# Heat and Mass Flow Through the Bulkhead in the Drift Scale Test

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## 1. INTRODUCTION

This white paper satisfies the agreement (TEF 2.1) reached between DOE and the NRC at the January 2001 Technical Exchange on Thermal Effects on Flow. The assessment of heat and mass loss through the bulkhead of the Drift Scale Test (DST) has been ongoing for approximately five years, has been well documented (see Section 3), and has been discussed openly, including at thermal test workshops. Because of this continuous and open interchange, the discussion in this white paper assumes that the reader is thoroughly familiar with the subject matter, and is presented in an informal style. By delineating DOE's position in a white paper rather than a formal technical report, the technical discussion is focussed on the specific information and assessments relevant to the key technical issue being addressed.

The main objective of the DST is to acquire a more in-depth understanding of the thermally driven coupled processes in the potential repository rocks. To meet this objective the DOE takes an approach of a close integration between modeling and measurements. Thermal-hydrological (TH) numerical models were constructed for the DST and test results were predicted prior to the commencement of the test. As the test progresses, test data are continuously being evaluated and compared to the model predictions. The level of agreement between the modeled and measured data of temperature and liquid saturation in the test block is used as a direct test of the models developed and provides basic insight into the thermal-hydrological processes.

The bulkhead separating the hot side of the Heated Drift from the unheated section is not perfectly sealed because bundles of power cable and instrument-wiring pass through the bulkhead (CRWMS M&O 1998a). The unsealed bulkhead acting as an open boundary for unmonitored heat and mass flow introduces an artifact in the test. The DOE's position is that the coupled processes are understood well enough to analyze this artifact quantitatively. The first three years of data support the validation of DST thermal-hydrological coupled-process models and current treatment of mass and energy loss through the bulkhead. Based on an assessment of the impact of the unmonitored heat/mass flow through the bulkhead on the DST results, the DOE's position is that these impacts are small enough that a measurement of heat and mass losses through the bulkhead of the DST does not appear necessary.

The DST results are intended for validation of models of thermally driven coupled processes in the rock, and measurements are not directly incorporated into TSPA models.

In this white paper, the technical bases are delineated for the DOE's understanding of heat and mass losses through the bulkhead, the effects of these losses on the test results, and the decision regarding measurements of heat and mass losses through the DST bulkhead. In addition, this paper also addresses uncertainty in the fate of thermally mobilized water in the DST and the effect of this uncertainty on conclusions drawn from the DST results.

## 2. SUMMARY AND CONCLUSIONS

Summary highlights of this white paper include the following:

1. Background information on the issue of heat and mass loss through the DST bulkhead is provided including (1) its identification, (2) steps taken by the DOE to address it, and (3) prior interactions between the DOE and the NRC on this issue.
2. Summation of completed measurements and a determination that complete and accurate measurement of heat and mass flow through the bulkhead is intrinsically difficult, uncertain, and unnecessary.
3. The DOE uses close integration between modeling and measurements in the DST to gain a more in-depth understanding of the thermal and hydrological processes in the repository rocks. Pre-test simulations were carried out to predict the outcome of the DST. DST data are being utilized to iteratively evaluate the accuracy of numerical models.
4. The DST TH models include:
   a. Open-boundary conditions throughout the DST modeled region.
   b. Radiative heat transfer from the canister heaters to the walls of the Heated Drift that is assumed to be 100 percent effective.
   c. Treatment of the rock matrix and fractures as two separate interacting continua.

   Prior to incorporating explicitly the wing-heater boreholes, a positive mean error for the DST thermal comparative analyses (of less than 15%) indicated that not all heat losses, including those through the bulkhead, were considered in the conceptual model.
5. The revised model treats the Heated Drift and the wing-heater boreholes as high-permeability conduits, allowing part of the vapor generated in the rock to pass through the bulkhead. Sensitivity studies show that for this different conceptual implementation of the open-boundary bulkhead, the mean error of the simulated and measured temperatures for approximately 1,700 sensors is reasonably small (a few $^{o}$C after 30 months of heating), indicating that the open-boundary representation for the bulkhead is appropriate.
6. The present understanding, based on global energy balance considerations applied to both simulated results and measured quantities within the rock mass, is that more than 70 percent of total heat input serves to raise the temperature of the rock, with the remainder shared between raising the temperature of water to boiling and vaporizing the water.
7. The model results also show that of all the vapor produced from heating, about a third moves to cooler regions of the rock mass and condenses, while

the rest is lost through the bulkhead via the Heated Drift. If the DST were a totally closed system, then the zones of increased liquid saturation in the test block would contain possibly three times the volume of water.

8. Locations of dry-out and condensation deduced from ERT, GPR, neutron logs and air permeability in general corroborate well with the simulated time evolution of the liquid-saturation changes in the matrix and fractures. This indicates that the modeling has captured the fate of the thermally mobilized water for the open-system DST despite the measurement uncertainty of the bulkhead heat loss.
9. Uncertainty in the fate of thermally mobilized water is discussed both implicitly and explicitly throughout this white paper. In summary, the uncertainty associated with the understanding of moisture redistribution in the DST is considered to be acceptable based on good agreement in the thermal and hydrological comparative analyses of corresponding measurements and simulations and other observations discussed in this white paper.
10. The favorable comparison of the DST models and observations for both temperatures and bulk moisture redistribution demonstrates that all the major components of the thermal hydrological processes are included in the TH process models (including the leakage through the bulkhead). Therefore the objectives of acquiring a more in-depth understanding of the coupled processes and validating the conceptual thermohydrological processes at a drift scale are being met in the DST.

In conclusion, the DST is large-scale, open-system, field test in which many intrinsic uncertainties exist including those associated with material properties, fracture characteristics, conceptualization in the process models, initial conditions as well as the boundary condition along the bulkhead. Despite these uncertainties, it is possible to satisfy the primary objective of the DST, which is to obtain a more in-depth understanding of coupled thermal-hydrological-mechanical-chemical processes anticipated to exist in the local rock mass surrounding the potential repository at Yucca Mountain. Specifically, this white paper has identified several advances in the understanding of coupled TH processes (as per the above summary and detailed discussion in Sections 3 through 5) despite the uncertainty of the boundary condition along the DST bulkhead. Consequently, the DST continues to serves as a key validation tool of relevant process models, including the TH models, even though intrinsic uncertainties exist such as those associated with the heat and mass loss through the bulkhead.

## 3.**BACKGROUND**

The issue of heat and mass loss through the DST bulkhead has been ongoing since the design of the DST approximately 5 years ago, a design in which the primary purpose of the bulkhead was to act as a thermal barrier (CRWMS M&O 1996) that includes safety considerations. Pre-test numerical simulations of the DST resulted in concerns about unmonitored heat and mass loss through the thermal bulkhead (Buscheck and Nitao, 1995). Recommendations included isolating the DST Heated Drift from direct pneumatic interference with the ESF tunnel system. This precaution was in itself problematic since safety concerns would develop if the pressure within the DST heated drift were allowed to increase.

On December 3, 1997, the heating of the DST was initiated. Within 40 days of the start of heating, moisture started to flow out of the bulkhead, as evidenced by condensation on various surfaces on the cool side of the bulkhead. This behavior was consistent with the heating of a large volume of rock that is highly fractured and approximately 90 percent saturated. As water in the rock boiled and turned to steam, the vapor moved under pressure gradient into cooler rocks, as well as into the Heated Drift and through the bulkhead. Also, the observed wetting on the cool side of the bulkhead alternated with drier conditions, with the latter coinciding with low relative humidity readings in the Heated Drift. Upon investigation, it became evident that barometric pumping was the cause for the intermittent wetting (Datta, 1998). Gas phase flow from the rock to the Heated Drift is driven by pressure gradient. Superimpose on the positive pressure gradient from the rock to the Heated Drift is the barometric pressure fluctuations. Therefore, as barometric pressure decreased, more vapor flowed from the rock into the Heated Drift and out the permeable bulkhead, while also increasing the relative humidity in the Heated Drift. Conversely, as the barometric pressure increased, less vapor flowed from the rock into the Heated Drift and the relative humidity decreased. Indeed, the relative humidity measurements in the Heated Drift vary inversely as the barometric pressure.

As the DST progressed into its second year of heating, the DOE decided to focus on heat and mass loss through the bulkhead and two other technical issues in a DOE/NRC Appendix 7 meeting held in Las Vegas on April 28, 1999 (CRWMS M&O 1999a). Many of the details of NRC’s concerns presented at the meeting were documented later in the year in Revision 2 of the Issue Resolution Status Report (IRSR) on the Key Technical Issue (KTI) for Thermal Effects on Flow (NRC 1999). Discussion at the Appendix 7 meeting included approaches used to measure both the conductive and convective heat losses through the bulkhead. NRC concurred with the proposed remedies to address conductive heat loss. These remedies consisted of either installing permanent heat flux meters to the bulkhead or insulating the cool side of the bulkhead.

Agreement was also reached regarding remedies to address convective heat loss. These remedies included sealing the bulkhead and proposed modifications of the existing system to measure convective heat loss. Modifications included continuous monitoring of water vapor flow through one or two small openings in the bulkhead. Also, it was agreed that the moisture monitoring data collected by LBNL for the Ambient Moisture Monitoring Program of the Exploratory Studies Facility would be evaluated to estimate moisture losses. Specifically, the plan was to utilize the relative humidity data in the cool side of the bulkhead from the Moisture Monitoring Program to estimate the moisture loss from the DST. However, the thermal test team concluded that the operational ventilation flow rates (between 50 and 150 million liters per hour) imposed just outside of the Heated Drift are too large to allow a direct measurement of changes in the monitored humidity data (Wagner 1999).

Between July 1998 and May 1999, several measurements of conductive and convective heat loss through the bulkhead were conducted (CRWMS M&O 1998b, 1999b, 1999c). Although these measurements were intended to quantify the losses, they also provided much insight into the difficulty of obtaining complete and precise measurements of conductive and convective losses. In October 1999, an Interoffice Correspondence (IOC) was prepared that summarized the findings to date (Wagner 1999). In summary, the original plan/design of the DST bulkhead was still considered satisfactory. The bulkhead was simply intended to provide a protective and primary thermal barrier to allow personnel, both visitors and workers, to observe the Heated Drift and to work in close proximity to the bulkhead/Heated Drift with minimal risk. After much scrutiny including determination of the difficulty in sealing the bulkhead, measurement of conductive and convective heat losses, simulation of the DST, and analyses of the measured and simulated behavior, it was determined that extensive and more accurate characterization of the heat loss through the bulkhead would be unnecessary as well as difficult and problematic. The October 1999 IOC concluded that the need to measure heat loss through the bulkhead depended on the accuracy of numerically simulating the thermal behavior in the DST. Analyses up to that time indicated that an assumed convective boundary condition resulted in good (within 15 percent) comparative agreement between measured and simulated temperatures. Thus, the artifact of heat and mass loss through this permeable boundary appeared to be properly modeled.

In March 2000, the DOE released a letter to the NRC that addressed Revision 2 of the IRSR on the KTI for Thermal Effects on Flow (DOE 2000). Included in this letter was discussion on heat and mass loss through the DST bulkhead. Basically, the discussion cited in the prior IOC (Wagner 1999) was reiterated, along with additional statements regarding the NRC document.

In the past five months, additional sensitivity calculations have been conducted to investigate the effect of convective losses from the wing-heater boreholes and the effect of barometric pumping (CRWMS M&O 2001a). These calculations have furthered the thermal test team’s understanding of heat-and-mass loss effects through the bulkhead. Revision 3 of the IRSR for KTIs on the TEF, which is the most current IRSR, reflects much of the more recent discussions cited above (NRC 2000). Also, related discussions at the Technical Exchange (held in Pleasanton, CA January 8-9, 2001) have been documented (CRWMS M&O 2001b). It was noted at this meeting that heat (energy) and mass losses need to be addressed in future thermal tests such as the Cross-Drift Thermal Test. This test, although not scheduled, may begin within the next 18 months.

## 4. MEASURING THE HEAT AND MASS FLOW THROUGH THE BULKHEAD

A summary listing of field efforts to address the issue of mass and heat loss through the bulkhead is provided below:

(1) Determination of conductive heat flux by applying a heat flux meter to seven locations on the bulkhead (five measurement locations were steel and two were glass);
(2) Added insulation on the cool side of the bulkhead;
(3) Estimation of convective heat loss by considering how much water vapor was removed from a small diameter pipe in the bulkhead during a 60-minute sampling period;
(4) Sealing of vapor leaks in the bulkhead, such as those in the camera door and cable outlets, to the extent practical.

A letter to the NRC from the DOE (DOE 2000) contained a discussion about the intrinsic difficulty in accurately and precisely measuring a highly heterogeneous moisture and heat flux from a diffuse source loss (DOE 2000). Considerable uncertainty was involved in item (3) above, because it is not known what fraction of moisture loss is captured in the measurement system as a result of the inherent leakage through bundles of power cable and instrument-wiring pathways. An alternate approach (to circumvent this uncertainty) would be to measure the moisture increase in the drift on the cool side of the bulkhead as an estimate of the mass loss from the convective heat flow from the DST. This measurement is nontrivial because of the substantial ventilation on the cool side of the bulkhead and the limitations of relative humidity measuring devices. These initial attempts to directly and to accurately measure the heat and mass loss through the DST bulkhead resulted in a consensus among the thermal test team that it was a difficult task. More importantly, based largely on the following discussion, a direct measurement of the heat and mass loss through the bulkhead is not needed to satisfy the primary objective of the DST.

## 5. THERMAL-HYDROLOGAL MODELING OF THE DRIFT SCALE TEST

### 5.1 Design and Pre-Test Simulations

As was mentioned previously, the objective of the DST is to acquire a more in-depth understanding of the thermally driven coupled processes. The approach is to implement a close integration between modeling and measurements. Modeling was involved in both the design and pre-heating phases of the DST, and continues throughout the test (CRWMS M&O 1998). Scoping calculations guided the design of the DST, particularly in determining the location of instrumented boreholes for monitoring the thermal, hydrological, mechanical, and chemical responses. Pre-test simulations to predict the outcome of the planned 8-year test accounted for realistic representation of the complex test geometry (as designed) in three-dimensions, using rock properties that were calibrated to site-specific pre-test characterization measurements. For modeling of the thermal hydrological processes (coupled transport of water, water vapor, air, and heat in heterogeneous porous and fractured media) the numerical tools used are the simulators TOUGH2 and NUFT. Both numerical codes account for the movement of gaseous and liquid phases (under pressure, viscosity, and gravity forces), transport of latent and sensible heat, and phase transition between liquid and vapor. Strict mass and energy balance is adhered to for every gridblock.

## 5.2 Interim Status of the DST Thermal-Hydrological (TH) Model

DST data are being utilized to iteratively re-evaluate the accuracy of the numerical model. Modifications since the pre-test conceptual/numerical model for the DST include representation of test configuration (such as as-built borehole and sensor locations) and test conditions (such as power input) that were not available when pre-test simulations were performed. Also, for certain elements in the conceptual model, it was possible to discriminate between alternative assumptions that were studied in the pre-heat predictions based on the first few months of heating-phase data. Hence, in the model, the assumptions and hypotheses supported by the measured data have been adopted. The continuous refinement of the conceptual/numerical model, based on a close integration of modeled prediction and measured data, led to the following model definition :

(1) **Open-boundary conditions exist throughout the DST modeled region**. These boundary conditions allow heat and moisture to flow through the boundaries to the Observation Drift, and through the bulkhead connecting the hot side of the Heated Drift to the cool side of the Heated Drift. In the pre-test simulations of the DST, a slightly thermally insulated open boundary was implemented on the Observation Drift to allow free flow of fluid; however, the Heated Drift and the thermally insulated bulkhead were treated as closed boundaries; that is, they were assumed to have zero thermal conductivity and be impermeable to fluid flow. A study of the simulated temperature for the first three months of heating indicated that in the immediate vicinity of the Heated Drift a prominent heat pipe should develop, but this was not observed in the measured data. That is, while the pre-test simulations indicated a distinct two-phase zone of water and vapor in the rock mass immediately around the Heated Drift, the measured temperature did not show this isothermal zone. This led the investigators to conclude that the Heated Drift did not act like a closed boundary, but rather as a conduit for vapor to escape. The numerical model was modified to implement the Heated Drift as a high-permeability conduit, and the bulkhead as an open boundary, and as expected, the modeled heat-pipe signature previously generated using the closed boundary disappeared from the simulations. The model shows vapor escaping through the bulkhead via the Heated Drift.

(2) **Radiative heat transfer from the canister heaters to the walls of the Heated Drift is assumed to be 100 percent effective**. Sensitivity studies in the pre-test predictive modeling indicate that the more effective the radiative heat transfer, the more uniform is the temperature distribution along the periphery of the Heated Drift. The first six months of temperature data along the Heated Drift show nearly uniform temperatures around and along the Heated Drift which demonstrates that radiative heat transfer is nearly 100 percent effective.

(3) **The DST thermal hydrological model treats the rock matrix and fractures as two separate interacting continua.** Observations from the Single Heater Test indicated the effective continuum model (ECM) was not suitable because moisture redistribution is better characterized by a TH model that allows the rock matrix and

fractures to act as two separate interacting continua. If liquid flow is uniformly distributed in all connected fractures, the entire fracture area is available for coupling of flow between the matrix and fracture, implying rather large fracture-matrix interactions. On the other hand, if only a fraction of the connected fractures actively conduct water, then the interaction between the fractures and matrix is far more limited. Both conceptual models: the former (the conventional dual-permeability model) and the latter (the dual-permeability model with the active fracture option) have been applied to the DST. The two conceptual models produce different flow phenomena. The Active Fracture Model tends to give more gravity drainage of condensate in the fractures and less imbibition into the matrix than the conventional dual-permeability model. This results in a more symmetrical condensation zone with respect to the heater horizon at early phases of heating than that predicted by the conventional dual permeability model. As the heating phase progresses, both models give rise to a more elongated zone of increased moisture below the heater horizon than above. The differences of the moisture redistribution predicted by these two conceptual models are too subtle to be discriminated by the geophysical data (from electrical resistivity tomography and crosshole radar tomography) for the DST.

A positive mean error for the DST thermal comparative analyses indicated that not all heat losses, including those through the bulkhead, were considered in the conceptual model. This observation was from comparison of simulated and measured temperatures involving approximately 1,700 thermal sensors located throughout the DST block during the first 18 months of heating. The mean error at 6, 12, and 18 months of heating was 0.7, 2.4, and 4.2 $^{o}$C respectively. Based on the positive mean error for the times and locations considered, it can be argued that the numerical model was not accounting for all the heat losses and predicting too much heat retention in the test block.

## 5.3 Heat Losses from the Test Block Based on Model Results

Model results show that a fraction of the vapor generated in the rock mass from heating enters the Heated Drift under a gas pressure gradient and then leaves through the permeable bulkhead. The numerical model explicitly calculates the heat and mass fluxes through every grid-block. Simulations show that the composition of the gas flux crossing the bulkhead boundary is composed almost entirely of vapor, and the heat flux is simply the enthalpy of the gas flux. That is, except for a multiplication constant, the mass and heat flux crossing the bulkhead boundary is one and the same. The vapor leaving the bulkhead carries with it the latent heat of condensation, constituting the dominant source of heat loss from the test. The loss from sensible heat is small compared to the convective heat loss (the difference of modeled conductive heat loss by assuming a perfectly thermally insulating bulkhead and a slightly conductive bulkhead using the thermal conductivity of the insulating fiberglass is about 1kW).

Results from the fourth comparison discussed in section 5.2 are based on a numerical model in which the wing-heater boreholes were modeled as rock with thermal sources inside. Because the Heated Drift acts as a high-permeability conduit for permitting vapor to leave through the bulkhead, it was postulated that the wing heaters could be modeled similarly as high-permeability conduits. Such an approach would allow transfer of additional vapor (and the heat) out through the bulkhead. This behavior was expected to further reduce the modeled temperature in the rock mass.

To test this hypothesis, investigators constructed an alternative DST TH numerical model to include the wing heater numerical gridblocks as high-permeability conduits. Again, the mean error between the simulated and measured temperature field from approximately 1,700 sensors was computed at different phases of heating. For this conceptual model, the values for mean error are 0.01, -0.15, 0.90, 1.06, 1.27 $^{o}$C respectively at 6, 12, 18, 24, and 30 months of heating. These values are considerably smaller than those in the fourth comparison discussed in the previous section, where the numerical model did not treat the wing-heater boreholes as preferential high-permeability flow paths. Since the wing-heater boreholes are connected to the Heated Drift, they allow for vapor generated in the rock mass around them to escape to the Heated Drift and subsequently out of the bulkhead. The thermal test team’s understanding of the causes of the heat and mass losses through the bulkhead led to this improved conceptual model for the wing-heater boreholes. Given the close agreement of the observed data and the model results, it appears that this approach accounts well for the transfer of the vapor between the rock mass and the open-air conduits to the bulkhead.

Simulations from this conceptual model that treats the wing heater numerical gridblocks as high permeability flow paths predict that the heat flux through the bulkhead peaks between 9 to 12 months of heating at about 38 kW, then steadily declines to around 26 kW at 4 years, the end of the planned heating phase. These numbers should be an upper bound because the model for the DST that treated the 50 wing heaters as a smeared heat source does not model each borehole explicitly. A lower bound would be that of the model in the fourth comparison discussed in the previous section. There the wing-heater boreholes were represented with rock properties, and the heat-loss peaks at about 25 kW and declines to about 16 kW at the end of 4 years of heating (CRWMS M&O 2001a). Precise values of heat loss would also depend on whether the numerical model implements the vapor-pressure lowering effect or not. With the relatively high residual liquid saturation (18%) assumed for the matrix, incorporation of vapor pressure lowering would decrease the volume of vapor generated, and in turn the vapor flow out of the bulkhead. Furthermore, the heat-loss numbers quoted above are for a conceptual model that has not taken into account the barometric pressure fluctuation. Barometric pumping is expected to induce additional vapor loss through the bulkhead. Sensitivity studies by numerical simulations show that barometric pumping may increase the convective heat loss up to 28 percent compared to that from a model with time-independent pressure-boundary conditions (CRWMS M&O 2001a).

Modeled results also show that very little moisture/heat is lost through the open boundary of the Observation Drift. This is the case because of (a) its distance from the heat source (the Observation Drift is parallel to the Heated Drift, its wall 30 m from the center of the Heated Drift and about 15 meters from the end of the wing-heater boreholes), and (b) the absence of high-permeability conduits connecting it to the heat sources. Because of this observation, the Cross-Drift Thermal Test was designed to ensure rock boundaries were a sufficient distance from the heaters (CRWMS M&O 2000).

In most models for the DST, the bulkhead is modeled as perfectly insulated. A sensitivity study assigning non-zero thermal conductivity to the bulkhead shows that the conductive heat loss through the bulkhead is insignificant compared to the convective heat loss. In other words, modeled results show that vapor loss through the bulkhead from the permeable Heated Drift constitutes the majority of the heat loss. Discussion above show that different conceptual variations of the open-boundary bulkhead do not give rise to identical simulated convective heat loss. Alternative conceptual models investigated include closed wing-heater boreholes, implementation of the open wing-heater boreholes with different approximations, incorporating or ignoring vapor pressure lowering, and effects of barometric pumping. Sensitivity studies show that for the different conceptualizations and combination thereof, the mean error of the simulated and measured temperatures for approximately 1,700 sensors is reasonably small (a few °C up to 30 months of heating), indicating that the open-boundary assumption for the bulkhead is appropriate.

## 5.4 Global Energy Balance

To gain further insight into how the heat input from the canister heaters in the Heated Drift and the wing heaters is partitioned in the rock mass and the pore water, the thermal test team (CRWMS M&O 2001a) applied a global energy accounting to both the numerical model output and the interpolated measured temperature. Energy supplied to the DST is spent in:

(1) raising the temperature of the rock mass,
(2) raising the temperature of the water, and
(3) supplying the heat of water vaporization.

Other energy uses, including heating of the air, are considered negligible. The heat of vaporization is returned to the rock for any water that condenses within the rock mass.

Global accounting is first applied to the numerical model. The numerical model calculates the temperature and liquid saturation for every gridblock at every time step. Consequently, the change in temperature ($\Delta T$) and the change in liquid saturation ($\Delta S_l$) from the start of heating is known for every gridblock at any specified time. Given the porosity, initial liquid saturation, and the initial temperature of the test block; $\Delta T$ and the heat capacity of rock and water are needed to compute the contribution to (1) and (2), while $\Delta S_l$ and the heat of vaporization are needed to compute the contribution to (3). The global accounting is obtained when contributions to (1), (2) and (3) are summed over all gridbocks. Applying this accounting to numerical model output at two years of heating results in the following energy distribution: 76% for heating up the rock, 12% for heating water, and 12% for vaporizing water.

Global accounting is also applied to the measured temperature. Because the temperature data are too diffusely distributed to interpolate throughout the entire three-dimensional domain, the interpolation has been reduced to a two-dimensional plane and scaled by the length of the Heated Drift. Further, since there was no measurement of $S_l$ for each interpolation gridblock, an assumption was made for assigning $\Delta S_l$ according to the temperature measurement for computing (3). The assumption was that whenever temperature was above boiling, the liquid saturation in that interpolation gridblock was given a residual liquid saturation of 0.02 (neutron log data indicate that residual saturation can vary from 0.02 to 0.2). Applying this accounting to the interpolated measured temperature again at two years of heating showed the energy distribution as follows: 77% for heating rock, 12% for heating water, and 11% for vaporizing water. Therefore, global accounting using either simulated temperature and saturation or measured temperatures yields similar results.

## 5.5 Water Balance

Since the numerical model explicitly calculates the liquid saturation at every gridblock, the total volume of vaporized water and the total volume of condensed water can be determined from the numerical model output. The difference of the two would be the moisture lost through vapor transport out of the bulkhead. As mass and energy balance is strictly adhered to in the numerical model, this number also equals the model output of the mass loss through the bulkhead (plus very little through the drift walls of the Observation Drift). Numerical-model results show that for the vapor generated, typically twice as much of it escapes through the bulkhead than condenses in the cooler rocks. That is, two thirds of the vaporized water appears to have been lost from the test via transport through the bulkhead. The water balance results indicate that if the DST was a totally closed system, then the zones of increased liquid saturation in the test block would contain possibly three times the current volume of water. The larger volume of water would translate to both an increase in the liquid saturation value in each gridblock, and an increase in the number of gridblocks that have liquid saturation raised above the pre-heat values.

## 5.6 Uncertainty in Fate of Thermally Mobilized Water

The condensed water from the vapor that is not lost through the bulkhead is redistributed in the rock mass. Presently, zones of increased and decreased water content (from pre-heat baseline) are being monitored in the DST by periodic geophysical methods and air-permeability measurements. These methods are useful for assessing qualitative changes, but do not give direct and reliable measured value of the absolute liquid saturation/moisture content of the matrix and fractures. In addition, the trends in the data for particular locations in the test are the most useful observations for validating the conceptual processes that control this moisture distribution. The electrical resistivity tomography (ERT), crosshole radar tomography (GPR) and neutron log data are used to validate the process models in the following manner. Simulated matrix liquid saturation contours at different phases of heating are generated in the appropriate planes of geophysical measurements. Zones of drying and wetting from the ERT and GPR tomograms at specific times of measurements are compared to the simulated contours of liquid saturation. Since neutron logging data are point measurements, locations of drying with time of heating as logged are compared to the progression of the drying front in the simulated liquid saturation. The thermal test team has made animations of both simulation and measurements to show they track each other closely.

While the geophysical measurements monitor mostly the water content changes in the matrix (the matrix porosity is at least an order of magnitude larger than the fracture porosity), periodic air injection tests are performed in the twelve hydrology boreholes to assess primarily the wetting and drying in the fractures. These measurements may also reflect any thermal mechanical and/or coupled hydrochemical processes that change fracture permeability (these latter effects are anticipated to be small compared to the thermal-hydrological effects in those zones of increased saturation). Wetting of fractures means increase resistance to air flow during air-injection tests, leading to a decrease in air permeability from its pre-heat value. These permeability data are used to validate the process model in the following manner. Simulated fracture liquid saturation contours at different phases of heating are generated in the planes of the 12 hydrology boreholes. Then the measured permeability values are compiled and correlated to the simulated fracture saturations. To do this, the measurements are taken quarterly in different borehole sections, with each normalized to its pre-heat value. It is observed that for those borehole sections situated in zones of increased liquid saturation as predicted by the numerical model, the measurements display a trend of decrease in permeability. As heating progresses and the drying around the Heated Drift and the wing heaters expands, certain borehole sections that were previously zones of increased liquid saturation would become zones of decreased (simulated) liquid saturation. Indeed, the measured permeability in some borehole sections below the wing heaters that have shown the largest decrease in permeability very early in the heating phase are observed to return later in the heating phase to their pre-heat levels.

It is evident from the discussion above that measurements for monitoring moisture redistribution in the DST are by nature indirect and qualitative. Nonetheless, locations of dry-out and condensation deduced from ERT, GPR, neutron logs and air permeability in general corroborate well with the simulated time evolution of the liquid-saturation changes in the matrix and fractures. This indicates that the modeling has captured the fate of the thermally mobilized water for the open-system DST, given the inherent uncertainty of the measurements. Were the DST an ideally closed system with no vapor loss through the bulkhead, the total volume of redistributed condensed water in the test block may be several times higher. The larger volume of condensate would perhaps promote more drainage down the fractures and cause more wetting below than above the heated horizon.

Although a closed boundary condition on the bulkhead to simulate a closed-system can be implemented, the geophysical methods do not discriminate as precisely as the models between the differences of moisture redistribution of the two cases: open and closed systems. Conversely, if the actual amount of vapor loss through the bulkhead were much larger than the range calculated, the wetting will be less, and it is not certain whether the geophysical methods can discriminate the different degree of wetting unless there was a qualitative change in the distribution. Therefore, the geophysical measurements are valuable for validating the thermal hydrological processes of boiling, drying, and condensation in the numerical models, but they are not that useful for differentiating the subtle differences of different degrees of wetting from alternative conceptual models. In this context, a direct measurement of heat/mass loss through the bulkhead would have little impact on the understanding and usage of the thermal-hydrological measurements and observations from the DST

## 5.7 Conclusions Drawn from the DST

Discussions in the previous sub-sections demonstrate the DOE's understanding of the fundamental thermal-hydrological processes in the DST, including the mass and energy loss through the bulkhead. The favorable comparison of the DST calculated and measured temperatures, and the corroboration of the calculated moisture redistribution and moisture measurements, indicate that the relevant thermal-hydrological processes are adequately addressed in the TH process models. Therefore the objectives of acquiring a more in-depth understanding of the coupled processes and validating the conceptual thermohydrologic processes at a drift scale are being met in the DST. Because of the DST, there is increased confidence in the prediction of repository performance when these same numerical models are applied to systems with different boundary conditions, different thermal loading, and different time-scale.

However, it should be emphasized that the measurements in the DST are not being applied directly to address performance issues. For example, the reduced volume of condensed water in the open-system (compared to that of an ideally closed system) can reduce the potential of seepage into the drift. Thus, it would not be appropriate to conclude that water will not seep into the potential emplacement drifts, because the DST remote camera has not shown water dripping into the Heated Drift. On the other hand, the DST has given the DOE confidence that important components of TH processes have not been omitted in the TH process models. These same process models can be, and have been, applied to actual repository conditions (heat load and spatial heterogeneity). If TH process models of anticipated repository conditions indicate seepage does not occur into the emplacement drifts, then the results are credible because the TH process models have been validated using DST measurements of thermal-hydrological responses.

Similarly, because of the smaller volume of condensed water in the open-system DST, the hydrological observations of possible fluid movement during the cool down phase of the DST may differ from that of a closed-system. Therefore, caution must be exercised not to directly apply the results of DST to performance issues. Rather, the increased understanding of coupled process behavior should be indirectly applied to performance issues through abstraction of observations and results.

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