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ISSUE RESOLUTION STATUS REPORT

KEY TECHNICAL ISSUE: THERMAL EFFECTS ON FLOW

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

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CONTENTS

CONTENTS (cont'd)

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QUALITY OF DATA, ANALYSES AND CODE DEVELOPMENT

DATA: No NRC- or 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: MULTIFLO Version 1.0 computational software was used for analyses contained in this report. This scientific and engineering software is 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 QAP-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 refocused prelicensing high-level radioactive waste (HLW) program is to focus all its activities on resolving the 10 key technical issues (KTIs) that are 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 1996.

Consistent with 10 CFR Part 60 requirements 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 at the staff level 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), regarding how the DOE 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. Pertinent additional information could raise new questions or comments regarding a previously resolved issue.

An important step in the staff's approach to issue resolution is to provide DOE with feedback regarding issue resolution before the viability assessment. Issue Resolution Status Reports (IRSRs) are the primary mechanisms that the staff will use to provide DOE feedback on the subissues making up the KTIs. IRSRs include: (i) acceptance criteria for issue resolution; and (ii) the status of resolution, including whether the staff currently has comments or questions. Feedback is also contained in the staff *Annual Progress Report*, which 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 be guidance for the staff review of information in the DOE viability assessment and other future documents, including the license application. The staff also plans to use the IRSRs in the future to develop the Standard Review Plan (SRP) for the repository license application. Each IRSR contains five sections, including this 'Introduction' in Section 1.0. Section 2.0 defines the KTI and all related subissues. Section 3.0 discusses the importance of the subissue to repository performance, including: (i) qualitative descriptions; (ii) reference to a total system performance (TSP) flowdown diagram; (iii) results of available sensitivity analyses; and (iv) relationship to DOE Waste Containment and Isolation Strategy (WCIS) (i.e., the approach to its safety case). Section 4.0 provides the staff's review methods and acceptance criteria, which indicate the basis for resolution of the subissue and that will be used by staff in subsequent reviews of DOE submittals. These acceptance criteria are guidance for staff and, indirectly, for DOE. The staff technical basis for its acceptance criteria will also be included to further document the rationale for staff decisions. Section 5.0 concludes the report with the status of resolution, 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.

2.0 KEY TECHNICAL ISSUE AND SUBISSUES

The Thermal Effects on Flow (TEF) KTI is focused on two areas. These two areas are:

- Thermally-driven redistribution of moisture through partially saturated, fractured, porous media caused by the emplacement of heat-generating HLW

- Temperature and humidity of the waste package (WP) environment

Redistribution of moisture driven by heat may result in extended periods of dryness in the proposed repository during either the period of high heat or during cooling. Redistribution of moisture driven by heat could result in channeling moisture toward the WP; a phenomenon that will be referred to as thermal reflux in this report. As explained in Section 3 of this report, it is necessary to understand the spatial and temporal effects of the thermal load on liquid and gas phase flux, and resultant effects on temperature and humidity of the WP environment in the vicinity of the proposed repository to have confidence in predictions of containment and long-term waste isolation. Because the focus of the staff review of the DOE program is on the adequacy of the DOE treatment of thermally-perturbed liquid and gas phase flux (particularly thermal reflux) in their testing, modeling and performance assessment (PA) program areas, this KTI is divided into three resolvable subissues as follows:

- Is the DOE thermal-hydrologic testing program, including performance confirmation testing, sufficient to assess the potential for thermal reflux to occur in the near field?

- Is the DOE thermal-hydrologic modeling approach sufficient to predict the nature and bounds of TEF in the near field?

- Does the DOE total system performance assessment (TSPA) adequately account for TEF?

The scope of this report encompasses all three subissues.

3.0 IMPORTANCE TO REPOSITORY PERFORMANCE

The staff is developing a strategy for assessing the performance of a proposed HLW repository at Yucca Mountain (YM), Nevada. As currently envisioned by the staff, those elements of this strategy necessary to demonstrate 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, upon which the staff review of key elements of the DOE TSPA will be based, are under development (IRSR and acceptance criteria on model abstraction, in preparation). 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 thermal-hydrologic 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 (Temperature, Humidity, and Chemistry)—The temperature and humidity of the WP environment are dependent on the liquid and gas phase flux through the repository. In addition, liquid water that refluxes into the underground facility and interacts with waste containers can affect the integrity of container material by accelerating corrosion, thereby, leading to the premature release of radionuclides from the WP.

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

- Fracture versus Matrix Flow—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 waste container and to determine whether there is a possibility for water to drip onto the waste canisters by refluxing through fractures.

- Spatial Distribution of Flow—The pathways for and 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).

Hence, the focus of this KTI is on thermal reflux as the potentially important thermal-hydrologic interaction within and between key elements of the engineered and natural subsystems of the repository.

3.1 U.S. Department of Energy Waste Containment and Isolation Strategy

The DOE presented a strategy for waste containment and isolation at the YM site in its 1988 Site Characterization Plan (SCP). Since that time, additional site characterization data have been obtained and the engineered system design has advanced. DOE is updating the WCIS to incorporate recent site characterization information, new repository and WP designs, more realistic performance predictions, and changing regulatory considerations (Brocoum, 1996). The updated DOE strategy defines attributes of the disposal system deemed important to containment and isolation. DOE has identified hypotheses that address attributes 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 is significantly less than net infiltration; (ii) fracture flow occurs within a limited volume of the repository host rock at any given time; (iii) seepage into the emplacement drifts will be limited to a small fraction of the incident percolation flux due to capillary forces; (iv) bounds can be placed on thermally-induced changes in seepage rates; and (v) heat produced by emplaced waste will reduce relative humidity in the vicinity of the WPs. Evaluating these hypotheses necessitates understanding the liquid and gas phase flux in the vicinity of the repository during the period of thermal perturbation, including the potential for thermal reflux.

3.2 Importance of Reflux Into the Underground Facility on Repository Performance

Liquid water that refluxes into emplacement drifts can potentially affect repository performance either by degrading the integrity of the waste container, by transporting radionuclides that have been released from failed waste containers, 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 WP 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 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 is elevated, particularly in regions where rock temperatures exceed the boiling point of water at the repository horizon. 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 WP for thermal-loading scenarios that result in a dry out zone that extends 100 m above and below the repository horizon. 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 either cycle between boiling and condensation, possibly interacting with a container, or exit the cell as vapor or liquid with or without ever coming into contact with a WP. This source of water will be available for refluxing 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 either ambient rock 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 and 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 Reflux on Waste Package Integrity

The propensity for WPs to corrode from dripping water is a complicated function of temperature, water chemistry, rock mineralization, container design and material selection, humidity, and duration and frequency of container exposure to bulk water (Mohanty, et al., 1997). Because of the uncertainty in most of these factors, the effect of dripping water on container corrosion can not 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 to be negligible in container corrosion (TRW Environmental Safety Systems, Inc., 1995). Corrosion is considered to occur only when the waste container is in contact with water in either the vapor or liquid phase. Currently, there is no firm consensus on which conceptual models best predict corrosion rates and corrosion mechanisms for conditions expected for repository conditions. DOE has assumed *two corrosion regimes, humid air corrosion and aqueous corrosion, differentiated by the degree* of relative humidity (TRW Environmental Safety Systems, Inc., 1995). Humid air corrosion is assumed to occur in the presence of a thin film of water in environments (i.e., relative humidity from about 65–75 percent up to 85–95 percent). Similarly, aqueous corrosion is assumed to occur when relative humidity exceeds 85 to 95 percent, a condition in which metal is considered 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. Aqueous corrosion is considered to be predominant in an environment with relative humidity in excess of 60 percent (Mohanty, et al., 1997).

Although corrosion of waste container materials may occur by a variety of different processes (i.e., crevice corrosion, stress corrosion cracking, microbially-influenced corrosion, and galvanic corrosion), two processes are considered dominant in corrosion of the WPs, either general corrosion or localized corrosion in the form of pitting and crevice corrosion. General corrosion typically occurs over large areas, whereas, localized pit corrosion is restricted to limited sites. For carbon steel, the outer container material, general corrosion can occur non-uniformly under low pH (i.e., less than about seven) and at a chloride concentration significantly greater than a minimum, $[Cl^-] \gg [Cl^-]_{min}$. General corrosion can also occur uniformly as either 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 either corrosion process to be active .

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

WP design currently consists of an outer barrier of corrosion allowance material (CAM) (i.e., carbon steel) and an inner barrier of corrosion resistant material (CRM). Alloy 825 was the candidate CRM in TSPA-95, but alternative materials, such as alloy 625 and c-22, are being considered in the new WP design (DOE, 1996). 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, however, 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 O_2 concentration. The states of these factors determine the corrosion potential, E_{corr}, of the waste container 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 very low rate of corrosion.

The introduction of bulk water onto a WP by dripping can affect corrosion mechanisms and rates in several ways. 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 either continuously or intermittently at a specific location would lead to degradation at that localized site. Finally, as mentioned, 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 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 either 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 Reflux on Radionuclide Transport From Failed Waste Packages

Water that refluxes into emplacement drifts can alter the temperature, relative humidity, and flux of (vapor or liquid phase) water proximal to the WPs. Process-level models will have to incorporate the effects of refluxing when predicting the heat and mass transfer near the WP to determine whether the refluxing phenomenon has an adverse affect on repository performance in terms of dose. Otherwise, liquid phase transport of radionuclides from WPs may not be conservatively predicted if refluxing mechanisms are not considered.

3.2.3 Effect of Reflux 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). Refluxing water 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 activities 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.

3.3 Consideration of Reflux in Previous Performance Assessments

The performance of the WP and the transport of radionuclides released from failed canisters are affected by the thermal-hydrology 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. Most notable of these PAs are the following: (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—*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 thermal-hydrologic effects resulting from heat-generated by the decay of HLW is summarized in the following sections.

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

Mechanisms and parameters that affect WP integrity

TSPA-93 used a source term module, YMIM, to determine the flux and time history of radionuclides released from the WPs. The integrity of the WPs is calculated in YMIM 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 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 either the conduction-only code, COYOTE (Gartling, 1982), an analytical solution, or ANSYS (a numerical simulator). The extent of the dry-out zone was calculated with an analytical model and V-TOUGH, a numerical code (Nitao, 1989). Flow-through fractures only are 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 by air oxidation, generalized aqueous corrosion, and localized pitting corrosion. All three corrosion mechanisms are, directly or indirectly (via property dependence), functions of temperature. Both generalized aqueous corrosion and localized pit corrosion require the presence of liquid water (which will only occur at sub-boiling temperatures) to proceed, therefore, liquid water flux is required to determine container performance, but the presence of water is indirectly indicated by temperature only. Relative humidity is not considered a factor in 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 the TSPA-93 PA. Therefore, fluxes of air and vapor movement, in addition to liquid water fluxes, have to be 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 V-TOUGH. However, heat flow for both analyses is predicted, using either COYOTE, a heat-conduction only simulator, 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 WP 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) and aqueous (bulk water) corrosion. Only general corrosion and pitting corrosion are considered in TSPA-95. In general, the outer barrier will degrade by either general corrosion alone or a combination of general corrosion and localized pitting corrosion. The inner barrier will degrade solely by localized pitting corrosion under aqueous conditions.

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

Effect of pore water and infiltration on released radionuclides

Subsequent to the failure of waste containers, 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 1-D 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 relative humidity are only indirectly important to flux predictions in the manner in which they affect mass balance and liquid flux calculations.

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

Mechanisms and parameters that affect WP integrity

Electric Power Research Institute (EPRI) used a code called IMARC (Integrated Multiple Assumptions and Release Calculations) 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 and humidity effects on general and pitting corrosion and microbiologically influenced corrosion. The container failure-fraction is estimated using a Weibell distribution. The presence or absence of liquid water during the heating period is incorporated into CBS performance calculations in IMARC as a probability-weighing coefficient. A total of 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 waste container does not contact liquid water, (ii) wet-drip—separate droplets of water fall across an air gap onto the waste container, (iii) episodic—liquid water contacts the waste container intermittently for limited periods of time, and (iv) moist-continuous. The three temperature regimes are: (i) waste containers whose surface temperatures rise substantially above boiling, (ii) waste containers whose surface temperatures rise to approximately the boiling point, and (iii) waste containers whose surface temperatures remain well below boiling. Fractions (or weightings) are assigned to each of the seven components to determine the probability of each scenario occurring. Therefore, wet conditions are considered in waste container failure by assigning probability factors that reflect a greater failure than dry conditions. The general approach to waste container failure taken in EPRI 96 is similar to the approach on refluxing taken in the REFLUX1 and REFLUX2 abstractions, included in Total Performance Assessment (TPA) Version 3.1 (See Section 3.4 of this report).

Effect of pore water and infiltration on released radionuclides

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

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

Mechanisms and parameters that affect WP integrity

Temperature is explicitly taken into account in three places in IPA Phase 2: (i) the gas velocity for the ^{14}C transport model; (ii) the 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 relative humidity 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 waste container with rock or rubble infilling material—where 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 due 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 either 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 above. 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.

3.4 NRC/CNWRA Sensitivity Analyses

The effect of heat and mass transfer processes on repository performance is assessed in terms of sensitivity to dose, in other words, the effect that the heat and mass transfer processes have on radionuclides released to the reference biosphere. This effect and the importance of values assigned to physical properties in the analyses are determined by systematically performed sensitivity analyses. Both process-level and abstracted models are formulated to represent the heat and mass transe e. processes anticipated to be active in the environment near the WPs. Process-level models are detailed models formulated on basic principals that govern heat and mass transfer for the range of expected conditions at the repository. The abstracted models are designed to represent the physical processes by extracting only higher order effects identified using process-level models. Both process-level and abstracted models are used in the TEF KTI to assess the effect heat and mass transfer mechanisms in terms of sensitivity of dose to variations in model assumptions and property assignments. A description of two abstracted refluxing models contained in the NRC TPA code is contained in Appendix B. The results of these ongoing sensitivity analyses will be documented in a separate report in FY 1998.

3.4.1 Parametric Evaluation of Temperature and Humidity of the Waste Package Environment using MULTIFLO

A parametric study is being conducted to pursue sensitivity analyses with the process-level multiphase numerical model. The results of the parametric study will be submitted to the TPA analyses via EBSPAC in terms of temperature and relative humidity for EBSFAIL and temperature, relative humidity, and water flow for EBSREL. TPA Version 3.1 will be used to calculate dose for each of the case studies. Results of this study will be documented in a separate report in FY 1998.

3.4.2 Analysis of the Effect of Thermally Driven Redistribution of Moisture on Repository Performance Using Total Performance Assessment Version 3.1

A sensitivity analysis is being performed to determine the sensitivity of dose to heat and mass transfer in the emplacement drift. The TPA Version 3.1 PA code is being used to assess this importance by considering the following:

- temperature and relative humidity predictions from the process-level numerical model,
- liquid water refluxing predictions from the process-level mechanistic fracture flow model, and
- rates and fluxes of refluxing water from abstracted models.

Results of the sensitivity analysis will be documented in a separate report in FY 1998.

Numerical Process-Level Model

The significance of temperature and relative humidity predicted with the numerical process-level model is assessed by inputing the tabular temperature and relative humidity data into TPA Version 3.1. The ranges of temperature and relative humidity considered are provided by the sensitivity analyses discussed above. The TPA analyses will be conducted to insure that assumptions and basecase values used in the TPA analyses will be consistent with those in the numerical process-level analyses.

Mechanistic Process-Level Model

A sensitivity analysis will be performed on a mechanistic fracture-flow, process-level model. Values for the parameters used in the mechanistic model will be varied over the full range of values considered reasonable. Predictions of liquid flux into emplacement drifts will be provided by these sensitivity analyses. Sensitivity of dose can be calculated to assess the effect of liquid flux on RT from the waste container, however, TPA Version 3.1 does not incorporate the effects of liquid water on container performance. Whether liquid water is important to container performance needs to be assessed, and if important, incorporated in the TPA code to determine sensitivity to dose based on the mechanistic process-level model predictions.

Abstracted Model

A sensitivity analysis will be performed on the abstracted reflux modules contained in TPA Version 3.1. Sensitivity of dose will be determined for variation in the input variables included in the REFLUX1 and REFLUX2 modules. TPA Version 3.1 will be used to randomly vary the values for the variables included in each of the two modules.

Values for the variables required in the two refluxing modules are selected external to TPA Version 3.1 for use in the TSPA sensitivity analyses. Dose sensitivity analyses are currently planned to assess the importance of refluxing using the REFLUX2 module. Input parameters for REFLUX2, such as initial and residual saturations of the rock units subject to dryout, are sufficiently well-known from site characterization activities for the purpose of this analysis. The extent of the dry-out zone can be predicted, using process-level analysis results [i.e., MULTIFLO simulations (Lichtner and Seth, 1997)]. The remaining three REFLUX2 input parameters (the duration of the reflux cycle, fraction of rock pore water lost per reflux cycle, and the fraction of infiltration water lost per reflux cycle) are not well known and contain a high level of uncertainty. Subsequent to the availability of TPA Version 3.1 code, sensitivity analyses will be performed to assess the importance of refluxing in the context of the REFLUX2 conceptual model and all inherent assumptions contained in the TPA Version 3.1 code. Because of the high uncertainty associated with the latter three input values, the ranges of values over which the sensitivity analyses will be performed will be large.

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 thermal-hydrologic interactions both within and between key elements of the engineered and natural subsystems of the repository, as discussed in Section 3. Acceptance criteria, upon which a more broad staff review of key elements of the DOE TSPA will be based, are under development. 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 DOE Thermal-Hydrologic Testing Program, Including Performance Confirmation Testing, Sufficient to Assess the Potential for Thermal Reflux To Occur in the Near Field?

This subissue relates to the sufficiency of the DOE thermal-hydrologic testing program to provide information used to verify conceptual models that DOE will use to evaluate thermally-driven flow in the near field. The 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

The DOE thermal-hydrologic testing program, including performance confirmation testing, with regard to TEF, is acceptable, if the following acceptance criteria have been met:

Programmatic Elements

- The DOE thermal-hydrologic testing program was developed, and data collected and documented, under acceptable quality assurance procedures.

- Expert elicitations may be used for, but not necessarily limited to, assessing whether conceptual models bound the range of thermally driven refluxing expected at YM, in addition to thermal-hydrologic testing to provide conservative bounds to estimates. All expert elicitations are conducted and documented in accordance with the guidance in NUREG-1563 (Kotra, et al., 1996) or other acceptable approaches.

Technical and Confirmatory Elements

- Thermal-hydrologic tests are designed and conducted:

  — with the explicit objective of testing conceptual and numerical models and such that critical thermal-hydrologic processes can be observed and measured. Of particular importance is to: (i) bound the effects of heterogeneities, including discrete features, such as fractures and faults; and (ii) bound the range of thermally-driven water.

  — 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 whether water refluxes back to the heaters during either the heating or cool-down phases of the tests.
- to evaluate the possibility for cyclic wetting/drying on WP surfaces to occur.

- It is acceptable to use thermal-hydrologic test results from other sites and programs so long as the test interpretations are tempered for application to the YM site.

- If the thermal-hydrologic testing program is not complete at the time of license application submittal, DOE has (i) explained why the testing program does not need to be completed for the license application; and (ii) 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 the DOE thermal-hydrologic 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 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

In order to provide timely comment to DOE on any staff concerns regarding its thermal-hydrologic testing program, the staff review of the DOE testing program has been active during FY97. Specifically, it has been important to make progress in issue resolution in advance of specific test start-up dates. In general, the staff review method has included a number of activities by the staff including:

- Review of DOE documents (both planning documents and reports summarizing results of tests to date) related to the thermal-hydrologic testing program.

- Review of the Peer Review of the DOE thermal-hydrologic testing and modeling program and subsequent DOE responses.

- Site visits to observe thermal test facilities and instrumentation.

- Appendix 7 meetings to discuss topics related the thermal-hydrologic testing.

- Observation of DOE test planning meetings and DOE technical meetings, where results of testing activities were discussed.

In the future, staff will continue to monitor the progress of DOE thermal-hydrologic tests (particularly, experiments recently started or to be started during FY98 such as the drift-scale test). In addition, staff, through the CNWRA, is conducting a laboratory-scale heater test to provide insight into thermally-driven reflux mechanisms (details of which will be presented in the next NRC Annual Report). A summary of concerns raised with DOE regarding the thermal-hydrologic 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 Doe Thermal-Hydrologic 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 the DOE thermal-hydrologic modeling approach (process-level models) to predict thermally-driven flow in the near field. The resolution of this subissue will be through the application of the acceptance criteria defined in Section 4.2.1 of this report.

4.2.1 Acceptance Criteria for Subissue 2

The DOE thermal-hydrologic 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 Elements

- The DOE thermal-hydrologic modeling analyses were developed and documented under acceptable quality assurance procedures.

- Expert elicitations may be used for, but not necessarily limited to, selecting a conceptual model and its parameters. All expert elicitations are conducted and documented in accordance with the guidance in NUREG-1563 (Kotra, et al., 1996) or other acceptable approaches.

Technical and Confirmatory Elements

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

  — Parameter values (single values, ranges, probability distributions, or bounding values) are either derived from site-specific data, or an analysis is included to show that 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 domain for conceptual models evaluated.

- 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 all significant design features.

  - Models are capable of accommodating variation in infiltration.

  - Conceptual model uncertainties have been defined and documented, and their effects on conclusions regarding performance have been 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, their limitations defined, and results appropriately considered.

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

- Coupling of processes has been evaluated using a methodology in accordance with the guidance in 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 fully-coupled models.

- The dimensionality of models, which include heterogeneity at appropriate scales and significant process couplings, may be reduced, if it is shown that the reduced dimension model bounds the predictions of the full dimension model.

- 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 their inclusion in the ECM produces a conservative effect on calculated overall performance.

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

- Results of process-level models have been verified by demonstrating consistency with results/observations from field-scale thermal-hydrologic 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 the DOE thermal-hydrologic modeling approach (process level models) to predict thermally- driven flow in the near field. Staff review of the DOE thermal-hydrologic analyses will place particular emphasis on those technical elements of the acceptance criteria 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 waste canisters 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 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 a decrease or increase of pathways.

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

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 in terms of 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), at the Climax mine (Patrick, 1986), and the University of Arizona Road Tunnel heater test[1]. It is expected that DOE will continue to develop thermal-hydrologic analyses to assess results from laboratory-scale tests, the Fran Ridge large block test, the Exploratory Studies Facility (ESF) single heater test, and ESF drift scale test. If these ongoing tests provide results relevant to refluxing water, the DOE models will be independently evaluated to ensure they provide predictions that conservatively estimate the nature and bounds of TEF in the near field. A summary of concerns raised with DOE regarding its thermal-hydrologic modeling efforts, and the status of resolution of this subissue at the staff level is provided in Section 5 of this report.

4.3 Subissue 3: Does the 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 the application of the acceptance criteria defined in Section 4.3.1. However, it should be noted 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.

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

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 the DOE TSPA, that relate to TEF, are acceptable.

4.3.1 Acceptance Criteria for Subissue 3

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

Programmatic Elements

- The DOE analyses were developed and documented under acceptable quality assurance procedures.

- Expert elicitations may be used for, but not necessarily limited to, justifying the use of abstracted models in the DOE TSPA. All expert elicitations are conducted and documented in accordance with the guidance in NUREG-1563 (Kotra, et al., 1996) or other acceptable procedures.

Technical and Confirmatory Elements

- 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 refluxing into an emplacement drift, if the abstracted model is shown to bound refluxing water predictions made using a process-level model.

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

  — Parameter values (single values, ranges, probability distributions or bounding values) are either derived from site-specific data, or an analysis is included to show that 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 domain for conceptual models evaluated.

- Descriptions of the conceptual and mathematical models used in the DOE TSPA are reasonably complete. Further, DOE should demonstrate that:

  — Performance affecting processes observed in available thermal-hydrologic tests and experiments have been identified and incorporated into the TSPA. Specifically, it is necessary to demonstrate that either liquid water will not reflux into the underground facility or incorporate 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 (GROA) underground facility design features, such as the addition of backfill, 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.

- Coupling of thermal processes has been evaluated, using a methodology in accordance with the guidance in 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 fully-coupled models.

- 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 terms of performance.

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

- Sensitivity and importance analyses have been conducted to assess the need for any 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 whether the DOE TSPA adequately accounts for TEF. Staff review of this aspect of the DOE TSPA will place particular emphasis on those technical elements of the acceptance criteria related to incorporating the potential adverse affects of refluxing water on the performance of the repository because:

- Liquid water that refluxes into the underground facility and interacts with waste canisters 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 waste container can be accelerated by liquid water introduced into the underground facility by thermally-driven refluxing.

4.3.3 Review Method for Subissue 3

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

- 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), *U.S. Department of Energy Thermohydrology Abstraction/Testing Workshop Results* (Francis, et al., 1997) and the *First Interim Report of the Total System Performance Assessment Peer Review Panel.*

- 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.

- The NRC/DOE technical exchanges on PA.

- Independent PAs by staff.

The DOE TSPA will continue to be evaluated independently by staff. In the remainder of FY97 and into FY98, emphasis will be on continued development and implementation of the NRC/CNWRA TPA code. The physics of refluxing water will be incorporated into either NRC/CNWRA process-level models or 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 the DOE for the TSPA-VA and TSPA-License Application, to assess the effect of refluxing water 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 issue, is provided in Section 5 of this report.

5.0 STATUS OF SUBISSUE RESOLUTION AT THE STAFF LEVEL

In recent years, staff have raised concerns about the DOE site characterization and PA program in areas related to TEF. These concerns have been documented in the following:

- *The U.S. Nuclear Regulatory Commission Staff Site Characterization Analysis of the U.S. Department of Energy Site Characterization Plan* (U.S. Nuclear Regulatory Commission, 1989)

- *The U.S. Nuclear Regulatory Commission/Center for Nuclear Waste Regulatory Analyses Audit Review of the U.S. Department of Energy Total System Performance Assessment 1995* (Austin, 1996a; Austin, 1996b)

- Letter from NRC to DOE with comments from the *Staff Review of the U.S. Department of Energy Thermohydrology Testing and Modeling Program* (Bell, 1997)

A summary of the topics from each source listed above with a discussion of technical items considered to be either resolved at the staff level or remaining open are provided in the following sections.

5.1 U.S. Nuclear Regulatory Commission Review of U.S. Department of Energy Site Characterization Plan

The U.S. Nuclear Regulatory Commission review of the U.S. Department of Energy Site Characterization Plan (U.S. Nuclear Regulatory Commission, 1989) resulted in two comments and one question within the scope of the TEF KTI. These are:

- 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 whether 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 5L of standing water per package to accumulate in the emplacement hole for the first 1000 yr following repository closure. How can the presence of standing water during the first 1000 yr be justified? What is the basis for 5L of standing water per canister being acceptable?

Comment 11 relates to Subissue 1 (sufficiency of the DOE thermal-hydrologic 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 the

DOE 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 has commented directly on the sufficiency of the DOE thermal testing and modeling program, as discussed in Section 5.3 of this report. Given the evolution of the DOE WCIS and of the DOE thermal-hydrologic 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 the DOE thermal-hydrologic modeling approach) and Subissue 3 (adequacy of treatment of TEF in the DOE 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 the DOE determination of design backfill requirements presented in the DOE SCP is outdated and,in that sense, Comment 73 is considered resolved. However, the staff notes that in the TSPA-VA plan, DOE has 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 thermal-hydrologic 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 thermal-hydrologic analyses supporting the DOE TSPA-VA, and new questions could arise regarding the process for determining the design requirements for backfill hydraulic conductivity or other parameters.

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

5.2 U.S. Nuclear Regulatory Commission Audit Review of U.S. Department of Energy TSPA-95

The NRC/CNWRA audit review of TSPA-95 identified two areas of concern related to Subissue 3 (adequacy of treatment of TEF in the DOE TSPA):

- Heat transfer calculations are not transparent and inconsistencies with previous estimates are not adequately explored (Austin, 1996a).

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

The CNWRA performed independent heat transfer calculations at drift scale to determine the time varying temperature and relative humidity at the surface of a typical 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 pre-backfill radiative heat transfer do not appear to be consistent with previous work and may not be realistic. The staff also concluded that the DOE calculation of backfill conductivity and pre-backfill radiative heat transfer are not sufficiently documented to allow a proper examination of the differences in results (for the pre-backfill period).

In addition to calculations of temperature in TSPA-95, the staff raised a concern regarding the conceptual models used in the thermal-hydrologic calculations. Three sets of analyses in TSPA-95 (Chapter 4) relate to thermal-hydrology: (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: (i) a paucity of data on geometric/hydraulic characteristics of fractures at YM; and (ii) 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.

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 thermal-hydrologic analyses. The presence of water, either as bulk liquid water 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, which accurately incorporate the mechanisms that dictate the saturation, flux of water through either the matrix or fractures, and the 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 thermal-hydrologic modeling can be assessed, at least in part, by comparing the ECM formulation results with results derived from alternative conceptual models. For example, one possible alternative conceptual model could be formulated from dual-porosity and/or dual-permeability 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 whether the ECM formulation adequately incorporates the important fluid transport mechanisms expected at the proposed repository.

In its TSPA-VA plan, DOE has noted staff concern about the transparency (and reproducibility) of its heat transfer calculations and the use of 2D versus 3D models (TRW Environmental Safety Systems, 1996b). Further, DOE also noted that preliminary modeling results, using both dual permeability (DKM) and ECM models, demonstrate that the results can be affected by the assumed conceptual flow model (TRW Environmental Safety Systems, 1996b). The concerns expressed by the staff about the dimensionality of models and assumed conceptual flow models have been included as key issues in the DOE 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 thermal-hydrologic modeling and TSPA issues (Francis, et al., 1997). Based on information provided by DOE at the recent NRC/DOE Technical Exchange on TSPA (held on July 21-22, 1997, in San Antonio, Texas), it appears DOE has made progress in implementing specific task plans related to thermal-hydrologic modeling for its TSPA-VA. However, staff feels it is necessary to be able to review in more detail the thermal-hydrologic modeling methodology being employed by DOE for its TSPA-VA, prior to resolving the above open items. An additional NRC/DOE TSPA-related Technical Exchange is tentatively scheduled for October, 1997. Staff may propose an additional Appendix 7 interaction focusing solely on thermal-hydrologic modeling for TSPA-VA.

5.3 U.S. Nuclear Regulatory Commission Review of U.S. Department of Energy Thermal Modeling and Testing Program

Staff reviewed recent information on the DOE thermohydrology testing and modeling program and submitted findings of the review to DOE (Bell, 1997). The objective of this review was to evaluate whether the program will provide the information necessary for the license application.

For this review, staff depended mainly on the January 1996 report by the PRT (U.S. Department of Energy, 1996) that was established by DOE to review its thermal-hydrology 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 NRC/DOE Exploratory Studies Facility Video Conference (September 1996).

This review identified no objections related to the DOE program, however, several comments that are related to Subissue 1 (sufficiency of the DOE thermal-hydrologic testing program) and Subissue 2 (sufficiency of the DOE thermal-hydrologic modeling approach) were generated First, there was a concern that an accelerated drift-scale heater test 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 and not provide the information necessary to differentiate among alternative heat and mass transfer conceptual models. Second, the applicability of either the ECM approach or alternative approaches to bound predictions of liquid flow to waste containers 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 below:

- Thermal Testing Strategy: The staff supports DOE approach of phased thermal testing at various scales from laboratory-scale testing to the Fran Ridge Large Block Test (LBT) to the alcove-scale single heater test to the drift-scale heater test. It is the belief 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 is a possible phenomenon of significant interest, because it may determine the time and rate of wetting of the waste containers and hence, the effectiveness in waste containment and subsequent RT. Of the thermal tests to be conducted at various scales, the drift-scale heater test 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 drift-scale heater test compared to the expected repository heat load will not mask potentially important phenomena.

- Adequacy of Conceptual Model: The influence of fractures on rates of water flow toward waste containers is a central question in estimating the life of waste containers. 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, which affect water flow and provide conservative bounds on water flow rates and subsequent effects on EBS performance.

- Effects of THC Coupling: The DOE testing and modeling strategy should include means for bounding the effects of THC coupled processes on repository performance. Some NRC/CNWRA- and DOE-sponsored work indicates that this three-process coupling may lead to significant changes in the near-field environment, and thus, influence waste container 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 the DOE thermal testing and modeling program (Brocoum, 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 drift-scale heater test (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, the DOE letter states that 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 post-boiling period. DOE cites analyses, which indicate that the zone of dryout may extend more than 300 m vertically which would suggest that refluxing will not be a concern until the post-boiling period. However, a peer review of the DOE TSPA interim report (*U.S. Department of Energy Total System Performance Assessment, 1997b*) 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 post-boiling period.

The second issue in the DOE letter addressed the NRC concern regarding conceptual models in thermal-hydrologic modeling. DOE noted that dual permeability models (DKM) and stochastic DKM conceptual models have undergone considerable refinement and development and are being implemented in at least the single-heater test analysis.

The third and last issue in the DOE response letter addressed the need for an approach to specify bounds for THC coupled effects. DOE indicated in its response that significant progress has been achieved in modeling of THC coupled effects. It cited several recent publications that document this progress. These documents and citations, provided in support of all three DOE responses, are currently under review. Decisions to close these items will be made after a review of the DOE letter (Brocoum, 1997) has been completed by the staff.

5.4 Items Resolved at the Staff Level

As noted in Section 5.1 of this report, a number of open items resulting from the staff review of the DOE SCP have been resolved (Comment 11, Comment 73 and Question 33). The open items were related to the three subissues identified in this report.

5.5 Open Items With the U.S. Department of Energy Program

As noted in Sections 5.2 and 5.3 of this report, items identified in the NRC audit review of the DOE TSPA-95 and the NRC review of the DOE thermal modeling and testing program remain open.

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APPENDIX A

DRAFT

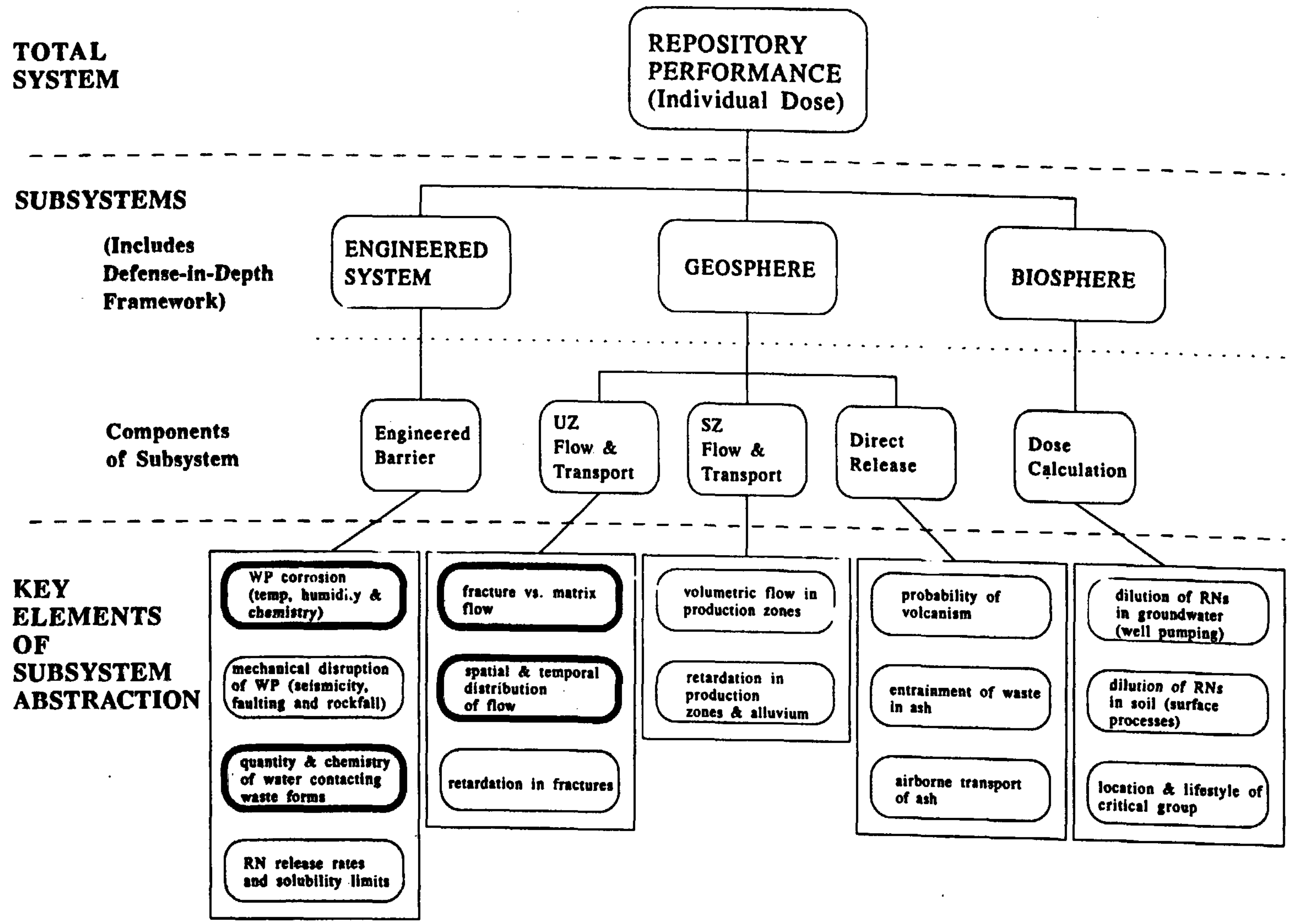

Figure A-1. Flowdown diagram for total system performance assessment. The Key Technical Issue of "Thermal Effects on Flow" provides direct input to the highlighted key elements.

APPENDIX B

APPENDIX B

Abstracted Models

The NRC/CNWRA performance assessment code TPA Version 3.1 contains two separate conceptual models to describe the propensity for water to reflux into the WP environment. The two options are contained as subroutines REFLUX1 and REFLUX2 in the near-field model, NFENV. Both refluxing models are conceptually-based and consistent with basic principles. The physics of the refluxing phenomenon are reflected in the data that are input into the models.

NFENV provides estimates of flow rates and chemical composition (i.e., pH and chloride concentration) of water contacting the WPs. The pH and chloride concentrations are based on table-lookup using results from the MULTIFLO code (Lichtner and Seth, 1996). MULTIFLO results are multiplied by a factor that is a sampled parameter to represent uncertainties in the data. The groundwater flow rates onto a WP are internally calculated in the NFENV module, using either the REFLUX1 or REFLUX2 model. Following are descriptions of the two conceptual models.

REFLUX1

In the REFLUX1 option, NFENV uses time-dependent temperature profiles generated by either an internal to the TPA code conduction-only heat transfer model or an external process-level model, which produces a lookup table for use in TPA, along with time-dependent water flux (q_{infil}) from input data 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 thermal-hydrologic conceptual model implemented in NFENV assumes that there are both matrix and fracture flow continua. It is assumed that a condensate zone layer exists in fractures at a rock mass temperature elevated above the boiling point T_{boil} isotherm with a thickness dependent upon q_{infil}, as shown in Figure B-1. 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 (since $T > T_{boil}$). 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 reflux zone penetrates the drift, water is assumed 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 perched zone is decreased accordingly.

The near-field thermal response to the heat pulse is assumed in REFLUX1 to be dominated by conduction and the near-field hydrology response is dominated by the temperature distribution. It is also assumed that the near-field moisture distribution reaches equilibrium rapidly relative to changes in the temperature field. Three input variables are required: (i) q_{infil}, the infiltration flux into the repository subarea; (ii) Z_{boil}, the elevation of the boiling isotherm above the repository at a given time; and (iii) q_{heat}, the thermal flux at Z_{boil}. Values for these variables must be derived from an independent source, such as process-level models, testing results, or data acquisition.

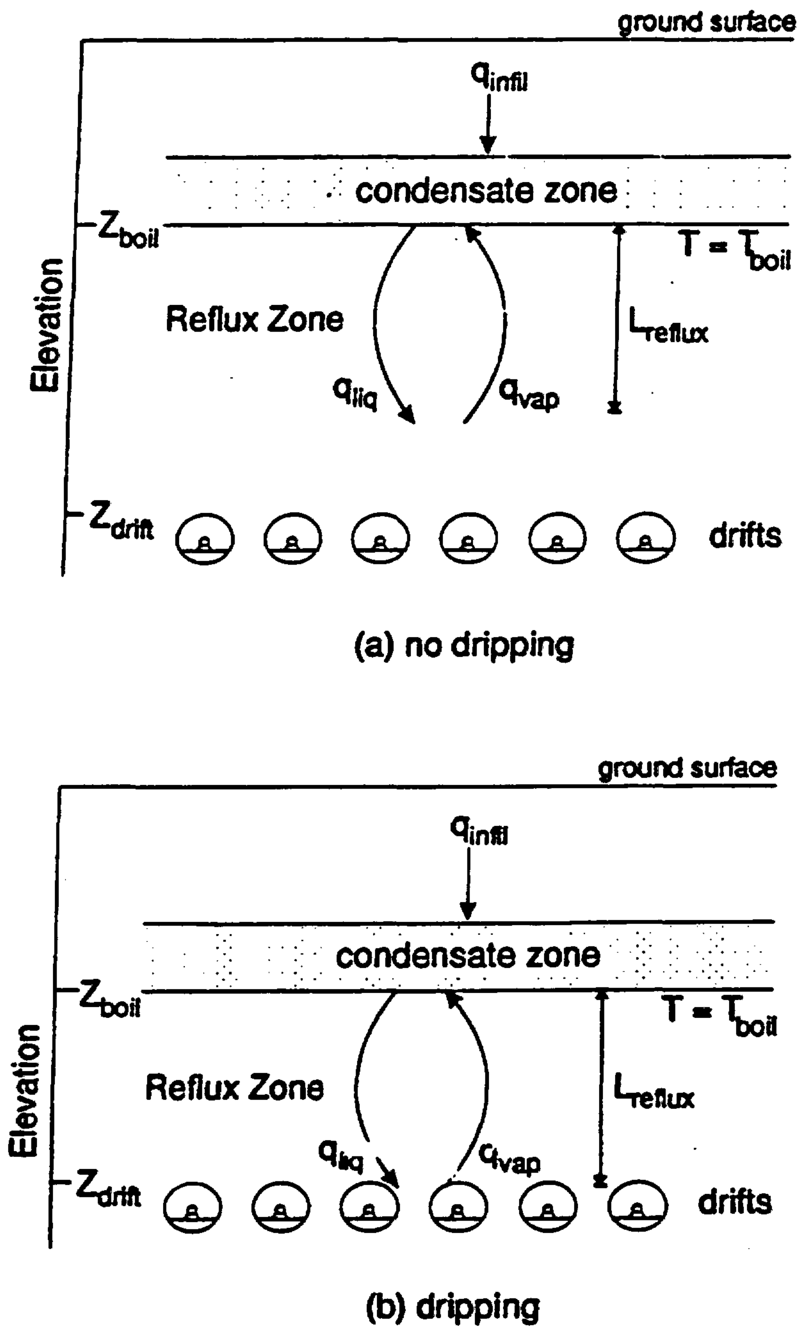

Figure B-1. Conceptualization of drift-scale thermal hydrologic model

A mass balance model is used to model the thickness of the perched water zone:

$$(\theta - \theta_r) \frac{\partial L_p}{\partial t} = q_{infil} - q_{perc} \quad \text{(B-1)}$$

where

θ = moisture content [-]
θ_r = residual moisture content [-]
L_p = thickness of the perched zone [m]
q_{perc} = percolation flux at the repository level [m/yr]
t = time [yr]

After it is determined that dripping in a drift can occur (i.e., $Z_{boil} - L_{reflux} < Z_{drift}$), the dripping flux is calculated. Because flow in the UZ is considered to be primarily through fractures, but not all fractures have flow, f_{local} is defined as the fraction of a subarea having fracture flow. As WPs cannot be dripped on if there is no flow, the fraction of drifts in which dripping occurs is also represented by f_{local}. The estimated value of volumetric flux of water into a drift, given that dripping occurs ($E[q_{drip}|q_{drip} > 0]$), is therefore, represented as:

$$E\left[q_{drip}|q_{drip} > 0\right] = \frac{q_{perc}}{f_{local}} \quad \text{(B-2)}$$

where q_{perc} is the percolation volumetric flux through the UZ above the drift, as determined by the FLOW module.

In drifts with $q_{drip}>0$ water can: (i) drip on a WP; or (ii) drip elsewhere, missing emplaced WPs. The fraction of q_{drip} that drips on a WP is represented by f_{hit}, a sampled parameter, which represents the fraction of the dripping flux that will contact the WP. EBSREL (a module of the TPA code) further partitions the flow contacting WPs into the portions contacting failed WPs and contacting WPs that have not failed, while EBSFAIL determines the fraction of WP that has failed due to corrosion. For release of contaminants from WP modeled by EBSREL, the volume of water available for dissolving radionuclides is then:

$$q_{drip} = E\left[q_{drip}|q_{drip} > 0\right] \times f_{hit} \quad \text{(B-3)}$$

In summary, NFENV provides temperature, RH, groundwater flow rate, and chemical properties information for determination of corrosion rates and WP failures. It also provides the flow rate of water onto a WP to the EBSREL module for dissolution of the WP contents following WP failure.

REFLUX2

An alternative refluxing conceptual model included in TPA Version 3.1 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 upon 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 condenses, where temperatures are below boiling. The condensate then flows back to the boiling zone. This return of condensate to the boiling zone is called refluxing. A particular unit of water may participate in the reflux cycle many times. With every cycle, some portion of the refluxing water may escape and flow away from the heat source, possibly toward the water table. The refluxing cycle can gain water from two sources: (i) infiltration from ground surface; and (ii) water vaporized from the dry-out zone in rock surrounding the WP. Water will continue to vaporize as long as temperatures remain above boiling, and water is available for vaporization.

The method to calculate the amount of water that refluxes each year is presented below. In general, the amount of water contributed to the refluxing cycle by infiltration and from vaporized pre-waste-emplacement ambient rock pore water are calculated separately. The fraction of water that escapes either as vapor or liquid in each cycle and the duration of each cycle are specified as input.

Reflux Derived From Infiltration

The amount of infiltration-derived water, R_I [m^3/m^2] that refluxes during year N, is:

$$R_I = \sum_{j=0}^{N-1} I_{N-j}(1 - L_I)^j \qquad \text{(B-4)}$$

which, for a constant infiltration rate, reduces to

$$R_I = \sum_{j=0}^{N-1} I(1 - L_I)^j \qquad \text{(B-5)}$$

where

I_j = infiltration flux at the repository for year j [m]
N = years after start of refluxing [-]
L_I = fraction of infiltration that escapes the reflux cycle each year [-]

Note that R_I converges to I/L_I for large N.

Reflux Derived From the Rock Pore Water

The total amount of water, D [m^3/m^2] vaporized from pre-waste-emplacement ambient rock pore water and available for refluxing is defined as:

$$D=(T)(n)(S-S_r) \tag{B-6}$$

where

T = thickness of dry-out zone [m]
n = porosity of rock [-]
S = liquid saturation [-]
S_r = residual saturation [-]

The thickness of the dry-out zone is calculated externally and provided as input into REFLUX2. Similarly, porosity, liquid saturation, and residual saturation are all provided as input into the refluxing module.

A portion of refluxing water may escape the refluxing cycle each year (L_D). In addition, the refluxing water may take more or less than a year to participate in a reflux cycle. The number of years required for water to complete one reflux cycle is P. Different formulas are used for calculations of the amount of water that refluxes in a particular year for cycles that require less than a year and cycles of greater- than-a-year duration. The first step is to determine the contribution to the refluxing cycle from rock pore water. For cycles less than a year, the amount of dry-out zone water that refluxes in year N is:

$$R_D=\sum_{j=0}^{\frac{1}{P}-1} D(1-L_D)^{\frac{N-1}{P}+j} \tag{B-7}$$

Similarly, for cycles of duration greater than a year, the amount of rock pore water that refluxes in a given year is:

$$R_D=\frac{\left[(D)(P-L_D)^{N-1}\right]}{P^N} \tag{B-8}$$

Total Reflux

The total amount of refluxing water derived from both infiltration and rock pore water vaporization in year N is:

$$R_T = R_I + R_D \tag{B-9}$$

For reflux cycles less than a year with a variable infiltration rate, the total amount of refluxing water is:

$$R_T = \sum_{j=0}^{N-1} I_{N-j}(1-L_I)^j + \sum_{j=0}^{\frac{1}{P}-1} D(1-L_D)^{\frac{N-1}{P}+j} \tag{B-10}$$

Similarly, the total amount of refluxing water for cycles greater than a year with a variable infiltration rate is:

$$R_T = \sum_{j=0}^{N-1} I_{N-j}(1-L_I)^j + \frac{\left[(D)(P-L_D)^{N-1}\right]}{P_N} \tag{B-11}$$

The predominant source of refluxing water may change with time. At early times, refluxing water may be dominated by water derived from the rock pore water. At later times, water derived from infiltration may dominate, if rock pore water near the WPs has been vaporized and removed from the refluxing cycles. In this case, the amount of refluxing water will converge to the value of $R_I = (I/L_I)$. If no losses from the refluxing cycle are experienced, the amount of refluxing water will grow at a rate equal to infiltration. The reflux cycle will cease once WP temperatures decrease below boiling.