COMMENTS ON WHITE PAPER: HEAT AND MASS FLOW THROUGH THE BULKHEAD IN THE DRIFT-SCALE TEST

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Attachment 1

CONTENTS

ACRONYMS

CNWRA	Center for Nuclear Waste Regulatory Analyses
CDTT	Cross-Drift Thermal Test
DOE	U.S. Department of Energy
DST	Drift-Scale (Heater) Test
FEP	features, events, and processes
NRC	U.S. Nuclear Regulatory Commission
TEF	thermal effects on flow
TH	thermohydrologic
TSPA	total system performance assessment
WRR	Water Resources Research

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QUALITY OF DATA, ANALYSES, AND CODE DEVELOPMENT

DATA: CNWRA developed no original data for this project. Sources for other data should be consulted for determining the level of quality for those data.

CODE: No computer codes were used or developed in preparation of this report.

1 INTRODUCTION

The white paper, Heat and Mass Flow Through the Bulkhead in the Drift-Scale Test, was produced by the U.S. Department of Energy (DOE) in response to an agreement reached at the DOE Technical Exchange on Thermal Effects on Flow (TEF)/U.S. Nuclear Regulatory Commission (NRC), January 8–9, 2001. The text of the agreement (referred to as TEF 2.1) is the following.

"Consider measuring losses of mass and energy through the bulkhead of the drift-scale test (DST) and provide the technical basis for any decision or method decided upon (include the intended use of the results of the DST such as verifying assumptions in FEP exclusion arguments or providing support for TSPA models[)]. The DOE should analyze uncertainty in the fate of thermally mobilized water in the DST and evaluate the effect this uncertainty has on conclusions drawn from the DST results. The DOE's position is that measuring mass and energy losses through the bulkhead of the DST is not necessary for the intended use of the DST results. 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. Results of the last two years of data support the validation of DST coupled-process models and the current treatment of mass and energy loss through the bulkhead. The DOE will provide the NRC a white paper on the technical basis for the DOE's understanding of heat and mass losses through the bulkhead and their effects by April 2001. This white paper will include the DOE's technical basis for its decision regarding measurements of heat and mass losses through the DST bulkhead. This white paper will address uncertainty in the fate of thermally mobilized water in the DST and also the effect this uncertainty has on conclusions drawn from the DST results. The NRC will provide comments on this white paper. The DOE will provide analyses of the effects of this uncertainty on the uses of the DST in response to NRC comments."[1]

[1]Reamer, C.W. *U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Thermal Effects on Flow, January 8–9, 2001.* Letter (January 26) to S. Brocoum, U.S. Department of Energy. Washington, DC: U.S. Nuclear Regulatory Commission. 2001.

2 MEASURING MASS AND ENERGY LOSSES THROUGH THE BULKHEAD OF THE DRIFT-SCALE TEST

2.1 U.S. DEPARTMENT OF ENERGY TECHNICAL BASIS FOR THE DECISION NOT TO MEASURE HEAT AND MASS LOSSES FROM DRIFT-SCALE TEST

The DOE technical basis for the decision not to measure losses of mass and energy escaping from the DST through the thermal bulkhead can be summarized by the following five main points:

(1) "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...," and "[t]he DST results are intended for validation of models of thermally driven coupled processes in the rock ..."

(2) The mean error between measured temperatures at 1,700 thermal sensors and modeled temperatures is small. In addition, qualitative comparisons of the modeled extent of dryout and moisture redistribution with geophysical data are reasonably good.

(3) Actual measurements of losses through the DST bulkhead are difficult and include significant uncertainty.

(4) "The DOE's position is that the coupled processes are understood well enough to analyze this artifact [unmonitored heat and mass flow through the DST bulkhead] quantitatively [using the DST model]."

(5) "[D]irect measurement of the heat and mass loss through the bulkhead is not needed to satisfy the primary objective of the DST."

2.2 COMMENTS ON THE U.S. DEPARTMENT OF ENERGY TECHNICAL BASIS FOR NOT MEASURING HEAT AND MASS LOSSES FROM DRIFT-SCALE TEST

The arguments presented in the DOE white paper for justifying the decision not to measure mass and energy losses through the DST bulkhead have been extensively discussed by the DOE thermal testing team for the past several years. At the Tenth Thermal Workshop in Berkeley, California, on May 11, 2000, it was argued that thermohydrologic models matching measured temperatures were sufficient to account for losses through the bulkhead.[1] Other DOE scientists at the workshop countered that such an approach is circular reasoning. Their countering argument was that the test could not be used to validate the model if, at the same time, the model was being used to infer the unmonitored boundary condition imposed by the bulkhead on the test. The NRC agrees that simultaneously using the DST results to validate a model while using the model to infer the boundary condition at the bulkhead is problematic.

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[1]Hughson, D. and L. Browning. *Tenth Thermal Test Workshop, Livermore, California, May 11, 2000: Trip Report.* Memorandum (May 30) to U.S. Nuclear Regulatory Commission. San Antonio, TX: Center for Nuclear Waste Regulatory Analyses. 2000.

The NRC has maintained that unmonitored mass and energy losses through the DST bulkhead increase the difficulty of interpreting the test results and decrease the utility of the test for validating thermohydrologic models (U.S. Nuclear Regulatory Commission, 2000). This position is partially substantiated by the evolution in the DOE understanding of the effects of bulkhead losses on the DST observations. The white paper states that dripping outside the bulkhead of the DST, observed beginning in the second month of heating, "was consistent with the heating of a large volume of rock that is highly fractured and approximately 90-percent saturated." But the observed dripping is also consistent with vapor escaping through the bulkhead and condensing in the cooler connecting drift. Thermohydrologic models were subsequently modified by DOE to allow for convection through the bulkhead. Preliminary measurements suggested 5 kW of conductive heat loss and from 2 to 20 kW of convective heat loss through the bulkhead (Civilian Radioactive Waste Management System Management and Operating Contractor, 1998). Later modeling studies found heat losses, peaking at 38 kW in the first year of heating then declining to 26 kW at 4 yr, were almost entirely from convection with only 1 kW of the loss occurring by conduction. These modeling studies, with the wingheater boreholes represented as high permeability conduits to facilitate the flow of vapor from the rock into the heated drift, resulted in a better match of modeled to measured temperatures. A DOE scientist at the Eleventh Thermal Workshop, October 5–6, 2000, reported on analyses suggesting that as much as two-thirds of the water heated to boiling in the DST escaped through the bulkhead.[2] The dripping in the connecting drift also provided an early indication of the effects of barometric pumping on the DST. More recent modeling sensitivity studies suggest that barometric pumping may increase convective heat loss through the bulkhead by as much as 42 percent (Civilian Radioactive Waste Management System Management and Operating Contractor, 2001). These efforts, and the summary provided in the white paper, illustrate the difficulties and uncertainties inherent in assessing the effect of losses through the bulkhead.

The difficulties and uncertainties in assessing the effect of losses through the bulkhead on DST results are recognized by DOE. Potential effects of losses through the bulkhead include reducing the volumes of heated rock and refluxing condensate and modifying thermohydrologic behavior in the near-field test environment. While the white paper claims that "a measurement of heat and mass losses through the bulkhead of the DST does not appear necessary," DOE scientists are developing plans to take a series of measurements in the connecting drift outside the bulkhead prior to initiating cooldown. At the Twelfth Thermal Test Workshop, R. Jones presented DOE plans to place relative humidity and temperature sensors in the connecting drift to monitor changes while ventilation is temporarily halted.[3] At the workshop, it was announced that the first measurement is planned for July 2001. The white paper presents only arguments against monitoring the bulkhead and concludes it is not necessary. There is no discussion in the white paper regarding the planned measurements or why they are being undertaken. The white paper summarizes arguments given by the DOE against monitoring losses through the bulkhead. This summary is a distillation of extensive discussions at thermal workshops and does not include arguments made by DOE scientists in favor of monitoring losses through the bulkhead at the DST.

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[2]Hughson, D. *Eleventh Thermal Test Workshop, Berkeley, California, October 5–6, 2000: Trip Report.* Memorandum (October 19) to U.S. Nuclear Regulatory Commission. San Antonio, TX: Center for Nuclear Waste Regulatory Analyses. 2000.

[3]Hughson, D. *Twelfth Thermal Test Workshop, Summerlin, Nevada, June 7–8, 2001: Trip Report.* Memorandum (July 9) to U.S. Nuclear Regulatory Commission. San Antonio, TX: Center for Nuclear Waste Regulatory Analyses. 2001.

3 USING DRIFT-SCALE TEST RESULTS TO SUPPORT PERFORMANCE ASSESSMENTS

3.1 UNCERTAINTY IN THE FATE OF THERMALLY MOBILIZED WATER IN THE DRIFT-SCALE TEST

A global energy balance of the DST, reported in the white paper, showed 77 percent of the energy input went into heating the rock, 12 percent into heating water, and 11 percent into boiling water. Of the water vaporized, approximately two-thirds escaped through the bulkhead and into the ventilation system while the remainder migrated into cooler regions of the rock and condensed. As stated in the white paper, "[i]f 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." The phrase "uncertainty in the fate of thermally mobilized water," however, is slightly misleading. The uncertainty of concern is not so much where the water went, but instead, how thermohydrological processes would have differed had three times as much water condensed in the zones of increased saturation within the DST rather than escaping through the bulkhead.

Models of the DST capture thermohydrological behavior that is well represented by volume-averaging assumptions, such as heat transport by conduction and the spatial distribution of dryout zones. But the models use homogeneous property assumptions for networks of discrete fractures and, thus, are unable to capture thermohydrological behavior in large, highly permeable discrete fractures, such as those observed at approximately 12 m and 35–40 m from the bulkhead near the heated drift at the DST. While it should be fairly straightforward to analyze the volume-averaged thermohydrological behavior of the DST for a closed system simply by running the validated model with a closed boundary representing the bulkhead, it is not possible to predict the thermohydrological behavior in discrete fractures for a closed system since these features are not included in the models.

3.2 EFFECT OF UNCERTAINTY FROM BULKHEAD LOSSES ON DRIFT-SCALE TEST RESULTS

The white paper emphasizes that "measurements in the DST are not being applied directly to address performance issues." "For example," the white paper goes on to say, "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." The white paper concludes that, "[i]f 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." The white paper ends with the following caveat:

"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."

The DOE reasoning is that, since there has been no dripping observed in the heated drift of the DST, and thermohydrological models validated against the DST show no seepage into the heated drift, seepage into emplacement drifts during the thermal period of the proposed repository is unlikely. This reasoning has at least two shortcomings. One shortcoming is that seepage into the heated drift of the DST may have been prevented by removal of two-thirds (as stated in the white paper) of the water from the condensation zone, and the other shortcoming is the thermohydrological models do not include a process that may lead to seepage into emplacement drifts during the thermal period. Experimental data collected near a high-permeability subvertical feature located at approximately 12 m from the bulkhead in the DST show preferential condensate drainage maintaining a temperature near boiling within the fracture while surrounding rock is dried out and temperatures are well above boiling. A mechanism by which liquid water could seep into emplacement drifts while temperatures within drifts are above boiling is by rivulets flowing preferentially in high-permeability subvertical fractures. Phillips (1996) showed that the distance water in a rivulet would remain in the liquid phase while surrounded by rock at above-boiling temperatures is proportional to the square root of the volumetric flow rate in the rivulet. Data from the DST indicate this process is occurring in several locations within the test block, such as at approximately 12 m and 35–40 m from the bulkhead (Civilian Radioactive Waste Management System Management and Operating Contractor, 2001), but this process is not incorporated into thermohydrological models that represent the fractures as a homogeneous continuum. Since losses through the bulkhead of the DST may be mitigating seepage into the heated drift and the thermohydrological models do not include the potentially important process of rivulet flow in discrete fractures, neither can be used as credible arguments that liquid water will not reach the engineered barriers in the emplacement drifts during the thermal period of the proposed repository.

4 PATH TOWARD RESOLUTION OF AGREEMENT TEF 2.1, MEASURING LOSSES OF MASS AND ENERGY THROUGH THE BULKHEAD OF THE DRIFT-SCALE TEST

Staff recommend DOE continue to pursue plans to measure losses of mass and energy through the bulkhead of the DST, as discussed at the Twelfth Thermal Workshop on June 8, 2001, and use these data in interpreting the test results.

Staff concerns remain that the full range of variability in thermohydrological processes and system states is not propagated from process models through model abstractions to performance assessments (U.S. Nuclear Regulatory Commission, 2000). For example, a comparison of several property sets against the DST data indicated the DST data are insufficient to allow discrimination between the different property sets (Civilian Radioactive Waste Management System Management and Operating Contractor, 2000). Because the thermal testing data cannot uniquely establish which property set is best, the range of model results produced by all the different property sets should be encompassed by the range of thermohydrologic conditions used for performance assessments. This concern is the subject of an agreement reached at the DOE/NRC technical exchange that says the DOE should "represent the full variability/uncertainty in … the abstraction of the thermodynamic variables." Losses of mass and energy through the bulkhead and the resulting saturation decrease in the condensation zones, however, may increase the uncertainty in using DST data to validate models and property sets for use in performance assessments. Therefore, as stated in agreement TEF 2.1, "[t]he DOE will provide analyses of the effects of this uncertainty [losses through the bulkhead] on the uses of the DST ..." in addition to analyses of other sources of model and data uncertainty.

The Cross-Drift Thermal Test (CDTT), planned to begin in fiscal year 2002, will provide an opportunity to test the DOE hypotheses that (i) thermally mobilized water will shed between emplacement drifts, (ii) there will be no penetration of the boiling isotherm by liquid water, and (iii) mobilized waters will have a chemistry benign to engineered barrier materials. The CDTT results may allay concerns regarding the unmonitored mass and energy losses through the bulkhead of the DST. To accomplish the goals of the CDTT, however, DOE should consider how heterogeneity in the fracture permeability affects condensate drainage through the boiling zone and the collection of water in the sampling boreholes. If data collected from the CDTT were to support the hypothesis that there will be no penetration of the boiling isotherm by liquid water, these data would need to be reconciled with evidence from the Large Block Test and the DST horizontal boreholes, which indicate penetration of the boiling isotherm by liquid water.

Heterogeneity in fracture network permeability and the presence of high-permeability subvertical fractures are not presently included in thermohydrological models of Yucca Mountain but will be considered in future studies as discussed and agreed to at the DOE/NRC Technical Exchange on Thermal Effects on Flow, January 8–9, 2001. Confidence in the ability of thermohydrolgic models to predict seepage into drifts during the repository thermal period would be significantly increased if these models represented the behavior of preferentially flowing rivulets in subvertical fractures. Part of this confidence building could be achieved by comparing numerical model results to theoretical analyses. As expressed in agreement TEF 2.8, "[t]he DOE will consider the NRC suggestion of comparing the numerical model results to the O.M. Phillips analytical solution documented in WRR (1996)."

5 CONCLUSION

The objective of the DST is to increase understanding of coupled thermohydrological processes in the fractured tuff of Yucca Mountain. These coupled thermohydrological processes involve thermal mobilization of matrix pore water, redistribution, condensation, and drainage through a complex network of fractures. Unfortunately, approximately two-thirds of the pore water thermally mobilized in the DST escaped from the test block through the bulkhead. Staff recognize that uncertainties exist in the data collected from the DST and that measurements of losses through the bulkhead may themselves be uncertain. However, staff are supportive of DOE plans to measure losses through the bulkhead in the fourth year of heating of the DST and believe they may help to resolve some concerns about the effects of these losses. Upon completion of agreement TEF 2.1 "[t]he DOE will provide analyses of the effects of this uncertainty [mass and energy losses through the bulkhead of the DST] on the uses of the DST in response to NRC comments."

6 REFERENCES

Civilian Radioactive Waste Management System Management and Operating Contractor. *Thermal Test Progress Report #2*. BABEAF000–01717–5700–00001. Revision 00. Las Vegas, NV: Civilian Radioactive Waste Management System Management and Operating Contractor. 1998.

Civilian Radioactive Waste Management System Management and Operating Contractor. *Thermal Tests: Thermal-Hydrological Analyses/Model Report*. ANL–NBSTH–000001. Revision 00. Las Vegas, NV: Civilian Radioactive Waste Management System Management and Operating Contractor. 2000.

Civilian Radioactive Waste Management System Management and Operating Contractor. *Thermal Test Progress Report #6*. Las Vegas, NV: Civilian Radioactive Waste Management System Management and Operating Contractor. 2001.

Phillips, O.M. Infiltration of a liquid finger down a fracture into superheated rock. *Water Resources Research* 32(6): 1,665–1,670. 1996.

U.S. Nuclear Regulatory Commission. *Issue Resolution Status Report—Key Technical Issue: Thermal Effects on Flow*. Revision 3. Washington, DC: U.S. Nuclear Regulatory Commission. 2000.

COMMENTS ON THE DRAFT CROSS DRIFT THERMAL TEST PLANNING REPORT

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Attachment 2

ABSTRACT

This report contains comments on the draft Cross Drift Thermal Test Planning Report, which was prepared for the Civilian Radioactive Waste Management System Management and Operating Contractor by Applied Research and Testing Programs of Las Vegas, Nevada. Comments on the thermal-hydrological and geochemical aspects of the draft Cross Drift Thermal Test Planning Report[1] focus primarily on the apparent discrepancy between the scope of the test and its objectives. The objectives of the test are much broader than the relatively limited scope of the test itself. Reassessing the test objectives and rephrasing them so it is clear what hypotheses are being tested and how test results will be used to confirm or reject those hypotheses would resolve most concerns raised in these comments. Two specific suggestions are made regarding the physical aspects of the test design. One is that the openings for water collection be designed as slots rather than as boreholes and the other is that geochemical models be used to assist with identifying the sampling locations. Comments on the thermal-mechanical aspects of the draft Cross Drift Thermal Test Planning Report focus on the importance of stress changes in interpreting measured rock displacements.

[1]Civilian Radioactive Waste Management System Management and Operating Contractor. *Cross Drift Thermal Test Planning Report*. Las Vegas, NV: Civilian Radioactive Waste Management System Management and Operating Contractor. DRAFT, August 2000.

CONTENTS

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This report was prepared to document work performed by the Center for Nuclear Waste Regulatory Analyses (CNWRA) for the U.S. Nuclear Regulatory Commission (NRC) under Contract No. NRC–02–97–009. The activities reported here were performed on behalf of the NRC Office of Nuclear Material Safety and Safeguards, Division of Waste Management. The report is an independent product of the CNWRA and does not necessarily reflect the views or regulatory position of the NRC.

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QUALITY OF DATA AND CODE DEVELOPMENT

DATA: Original CNWRA data contained in this report were generated in accordance with quality assurance (QA) procedures. QA of the original documents should be referenced for all other data reviewed in this report. Calculations were recorded in Scientific Notebook 384.

CODE: The software program MATHEMATICA 4.0 was used for calculations in this report in accordance with CNWRA QA procedures.

1 REITERATION OF THE OBJECTIVES OF THE CROSS DRIFT THERMAL TEST

As stated in chapter 2.0 of the draft Cross Drift Thermal Test Planning Report,[1] the overall objective of the Cross Drift Thermal Test (CDTT) is similar to previous thermal tests conducted at Yucca Mountain, Nevada [i.e., the Large Block Test (LBT), Single Heater Test, and Drift-Scale Heater Test (DST)]. That is, the main objective is to "better understand the coupled thermal-mechanical-hydrological-chemical processes in the near field." Six specific objectives of the CDTT as listed in chapter 2.0 of the planning report are

1. To test or investigate the premise that heat-mobilized pore water will shed/drain between emplacement drifts to below the repository horizon,

2. To test or investigate the premise that liquid water can penetrate through zones/regions at or above boiling temperature,

3. To measure the rock properties of Tptpll (the lower lithophysal unit) listed below in order of priority,

   - hydrologic properties
   - thermal and mechanical properties
   - chemical (mineralogical) properties

4. To test or investigate the premise that there would be no long-term seepage into the emplacement drifts and that the chemistry of seepage water, if any, will be benign to the engineered components,

5. To test or investigate the premise that composition of gas in the emplacement drift will be benign to the engineered components,

6. Minor other objectives.

[1]Civilian Radioactive Waste Management System Management and Operating Contractor. *Cross Drift Thermal Test Planning Report*. Las Vegas, NV: Civilian Radioactive Waste Management System Management and Operating Contractor. DRAFT, August 2000.

2 COMMENTS ON THE THERMAL-HYDROLOGICAL ASPECTS OF THE CROSS DRIFT THERMAL TEST

The following comments concern the thermal-hydrological (TH) aspects of the CDTT. Comments on geochemical aspects of the CDTT are deferred to chapter 4.0, and comments on thermal-mechanical aspects of the CDTT are in chapter 6.

Comment (2-a). Objectives of the CDTT could be better phrased to clarify what hypotheses are being tested and how data from the test will support or refute those hypotheses.

The second test objective is to investigate the premise that liquid water can penetrate into zones of above-boiling temperature. Some data from the DST, however, already indicate preferential flow through fractures into zones where surrounding rock temperatures are above boiling. For example, temperatures in Borehole 79 of the DST remain at nominal boiling through day 480 at $y \approx 35$m and through day 600 at $y \approx 12$m while adjacent detectors approximately, 1 m apart, as indicated by the length scale of the graph, rise 5–10 °C above boiling (Civilian Radioactive Waste Management System Management and Operating Contractor, 2000a, figure 2.1-15, page 21). The same locations show elevated saturations at days 364 and 554 in the neutron probe logs with adjacent zones appearing drier (Civilian Radioactive Waste Management System Management and Operating Contractor, 2000a, figure 2.6-8, page 50). This signature of increased saturation and depression of the boiling isotherm could indicate preferential flow of condensate by gravity drainage through a subvertical fracture into a zone where surrounding rock temperatures are above boiling. Data from the LBT also indicate preferential flow into above-boiling regions. Sudden temperature drops in temperature detectors TT1–14 at 2,525 hr (June 13, 1997) and TT2–14 at 4,475 hr (September 2, 1997) (Civilian Radioactive Waste Management System Management and Operating Contractor, 2000b, figures 3-33 and 3-34) of the LBT resulted from fracture flow of either refluxing condensate or precipitation into above-boiling regions and depression of temperature to the boiling point.

Theoretical analyses and laboratory experiments (Phillips, 1996; Woods, 1999; Hughson et al., 2000) demonstrate penetration of liquid water into fractures in media at above-boiling temperatures. Research previously conducted for development of geothermal fields, theoretical analyses, laboratory experiments, and results from the DST and LBT already appear to have assessed adequately the veracity of the hypothesis in objective 2. The relevant question for the proposed repository at Yucca Mountain is whether there are mechanisms capable of sufficiently focusing condensate drainage for liquid water to penetrate above-boiling zones and enter emplacement drifts. This open question is alluded to in the fourth objective, but "long-term seepage into emplacement drifts" in the context of a geological repository is on a time scale of thousands of years, whereas the CDTT is planned for a heating phase of only 9 mo. The scope of the test objectives should be compatible with the scope of the test and posed so that it is clear how the test data will either support or refute the hypotheses.

Comment (2-b). Heat-mobilized pore water or water injected above the heated boreholes could penetrate zones of above-boiling temperature and not be detected.

Water ponded or injected into fractured welded tuff at Yucca Mountain tends to flow in rivulets following high-angle permeable fractures. This flow pattern was seen from dye-colored water injected in liquid release tests into the exploratory studies facility niches (e.g., Wang et al., 1998, figure 2.20, page 2F–21 and figure 2.21, page 2F–22) and in naturally occurring seepage (Wang et al., 1999, figure 4, page 331). Focusing of injected water into preferential rivulets occurred in the niche tests for flow paths of less than 1 m long.

Condensate drainage focused into a preferentially flowing rivulet may penetrate an above-boiling region for a distance characterized by Phillips' length scale, the square of which is proportional to the volumetric flow rate of the rivulet and inversely proportional to the product of temperature gradient and thermal conductivity of the rock (Phillips, 1996).

Three geophysical techniques are to be used to detect and follow thermally mobilized water in the CDTT block. These techniques are electrical resistivity tomography (ERT), neutron probe logging, and ground penetrating radar (GPR). As previously mentioned, neutron probe data, along with temperature measurements from the DST, indicate some preferential flow through subvertical fractures (e.g., Borehole 79). Such observations, given the limited detection range of the neutron probe, however, are coincident on the intersection of a flowing rivulet with a neutron probe borehole. In contrast, ERT and GPR techniques detect moisture content changes over larger regions, but the volume averaging may mask preferential flow in fractures, into above-boiling regions, except perhaps in exceptional cases such as the finger of condensate drainage seen in ERT images below the DST (Civilian Radioactive Waste Management System Management and Operating Contractor, 1999, figure 3.4-1, page 3-27, and figure 3.4-3, page 3-29).

A porous media continuum conceptual model representation of unsaturated flow through a heterogeneous network of fractures fails to account for either the gravity fingering of wetting front instability or focusing of flow preferentially along permeable discrete fractures. Yet, these are the mechanisms that could result in rivulet flow into above-boiling regions. Good comparisons between calibrated porous media continuum models and volume-averaged ERT and GPR measurements could lead to false confidence in model simulations even though both model and data failed to capture the mechanisms causing liquid water to flow into above-boiling regions.

Comment (2-c). Condensate drainage below the heater horizon may bypass the collection boreholes.

Three boreholes for collection of condensate drainage and injected water are to be extended approximately 2 m below the heater plane parallel to the boreholes containing the heater elements. Quoting from page 8 of the draft CDTT Planning Report:

> "These holes are strategically placed immediately below the anticipated boiling zone around the inner heaters, and are designed to intercept any liquid water that may travel to them."

From table 5-1 of the CDTT Planning Report, these boreholes are to be 0.101 m in diameter and angled 3° upward. Homogeneous porous media continuum properties representing the network of fractures in the CDTT block from table 1 of the CDTT Planning Report, used for the preliminary scoping calculations, are fracture permeability of 1.29×10^{-12} m^2 and a fracture van Genuchten alpha parameter of 7.39×10^{-4} Pa^{-1}. Presuming the borehole can be approximated as a horizontal cylinder and assuming equivalence between the van Genuchten and Gardner alpha parameters, these properties give a seepage threshold for the collection boreholes of 274,827 mm/yr (Philip et al., 1989).[1] Regarding the effect of the 3° borehole angle, note that the seepage threshold for cylindrical openings increases as the angle from the horizontal increases (Philip, 1989). From preliminary scoping calculations in the CDTT Planning Report, condensate fluxes were simulated ranging from about 150 mm/yr using the dual permeability model (CDTT Planning Report,

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[1]For water viscosity of $1.002 \times 10^{-3} \dfrac{\text{kg}}{\text{m} \cdot \text{s}}$ and density of $998.3 \dfrac{\text{kg}}{\text{m}^3}$

figure 4-3b, page 22) to about 6,000 mm/yr using the equivalent continuum model (CDTT Planning Report figure 4-2b, page 21). Therefore, the collection of condensate drainage in the collection boreholes will depend on heterogeneities in the fracture properties and on mechanisms of flow focusing. Yet, as discussed in comments (2-a) and (2-b), neither heterogeneities in fracture properties nor mechanisms of flow focusing in fractures were considered in the CDTT Planning Report.

3 RECOMMENDATIONS FOR THE THERMAL-HYDROLOGICAL ASPECTS OF THE CROSS DRIFT THERMAL TEST

Recommendation (3-a). Consider designing openings for collection of thermally mobilized and injected water as slots rather than as cylindrical boreholes.

Again, assuming a homogeneous porous medium continuum approximation for the fracture network and the same hydrologic properties as in comment (2-c), a horizontal slot-shaped opening 2 m wide would have a seepage threshold of 6,650 mm/yr. This threshold would be reduced to 1,184 mm/yr for an opening 5 m wide. While this is still large compared to the expected fluxes from condensate drainage, it is about two orders of magnitude lower than the seepage threshold of the collection boreholes. Collection containers with divided pans (e.g., ice cube trays) may provide more detailed information on the flow paths of thermally mobilized and injected water. Such information may be used to corroborate ERT, GPR, neutron probe, and temperature data potentially indicating preferential fracture flow.

Recommendation (3-b). Consider evaluating fracture heterogeneity in TH modeling of the CDTT.

Our scoping calculations of heat transport by conduction indicate that energy losses from the test block boundaries into the thermal alcove will be small. While incorporating heterogeneous fractured rock properties into TH simulations may change these estimates slightly, a potentially more significant aspect of heterogeneous fracture properties involves the second test objective. Liquid water is excluded from regions at above-boiling temperature by vaporization in flow models using homogeneous porous media properties. However, water in liquid form can penetrate into regions above boiling when seepage or condensate drainage is focused into preferentially flowing rivulets. The physical mechanisms by which this occurs are discussed by Phillips (1996) and Woods (1999). The important consideration for the CDTT is that heterogeneity in the fracture network provides a physical mechanism for focusing of flow. Modeling of the CDTT using homogeneous properties is unlikely to show liquid water in above-boiling regions even if the phenomenon should occur and be detected in the CDTT. However, should data from the CDTT show boiling point depression and a corresponding increase in saturation indicating flow of water into above-boiling regions, models would need to be capable of representing this TH behavior to assess the potential impact on repository barriers.

4 COMMENTS ON THE GEOCHEMICAL ASPECTS OF THE CROSS DRIFT THERMAL TEST

Comment (4-a). Design of the geochemical components of the CDTT, as presented in the planning report, are insufficient to address the scope of test objectives 4 and 5.

Simulations of the DST demonstrate that one the greatest challenges in developing reliable, thermal-hydrological-chemical (THC) models is validating the model against measured chemical compositions (Civilian Radioactive Waste Management System Management and Operating Contractor, 2000c). Preliminary scoping calculations, as were done for the TH aspects of the CDTT using a coupled THC model to predict chemical and isotopic compositions, are essential for selecting the most appropriate sampling locations. For example, collecting gas and condensate drainage below the heater horizon may be of limited use for calibrating THC models and provides little information on fluid compositions that may impact engineered barriers. Preliminary scoping simulations for coupled THC processes, however, could be used to locate gas and liquid sampling ports. Coordinating the test design of fluid sampling ports with modeling coupled THC processes would facilitate the THC model validation efforts and improve the understanding of near-field environments that potentially might impact engineered barriers.

Test objectives 4 and 5 could be rephrased to focus on increasing the understanding of coupled THC processes, in accordance with the general test objective of understanding processes and rock characteristics that affect processes. Thus, knowledge obtained can be applied to other rock types in the repository. Such a strategy might emphasize analysis and interpretation of fluid samples collected from the CDTT using coupled THC models, compare and validate models developed from previous thermal tests, and increase confidence in model predictions of gas and water compositions potentially contacting engineered barriers. This approach would strengthen the overall test objective of understanding both coupled THC processes and the near-field environment.

Another possible strategy is to focus test objectives 4 and 5 on the collection, analysis, and interpretation of water, gas, and rock samples in order to increase the understanding of coupled THC processes in the Topopah Spring fractured tuff environment. This approach should help to increase confidence in predictions of water and gas compositions potentially seeping into a repository environment. An objective of this approach might be to compare fully coupled THC models of the CDTT, prior to and following the test, with models developed from the DST. This approach would strengthen the overall test objectives of understanding the processes and the features and rock characteristics that affect the processes so the knowledge can be applied to other rock types.

Comment (4-b). The CDTT Planning Report fails to provide information on what chemical and isotopic components will be measured or how uncertainties in the analytical data will be evaluated and treated.

Different techniques for extracting pore water samples from cores (e.g., compression, ultracentrifugation, or vacuum distillation) contribute different uncertainties to measured pore water concentrations. Uncertainties in measured pore water concentrations are exacerbated also by the small sample volumes typically obtained from cores. Browning et al. (2000) evaluated analytical pore water compositions from Yucca Mountain (Yang et al., 1996, 1998) for internal thermodynamic consistency and found significant ionic charge imbalances, unequilibrated aqueous speciation relationships, and erratic variability with depth. Various assumptions and calculations generally are required to restore internal thermodynamic consistency to analytical pore water data (Apps, 1997; Browning et al., 2000) and these assumptions constitute a significant part of the data interpretation. These uncertainties in pore water compositions are examples of how collection and analysis techniques affect data. The CDTT Planning Report should include a discussion of how data uncertainty will be assessed and the effects evaluated. Interpretation of measured chemical and isotopic data can be complicated also by uncertainty in the rock pathways followed by fluids to the sampling locations. Data uncertainty must be evaluated to make meaningful comparisons between the measured and modeled fluid compositions during and after the test and to determine initial conditions. All significant sources of uncertainty in the measured chemical and isotopic data should be documented and used to evaluate the reliability of experimental and modeling results.

5 RECOMMENDATIONS FOR THE GEOCHEMICAL ASPECTS OF THE CROSS DRIFT THERMAL TEST

Recommendation (5-a). In the CDTT Planning Report, list the chemical and isotopic components to be measured and describe how these data will be interpreted to assess completion of the test objectives. A discussion of the strategy used to select gas, water, and rock sampling locations should include a complete description of the sampling plan, how the sampling plan was designed, and how it will help attain the test objectives.

Recommendation (5-b). Provide a more detailed discussion of the test objectives and the criteria that will be used to determine whether those objectives are achieved. Consider redirecting the geochemical objectives of the CDTT Planning Report toward analyses and understanding of coupled THC processes in a fractured rock environment. Analyses of fluid and rock samples should be performed on samples collected from locations where critical processes are believed to be active based on preliminary simulations of coupled THC processes. Design of the sampling program, including analyses of data uncertainty, should be coordinated with THC modeling to provide strong data support for increasing confidence in models of coupled THC processes.

6 COMMENTS ON THE THERMAL-MECHANICAL ASPECTS OF THE CROSS DRIFT THERMAL TEST

The CDTT Planning Report includes thermal-mechanical measurements to determine the Young's modulus and thermal expansivity of the Tptll rock mass. These are

- Displacements measured using multiple-point borehole extensometers (MPBX), which determine the change in length of pre-selected gauge lengths along a borehole wall

- Displacement-slope measurements with tiltmeters, which will be interpreted to obtain the spatial distributions of displacement

- Temperature measurements along the length of each MPBX

- Two plate-loading tests to determine ambient and heated rock-mass moduli

- Acoustic emission (AE) monitoring, using a three-dimensional array of sensors monitored continuously during excavation and thermal loading to map the spatial and temporal distributions of AE activity. Second, seismic sources will be provided periodically along the thermal alcove and injection alcove walls to generate calibration data for seismic wave velocity. Changes in P- and S-wave parameters (velocity attenuation) will be used to map water content and rock properties as a function of time.

Comment (6-a). Measured displacements (from MPBX and tiltmeter data) and temperature changes are to be used to determine the rock-mass thermal expansivity. However, these data (i.e., the *in-situ* displacements and temperature changes) alone will not be sufficient to determine the rock-mass thermal expansivity. The determination of thermal expansivity requires displacements measured during a condition in which the test subject can expand freely {i.e., without causing or encountering a change in stress [e.g., ASTM D 4535 (American Society for Testing and Materials, 2000)]}. Therefore, to determine the thermal expansivity of a rock mass using the measured deformation of a gauge length, the measured data must be subjected to an interpretation that accounts for the stress change experienced by the test specimen during the test.

Comment (6-b). Mechanical-response measurements from the CDTT and the DST are to be used to "undertake a comprehensive comparison of the two welded tuff units including determination of rock mass modulus as well as providing data against which analytical models can be compared" (section 7.3.4, CDTT Planning Report). It is, however, doubtful that the measured mechanical-response data will be sufficient to achieve this objective, because of the following reasons:

- The plate-loading test data from the DST and CDTT will give at most two data points in the empirical relationship between rock-mass modulus and quality index.

- Stress-change measurements are required to permit an unambiguous interpretation of the displacements and temperature change to determine the rock-mass thermal expansivity and Young's modulus. There was, however, no measurement of stress change in the DST, and none is planned for the CDTT.

- Although the AE data may be used to determine Young's modulus for the average rock mass along the wave-transmission path, the rock-mass volume sampled by a given AE signal may be too large to allow assigning the calculated Young's modulus to a specific value of rock-mass quality index. Furthermore, the wave transmission path may be different for each AE signal if the source locations vary as would be expected.

- Although the AE source mechanisms may be interpreted to obtain rock-strength data, such interpretation would require knowledge of the stress state at a given source location.

7 RECOMMENDATIONS FOR THE THERMAL-MECHANICAL ASPECTS OF THE CROSS DRIFT THERMAL TEST

Recommendation (7-a). The U.S. Department of Energy should consider including the measurement of stress change in the plans for the CDTT to reduce the uncertainties associated with interpretation of measured displacements, temperature change, and acoustic emission. The potential benefit from the stress-change measurements would increase as the number of measurements increases. Furthermore, some of the intended interpretations (e.g., determination of thermal expansivity) clearly require a knowledge of the stress change. It is admittedly difficult, if at all possible, to obtain sufficient stress-change data to eliminate ambiguity from interpretation of the displacements and temperature, but the value of the overall data interpretation would be enhanced if stress-change measurements were included.

Recommendation (7-b). The uncertainties related to path dependence of AE signals can be reduced through the sensor-array design (e.g., Talebi and Young, 1992). However, the CDTT Planning Report did not provide sufficient information to permit specific recommendations regarding the current proposed design.

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