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 1

SEPTEMBER 1998

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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

Change pages (cont'd)

Revision #	Section/ Paragraph	Date	Modification
1	4.3.3/1	Sept 1998	additional references added to review method
1	5.0/all	Sept 1998	material contained in status section was increased -- entire chapter was reorganized to address each subissue separately
1	5.1/all	Sept 1998	new section added to describe status of issue resolution of Subissue 1
1	5.4/5-16	Sept 1998	evaluation of 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)

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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 10 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 of 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 thermal effect on flow (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 Waste Containment and Isolation Strategy (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, 1998). 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 rélease
- 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 8,000 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. Currently, there is no firm consensus on corrosion rates and corrosion mechanisms for conditions expected for the repository conditions. DOE treats corrosion of the outer WP layer of corrosion allowance material (CAM) differently from the inner layer of corrosion resistant material (CRM). 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 of 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, but not yet for the outer layer (e.g., CAM). 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

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[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.

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 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 corrosion of the outer layer (e.g., CAM) of the WP to exposure to liquid water and stated intentions to directly 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 thermohydrologic model using NUFT will provide predictions of temperature and liquid saturation to waste-form degradation and radionuclide transport calculations by the RIP code. The nonisothermal drift-scale 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.

3.4 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: 1) infiltration from ground surface; and 2) 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/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: 1) flow convergence/divergence; 2) flow multiplication; and; 3) 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 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.

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: 1) length of the reflux zone, and 2) 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).

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		

Table 2. Sensitivity of predicted repository performance to REFLUX1 parameters

Parameter	5 km, 20,000 Yrs.		20 km, 100,000 Yrs.	
	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 yrs.)	Maximum Amount of Water Contacting WPs (mm/10,000 yrs.)
Thickness of Reflux Zone (range = 10 m - 200 m)	2357	2357
Perched Bucket Volume (range = 0.2 - 0.8)	2353	2353

REFLUX2 Submodule

Four REFLUX2 parameters were varied: 1) thickness of the dry-out zone; 2) reflux cycle period; 3) fraction of infiltration-derived water that escapes the reflux cycle each year; 4) and 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: 1) 1.0 mm/yr; 2) 5.5 mm/yr; and 3) 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.

Table 4. Sensitivity of predicted repository performance to REFLUX2 parameters

Parameter	5 km, 20,000 Yrs.		20 km, 100,000 Yrs.	
	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 m - 200 m)	0.0	0.0	0.0	0.0
Reflux Cycle Period (range = 1 - 3,000)	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 yrs)	Maximum Amount of Water Contacting Waste Packages (mm/10,000 yrs)
Thickness of Dry-out Zone (range = 10 m - 200 m)	2403	3328
Reflux Cycle Period (range = 1 - 3,000)	2504	2844
Fraction Infiltration-Derived Water Escaping (range = 0 - 1)	2807	2842
Fraction Dry-out Zone Derived Water Escaping (range = 0-1)	2602	2844

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: 1) degrading the integrity of the WP, and 2) 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 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 (A) procedures. 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:
  - — with the explicit objective of testing conceptual and numerical models so critical thermohydrologic processes can be observed and measured. Of particular importance are to bound the effects of heterogeneities, including discrete features, such as fractures and faults; and bound the range of thermally-driven flux;

- with explicit consideration of thermal-hydrologic, thermal-chemical, and hydrologic-chemical couplings;
- at different scales to discern scale effects on observed phenomena;
- for temperature ranges expected for repository conditions;
- to determine if water refluxes back to the heaters during either the heating or cool-down phases of the tests; and
- to evaluate the possibility for occurrence of cyclic wetting/drying on WP surfaces.

Technical Acceptance Criterion 2

- Thermohydrologic test results from other sites and programs have been tempered for application 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:

— 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.

— 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:

— Models are based on well-accepted principles of heat and mass transfer applicable to unsaturated geologic media.

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

— 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.

— Models include all significant repository design features.

— Models are capable of accommodating variation in infiltration.

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

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

— Alternative models and modeling approaches, which are consistent with available data and current scientific understanding, have been investigated, limitations defined, and results appropriately considered.

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

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 Exploratory Studies Facility (ESF) single-heater test (SHT), and the ESF drift-scale heater 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.

[2]D.D. Evans, personal communication with R.T. Green, 1986.

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:

  — 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.

  — 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:

  — Performance affecting 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.

  — 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.

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

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

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

— 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 is evaluated in the context of the acceptance criteria for Subissue 1. Evaluation of DOE's thermohydrologic testing and modeling program in the context of Subissues 2 and 3 will be provided in FY1999 (Revision 2 of this IRSR).

In addition, in recent years, and prior to development of the acceptance criteria provided in this IRSR, staff have raised concerns about DOE's site characterization and PA program in areas related to TEF. 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)

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

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?

5.1.1 Programmatic Acceptance Criterion 1

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

DOE is subject to two levels of auditing of its QA procedures. The Civilian Radioactive Waste Management System, Management and Operating (CRWMS M&O) contractor is conducting periodic vertical slice reviews to determine if there are weaknesses in the defensibility and documentation of DOE's program based on generally accepted nuclear QA principles. These audits are internal to the CRWMS M&O program. DOE's thermohydrologic testing program has not yet been subjected to a vertical slice review by CRWMS M&O.

Additionally, DOE's thermohydrologic testing programs are being conducted under a QA program that has been accepted by the CRWMS M&O Office of Quality Assurance (OQA). Therefore, data collected under this program should be acceptable. The OQA has performed audits and surveilences of the thermohydrologic testing programs. NRC staff participated as observers in OQA audits and surveilences.

To date, no questions or comments related to QA of data collected under DOE's thermohydrologic testing program have been raised by the staff. In the future, the results of audits and surveilences, conducted with respect to data collected under DOE's thermohydrologic testing program to be submitted as part of the TSPA-VA and LA, will be reviewed by NRC staff.

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 is scheduled for completion prior to the end of FY1998.

To date, no questions or comments regarding the use of expert elicitation, in areas related to TEF, have been raised by the staff. The expert elicitation process of the near-field/altered zone will be evaluated upon receipt of the final report.

5.1.3 Technical Acceptance Criterion 1

Thermohydrologic tests are designed and conducted:

- With the explicit objective of testing conceptual and numerical models so critical thermohydrologic processes can be observed and measured. Of particular importance are to bound the effects of heterogeneities, including discrete features, such as fractures and faults; and bound the range of thermally driven water.

DOE has initiated a series of niche studies to investigate seepage through partially saturated fractured rock under nonisothermal 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 bounding the effects of heterogeneities, such as fractures and faults, under nonisothermal conditions. In addition, DOE has designed, and is conducting, the field-scale DST. The DST facility is large enough (50-m long, 5-m diameter drift) to intersect a significant volume of the TSw at the proposed repository horizon (TRW Environmental Safety Systems, Inc., 1997). At this time, the staff has no further questions or comments regarding the design and conduct of thermohydrologic tests at YM to bound the effects of heterogeneities and bound the range of thermally driven water. The staff will continue to evaluate the data from these tests as they are made available.

- With explicit consideration of thermal-hydrologic, 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 thermal-hydrologic, thermal-chemical, and hydrologic-chemical couplings will be evaluated using this evidence. The success of the sampling procedures and the importance of the thermal-hydrologic, thermal-chemical, and hydrologic-chemical couplings will be evaluated after the results from these tests are made available and analyzed. The importance of these couplings should not be dismissed prior to analysis of thermal-hydrologic, thermal-chemical, and hydrologic-chemical data that will be provided by the LBT, SHT, and DST.

- 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. At this time, the staff has no further questions or comments regarding the scale at which DOE's thermohydrologic tests are being conducted.

- For temperature ranges expected for repository 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. Maximum temperatures expected for repository conditions are predicted using numerical models. Numerical predictions for temperature are dependent on the model conceptualization. Temperatures predicted using an ECM are not necessarily consistent with predictions made with dual permeability models (DKM) conceptualization. This discrepancy in simulated temperatures leads to uncertainty in predicting repository temperatures. Appropriateness of thermohydrologic test temperatures cannot be assessed until numerical predictions of the repository thermohydrologic response are made within a known degree of uncertainty. However, because DOE has incorporated variable thermal load instrumentation in the DST to keep the maximum drift wall temperature within the range of predicted repository temperatures, the staff has no further questions or comments regarding the design temperature ranges of the thermohydrologic tests (a more detailed discussion of previous staff comments about test temperatures, and DOE's response to those comments, is provided in Section 5.4 of this IRSR).

- 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.

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

Investigations of conditions that lead to seepage have been undertaken by DOE in various niche studies. None of these investigations, however, address non-isothermal effects caused by the HLW. Nor do the studies address episodic events that would lead to cyclic drying and wetting. Therefore, DOE has not yet addressed, at least experimentally, the possibility for cyclic wetting/drying on WP surfaces.

5.1.4 Technical Acceptance Criterion 2

- Thermohydrologic test results from other sites and programs have been tempered for application 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.

5.1.5 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.

5.2 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.

5.3 U.S. NUCLEAR REGULATORY COMMISSION AUDIT REVIEW OF THE U.S. DEPARTMENT OF ENERGY TOTAL SYSTEM PERFORMANCE ASSESSMENT–95

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 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; and 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.

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

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 thermal-hydrologic-chemical (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, 1997). 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 dual permeability models 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.

5.5 ITEMS RESOLVED AT THE STAFF LEVEL

As noted in Section 5.2 of this report, a number of open items resulting from the staff review of DOE's SCP have been resolved (Comments 11 and 73, and Question 33). The open items were related to the three subissues identified in this report.

As noted in Section 5.4 of this report, three open items resulting from the staff review of DOE's thermal testing and modeling program have been resolved. The open items were related to the subissues identified in this report.

5.6 OPEN ITEMS WITH THE U.S. DEPARTMENT OF ENERGY PROGRAM

The staff has evaluated DOE's thermohydrologic testing program, in the context of the acceptance criteria for Subissue 1, as provided in Section 5.1 of this report. No specific questions or comments about DOE's thermohydrologic testing program resulted from this evaluation. However, it is important to note that DOE's thermohydrologic testing program is a long-term program. Evaluation of significant technical aspects of TEF, such as: (i) coupled thermal processes; (ii) water reflux toward heat sources; and (iii) potential cyclic wetting/drying of WP surfaces requires analysis of longer-term data from the DST than is currently available. It would be inappropriate to conclude that the staff will have no more questions or comments about thermohydrologic testing in the future. In addition, with the current program focus on DOE's TSPA-VA, as well as DOE's plans for developing the LA, it is premature to initiate detailed evaluation of DOE's plans for long-term, performance confirmation testing. The staff will continue to monitor the progress of thermohydrologic testing at YM, independently analyze available data, and attend DOE's Quarterly Progress Meetings.

As noted in Section 5.3 of this report, items identified in the NRC/CNWRA Audit Review of DOE'S TSPA–95 remain open. These open items will be re-evaluated in FY1999 as part of the staff review of DOE's TSPA-VA.

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APPENDIX

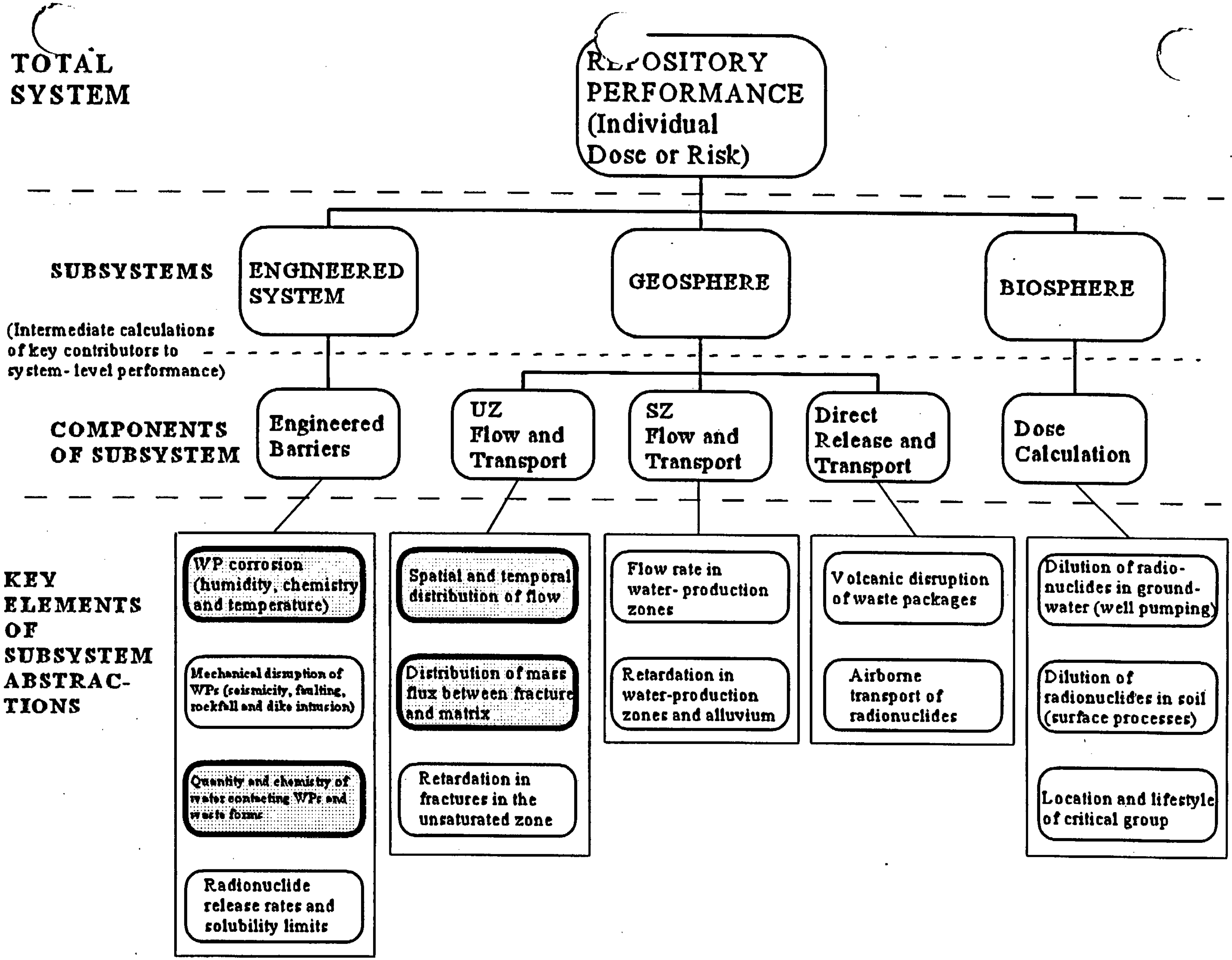

Figure A-1. Flowdown diagram for total system performance assessment. This KTI, Thermal Effects on Flow, provides input to the highlighted key elements.