOE's program is on the adequacy of DOE's treatment of thermally perturbed liquid phase and gas phase fluxes (particularly thermal reflux) in testing, modeling, and performance assessment (PA) program areas, this KTI is divided into three resolvable subissues:

- 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 scope of this IRSR encompasses all three subissues. In this revision, DOE's thermohydrologic testing program is evaluated in the context of the acceptance criteria for Subissue 1. Evaluation of DOE's thermohydrologic modeling program in the context of the acceptance criteria for Subissues 2 and 3 will be provided in FY1999 (Revision 2 of this IRSR).

3.0 IMPORTANCE TO REPOSITORY PERFORMANCE

The staff is developing a strategy for reviewing the performance of a proposed HLW repository at Yucca Mountain (YM), Nevada. As currently envisioned, the elements of this strategy necessary to determine acceptability of repository performance are defined as key elements of the subsystem abstraction (KESA). The KESA are illustrated in Figure A-1 in Appendix A. Acceptance criteria, for the key elements of DOE's TSPA, are under development. As noted in the following sections of this report, this KTI on TEF is currently considered to be an important factor in repository performance. For DOE to adequately demonstrate and quantify the consequences that TEF might have on repository performance in its TSPA, it must consider the thermohydrologic interactions both within and between key elements of the engineered and natural subsystems of the repository. As highlighted in Figure A-1, TEF is an important factor that needs to be abstracted into four of the key elements of the engineered and natural subsystems:

- WP Corrosion (RH, Temperature, and Chemistry)—The temperature and RH of the WP 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 WPs can affect the integrity of canister material by accelerating corrosion mechanism, thereby leading to potential premature release of radionuclides from the WP.

- Quantity and Chemistry of Water Contacting WPs and Waste Forms—Degradation of the waste form and release from WPs is a function of the amount of liquid water available whether as incident percolation flux during the isothermal period or as thermal reflux.

- Distribution of mass flux between fracture and matrix. An important aspect of TEF is to investigate gravity-driven refluxing in vertical or near-vertical fractures in the near-field rock above a heat generating WP and to determine if there is a possibility for water to drip onto the WPs by refluxing through fractures.

- Spatial and Temporal Distribution of Flow—The pathways for flux from percolating water can vary both spatially and temporally in response to changes in surface infiltration and anthropogenic changes due to the repository (i.e., thermal reflux, chemical changes in the near field).

3.1 U.S. DEPARTMENT OF ENERGY REPOSITORY SAFETY STRATEGY

DOE presented a strategy for waste containment and isolation at the YM site 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. DOE updated the WCIS to incorporate additional site characterization information, newer repository and WP designs, more realistic performance predictions, and changing regulatory considerations (U.S. Department of Energy, 1996a). The WCIS has now been further updated and renamed "The Repository Safety Strategy" (U.S. Department of Energy, 1998a). The latest DOE strategy defines attributes of the HLW disposal system deemed important to containment and isolation. These attributes include:

- Limited water contacting WPs
- Long WP lifetime
- Slow rate of radionuclide release
- Concentration reduction of radionuclides during transport

DOE has identified hypotheses about those attributes, which are to be evaluated within this KTI, albeit only in the context of the period of thermal perturbation of the repository. Five of these hypotheses are: (i) percolation flux at repository depth can be bounded; (ii) seepage into drifts will be a fraction of percolation flux; (iii) seepage that contacts WPs can be limited; (iv) thermally-induced seepage can be bounded; and (v) heat reduces RH at WP surface. Evaluating these hypotheses necessitates understanding the liquid phase and gas phase fluxes in the vicinity of the repository during the period of thermal perturbation, including the potential for thermal reflux.

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 WP, by transporting radionuclides released from WPs, or by altering hydraulic or transport pathways in the ground control structures, inverts, or host rock.

The effect of heat emanating from WPs 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 WP-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 WPs. Water that has entered a vaporization/condensation cell encompassing a WP can cycle between boiling and condensation, possibly interacting with a container, or exit the cell as vapor or liquid with or without contacting a WP. This source of water will be available for refluxing as liquid or for contributing to RH as vapor until rock temperatures are no longer increasing and all vaporized rock water has left the vaporization/condensation cell containing the WP. 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 WPs and negligible amounts of vaporized rock water succeed in returning as condensate to the WP environment.

The ultimate fate of ambient rock-pore water or percolating water in the WP 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 WP 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 WPs 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 WPs may occur with or without the presence of water. Corrosion in the absence of water, referred to as dry-air corrosion, is considered by DOE and also by NRC to be negligible in container corrosion (TRW Environmental Safety Systems, Inc., 1995). Corrosion is considered to occur only when the WP is in contact with water in the vapor or liquid phase. DOE treats corrosion of the outer WP 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 RH (TRW Environmental Safety Systems, Inc., 1995). Humid air corrosion occurs in the presence of a thin film of water in environments (i.e., RH from about 65–75 percent to 85–95 percent). Similarly, aqueous corrosion occurs when RH 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 RH at which humid air corrosion or aqueous corrosion are experienced may differ. In addition to these two corrosion regimes, 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 PAs by lowering the threshold of RH at which the onset of humid air or aqueous corrosion begins.

Although corrosion of WP 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 WPs—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 RH, the occurrences and rates of general and pitting corrosion are dependent on temperature and chloride concentration. Formulas describing the relationship among RH, temperature, and chloride concentration can be found in Mohanty, et al. (1997) for example. In general, corrosion rates increase with temperature, RH, 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 RH may be decreased), which may lead to accelerated corrosion rates (Tsuru, et al., 1995).

WP design currently consists 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 C-22 is considered in the new WP design (U.S. Department of Energy, 1996b). The intent of shielding WPs with CAM is not to completely prevent corrosion, instead it is designed to allow corrosion to advance relatively uniformly, but slowly, over large areas. Conversely, pitting corrosion advances relatively quickly but is restricted to small areas. Ideally, a container will corrode slowly by general corrosion of the outer barrier, or if rapid pitting penetrates the outer barrier, protection of the inner barrier can be enhanced by galvanic coupling of the two barriers.

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 WP 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 WP by dripping can affect corrosion mechanisms and rates in several ways (Walton, 1993). First, water dripping from the concrete structures or rock mass can provide significant quantities of strong anions, in general, and chloride, in particular, to the WP 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 WP 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, RH, and flux of (vapor or liquid phase) water proximal to the WPs. Process-level models should consider all the potential water entering emplacement drifts, including refluxing, when predicting the heat and mass transfer near the WP. Results from process-level models and PAs 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 WPs is conservatively estimated.

3.2.3 Effect of Thermally Driven Water on Hydraulic and Transport Pathways

The final design of the emplacement drifts is under study and has not been specified. Design options include, for example, the incorporation of ground control structures, inverts, backfill, and drip shields (U.S. Department of Energy, 1997a). Liquid water entering the emplacement drifts has the potential to transport significant quantities of minerals to the WP surface as part of vaporization/condensation cells driven by WP 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 Evolution of the Near-Field Environment KTI.

3.3 CONSIDERATION OF THERMALLY DRIVEN WATER IN PREVIOUS PERFORMANCE ASSESSMENTS

The performance of the WP and the transport of radionuclides released from failed WPs are affected by the thermohydrology of the environment in the vicinity of the WPs. Predicting heat and mass transfer in the near field of the WPs has been an integral component of recent PAs of the proposed repository at YM. The following are most notable of these PAs: (i) two performed by 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 NRC—*Iterative Performance Assessment, Phase 2* (IPA Phase 2) (Wescott, et al., 1995). The manner in which each study incorporates the thermohydrological effects resulting from heat generated by the decay of HLW is summarized in the following sections. Included in this summary are DOE and NRC program modifications as described at the May 1998 DOE/NRC Technical Exchange on PA 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 WPs. The integrity of the WPs is calculated in YMIN as a function of temperature and whether the WPs are dry or wet. Wet WPs 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 WP. 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 PA, 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. RH is not considered a factor in WP 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 WPs is a function of spent fuel, WP, 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

Mechanisms and Parameters That Affect Waste Package Integrity

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 RH 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 RH greater than 85–95 percent. Thus, the contact with liquid water is not explicitly considered in container performance.

Effect of Pore Water and Infiltration on Released Radionuclides

Subsequent to the failure of WPs, radionuclides are transported from the point of release to the saturated zone (SZ) in the liquid phase. Geosphere transport of radionuclides in the gaseous phase of the unsaturated zone (UZ) 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 SZ. Liquid flux through the UZ 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 RH 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

Mechanisms and Parameters That Affect Waste Package Integrity

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 PA, four moisture settings each at three different temperature regimes. The four moisture settings are: (i) dry—the WP does not contact liquid water; (ii) wet-drip—separate droplets of water fall across an air gap onto the WP; (iii) episodic—liquid water contacts the WP intermittently for limited periods of time; and (iv) moist-continuous—liquid water is in continuous contact with the WP. The three temperature regimes are: (i) WPs whose surface temperatures rise substantially above boiling; (ii) WPs whose surface temperatures rise to approximately the boiling point; and (iii) WPs 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 WP failure by assigning probability factors that reflect a greater failure than dry conditions. The general approach to WP 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 WP is considered in the EPRI source-term code, IMARC: COMPASS (Zhou and Salter, 1995). The rate at which advective liquid water leaves the WP is equivalent to the rate of water dripping into the WP. On encountering the concrete barrier below the WP, 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 WPs subsequent to container failure. Temperature and RH 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 WP is contingent on WP corrosion. The WPs are assumed to remain dry and no corrosion of the WPs occurs until the temperature falls below the boiling isotherm in the repository environment, 96 °C. The integrity of the WP in IPA Phase 2 is not directly dependent on RH or liquid water.

Effect of Pore Water and Infiltration on Released Radionuclides

Several mechanisms that can lead to water contact with WPs 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 WP with rock or rubble infilling material—the air gap surrounding the WP becomes filled with rubble material or the WP is tilted against the borehole wall; (iii) condensation of water onto surface of the WPs—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 WP—the unlikely occurrence where the WP 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 WP and the threshold of water in the WP that must be exceeded before outflow occurs are functions of the first three mechanisms listed previously. Advective transport of radionuclides from the WP to the natural environment is solely a function of the outflow of water from the WP 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 DOE's TSPA-VA Methods and Assumptions Document, DOE will use thermohydrologic modeling results to provide RH, air mass fraction, gas-phase flow rate in the drift, temperature of the WP, 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 UZ 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 UZ flow and thermohydrogeologic modeling, mountain-scale UZ flow and thermohydrogeologic 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 WPs 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 current DOE subsystem model for evaluating degradation of the WP is WAPDEG (Civilian Radioactive Waste Management System, Management and Operating Contractor, 1997). Corrosion of the outer barrier is currently based on an empirical formulation. Mechanistic models of corrosion are under development. These models will be incorporated into WAPDEG when available.

The current DOE model 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 RH. 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 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, RH, 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 for the TSPA-VA.

Effect of Pore Water and Infiltration on Transport of Released Radionuclides

Thermohydrologic results will be used to provide liquid-phase flow fields for the UZ 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 UZ 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[1]

Mechanisms and Processes That Affect Waste Package Integrity

Information exchanged between DOE and NRC at the May 1998 Technical Exchange on PA indicates that both DOE's and NRC's approaches to incorporating TEF into their respective PAs have been modified. DOE recognizes that WP 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 now incorporates the effects of liquid water by dripping on corrosion predictions for the inner layer (e.g., CRM) of the WP. 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 RH, 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, RH, and liquid saturation to the near-field geochemical models (EQ3/6) and predictions of temperature and RH to WAPDEG. Temperature and RH 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 PA 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 WP degradation model, which indicates the drift-scale thermohydrologic model will provide information on WP temperature, RH, 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

[1] A summary of the May 1998, U.S. Department of Energy/U.S. Nuclear Regulatory Commission Performance Assessment Technical Exchange will be issued with a copy of its presentation view graphs for reference.

WAPDEG that differs from the version to be used in the TSPA-VA. Although not a nonisothermal calculation, drift-scale UZ flow models (TOUGH2) will calculate the fraction of WPs with seeps.

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 WP corrosion. Both DOE's and NRC's programs acknowledged the importance of assessing the propensity to corrode the outer layer (e.g., CAM) of the WP by exposure to liquid water. Both programs indicated intentions to address the issue.

Effect of Pore Water and Infiltration on Transport of Released Radionuclides

Radionuclides will be transported from the WPs by advection only when drips are present; otherwise, transport is by diffusion. The drift-scale thermal-hydrologic (TH) 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 UZ-flow model (TOUGH2) will provide values for the fraction of WPs with seeps and the seep flow rate. The nonisothermal, mountain-scale UZ-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 YM to provide information on the progress of the YM Site Characterization Project. The VA also identified critical issues that must be addressed before a decision is made to recommend the YM 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 TH processes to be used in the TSPA-SR and TSPA-VA.

Technical Basis Document—Chapter 2: Unsaturated Zone Hydrology Model

Chapter 2 of the TBD addresses the UZ 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 WPs. The method used a dual permeability model (DKM) and a geostatistical description of the fracture heterogeneity.

The 3D UZ flow model was used to calculate the percolation flux and seepage velocity. In the UZ 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 UZ (TRW Environmental Safety Systems, Inc., 1998, pg 2-34). As a result predictions of focused fracture flow may be suppressed. Although 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, 1999).

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 RH 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 RH. The less than 100 percent RH 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 RH (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 RH 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 RH 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 YM would not exist under pre-existing, ambient or nonventilated, ambient RH 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 RH 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 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 WP 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).

Technical Basis Document—Chapter 3: Thermal Hydrology

The DOE uses a multiscale modeling approach to abstract TH processes into its TSPAs. The multiscale approach combines 1D, 2D, and 3D drift-scale thermal models and TH models with a conduction-only 3D mountain-scale model. These models were used in the TSPA-VA to estimate WP 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 TH 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, TH 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, TH submodel that computes average temperature and RH 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 UZ 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 WP are represented with rectangular geometry. Radiative heat transfer is included. Local topography, hydrostratigraphy, thermal properties, hydrological properties, BCs, and initial temperature are consistent with UZ site-scale model. Thermal and hydrological properties are homogeneous within hydrostratigraphic units. Heat source is an average of the seven individual WPs (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 TH 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 TH 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 TH multiscale modeling and abstraction method include the following:

  - Perimeter-averaged, drift-wall temperature
  - Perimeter-averaged, drift-wall RH
  - 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. RH is calculated using temperatures. Conduction-only predicted temperatures over-predict temperature relative to a TH model; however, conduction-only allows for finer spatial discretization. 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, BCs, and initial temperature are consistent with UZ 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 RHs. 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, BCs, and initial temperature are consistent with UZ 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 TH 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 RHs for different WP types along the drift. The DDT contains seven (i.e., six full packages and two ½ packages) representative WPs 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 RH among packages along the drifts. 1D vertical heat flow in the UZ 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 WP are approximated using rectangular geometrical representations. Radiative heat transfer in the drift is included. Local topography, hydrostratigraphy, thermal properties, hydrological properties, BCs, and initial temperature are consistent with UZ site-scale model. Thermal and hydrological properties are homogeneous within hydrostratigraphic units. The SDT, LDTH, and DDT models all assume the same seven WP types. An important role for the DDT model in the multiscale TH modeling approach is to represent the drift-wall temperature differences that occur between specific WP locations that are defined relative to the average drift-wall temperature along the drift. Another role is to determine the temperature between the WP and the average drift-wall temperature. The DDT submodel inputs to the TH multiscale modeling and abstraction method include the following: (i) WP-location-specific temperature differences from the average drift-wall temperature along the drift and (ii) WP-location-specific temperature differences between the WP and the average drift-wall temperature along the drift. The DDT model predicts slightly higher absolute drift-wall and

WP temperatures than does the DDTH model, but the two models produce very similar temperature differences at each of the WP 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 TH calculations.
- Because the thermal perturbation to the UZ flow field is generally short lived, it is not included in radionuclide transport through the UZ.
- 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 WP 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 base case. 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 RH (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 WP temperature and RH, 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 TH calculations (TRW Environmental Safety Systems, Inc., 1998, pg 3-13). All mountain-scale TH models were completed with the TOUGH2 flow code. The TH multiscale modeling and abstraction method provided temperature and RH at the surface of the WP, the drift-wall temperature, and liquid saturation in

the invert. 1D and 2D TH simulations are acceptable at the mountain scale, but 3D simulations are necessary to obtain the WP 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 TH mountain-scale simulations (TRW Environmental Safety Systems, Inc., 1998, pg 3-85).

The net result of the TH multiscale modeling and abstraction process is a discrete-heat source, mountain-scale, TH model (DMTH). It is an abstracted process that accounts for WP variability, fracture flow in a DKM conceptualization, and edge effects of a finite-sized repository. In its current formulation, the TH 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 TH 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, TH 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 TH 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 WP heating" (TRW Environmental Safety Systems, Inc., 1998, pg 3-12).

Property Values and Model Input

TH analyses were run using a base case set of thermal and hydrological properties. In all the TH 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 TH 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 PA 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 base case was calibrated to widely varying infiltration rates. The DKM/Weeps property set was developed to allow more fracture flow to occur in the UZ, 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 TH property set was used to represent rewetting uncertainty characterized by TH processes (TRW Environmental Safety Systems, Inc., 1998, pg 3-70). The TH property set was developed to provide a better match with the results of the SHT temperature data. This property set is similar to the base case, 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 RH 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
- WP conduction-only axial temperature variation
- WP 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 WP 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 RH at the WP, the drift-wall matrix saturation, and the invert liquid-phase saturation are calculated by interpolation for each WP type, as a function of location in the repository (TRW Environmental Safety Systems, Inc., 1998, pg 3-91).

- RH at the drift wall
- Drift-wall matrix saturation
- Invert liquid-phase saturation

Step 6

Determine the distribution of WP temperature for each WP type. This step determines the distribution of WP temperature as a function of WP 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 RH on the WP for each WP type. The final step is to determine the distribution of RH on WPs throughout the repository area for each WP type where RH(wp) = RH(dw)[P(sat)(Tdw)/P(sat)(Twp)].

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

Constructing Probability Density Functions of Engineered-Barrier System Thermal-Hydrologic Conditions

Predictions from the TH 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:

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

For WP analysis, the process of "binning" the WP 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) WP types into a single CSNF WP category and group the co-disposal HLW packages with the separate-disposal DOE spent nuclear fuel (SNF) WPs into a single HLW-package category.

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

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

Base Case Analysis

Mountain-Scale Results

The air-mass fraction and the gas-flow rates in the repository were generated using the 2D G-ECM mountain-scale, TH model. [It is assumed that 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 WP 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 WPs 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 WPs 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 UZ 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 WPs maintain boiling temperatures for 1000 to approximately 4000 years. Other WPs 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 TH multiscale modeling and abstraction method. Model predictions using the TH property set result in higher temperatures (and hence lower RHs) for approximately 10,000 years after waste emplacement (TRW Environmental Safety Systems, Inc., 1998, pg 3-100). These WP temperature and RH response curves are input into WP corrosion models, such as WAPDEG, to predict the overall lifetime of a WP in a repository drift. With the specification of a threshold temperature, a RH threshold for humid-air corrosion, a RH 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 WPs through and out of the EBS (TRW Environmental Safety Systems, Inc., 1998, pg 3-104).

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

The TH 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 WP 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 base case, reduction of RH is limited to about 1000 years or less for most WPs (TRW Environmental Safety Systems, Inc., 1998, pg 107).

Sensitivity Studies and Model Analysis

To instill greater confidence that the abstraction modeling approach represents the TH processes expected to occur at YM, PA 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 TH models to approximate edge effects, includes WP-to-WP 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 TH 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 °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).

Assessment of Rock Dryout Surrounding Drifts

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 RHs 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 WP 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 WPs 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 RH is maintained below 85 percent for approximately 3000 years or more. For the quartz sand, the RH 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 WP surroundings (TRW Environmental Safety Systems, Inc., 1998, pg 3-131).

Comparison of Drift Segments

This sensitivity study is performed with the PA (testing) drift-scale models; it is not a result of the TH 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 WPs in the cold drift segment have a RH 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 WPs during the first 5000 years can be ignored (TRW Environmental Safety Systems, Inc., 1998, pg 3-84). It is recommended by DOE that in future analyses, in particular for the LA, the drift segment study be performed using the TH 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 WPs will fail by a corrosion mechanism 10,000 years after waste emplacement. Consequently, perturbations in the UZ flow fields during the first 5000 years after waste emplacement in YM 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 UZ 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 TH 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 TH 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 TH 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 WPs contacted by water seeping into drifts and seep flow rate, which is the rate of flow of water dripping onto one of the WPs that has seepage. To apply the seepage abstraction to a TH 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).

Thermal-Hydrologic Results of Rockfall

The rockfall sensitivity study was performed using the 3D, drift-scale, TH 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 WP in addition to changing the geometry of the drift ceiling asperities and the distance from the WP 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 TH 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 UZ containing silica (TRW Environmental Safety Systems, Inc., 1998, pg 3-156). The WP response curves, (such as temperature and RH) are different for each case considered; however, the differences are not large enough to cause an appreciable response from the WP corrosion models used to compute the degradation of the canister. Based on this result, THC effects are neglected for the base-case TH 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 LA (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 RH in the rockfall zone surrounding the WP may be very detrimental to performance of the WP (TRW Environmental Safety Systems, Inc., 1998, pg 3-159). A sensitivity study using a TH model to investigate the effects on an open drift indicated a substantial deviation from the base case (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 WPs 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 RH 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 TH models. The results of the heating period of this large-scale test will be available in time for the TSPA for the LA. This test is to provide information of drift-scale movement of heat through rock at YM 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. Initial results from the SHT seem to indicate 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). The DOE indicates that more small-scale heater tests are to be conducted in repository specific units.

The use of natural analog 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 TH model appears to be an acceptable systematic analysis of TEF at the proposed YM 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 TH 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 TH processes on seepage for the entire repository performance period. TH 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 WP until the WP temperature decreases below boiling is not conservative.

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

The principal factor leading to WP 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 WP would most likely occur through dripping, and water vapor exposure would occur when the RH is sufficiently high. If water is in the repository environment, then the quantity and chemistry of the water contacting the WP 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 WP to wet/dry cycles.

In the presence of water, the WP surface undergoes either humid-air or aqueous corrosion. Although the specific values for RH are adjustable, humid-air corrosion is expected at a RH greater than about 70 but less than about 85 percent. Aqueous corrosion occurs at RH greater than about 85 percent. Dripping is included only in terms of its effect on RH, that is, aqueous corrosion is assumed active when RH 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 RH is low (i.e., less than 85 percent). This possibility recognizes those instances in which the WP surface would experience humid-air corrosion even in the presence of dripping until the RH is increased and aqueous corrosion is experienced. This 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 RH).

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 WP would be highly concentrated. Drips with very high mineral concentration was observed in laboratory-scale heater tests (Green and Prikryl, 1998, 1999). The highly concentrated liquid-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 WP, the potentially corrosive salts from the drips would remain on the WP surface after the water was removed. Neglecting the potential for dripping onto WPs when drift-air temperatures exceed boiling and high mineral concentrations in drips when RH is less than the threshold for aqueous corrosion is not a conservative assumption. The DOE acknowledges that salt deposition on a WP 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 WP 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 WP 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 base case.

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. This expectation is not consistent with results from laboratory-scale heater experiments that experienced deposition of corrosive precipitates in the drift during the heating phase of the experiments (Green and Prikryl, 1998, 1999). Phenomenological results from these tests are relevant even though the chemical environment of the tests differs from YM.

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 WPs 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 WP (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 or 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 YM 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 YM 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 WPs 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 WP. 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 WP. 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 WP 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 WP. 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 WP during times the temperature of the WP 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 WPs, 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 WP. 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 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 thermohydrological 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 WP 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).

A drift-scale model of heat and mass transfer was formulated to provide temperature, saturation, and RH 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 WP) 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 WP to the mid-point between WPs 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 WP 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 WP was 0.8 m wide and 1.6 m tall. The half-length of the WP 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). 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 differ from values contained in the current TPA basecase property set. Process-level model runs at infiltration rates of 1.0, 5.5, and 10.0 mm/yr have only been successful using several property values taken from TSPA–93 and TSPA–95. 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. Attempts are ongoing to incorporate the current TPA basecase values into the process-level models.

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

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

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.

REFLUX1 Submodule

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 WPs (Table 3).

REFLUX2 Submodule

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 WPs (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 temperature and RH data produced by these simulations were used in TPA Version 3.1.1 to evaluate the effects of temperature and RH on predicted repository performance. The highest temperatures were predicted for the lower infiltration rates and the highest RHs 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 RH. The performance measures examined were peak total dose of radionuclides in groundwater at the assumed 5 km critical group location, time of first WP failure due to corrosion, and number of WP 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 WP and altering the transport of radionuclides once released from the WP. The integrity of the WP 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 WPs, as modeled in TPA Version 3.1.1, is not affected by the presence of liquid water at the WP surface, other than as an indication that aqueous corrosion conditions prevail for a RH exceeding 80 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 WPs. TPA Version 3.1.1 sensitivity analyses, however, indicate no significant effect is realized from refluxing water interacting with the WPs. This is explained, at least in part, by the potentially large volume of pore water mobilized during heating would have already been transported away from the repository prior to WP 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)	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)	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)	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 (range = 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)	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

For DOE to adequately demonstrate and quantify the consequences that TEF might have on repository performance, it needs to consider thermohydrologic interactions both within and between key elements of the engineered and natural subsystems of the repository, as discussed in Section 3.0. Acceptance criteria, on which a more broad staff review of key elements of DOE's TSPA will be based, are presented in the IRSR on TSPA and integration. It should be noted that the acceptance criteria for this KTI and related subissues are subsidiary to and designed to complement the broader-level acceptance criteria for the abstraction of the key elements.

4.1 SUBISSUE 1: IS THE U.S. DEPARTMENT OF ENERGY THERMOHYDROLOGIC TESTING PROGRAM, INCLUDING PERFORMANCE CONFIRMATION TESTING, SUFFICIENT TO EVALUATE THE POTENTIAL FOR THERMAL REFLUX TO OCCUR IN THE NEAR FIELD?

This subissue relates to the sufficiency of DOE's thermohydrologic testing program to provide information used to verify conceptual models that DOE will use to evaluate thermally-driven flow in the near field. Resolution of this subissue will be through the application of the acceptance criteria defined in Section 4.1.1 of this report.

4.1.1 Acceptance Criteria for Subissue 1

DOE's thermohydrologic testing program, including performance confirmation testing, with regard to TEF, is acceptable if the following acceptance criteria have been met:

Programmatic Acceptance Criterion 1

- DOE's thermohydrologic testing program was developed under acceptable quality assurance procedures (QAP). Data were collected and documented under purview of these procedures.

Programmatic Acceptance 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.

Technical Acceptance Criterion 1

- Thermohydrologic tests are designed and conducted:

  1.1 With the explicit objective of testing conceptual and numerical models so that critical thermohydrologic processes can be observed and measured.

  1.2 With explicit consideration of TH, thermal-chemical, and hydrologic-chemical couplings;

1.3 At different scales to discern scale effects on observed phenomena;

1.4 For temperature ranges expected under repository operating conditions;

1.5 To determine if water refluxes back to the heaters during either the heating or cool-down phases of the tests; and

1.6 To evaluate the possibility for occurrence of cyclic wetting/drying on WP surfaces.

1.7 To account for all mass and energy losses/gains in the model system

1.8 Such that the model environment is sufficiently characterized so that the level of uncertainty in property values does not result in unacceptable uncertainty in thermal test interpretation

1.9 Such that accuracy in the measurement of the test environment saturation is sufficient to discern the relative ability of different conceptual models to represent the TH processes in heated partially saturated, fractured porous media

Technical Acceptance Criterion 2

- Thermohydrologic test results from other sites and programs have been analyzed and applied, as appropriate, to the YM site.

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.

4.1.2 Technical Basis for Acceptance Criteria for Subissue 1

The acceptance criteria outlined in Section 4.1.1 are designed to enable staff to critically evaluate the sufficiency of DOE's thermohydrologic testing program to provide information needed to verify conceptual models used to predict thermally driven flow in the near field. The most important technical element of the acceptance criteria relates to designing and conducting tests to evaluate repository conditions that could lead to refluxing of water into the underground facility. Ample evidence suggests that rock water mobilized soon after the onset of heating can condense sufficiently near the heat source, such that water refluxing back to the heat source is possible, even during periods when the output of the heat source is high (Johnstone, et al., 1985; Patrick, 1986; Ramirez, 1991). Hence, the fate of vaporized rock water, in addition to percolating water or any other water whose fate may be thermally affected near the WPs, needs to be assessed. At present, staff considers thermally driven water to be potentially important to waste containment and overall performance; therefore, the tests should be capable of observing this phenomenon.

4.1.3 Review Method for Subissue 1

To provide timely comment to DOE regarding its thermohydrologic testing program, staff review of DOE's testing program has been active during FY1997–1998. Specifically, it has been important to make progress in issue resolution in advance of specific test conclusions. In general, the staff review method included a variety of activities:

- Reviewing DOE documents (both planning documents and reports summarizing results of tests to date) related to the thermohydrologic testing program
- Reviewing the peer review of the DOE thermohydrologic testing and modeling program and subsequent DOE responses
- Visiting sites to observe thermal test facilities and instrumentation
- Participating in appendix 7 meetings to discuss topics related the thermohydrologic testing
- Observing DOE test planning and technical meetings, where results of testing activities were discussed

In the future, staff will continue to monitor the progress of DOE thermohydrologic tests (particularly, experiments recently started or to be started during FY1998, such as the drift-scale test). In addition, CNWRA staff is conducting a laboratory-scale heater test to provide insight into thermally driven reflux mechanisms (details will be presented in the next NRC annual report). A summary of concerns raised with DOE regarding the thermohydrologic testing program and the status of resolution of this subissue at the staff level is provided in Section 5 of this report.

4.2 SUBISSUE 2: IS THE U.S. DEPARTMENT OF ENERGY THERMOHYDROLOGIC MODELING APPROACH SUFFICIENT TO PREDICT THE NATURE AND BOUNDS OF THERMAL EFFECTS ON FLOW IN THE NEAR FIELD?

This subissue relates to the sufficiency of DOE's thermohydrologic modeling approach (process-level models) to predict thermally-driven flow in the near field. Resolution of this subissue will be through application of the acceptance criteria defined in section 4.2.1 of this report.

4.2.1 Acceptance Criteria for Subissue 2

DOE's thermohydrologic modeling analyses (process-level models) used to predict thermally driven flow in the near field are acceptable if the following acceptance criteria are met:

Programmatic Acceptance Criterion 1

- DOE's thermohydrologic modeling analyses were developed and documented under acceptable QA procedures.

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.

Technical Acceptance Criterion 1

- Sufficient data are available to adequately define relevant parameters, parameter values, and conceptual models. Specifically, DOE should demonstrate that:

  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.

  1.2 Analyses are consistent with site characteristics in establishing initial conditions, boundary conditions, and computational domains for conceptual models evaluated.

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

  2.2 Models include, at a minimum, the processes of evaporation and condensation and the effects of discrete geologic features

  2.3 Models include, at a minimum, an evaluation of important thermohydrological 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

  2.4 Models include all significant repository design features

  2.5 Models are capable of accommodating variation in infiltration

  2.6 Conceptual model uncertainties have been defined and documented and effects on conclusions regarding performance assessed

  2.7 Mathematical models are consistent with conceptual models, based on consideration of site characteristics

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

2.9 Results from different mathematical models have been compared to judge robustness of results

2.10 Models used to predict shedding around emplacement drifts are shown to contain an adequate level of heterogeneity in media properties

2.11 TH models have been demonstrated to be appropriate for the temperature regime expected at the repository

2.12 Models include radiative heat transport unless it is shown that radiative heat loss by a WP is not significant

2.13 Models include the effect of ventilation particularly if ventilation could result in deposition or condensation of moisture on a WP surface

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

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 horizon

2.16 Physical mechanisms such as penetration of the boiling isotherm by flow down a fracture are not omitted from model predictions due to over-simplification of the physical medium or the conceptual model

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.

Technical Acceptance Criterion 4

- 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.

Technical Acceptance Criterion 5

- 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.

Technical Acceptance Criterion 6

- Accepted and well-documented procedures have been adopted to construct and calibrate numerical models used.

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.

4.2.2 Technical Basis for Acceptance Criteria for Subissue 2

The acceptance criteria outlined in Section 4.2.1 are designed to enable the staff to critically evaluate the sufficiency of DOE's thermohydrologic modeling approach (process-level models) to predict thermally driven flow in the near field. Staff review of DOE's thermohydrologic analyses will place particular emphasis on technical elements of the acceptance criteria that are related to incorporating the physics of refluxing of water into conceptual and numerical models because:

- Liquid water that refluxes into the underground facility and interacts with WPs may affect the integrity of canister material by accelerating corrosion mechanisms, thereby leading to the premature release of radionuclides from the WP.

- Water introduced into the underground facility by dripping can alter hydraulic and transport pathways by reacting with the ground control structures, concrete inverts at the base of the drifts, or with minerals within the host rock. Mineral precipitation or dissolution resulting from dripping into the underground facility can lead to an alteration of pathways.

- The transport of radionuclides released to the geosphere after the failure of the WP can be accelerated by liquid water introduced into the underground facility by thermally driven water movement.

4.2.3 Review Method for Subissue 2

Conceptual and numerical models used by DOE to predict thermally driven flow will be evaluated independently by the staff based on the models' ability to predict water refluxing events that occurred during the heating phase, such as those observed during field heater tests conducted at G-tunnel (Johnstone, et al., 1985; Ramirez, 1991), the Climax Mine (Patrick, 1986), and the University of Arizona Road Tunnel[2]. It is expected that DOE will continue to develop thermohydrologic analyses to assess results from laboratory-scale tests, the Fran Ridge large block test (LBT), the ESF single-heater test (SHT), and the ESF drift-scale heater

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Evans, personal communication with R.T. Green, 1986.

test (DST). If these ongoing tests provide results relevant to refluxing water, DOE's models will be independently evaluated to ensure they provide predictions that conservatively estimate the nature and bounds of thermal effects on flow in the near field. A summary of concerns raised with DOE regarding its thermohydrologic modeling efforts and the status of resolution of this subissue at the staff level are included in Section 5 of this report.

4.3 SUBISSUE 3: DOES THE U.S. DEPARTMENT OF ENERGY TOTAL SYSTEM PERFORMANCE ASSESSMENT ADEQUATELY ACCOUNT FOR THERMAL EFFECTS ON FLOW?

This subissue relates to DOE demonstration of the adequacy of its TSPA with respect to TEF. The resolution of this subissue will be through application of the acceptance criteria defined in Section 4.3.1. It should be noted, however, that resolution of the subissue is not intended to be interpreted as, or deemed to be, a determination of the acceptability of the entire DOE TSPA. Because the acceptance criteria in section 4.3.1 complement the acceptance criteria to be applied to a determination of the acceptability of the complete DOE TSPA (under development by staff), it follows that resolution of this subissue will result only in a determination that those aspects of DOE's TSPA relating to TEF are acceptable.

4.3.1 Acceptance Criteria for Subissue 3

Those aspects of DOE's analysis of TSP that relate to TEF are acceptable, if the following acceptance criteria are met:

Programmatic Acceptance Criterion 1

- DOE's analyses were developed and documented under acceptable QA procedures.

Programmatic Acceptance Criterion 2

- 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.

Technical Acceptance Criterion 1

- 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 model predictions of the influx of water as liquid or vapor into an emplacement drift.

Technical Acceptance Criterion 2

- Sufficient data are available to adequately define relevant parameters, parameter values and conceptual models. Specifically, DOE should demonstrate that:

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.

2.2 Analyses are consistent with site characteristics in establishing initial conditions, boundary conditions, and computational domains for conceptual models evaluated.

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.

3.2 Significant Geologic Repository Operations Area 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.

3.3 Conceptual model uncertainties have been defined and documented, and their effects on conclusions regarding TSP have been assessed.

3.4 Mathematical models are consistent with conceptual models, based on consideration of site characteristics.

3.5 Alternative models and modeling approaches, consistent with available data and current scientific understanding, are investigated; limitations defined; and results appropriately considered.

3.6 Results from different mathematical models have been compared to judge robustness of results.

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.

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.

Technical Acceptance Criterion 6

- Results of the TSPA related to TEF have been verified by demonstrating consistency with results of process-level models.

Technical Acceptance Criteria 7

- Sensitivity and importance analyses were conducted to assess the need for additional data or information with respect to TEF.

4.3.2 Technical Basis for Acceptance Criteria for Subissue 3

The acceptance criteria outlined in Section 4.3.1 are designed to enable the staff to determine if DOE's TSPA adequately accounts for TEF. Staff review of this aspect of DOE's TSPA will place particular emphasis on those technical elements of the acceptance criteria related to incorporating the potential adverse affects from the influx of water as liquid or vapor into an emplacement drift on the performance of the repository because:

- Water that enters the underground facility as liquid or vapor and interacts with WPs can affect the integrity of canister material by accelerating corrosion mechanisms, thereby leading to the premature release of radionuclides from the WP.

- Water introduced into the underground facility by dripping can alter hydraulic and transport pathways by reacting with the concrete inverts at the base of the drifts or with minerals comprising the host rock. Mineral precipitation or dissolution resulting from dripping into the underground facility can lead to a decrease or increase of pathways.

- The transport of radionuclides released to the geosphere after the failure of the WP can be accelerated by liquid water introduced into the underground facility by thermally driven moisture movement.

4.3.3 Review Method for Subissue 3

The staff review method for this subissue has included a variety of activities by the staff:

- Review of DOE documents, such as the *U.S. Department of Energy Total System Performance Assessment-Viability Assessment Plan* (TRW Environmental Safety Systems, Inc., 1996a); the *U.S. Department of Energy Thermohydrology Abstraction/Testing Workshop Results* (Francis, et al., 1997); the *First Interim Report of the Total System Performance Assessment Peer Review Panel*; and the *Total System Performance Assessment-Viability Assessment, Methods and Assumptions* (TRW Environmental Safety Systems, Inc., 1997).

- Observation of DOE planning meetings on PA, such as the DOE Thermohydrology Abstraction/Testing Workshop.

- Review of DOE PAs, such as TSPA–93 and TSPA–95, as well as PAs performed by other parties, such as EPRI.

- Participation in the NRC/DOE technical exchanges on PA.

- Performance of independent PAs by staff.

DOE's TSPA will be evaluated independently by staff. In the remainder of FY1998 and into FY1999, emphasis will be on development and implementation of the NRC/CNWRA TPA code. The physics of refluxing water will be incorporated into both NRC/CNWRA process-level models and as abstractions into the NRC/CNWRA TPA code to assess the sensitivity of dose effect of refluxing water. Results from these analyses will be compared with conceptual and numerical model results and evaluations of laboratory- and field-scale testing conducted by DOE for the TSPA-VA and LA to assess the effect of water entering the emplacement drift as liquid or vapor on the performance of the repository. A summary of concerns raised with DOE regarding its TSPA, as related to TEF, and the status of resolution of this subissue, are included in Section 5 of this report.

5.0 STATUS OF SUBISSUE RESOLUTION AT THE STAFF LEVEL

Subissue acceptance criteria are identified in Section 4. In this section, DOE's thermohydrologic testing program, TEF related process-level modeling, and TEF related TSPA models are evaluated in the context of the acceptance criteria.

In addition, the staff has raised concerns about DOE's site characterization and PA program, in areas related to TEF, in reports other than this IRSR. These additional concerns were documented in the following materials:

- *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, b)
- Letter from NRC to DOE with comments from the staff review of *DOE Thermohydrology Testing and Modeling Program* (U.S. Nuclear Regulatory Commission, 1997)
- NRC Staff Review of the TSPA-VA (Secy-99-074) (Travers, 1999)

Summaries of the resolution of the subissue acceptance criteria and topics from each source listed previously is discussed in the following sections. Included in the summaries are discussions of technical items considered to be resolved at the staff level or remaining open. The resolution status of all acceptance criteria, for each subissue, is provided in Table 7.

5.1 RESOLUTION OF SUBISSUE 1: IS THE U.S. DEPARTMENT OF ENERGY THERMOHYDROLOGIC TESTING PROGRAM, INCLUDING PERFORMANCE CONFIRMATION TESTING, SUFFICIENT TO EVALUATE THE POTENTIAL FOR THERMAL REFLUX TO OCCUR IN THE NEAR FIELD?

This section documents the status of an ongoing evaluation of the DOE thermal testing program. The DOE is relying on results from thermal tests to formulate and assess conceptual models of TH processes. The models will be used to predict heat and mass transfer during the performance period of the proposed HLW repository at YM. The two thermal tests most frequently cited in DOE evaluations and analyses are the single heater test (SHT) and the Drift-Scale Test (DST), both conducted in the ESF Thermal Testing Facility. Results from one other recent heater test, the Fran Ridge LBT and several previously conducted thermal tests, most notably at G-Tunnel (Johnstone, et al., 1985; Buscheck, et al., 1991; Ramirez, 1991) and the Climax mine (Patrick, 1986), have not been directly cited in TH model evaluations and PAs. Results from these earlier tests were primarily used by the DOE to advance the development of TH conceptual models and the design of subsequent thermal tests. The following are descriptions of the objectives of the three most recent thermal tests conducted by the DOE; the LBT, SHT, and DST; as written in DOE reports.

Table 7. Summary of acceptance criteria status of resolution

Subissue	Acceptance Criterion	Resolution Status
1	Programmatic 1	open
1	Programmatic 2	closed
1	Technical 1.1	closed
1	Technical 1.2	closed
1	Technical 1.3	closed
1	Technical 1.4	closed
1	Technical 1.5	closed
1	Technical 1.6	closed
1	Technical 1.7	open
1	Technical 1.8	closed
1	Technical 1.9	closed
1	Technical 2	closed
1	Technical 3	closed
2	Programmatic 1	open
[illegible]	Programmatic 2	closed
2	Technical 1.1	closed
2	Technical 1.2	closed
2	Technical 2.1	closed
2	Technical 2.2	open
2	Technical 2.3	open
2	Technical 2.4	open
2	Technical 2.5	open
2	Technical 2.6	open
2	Technical 2.7	closed
2	Technical 2.8	open
2	Technical 2.9	open
2	Technical 2.10	open
2	Technical 2.11	open
	Technical 2.12	closed

Table 7. Summary of acceptance criteria status of resolution

Subissue	Acceptance Criterion	Resolution Status
2	Technical 2.13	open
2	Technical 2.14	open
2	Technical 2.15	open
2	Technical 2.16	open
2	Technical 3	open
2	Technical 4	open
2	Technical 5	open
2	Technical 6	closed
2	Technical 7	closed
3	Programmatic 1	open
3	Programmatic 2	closed
3	Technical 1	open
3	Technical 2.1	closed
3	Technical 2.2	closed
3	Technical 3.1	open
3	Technical 3.2	closed
3	Technical 3.3	open
3	Technical 3.4	open
3	Technical 3.5	open
3	Technical 3.6	open
3	Technical 4	open
3	Technical 5	open
3	Technical 6	open
3	Technical 7	closed

The test objectives of the LBT were to (Lin, 1994)

- "Assist in understanding the processes that are expected to occur within the near field and altered zone environments,
- Provide a test of the models and conceptualizations, and
- Allow evaluation of techniques and equipment that will be used in subsequent *in situ* tests."

(The third objective is less applicable because the LBT did not start early enough to provide these data prior to fielding of the *in situ* tests.)

The test objectives of the SHT were stated as (TRW Environmental Safety Systems, Inc., 1996c)

> "The primary purpose was to study the thermal-mechanical response of the heater block. The SHT is too small and did not have adequate access for a complete study of the coupled thermal-mechanical-hydrological-chemical processes. The SHT was also used as a shake-down/scoping study for the thermal-hydrological-chemical processes. The neutron probe measurements were calibrated using information collected in the SHT."

The test objectives of the DST were stated as (U.S. Department of Energy, 1995)

> "The primary objective of the DST is to develop a more in-depth understanding of the *in situ* coupled TMHC processes anticipated in the local rock mass surrounding the proposed repository. The primary objective is augmented by a series of complementary objectives that are mostly divided among the four processes.

- 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
- Mechanical
  - Measure rock-mass TM properties at ambient and elevated temperatures
  - Evaluate ground support response under controlled conditions
  - Measure drift convergence at elevated temperatures
  - Observe effects of thermal loading on prototypical ground support systems and overall room stability
- 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

- Chemical
  - Observe corrosion products on typical WP materials emplaced in the heated drift (HD) and boreholes
  - Observe changes in water chemistry, mineralogy, and rock chemistry during heating and cooling
  - Observe impacts of introduced materials (ground support, etc.) on water and rock chemistry
  - Observe thermal effects on ground support materials

- Overall
  - Evaluate conceptual models that calculate the coupled TMHC behavior such that realistic bounds can be developed for the expected near-field environment."

(In the above quotation, TM and HD are acronyms for thermal-mechanical and heated drift.)

The DOE suggested hypothesis testing as a means to evaluate conceptual models (Buscheck and Nitao, 1995), and a list of hypotheses for TH models was identified. The hypotheses are arranged into two categories, one set addressing a minimally heated (MH) repository and the second set addressing a constructively heated (CH) repository. Those hypotheses addressing the MH repository (Buscheck and Nitao, 1995) include:

- "MH-1: Mountain- and drift-scale buoyant gas-phase convection does not significantly mobilize moisture in the UZ.

- MH-2: Vapor diffusion does not significantly mobilize moisture in the UZ.

- MH-3: Heterogeneity in the heat load distribution and/or in gas- and liquid-phase pathways does not focus enough condensate drainage to drip onto WPs or to significantly increase liquid-phase flow in the UZ."

(In the previous quote, WP refers to waste package.)

The following hypotheses for the CH repository include subsidiary hypotheses to help resolve the primary hypotheses (Buscheck and Nitao, 1995)

- "CH-1: Heat, vapor, and liquid flow (including heterogeneous fracture flow) near WPs are dominated by heat conduction (and possibly vapor diffusion) and are therefore predictable.

  - CH-1a: Mountain-scale, buoyant gas-phase convection does not dominate flow in the UZ.

  - CH-1b: The net infiltration flux above the repository (and below the PTn) is not high enough to substantially decrease the vertical thickness of the superheated zone (the zone of above-boiling temperatures) above the repository.

— CH-1c: The integrity of the superheated zone is not substantially compromised by variability in the heat load distribution (including edge-cooling effects) or by heterogeneity in the distribution of infiltration flux and condensate drainage. In other words, focused advective liquid-phase flow does not overwhelm the decay-heat driven heat flux enough to permanently collapse (down to WP locations) local regions of the superheated zone.

- CH-2: WP temperatures above the boiling point, and/or a ΔT between the WP and drift wall, will result in a significant reduction in RH and the absence of mobile liquid water on WPs.

  — CH-2a: Variability in the heat load distribution and/or heterogeneity in gas- and liquid-phase (fracture) pathways does not focus enough infiltration flux and condensate drainage to drip onto WPs.

  — CH-2b: Vaporization and vapor flow are not throttled by low k_b to cause a large enough increase in P_g that suppresses RH reduction.

- CH-3: Ambient (humid) WP conditions are restored after WP temperatures have substantially cooled (i.e., well after the end of the boiling period).

  — CH-3a: The net infiltration flux above the repository (and below the PTn unit) is not high enough to allow the rewetting front in the rock matrix to closely follow the retreat of the nominal boiling front."

'he previous quotations, ΔT indicates temperature difference, k_b means bulk permeability, stands for the Paintbrush nonwelded tuff geological unit, P_g is pressure in the gas phase, and RH is relative humidity. The wording of hypothesis CH-3 is interpreted to mean that ambient conditions will not be restored immediately, as the boiling front recedes, but that dry conditions will remain for a long period of time while the rock mass slowly rewets.)

5.1.1 Programmatic Acceptance Criterion 1

- DOE's thermohydrologic testing program was developed, and data collected and documented, under acceptable QA procedures.

Although NRC staff has reviewed and accepted the DOE QA program, DOE has consistently had problems implementing the program. We have already noted our concerns with DOE's QA program (U.S. Nuclear Regulatory Commission, 1999). As of May 18, 1999, three QA deficiency reports concerning issues related to TH effects on flow remain open. Each of these reports has remained open for over one year. The three reports are LLNL-98-D-007, LVMO-98-D-064, and LLNL-98-D-065. Different aspects of the DST program are covered by these reports. The DST is one of the main bases for abstracting thermal effects on flow. DOE should vigorously pursue closing these deficiency reports. We will continue to attend DOE-sponsored meetings and QA audits to ensure that the deficiencies identified above are being addressed as part of the DOE program to develop a license application

Status: Open.

5.1.2 Programmatic Acceptance 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.

DOE has conducted an expert elicitation on the near-field/altered zone. TEF issues are considered part of the near-field/altered zone subject area. The final report by the expert elicitation panel was issued in May, 1998. To date, no questions or comments regarding the use of expert elicitation, in areas related to TEF, have been raised by the staff.

Status: Closed. The staff has no further questions at this time.

5.1.3 Technical Acceptance Criterion 1

- Thermohydrologic tests are designed and conducted:

  1.1 With the explicit objective of testing conceptual and numerical models so that critical thermohydrologic processes can be observed and measured.

The SHT and the DST offer the first opportunity to observe large-scale TH processes operating in one of the proposed repository horizon geologic units, the Topopah Springs middle nonlithophysal unit (Tptpmn). Prior to the conduct of these two tests, the bulk response of the partially saturated, fractured porous medium to thermal effects was not known. For example, it was not known if the hydrostratigraphic unit in which the test was conducted would act to throttle gas pressure buildup or if the bulk permeability would be sufficiently large so that gas would dissipate through the porous media, avoiding a pressure buildup. Additionally, in the absence of credible DCM flow codes, TSPAs performed prior to the TSPA-VA (U.S. Department of Energy, 1998b) represented the porous media using an ECM, thereby neglecting the effects of independent fracture flow near the emplacement drifts. NRC staff identified a lack of confidence in simulating TH processes with ECM conceptual models, particularly in regions of fracture flow close to heat sources in emplacement drifts[3]. The development of DCM conceptual models led to an improved representation of TH processes. Finally, DOE has initiated a series of niche studies to investigate seepage through partially saturated fractured rock under ambient conditions. These tests are being conducted in the ESF at the proposed repository horizon (Wang, et al., 1997). Results from the niche studies will assist in testing conceptual and numerical models ambient (isothermal) conditions.

A summary of DOE's thermohydrologic test objectives was provided in Section 5.1. The staff has not identified any concerns with stated test objectives.

Status: Closed. The staff has no further questions at this time.

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[3]Bell, M.J. 1997. Letter (January 23) to S.J. Brocum, U.S. Department of Energy. Comments on the U.S. Department of Energy's Thermohydrology Testing and Modeling Program. Washington, DC: U.S. Nuclear Regulatory Commission.

1.2 With explicit consideration of TH, thermal-chemical, and hydrologic-chemical couplings;

The LBT, SHT, and DST were equipped with apparatus to sample for evidence of chemical activity during the respective tests. The TH, thermal-chemical, and hydrologic-chemical couplings will be evaluated using this evidence. The success of the sampling procedures and the importance of the TH, thermal-chemical, and hydrologic-chemical couplings are being evaluated after the results from these tests are made available and analyzed. The importance of these couplings should not be dismissed prior to full analysis of TH, thermal-chemical, and hydrologic-chemical data that will be provided by the LBT, SHT, and DST.

Status: Closed. The staff has no further questions at this time.

1.3 At different scales to discern scale effects on observed phenomena;

DOE is conducting thermohydrologic testing in the laboratory at a 0.5 m scale and in the field at the different scales of the LBT, SHT, and DST. Results from these tests will be analyzed to discern scale effects on key heat and mass transfer processes.

Status: Closed. The staff has no further questions at this time.

1.4 For temperature ranges expected for repository operating conditions;

DOE currently has three field-scale thermohydrologic tests at varying stages of implementation. The LBT and SHT have completed their heating periods. The DST is in the first year of a planned 4-year heating phase. The maximum temperature attained during the conduct of LBT was 170 °C and for SHT was 165 °C. The maximum planned drift wall temperature for the DST is 200 °C. Planned temperatures for the DST are consistent with expected conditions for an 85 MTU thermal load. However, current design changes being considered by DOE include a lower repository heat loading.

Status: Closed. The staff has no further questions at this time. The staff will further consider this criterion pending DOE approval of design changes currently under consideration.

1.5 To determine if water refluxes back to the heaters during the heating or cool-down phases of the tests;

Water reflux back to the heaters was not observed during the heating phase of either the LBT or SHT; however, neither test was explicitly designed to directly detect refluxing water at the heaters during the heating phase. The LBT and SHT will be monitored for water refluxing back to the heaters during the cool-down phase (scheduled for completion in January 1999 for the SHT and July 1999 for the LBT) to the extent possible. Similar to the heating phase, however, no direct measurement of refluxing water at the heater will be available during the cool-down phase.

The DST was designed and constructed to permit viewing the interior of the heater drift. Visual observation and camera shots through a window in the bulkhead door are to be used to detect the occurrence of refluxing water that enters the drift air space. Temperature measurements

within the rock mass are to be used to indicate areas where refluxing water decreases the temperature of the fracture surface to below boiling temperature. The sensitivity of the two reflux detection systems can be tested against each other. For example, if refluxing water is detected by one system but not detected by the other, less confidence would be assigned to the nondetecting system. The occurrence of limited or minor amounts of refluxing water, however, may not be detectable with either system. This nondetection may not be a problem if the water neither enters the drift nor increases the RH of the drift air. If refluxing water causes either of these processes to occur, the lack of detection could result in nonconservative repository performance predictions. Performance of the DST will be monitored for the presence of refluxing water and the success of the refluxing water detection systems. Although the staff has no specific, unresolved, questions or comments regarding the design and conduct of DOE's thermohydrologic tests to determine if water refluxes back to the heaters, the staff believes that it has not yet been demonstrated that the DST instrumentation is capable of detecting water return to the heaters.

Status: Closed. The staff has no further questions at this time. Staff will continue to monitor the results of the DST as information becomes available.

1.6 To evaluate the possibility for occurrence of cyclic wetting/drying on WP surfaces;

The potential for accelerated corrosion rates due to wetting/drying cycles was discussed in Section 3.2.1 of this IRSR. DOE has indicated that they have started laboratory experiments on the effects of cyclic wetting/drying on the WP and that they plan to consider this item for performance confirmation (U.S. Department of Energy, 1999). Because DOE has changed the design for the WP from carbon steel to C-22, accelerated corrosion from cyclic wetting/drying is much less of a concern. Therefore, this criterion is considered closed. The topic could be revisited subject to future design changes by DOE.

Status: Closed. The staff has no further questions at this time.

1.7 To account for all mass and energy losses/gains in the thermal test system;

The DOE intends to use results from the DST to test conceptual and mathematical models. Mass and energy losses through the thermal bulkhead of the heated drift are not being monitored. NRC has raised concerns that uncertainty in analyses may result from these unmonitored losses. Heat and mass loss through the thermal bulkhead of the DST is to be addressed at a NRC/DOE Appendix 7 meeting on April 28, 1999.

The DST test was energized in December 1997 (TRW Environmental Safety Systems, Inc., 1997). The DST was designed before results from the earlier SHT were evaluated. Therefore, lessons learned during the evaluation of the SHT were not reflected in the DST design (TRW Environmental Safety Systems, Inc., 1997). In particular, the hydrology monitoring boreholes were not placed at a sufficient depth below the DST HD to monitor changes in saturation. Changes in saturation at this depth have been identified as important in discriminating between the ECM and DCM. The DCM is also referred to as a DKM (Birkholzer and Tsang, 1997).

Early results from the DST provide an opportunity to assess whether the DST will lead to resolution of the MH and CH repository hypotheses. Of particular interest in the DST are

rvations made at the insulated thermal bulkhead at the open (east) end of the HD. Air and r vapor flow through gaps in the bulkhead has been observed. This flow is consistent with the DST design plans in that the bulkhead was designed as a thermal barrier and not as an impediment to gas flow. There were concerns that excessive pressure could build in the HD creating a potentially dangerous situation. Therefore, the bulkhead was neither designed nor constructed to allow for a pressure buildup in the HD. In addition, it was questionable whether a bulkhead could be installed that would effectively restrict the flow of air through the open end of the HD.

Although the direction of gas flow through the bulkhead changes in response to changes in atmospheric pressure, the predominate direction of water vapor flow has been out of the heated portion of the HD 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 HD and accentuated by the presence of ventilation ducts near the bulkhead. Although reduced moisture in the WP environment is a positive attribute for the proposed repository, inadvertent moisture loss in the DST, which will not be experienced under actual repository conditions, will make the ESF hard to interpret. Neither the flux of air nor water vapor passing through the bulkhead has been monitored. This unmeasured loss of mass from the HD complicates analysis of the DST results and may ultimately compromise the utility of the DST in evaluating coupled TMHC processes during the thermal phase of the proposed repository design. There is concern that, during cooling following the heated phase of the test, return flow of air with a smaller water vapor fraction will lead to excessive dryout of the DST environment (Buscheck, et al., 1997).

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 HD (Buscheck, et al., 1997). This interpretation, based on an ECM conceptualization, is also sensitive to the pr values assigned to the air space of the HD and the manner in which air flow through the HD is represented. As a result, there remains uncertainty in the effect of gas venting on TH processes observed at the DST.

The DOE hypotheses (Buscheck and Nitao, 1995) are reviewed here in view of the current level of information provided by the DST. The relatively high temperature regime of the DST restricts hypothesis testing to the constructively heated repository hypotheses.

- CH-1: Heat, vapor, and liquid flow are altered by heat and mass loss through the bulkhead. Thus, at a minimum, this loss of mass must be accounted for if results from the DST are to be used to assess flow in the proposed repository emplacement drifts, unless a ventilated repository design is chosen.

  - CH-1a: Gas pressure released from the HD through the bulkhead and into the ESF diminishes the utility of the DST for evaluating whether the permeability of the rock mass is sufficiently low so as to throttle gas pressure build up. Thus, the propensity for mountain-scale, buoyant gas-phase convection in the UZ is unlikely to be assessed using results from the DST.

  - CH-1b: The removal of water vapor from the heated drift substantially compromises the utility of the DST for assessing movement of moisture from the zone above the repository horizon and below the PTn.

— CH-1c: The variability of heat loads in an emplacement drift is not addressed by the DST. If a line-load repository design is selected, however, heat loading along emplacement drifts may be fairly uniform.

- CH-2: Measurements of RH in the heated drift represent conditions in which water vapor and heat are removed by venting through the bulkhead. These conditions may not exist in the proposed repository emplacement drifts unless the repository design also provides for ventilation in the emplacement drifts.

  — CH-2a: The removal of water vapor from the heated drift by ventilation may render potential focused infiltration flux and condensate drainage into the heated drift of the DST undetectable. Thus it is difficult to say what might have happened had water vapor not been removed. The DST represents processes that might be expected in a ventilated emplacement drift where ventilation would likely reduce condensate drainage from the rock mass into the emplacement drift.

  — CH-2b: Release of gas pressure from the heated drift of the DST increases uncertainty in assessing whether the host rock at the DST acts to throttle or not throttle gas pressure buildup.

- CH-3: Removal of moisture from the heated drift during the boiling period of the DST may result in more drying of the host rock than would otherwise occur. Restoration of ambient (humid) conditions in the heated drift may thus be delayed by this additional loss of moisture from the host rock. Assuming that this additional drying would also occur in the proposed repository emplacement drifts would be nonconservative, unless the repository design also provides for ventilation and the removal of water vapor from emplacement drifts.

  — CH-3a: Removal of heat and moisture from the heated drift in the DST will increase the moisture loss from the host rock. Evaluation of the rewetting of the host rock following retreat of the nominal boiling front in the presence of ventilation may be misleading, unless the repository design provides for the removal of gas from emplacement drifts, because the ventilation may result in slower rewetting than would otherwise occur.

The central concern with the DST is that unmonitored heat and mass loss through the thermal bulkhead compromises the utility of the DST in assessing thermally driven water liquid and vapor flow. It should be noted that this concern was recognized by the DOE during preliminary pretest modeling analysis as quoted in the following paragraph (Buscheck and Nitao, 1995).

> "On the basis of this analysis, it appears that the single-drift, winged thermal test can clearly discriminate between the throttled and unthrottled nonbuoyant T-H regimes within the first 1 to 2 years of full-power heating .... However, one must note the importance of isolating the heater drift from direct pneumatic interference with the rest of the tunnel system in the ESF. If the heater drift were not sufficiently isolated from the tunnel system, the buildup in gas-phase pressure in the heater drift (and the resultant throttled dryout behavior) might be compromised. It is therefore important that measures be taken to pneumatically isolate the heater drift from the rest of the ESF tunnel system. Because of safety concerns, it may not be possible to allow P_g to build up in the heater drift more than a few tenths of an atmosphere. It may therefore be necessary to bleed off some of the P_g buildup and monitor the flux of water vapor leaving the heater drift through such a pressure relief system. The vapor flux through this system would be indicative of the

degree of throttling of advective dryout that would have occurred had the P_g buildup not been limited by bleeding off the excess steam."

The spatial and temporal dimensions of the DST make it the most likely candidate of the DOE thermal tests to provide data to test TH conceptual and mathematical models. It is important that the DST provide information on the TH flow regimes governing the magnitude and direction of water vapor and liquid water flow. Of concern is the possibility that heterogeneities in repository rock properties could promote focusing of condensate flow, resulting in liquid water contacting the WP even though, on average, the drifts remain dry (Buscheck and Nitao, 1994). Simulations of the evolution of temperature and moisture movement in the DST prior to the onset of the test were performed by Buscheck and Nitao (1995) using V-TOUGH, Buscheck, et al. (1997) using NUFT, and Birkholzer and Tsang (1997) using TOUGH2. A status report on independent analysis of the DST conducted by NRC/CNWRA is contained in Hughson and Green (1999) and described here.

The DST is modeled at the CNWRA using a DCM formulation of the coupled heat, two-phase fluid flow, and reactive transport code MULTIFLO (Lichtner and Seth, 1998). The DCM formulation treats fractures and matrix as separate continua connected via a fracture-matrix interaction parameter. Although additional uncertainty is associated with the characterization and estimation of this interaction parameter, the resulting DCM model predictions of matrix and fracture saturations more closely match field observations in which the matrix and fracture systems are not in hydraulic equilibrium. As compared to a single continuum or the ECM, the DCM results in substantially more gravity drainage of condensate through the fractures and thus different dryout and moisture redistribution behaviors under thermal loading conditions. However, the ECM conceptualization was used in all DST pretest analyses by Buscheck and Nitao (1995), Buscheck, et al. (1997), and Birkholzer and Tsang (1997), with the exception of sensitivity analyses by Birkholzer and Tsang (1997) which used the DKM.

CNWRA model is a relatively simplistic representation of a complex system of coupled heat and mass flow through heterogeneous fractured rock. Matrix and fracture properties and fracture-matrix interaction in the model are treated as homogeneous when in fact they are heterogeneous and not known in detail. No-flow boundary conditions are assumed along the vertical sides of the model when in fact gas in the fractures is free to flow laterally as well as vertically. 2D flow is assumed when in fact flow in the system is 3D. Ventilation is neglected in this model even though gas venting occurs through the thermal bulkhead of the HD (sensitivity analysis of moisture loss through the bulkhead is presented later in this section). The heat source is roughly averaged over the entire drift and wing heater area. Despite these simplifying assumptions and approximations, the model results match measured temperatures quite well. While this may be seen as some kind of model validation, more likely the good match to measured temperatures is a result of internal averaging inherent in the parabolic partial differential equation governing heat conduction (Pruess, 1999). Rather than somehow validating the model, a good match between modeled temperatures and measurements appears to have relatively little significance in understanding coupled TMHC processes or moisture redistribution in a heterogeneous system. This agreement suggests that heat transfer is primarily by conduction and thus is relatively insensitive to the effects of heterogeneities or the details of liquid and vapor transport. This reasonably good match to temperature measurements, however, certainly does not validate the model.

Water vapor flow through the thermal bulkhead and into the ventilation ducts has removed an unknown quantity of water from the HD. Concerns are raised regarding the effect the additional uncertainty caused by unmonitored water mass and heat loss through the thermal bulkhead

may have on interpretation of DST data. This mass and energy loss, and also the presence of ventilation directed at the bulkhead, may render the DST an open system which can lead to increased modeling uncertainty. This modeling uncertainty can lead to increased uncertainty in PAs that are based on conceptual models evaluated and calibrated against the DST. To examine possible consequences of this mass loss from the system, a sensitivity analysis was performed by modeling loss through the bulkhead as a distributed sink term in the top portion of the HD. The results show an increase in the extent of drying in the fracture continuum due to simulated water vapor loss through the bulkhead. Justification for either not monitoring heat and mass loss through the bulkhead or not prohibiting these losses has not been provided by the DOE. This topic was discussed at a NRC/DOE Appendix 7 meeting on held on April 18, 1999. DOE indicated that they would evaluate methods for monitoring heat and mass loss through the bulkhead within the framework of the existing budget.

Status: Open.

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

The DOE has measured the hydraulic and physical properties of the media present at its thermal tests. Sensitivity analyses can help determine if potential measurement error is within the variability due to natural heterogeneity. Additional assessment and analysis may be required for those variables which indicate that the impact of measurement error on model predictions is unacceptably large.

Status: Closed. The staff has no further questions at this time.

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

The DOE is using several instrumentation technologies to measure saturation in the medium surrounding its thermal tests. Of greatest relevance is instrumentation used to measure saturation and related changes at the DST. These measurements are not yet available for independent evaluation.

Status: Closed. The staff has no further questions at this time. The staff will review saturation data from the DST when available.

5.1.4 Technical Acceptance Criterion 2

- Thermohydrologic test results from other sites and programs have been analyzed and applied, as appropriate, to the YM site.

DOE is focusing on thermohydrologic testing at YM. It is unlikely that thermohydrologic test results from other sites and programs will be solely depended upon to reach conclusions about the performance of a geologic repository at YM. To date, the staff has not raised any concerns about the applicability to YM of test results from other sites and programs.

Status: Closed. The staff has no further questions at this time.

1.5 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.

The staff will continue to monitor the progress of thermohydrologic testing at YM by attending the DOE quarterly progress meetings. In addition, the staff will review those aspects of DOE's performance confirmation program related to thermohydrologic testing as the performance confirmation program evolves. To date, no specific questions or comments regarding thermohydrologic testing aspects of DOE's performance confirmation program have been raised by the staff.

Status: Closed. The staff has no further questions at this time.

5.2 RESOLUTION OF SUBISSUE 2: IS THE U.S. DEPARTMENT OF ENERGY THERMOHYDROLOGIC MODELING APPROACH SUFFICIENT TO PREDICT THE NATURE AND BOUNDS OF THERMAL EFFECTS ON FLOW IN THE NEAR FIELD

This section draws upon the summary and review of DOE's TSPA-VA and TBD provided in Section 3.3.7 of this IRSR. Any significant comments or concerns developed in Section 3.3.7 have been included in the following evaluations of specific acceptance criteria.

5.2.1 Programmatic Acceptance Criterion 1

- DOE's thermohydrologic modeling analyses were developed and documented under acceptable QA procedures.

In DOE's TSPA it was acknowledged that "analyses presented within were not performed with qualified data sets, all results within this report are considered unqualified" (TRW Environmental Safety Systems, Inc., 1998; Section 4.4.1). We have already noted our concerns with DOE's QA program (U.S. Nuclear Regulatory Commission, 1999). Although DOE's VA was not intended to be a Quality Controlled document, we are concerned that limited time remains for DOE to qualify these data. We have formed an NRC QA Task Force to conduct an independent and objective review of the DOE HLW QA program and its implementation (Travers, 1999). We will continue to attend DOE-sponsored meetings and QA audits to ensure that the deficiency identified above is being addressed as part of the DOE program to develop a license application. Presentations at the recent THCP Workshop and the IDGE Workshop indicate that DOE will focus on qualifying the data and models used in the TSPA-LA.

Status: Open.

5.2.2 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.

DOE has conducted an expert elicitation on the near-field/altered zone. TEF issues are considered part of the near-field/altered zone subject area. The final report by the expert

elicitation panel was issued in May, 1998. To date, no questions or comments regarding the use of expert elicitation, in areas related to TEF, have been raised by the staff.

Status: Closed. The staff has no further questions at this time.

5.2.3 Technical Acceptance Criterion 1

- Sufficient data are available to adequately define relevant parameters, parameter values, and conceptual models. Specifically, DOE should demonstrate that:

  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.

DOE uses a reference base case data set in process-level models and abstracted TSPA models. Parameter values for the reference base case are periodically updated, however, the frequency of the updates is not sufficiently short to provide values in a timely manner. For example, fracture porosity values of 1.24×10^{-4}, based on fracture mapping (TRW Environmental Systems, Inc., 1998, pg 2-91), are contained in the reference base case data set. Recently reported fracture porosities obtained by DOE using gas tracer tests from the niche studies significantly exceed those porosities based on mapping and included in the reference base case data set (Hughson, 1999). Higher values of porosity has a direct impact on results.

The effect of heterogeneity needs to be included in the models to capture critical heat and mass transfer mechanisms (refer to discussion in Section 3.3.7). In particular, focused recharge into the drift may be in appropriately omitted if sufficient data heterogeneity is not included to adequately represent the heterogeneity of the site. This heterogeneity can be included by treating the media stochastically, including discrete features in the model, or any other acceptable characterization methodology.

There is insufficient evidence to demonstrate that the assumed parameter values lead to a conservative effect on performance. This conclusion is based on the observation that acceptable and appropriate values for the base case parameters are not yet determined. It is assumed that at the time when acceptable and appropriate parameter values have been incorporated into the reference base case data set, DOE will provide appropriate results from sensitivity analyses to demonstrate that the assumed parameters values lead to a conservative effect on performance.

Status: Closed. The staff has no further questions at this time. The staff will review the reference data set used in DOE's TSPA-LA to ensure consistency with available field data.

  1.2 Analyses are consistent with site characteristics in establishing initial conditions, boundary conditions, and computational domains for conceptual models evaluated.

The DOE multiscale modeling approach provides an acceptable method to establish initial conditions, boundary conditions, and computational domains that are consistent with site characteristics (subject to comment noted under Subissue 2 technical acceptance criterion 5).

The USFIC KTI has determined that the DOE has identified the atmospheric boundary condition with an acceptable level of uncertainty.

Status: Closed. The staff has no further questions at this time.

5.2.4 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

The NUFT and TOUGH2 codes are used by DOE to simulate heat and mass transfer through partially saturated, fractured porous media. These codes are based on well-accepted principles of heat and mass transfer applicable to unsaturated geologic media.

Status: Closed. The staff has no further questions at this time.

  2.2 Models include, at a minimum, the processes of evaporation and condensation and the effects of discrete geologic features

DOE models include the processes of evaporation and condensation. DOE has not yet demonstrated that their models incorporate the effects of discrete geologic features. Discrete geologic features can be of critical importance in regions near emplacement drifts by influencing the amount of seepage into the drift, causing focusing of flow through partially saturated fractured media, and influencing the flow pathways of refluxing water near the drifts.

Status: Open.

  2.3 Models include, at a minimum, an evaluation of important thermohydrological 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

The degree of multidrift dry-out zone coalescence will be a function of the thermal load specified in the final design of the repository. Recent, proposed design modifications by DOE to reduce the repository thermal load to 60 MTU/acre will minimize, if not eliminate, dry-out zone coalescence. Recent DOE models that include the DKM conceptualization appear to adequately predict the extent of dryout surrounding the emplacement drifts. However, a more complete evaluation of the DKM conceptual model will require results from a longer duration of the DOE's DST than currently available, or some other long-term large-scale heater test in a fractured, porous medium.

Simulation of lateral movement of condensate and condensate drainage through fractures has not been adequately demonstrated by DOE. The effects of discrete geologic features on rapid and episodic moisture redistribution need to be incorporated, directly or indirectly, into the conceptual models used by DOE.

Models used to predict formation of cold traps should include the effects of radiative heat transfer and ventilation. Current DOE models predictions of cold trap formation do not yet contain both the effect of ventilation and radiative heat transfer.

The multiscale TH modeling approach, which uses loosely coupled drift- and mountain-scale models, appears to adequately investigate repository edge effects.

Status: Open.

2.4 Models include all significant repository design features

Although the final design of the repository has not been determined, proposed modifications to the TSPA-VA repository design include use of dripshields, backfill and ventilation. The effects of such design features have been shown to have a significant effect on moisture redistribution. Therefore, these design features need to be incorporated into the models used to simulate heat and mass transfer through partially saturated, fractured porous media.

Status: Open.

2.5 Models are capable of accommodating variation in infiltration

TSPA analyses by DOE and TPA analyses by NRC conclusively indicate that the performance of the repository will be significantly affected by the level of infiltration entering the repository horizon. Site characterization activities indicate a wide spatial variation in infiltration rates. The DOE multiscale modeling approach needs to include the effects of spatially variable infiltration coupled with the variable heat load effect of the repository edge. The DOE models appear to be capable of accommodating variation in infiltration, however, this has not been demonstrated.

Status: Open.

2.6 Conceptual model uncertainties have been defined and documented and effects on conclusions regarding performance assessed

The DOE has included the dual continuum conceptualization (i.e., DKM) in the NUFT and TOUGH2 codes. The level of uncertainty in the models is assessed by comparing model simulations with observations from controlled experiments or analog sites. The DST was designed to provide measurable evidence of heat and mass transfer through fractured porous media. DOE needs to demonstrate that their models are unambiguously consistent with physical observations of the DST or some other appropriate heater test or analog site. That is, test cases or analog sites that do not provide adequate information to discriminate between conceptual models cannot be used to reduce conceptual model uncertainty. DOE has not yet defined and documented conceptual model uncertainty.

Status: Open.

2.7 Mathematical models are consistent with conceptual models, based on consideration of site characteristics

The mass balance of models needs to be confirmed to ensure that mathematical and conceptual models are consistent, based on consideration of site characteristics. This balance

has not yet been demonstrated by the comparison of simulations from the NUFT or TOUGH2 codes and observations of the DST.

The mathematical models need to incorporate all significant components contained in the conceptual models. Mathematical models used by DOE have been described. The descriptions indicate that all significant components in the mathematical models are incorporated in conceptual mathematical models. Descriptions of the NUFT and TOUGH2 codes confirm that the mathematical models are consistent with conceptual models.

Status: Closed. The staff has no further questions at this time.

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

Alternative process-level models are not provided for critical process-level heat and mass transfer mechanisms. For example, refluxing into the drift during the heating period can have profound effects on TSP, however, an alternative model of these processes has not been formulated to provide confidence in the original conceptual and mathematical models. In addition, results from an alternative model for seepage into a drift which indicates significantly higher levels of seepage are not used in subsequent models and analyses.

Status: Open.

2.9 Results from different mathematical models have been compared to judge robustness of models

Different mathematical models are reflected in the different conceptual models used to simulate heat and mass transfer through porous media. In particular, the results of predictions made using ECM, G-ECM, and DKM conceptualizations have been compared. Adequate data are not available to compare these different conceptual models nor the mathematical models upon which the conceptual models are based. Full comparison of the model results from different mathematical models cannot be completed in the absence of field-scale measurements taken over sufficiently long durations and large spatial distances.

Status: Open.

2.10 Models used to predict shedding around emplacement drifts are shown to contain an adequate level of heterogeneity in media properties

DOE models used to predict moisture redistribution near emplacement drifts do not have the capability to predict penetration of the boiling isotherm by water flowing down a fracture. Seepage models have not been demonstrated to predict the amount of water entering an emplacement drift with an acceptable level of uncertainty. DOE models need to adequately represent these heat and mass transfer mechanisms in heterogeneous media to adequately predict shedding around emplacement drifts.

Status: Open.

2.11 TH models have been demonstrated to be appropriate for the temperature regime expected at the repository

The final design, including heat load, of the repository has not been defined. The temperature regime of the repository cannot be predicted until the final repository design has been designated. The use of large-scale heater test results or analog site observations will be useful in this demonstration. DOE will need to show that the TH model predictions are consistent with test results or analog site observations for the appropriate temperature regime. Once the design heat load has been finalized, DOE will have to demonstrate that heater test results of analog site observations, used to support TH models, are consistent with predicted temperature regimes.

Status: Open.

2.12 Models include radiative heat transport unless it is shown that radiative heat loss by a WP is not significant

The multiscale TH models include radiative heat transfer at the drift scale. DOE model results indicate that radiative heat loss by a WP can be significant.

Status: Closed. The staff has no further questions at this time.

2.13 Models include the effect of ventilation particularly if ventilation could result in deposition or condensation of moisture on a WP surface

DOE has not demonstrated that ventilation is included in their models. Ventilation could remove moisture from one portion of the repository environment and deposit it elsewhere with negative consequences (i.e., inducing increased WP corrosion at the point of condensation). DOE models have not been demonstrated to include the potential negative effects of ventilation.

Status: Open.

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

DOE models have not been demonstrated to contain an adequate level of heterogeneity so that mechanisms such as dripping from refluxing during heating periods or from seepage under isothermal conditions are adequately and appropriately represented, provided the appropriate heat and mass transfer mechanisms are included in the conceptual and mathematical models.

Status: Open.

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 horizon

DOE has not demonstrated that their models contain sufficient physical detail to take credit for capillary diversion. Recent analyses (Hughson and Dodge, 1999) indicate that non-uniformity in drift wall surfaces can lead to dripping. Previous continuum models used by DOE indicated capillary diversion around drift openings when the effects of drift wall irregularities were not included.

Status: Open.

2.16 Physical mechanisms such as penetration of the boiling isotherm by flow down a fracture are not omitted due to over-simplification of the physical medium or the conceptual model

DOE conceptual models have not been demonstrated to contain all necessary mechanisms to ensure that all processes that could lead to water introduction into the drift and onto WPs are included. Mechanisms that provide for the penetration of the boiling isotherm are not included in the DOE conceptual model. Seepage and dripping into emplacement drifts under isothermal conditions have not been demonstrated to be adequately included in the DOE conceptual models.

Status: Open.

5.2.5 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.

The TEF KTI is focused primarily on the coupling of TH processes. Interest in the broader coupling of THMC processes is limited to the effects on water flow into or out of the WP environment that would result from permeability changes due to either TC or TM processes. This criterion will be evaluated in Revision 2 of the TEF IRSR. Other issues related to coupled THMC processes are addressed in the Evolution of the Near-Field (ENFE) IRSR and the Repository Design and Thermal Mechanical Effects (RDTME) IRSR.

Status: Open.

5.2.6 Technical Acceptance Criterion 4

- 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.

The DOE multiscale modeling approach includes models of different dimension. Results from the reduced dimensionality models have been shown in TSPA-VA to be consistent with the full dimension models. This consistency is interpreted by DOE to support the conclusion that lower dimensional models bound results from models with full dimensionality. However, after review of the TSPA-VA, it is not clear if two-dimensional, mountain-scale, TH 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 DOE's 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 DOE's mountain-scale submodel (TRW Environmental Safety Systems, Inc., 1998, pg 3-12 and 3-13).

Status: Open.

5.2.7 Technical Acceptance Criterion 5

- 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.

DOE has developed a dual continuum conceptual model (DKM) to simulate heat and mass transfer through media where flow through fractures is not in hydraulic equilibrium with flow through rock matrix. DOE uses the ECM conceptual model for occurrences where rapid flow through fractures does not have a critical effect on TSP. DOE has indicated in the TSPA-VA the conditions for which each conceptual model is appropriate. 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 in TSP calculations.

Status: Open.

5.2.8 Technical Acceptance Criterion 6

- Accepted and well-documented procedures have been adopted to construct and calibrate numerical models used.

DOE has not documented all procedures adopted to construct and calibrate numerical models used.

Status: Closed. The staff has no further questions at this time. The staff will review techniques used by DOE to construct and calibrate numerical models used when available.

5.2.9 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.

DOE conducts quarterly workshops to present results from their TH testing program. The TH testing results are compared with TH model simulations at the workshops. Results from the tests and model simulations are not yet documented.

Status: Closed. The staff has no further questions at this time. The staff will continue to attend DOE's quarterly workshops and will review DOE comparisons of DST data and model simulations when available.

RESOLUTION OF SUBISSUE 3: DOES THE U.S. DEPARTMENT OF ENERGY TOTAL SYSTEM PERFORMANCE ASSESSMENT ADEQUATELY ACCOUNT FOR THERMAL EFFECTS ON FLOW?

This section draws upon the summary and review of DOE's TSPA-VA and TBD provided in Section 3.3.7 of this IRSR. Any significant comments or concerns developed in Section 3.3.7 have been included in the following evaluations of specific acceptance criteria.

5.3.1 Programmatic Acceptance Criterion 1

- DOE's analyses were developed and documented under acceptable QA procedures.

In DOE's TSPA it was acknowledged that "analyses presented within were not performed with qualified data sets, all results within this report are considered unqualified" (TRW Environmental Safety Systems, Inc., 1998; Section 4.4.1). We have already noted our concerns with DOE's QA program (U.S. Nuclear Regulatory Commission, 1999). Although DOE's VA was not intended to be a Quality Controlled document, we are concerned that limited time remains for DOE to qualify these data. We have formed an NRC QA Task Force to conduct an independent and objective review of the DOE HLW QA program and its implementation (Travers, 1999). We will continue to attend DOE-sponsored meetings and QA audits to ensure that the deficiency identified above is being addressed as part of the DOE program to develop a license application. Presentations at the recent THCP Workshop and the IDGE Workshop indicate that DOE will focus on qualifying the data and models used in the TSPA-LA.

Status: Open.

5 Programmatic Acceptance Criterion 2

- 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.

DOE has conducted an expert elicitation on the near-field/altered zone. TEF issues are considered part of the near-field/altered zone subject area. The final report by the expert elicitation panel was issued in May, 1998. To date, no questions or comments regarding the use of expert elicitation, in areas related to TEF, have been raised by the staff.

Status: Closed. The staff has no further questions at this time.

5.3.3 Technical Acceptance Criterion 1

- 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 model predictions of the influx of water as liquid or vapor into an emplacement drift.

DOE has not yet demonstrated that the abstracted models used to bound process-level models that predict water influx into an emplacement drift are conservative because DOE process-level

models do not yet incorporate all potentially important heat and mass transfer mechanisms. Refer to the discussion in Section 5.3.8 and Section 3.3.7 of this IRSR.

Status: Open.

5.3.4 Technical Acceptance Criterion 2

- Sufficient data are available to adequately define relevant parameters, parameter values and conceptual models. Specifically, DOE should demonstrate that:

  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.

DOE uses a reference base case data set in process-level models and abstracted TSPA models. Parameter values for the reference base case are periodically updated, however, the frequency of the updates is not sufficiently short to ensure the most recent data are used in analyses. For example, fracture porosity values of 1.24×10^{-4}, based on fracture mapping (TRW Environmental Systems, Inc., 1998, pg 2-91), are contained in the reference base case data set. Recently reported fracture porosities obtained by DOE using gas tracer tests from the niche studies significantly exceed those porosities based on mapping and included in the reference base case data set (Hughson, 1999). Higher values of porosity has a direct impact on results.

The effect of heterogeneity needs to be included in the models to capture critical heat and mass transfer mechanisms (refer to discussion in Section 3.3.7). In particular, focused recharge into the drift may be in appropriately omitted if sufficient data heterogeneity is not included to adequately represent the heterogeneity of the site. This heterogeneity can be included by treating the media stochastically, including discrete features in the model, or any other acceptable characterization methodology.

There is insufficient evidence to demonstrate that the assumed parameter values lead to a conservative effect on performance. This conclusion is based on the observation that acceptable and appropriate values for the base case parameters are not yet determined. It is assumed that at the time when acceptable and appropriate parameter values have been incorporated into the reference base case data set, DOE will provide appropriate results from sensitivity analyses to demonstrate that the assumed parameters values lead to a conservative effect on performance.

Status: Closed. The staff has no further questions at this time. The staff will review the reference data set used in DOE's TSPA-LA to ensure consistency with available field data.

  2.2 Analyses are consistent with site characteristics in establishing initial conditions, boundary conditions, and computational domains for conceptual models evaluated.

The DOE multiscale modeling approach provides an acceptable method to establish initial conditions, boundary conditions, and computational domains that are consistent with site characteristics (subject to comment noted under technical acceptance criterion 5). However,

re remains uncertainty in values considered appropriate for infiltration at the atmospheric ndary. Additional site characterization and sensitivity analyses will be required to resolve this uncertainty to an acceptable level.

Status: Closed. The staff has no further questions at this time. The USFIC KTI will monitor DOE progress is determining the atmospheric boundary condition.

5.3.5 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 mechanism, 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.

DOE conceptual and mathematical models incorporated into the TSPA do not yet include, either directly or as an abstraction, the heat and mass transport mechanisms that could lead to water refluxing into the drift, particularly during the heating period. For example, DOE models do not include mechanisms that could lead to depression of the boiling isotherm by water flowing down a fracture. DOE models in the TSPA-VA assume that no water can enter the drift at all times when drift wall temperatures exceed boiling (TRW Environmental Safety Systems, 1998, pg 3-142). This assumption is not conservative. In addition, the TSPA-VA nption of no dripping into the drift during the first 5000 years of heating is not conservative.

DOE models are based on a continuum approach that assigns bulk averaged properties to the site media. The continuum-based models can mask the potential effects of processes that could lead to water being introduced into the drift causing accelerated corrosion of the WP, transport of radionuclides, and alteration of hydraulic and transport pathways. Sufficient natural heterogeneity is required in the models to ensure critical heat and mass transfer mechanisms are not masked.

DOE conducted additional analyses based on alternative models of seepage into a drift (TRW Environmental Safety Systems, Inc., 1998, pg 2-105). The amount of seepage predicted for this alternative model significantly exceeded the amount of seepage predicted with the standard model. Analyses or models predicated on the results of the seepage models should use the results of the "high-seepage" alternative model to be conservative.

Status: Open.

  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.

The reference design to be used in DOE's TSPA-LA is being revised. The final reference design has not yet been approved by DOE, and could be modified in the future. Therefore, not all ical design features that will be included in the final design are known at this time. The

effects of dripshields and backfill on system performance have not yet been completely assessed. Other design features, in addition to dripshields and backfill, may need to be evaluated in the future.

Status: Closed. The staff has no further questions at this time. The staff will review DOE's TSPA-LA to ensure that all significant GROA design features have been incorporated into the analysis.

3.3 Conceptual model uncertainties have been defined and documented, and their effects on conclusions regarding TSP have been assessed.

The TSPA-VA provided more sophisticated and comprehensive conceptual models than did earlier TSPAs. Foremost in these enhancements is the capability of dual continuum modeling. This enhancement allows for fracture flow thermodynamically independent from matrix flow. Nonetheless, current DOE conceptual models do not incorporate heat and mass transport mechanisms that could indicate water reflux into the drift during and after the heating period. The effects of refluxed water need to be incorporated into the TSPA.

Status: Open.

3.4 Mathematical models are consistent with conceptual models, based on consideration of site characteristics.

The mass balance of models needs to be confirmed to ensure the mathematical and conceptual models are consistent, based on consideration of site characteristics. This balance has not yet been demonstrated.

Status: Open.

3.5 Alternative models and modeling approaches, consistent with available data and current scientific understanding, are investigated; limitations defined; and results appropriately considered.

An alternative modeling approach to the multiscale modeling approach is developed by DOE in the TSPA-VA. The alternative approach is based on a G-ECM conceptualization. Results from this model are consistent with the multi-scale model results.

Alternative process-level models, however, are not provided for critical heat and mass transfer mechanisms. For example, refluxing into the drift during the heating period can have profound effects on TSP, however, an alternative model of such a process has not been formulated to provide confidence in the original conceptual and mathematical models. In addition, results from an alternative DOE model for seepage into a drift that indicate significantly higher levels of seepage rates should be considered in the TSPA to ensure the TSPA is conservative.

Status: Open.

3.6 Results from different mathematical models have been compared to judge robustness of models.

Different mathematical models are reflected in the different conceptual models used to simulate heat and mass transfer through porous media. In particular, the results of predictions made

'sing ECM, E-ECM, and DKM conceptualizations have been compared. Comparisons in the SPA-VA indicate the different conceptualizations provide similar predictions. Expanded sensitivity analyses using the various conceptual models should provide an assessment of the robustness of the models.

Status: Open.

5.3.6 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.

The TEF KTI is focused primarily on the coupling of TH processes. Interest in the broader coupling of THMC processes is limited to the effects on water flow into or out of the WP environment that would result from permeability changes due to either TC or TM processes. This criterion will be evaluated in Revision 2 of the TEF IRSR. Other issues related to coupled THMC processes are addressed in the Evolution of the Near-Field (ENFE) IRSR and the Repository Design and Thermal Mechanical Effects (RDTME) IRSR

Status: Open.

5.3.7 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.

The DOE multiscale modeling approach includes models of different dimension. Results from the reduced dimensionality models have been shown in TSPA-VA to be consistent with the full dimension models. This consistency is interpreted by DOE to support the conclusion that lower dimensional models bound results from models with full dimensionality. However, after review of the TSPA-VA, it is not clear if two-dimensional, mountain-scale, TH 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 DOE's 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 DOE's mountain-scale submodel (TRW Environmental Safety Systems, Inc., 1998, pg 3-12 and 3-13).

Status: Open.

5.3.8 Technical Acceptance Criterion 6

- Results of the TSPA related to TEF have been verified by demonstrating consistency with results of process-level models.

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 DOE process-level models at this time. Therefore, in the absence of process-level models

that represent these mechanisms, results from DOE's TSPA analyses cannot be verified as consistent with the process-level models.

Status: Open.

5.3.9 Technical Acceptance Criterion 7

- Sensitivity and importance analyses were conducted to assess the need for additional data or information with respect to TEF.

DOE has conducted sensitivity analyses in TSPA-VA to determine which changes in data result in critical impact on performance. These sensitivity analyses need to be repeated when all necessary heat and mass transfer mechanisms are adequately incorporated into the process-level models. Based on information provided at the recent NRC/DOE technical exchange on TSPA (May 1999), DOE is expending considerable effort at planning and undertaking new sensitivity and importance analyses.

Status: Closed. The staff has no further questions at this time. Results of new analyses will be reviewed when completed and made available.

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

The NRC review of 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 WP 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 DOE's thermohydrologic testing program. Since the time of Comment 11 (1989), DOE has developed a number of hypotheses about attributes of the disposal system deemed important to containment and isolation as part of 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 has engaged in numerous interactions with DOE and commented directly on the sufficiency of DOE's thermohydrologic testing and modeling programs, as discussed in section 5.3 of this report. Given the evolution of DOE's WCIS and DOE's thermohydrologic testing program since 1989, Comment 11 has been superseded by the

focused review of the evolving DOE program by NRC. Hence, Comment 11 is considered resolved.

Comment 73 relates to Subissue 2, sufficiency of DOE's thermohydrologic modeling approach and Subissue 3, adequacy of treatment of TEF in DOE's TSPA. At the time, Comment 73 was prepared, repository design was considerably different than the current 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 DOE's determination of design backfill requirements presented in DOE's SCP is outdated and, in that sense, Comment 73 is considered resolved. The staff notes that in the TSPA-VA plan, however, 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., 1996b). Clearly, thermal modeling requires sufficient data (or design requirements) to adequately define relevant parameters, parameter values, and conceptual models. Although Comment 73 is considered resolved, staff will continue to review the bases underlying the parameter values used in thermohydrologic analyses supporting 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 DOE's TSPA. Since the time of question 33, there has been considerable change in DOE's reference repository design. The WPs will no longer be placed in vertical boreholes, hence, the question about design goals for, or estimates of, the amount of standing water in WP 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 WPs as liquid or vapor is a significant question that will continue to be tracked by the staff.

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 DOE's TSPA–95 identified two areas of concern related to Subissue 3, adequacy of treatment of TEF in 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 DOE's TSPA-95 rendered moot by 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 RH at the surface of a typical WP. The staff used both a heat-conduction-only model and a multiphase-flow model, simulating heat and mass transfer. The staff concluded that 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 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 YM 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 WPs 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 WP 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 WP. 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 WP 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, 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., 1996b). Further, 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., 1996b). The concerns expressed by the staff about the dimensionality of models and assumed conceptual flow models have been included as key issues in DOE's thermal-hydrology abstraction/testing workshop (Francis, et al., 1997; Table 1-1, Key Issues List). 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 DOE at the DOE/NRC Technical Exchange on TSPA, July 21–22, 1997, San Antonio, Texas, it appears 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 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 DOE's TSPA-95 to be resolved based on review of 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 recent information on DOE's thermohydrology testing and modeling program and submitted comments to DOE (U.S. Nuclear Regulatory Commission, 1997). The objective of this review was to evaluate if the program will provide information necessary for the LA.

For this review, staff depended mainly on the January 1996 report by the peer review team (PRT) (U.S. Department of Energy, 1996c) established by 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 DOE's program; however, several comments related to Subissue 1, sufficiency of DOE's thermohydrologic testing program and Subissue 2, sufficiency of 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 WPs 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 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 WPs 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 WPs is a central question in estimating the life of WPs. 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. 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: 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 WP 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 DOE, then THC coupled effects need to be evaluated using more robust THC models.

DOE sent a response to the NRC letter review of 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. 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 DOE to adjust the thermal load during the conduct of the DST. Although not identified as a firm test limitation, 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. 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 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.

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.

NRC Evaluation: Staff considers 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 DOE's response adequately addresses the original comment.

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.

DOE Response: Current and future analyses are and will be conducted using DKMs 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. DOE recognizes the thermal testing data that will be available for the LA will be limited and will need to be confirmed by additional data collected during performance confirmation.

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 DOE's response adequately addresses the original comment.

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

DOE Response: 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. DOE will provide documentation to ensure staff are aware that THC phenomena are observed, monitored, and sampled in 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.

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

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 WPs are inadequate to describe the process and extent of potential dripping under ambient and thermally altered conditions. This concern is an issue because both DOE and NRC PA analyses indicate that the fraction of WPs contacted by water is the most important factor affecting dose along the groundwater pathway. Further, NRC staff view the current DOE testing and modeling plans as insufficient to resolve this issue prior to LA. There are activities that DOE could complete prior to LA that would provide additional support for addressing this issue.

Importance:

The quantity and chemistry of water contacting the WP are the major factors in determining the lifetime of the WP. Radionuclide release rates from breached WPs are also dependent on the quantity and chemistry of water contacting the WPs and, subsequently, the waste forms. Degradation of WPs 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 WPs 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 WPs, and the chemistry of water on WPs. In addition, the DOE has recognized that its current PA models do not adequately capture the effects of coupled processes on the quantity and chemistry of water contacting WPs. 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 LA Plan are unlikely to provide an adequate licensing basis for assessing the quantity and chemistry of water contacting WPs 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 LA do not provide an adequate basis to support the seepage abstraction (Hughson, 1999). Two activities were suggested by members of the peer review panel (Hughson, 1999), that could be completed prior to LA and would lead to a more defensible approach for addressing the quantity and chemistry of water contacting the WPs 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.

Additional Background:

The data and processes necessary to describe the quantity and chemistry of water contacting WPs and waste forms through abstraction in a PA have been addressed in several IRSRs (U.S. Nuclear Regulatory Commission, 1998a,b,c,d). In addition, the importance of characterizing thermal perturbations to UZ flow fields during the heating phase and considering

coupled THMC processes in PA was discussed in letters to the DOE (U.S. Nuclear Regulatory Commission, 1997, 1998e).

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 PAs (Hughson, 1999). 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 WP performance have been presented to the DOE (U.S. Nuclear Regulatory Commission, 1997, 1998c). 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, 1999). Many alteration products of tuff and engineered materials are likely to affect the chemistry and water contacting WPs, which in turn can affect corrosion rates, waste form altering rates, and radionuclide solubility and specification (U.S. Nuclear Regulatory Commission, 1998d). 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 LA. The amount of data required for the LA, 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 WPs and waste forms to the DOE safety case.

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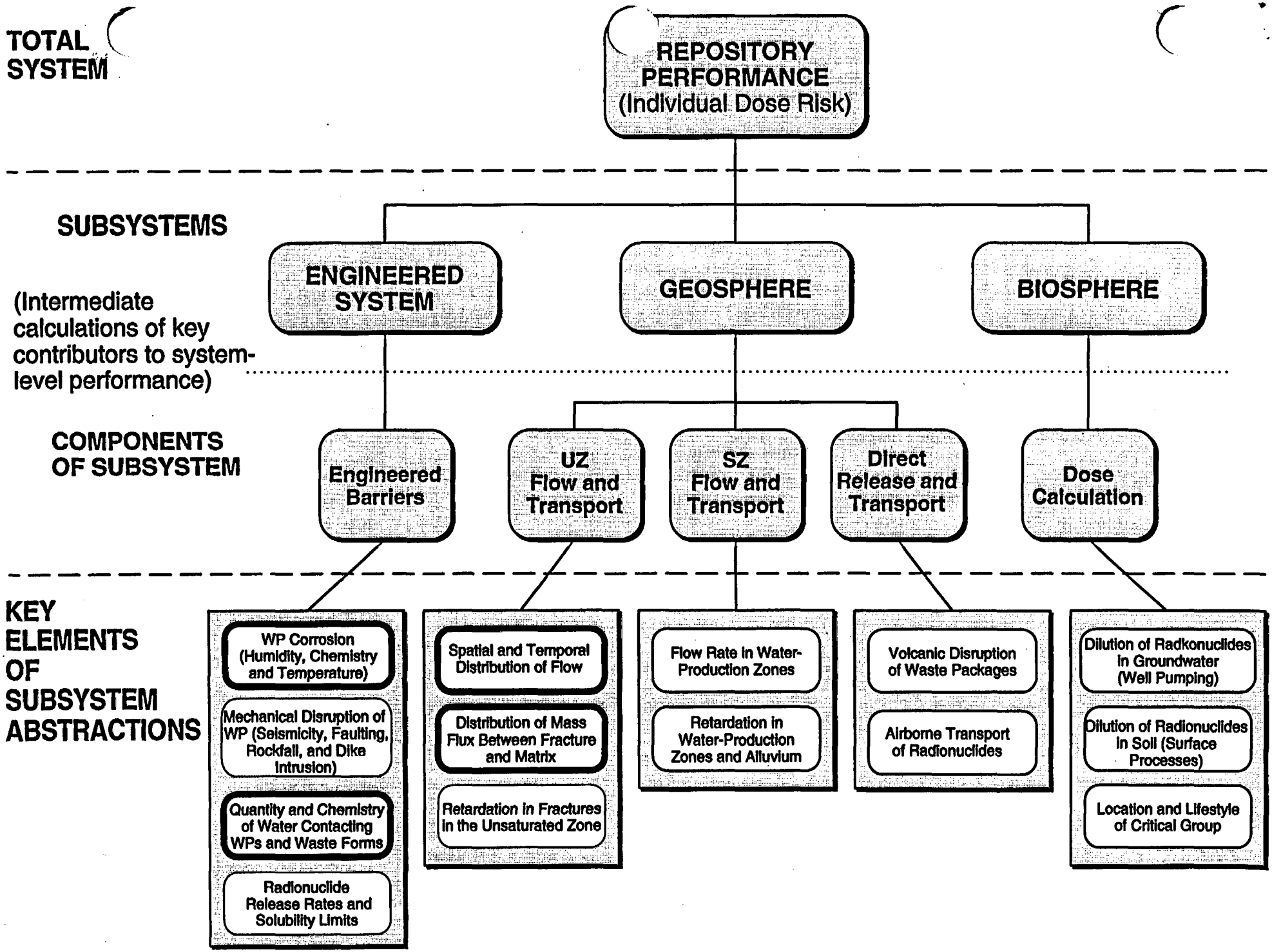
APPENDIX


TOTAL SYSTEM
REPOSITORY PERFORMANCE (Individual Dose Risk)
SUBSYSTEMS
(Intermediate calculations of key contributors to system-level performance)
ENGINEERED SYSTEM
GEOSPHERE
BIOSPHERE
COMPONENTS OF SUBSYSTEM
Engineered Barriers
UZ Flow and Transport
SZ Flow and Transport
Direct Release and Transport
Dose Calculation
KEY ELEMENTS OF SUBSYSTEM ABSTRACTIONS
WP Corrosion (Humidity, Chemistry and Temperature)
Mechanical Disruption of WP (Seismicity, Faulting, Rockfall, and Dike Intrusion)
Quantity and Chemistry of Water Contacting WPs and Waste Forms
Radionuclide Release Rates and Solubility Limits
Spatial and Temporal Distribution of Flow
Distribution of Mass Flux Between Fracture and Matrix
Retardation in Fractures in the Unsaturated Zone
Flow Rate in Water-Production Zones
Retardation in Water-Production Zones and Alluvium
Volcanic Disruption of Waste Packages
Airborne Transport of Radionuclides
Dilution of Radionuclides in Groundwater (Well Pumping)
Dilution of Radionuclides in Soil (Surface Processes)
Location and Lifestyle of Critical Group