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SUBJECT: NWTRB FULL MEETING ON THERMAL LOADING

I attended the NWTRB meeting on heat loading at Yucca Mountain, "Thermal Loading, The Integration of Science and Engineering" held July 13-14, 1993 in Denver. The TRB assembled a diverse group of scientists to present their expertise on the thermal loading questions. There were 33 formal presentations and two round table discussions. The following are summaries of some of the presentations, comments and discussions during the meetings that I found interesting from the performance assessment point of view.

Introductory Material

Don Langmuir of the TRB began the meeting by pointing out that there has not been an adequate evaluation of the technical merits and uncertainties of various thermal loading strategies. The primary goal should be to ensure a safe repository, and technical analysis should not be sacrificed to meet unrealistic schedules.

The Extended Dry option would use a smaller area, and fewer but larger waste packages. Thermal loading will have a multitude of consequences to the performance of the repository, including fuel and cladding performance, canister corrosion, transport of radionuclides, retrievability, cost and predictability of performance. Looking at the effects of thermal loading from the point of view of any particular physical process does not tell the whole story, since performance may be improved by the effects of higher heat loads on some processes (e.g., isolating waste from liquid water) while performance may be degraded by the effects of higher heat loads on other processes (e.g., rock alteration). There were many indications over the two days of the meeting that overall repository performance assessment should play a crucial rule in deciding the proper course of action for thermal loading and other design considerations.

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Key data inputs needed for the decision include site characterization data, block and in situ heater tests, information of coupled processes, and geothermal analogs. Heater tests might not give information in time for decisions about repository design, so there will have to be reliance on other data such as from geothermal reservoirs.

Programmatic Considerations

Steven Saterlie of the M&O presented further planning studies for the thermal loading proposal. One interesting point that came up in his presentation is that the Multi-Purpose Container designed to hold up to 21 PWR fuel assemblies can still be used to transport the fuel to the repository, even if emplacing them in the drifts proves to be unworkable. The fuel would have to be repackaged at the site, however.

David Stahl, from the M&O, gave an overview of thermal loading testing needs and plans, related to determining the viability of various thermal loading strategies, including the Extended-Dry repository concept in which thermal loading would be high enough to keep the repository dry for thousands of years. There will be a number of laboratory and field tests to collect data in support of the thermal loading decisions. The Small Block tests at LLNL will evaluate the properties of the rock, validate block stability codes and other models. The Large Block Tests at Fran Ridge will include heater experiments on a much larger scale to evaluate coupled thermal, mechanical, hydrological and geochemical processes. The In Situ heater tests will emplace heaters underground to evaluate processes on a much larger spatial and temporal scale. There will be abbreviated heater tests starting in June 1996 because there needs to be an early decision on the thermal loading questions. Longer heater tests will be run in parallel however for an indefinite period. There will also be heater experiments in situ that will deal with rock mass response to thermal loads and the stability of openings. These will be scheduled for late 1996. DOE will also have a major geothermal natural analog study in New Zealand. The major objectives will be to evaluate a real site with active hydrogeochemical processes, validate models and evaluate performance of man-made materials. Other natural analog studies related to the thermal loading decision include several other geothermal energy sites, and the Yucca Mountain site itself. Beyond the formal heater tests, there will be performance confirmation monitoring for 50-200 years after commencement of waste emplacement.

Geochemical Modeling

David Bish of Los Alamos National Laboratories discussed the notion of using the alteration of Yucca Mountain rocks from the periods of volcanism 11 million years ago as a self-analog for a hot repository. There is ample evidence of past hydrothermal system in northern Yucca Mountain lasting about 1 million years, with evidence of mineral alteration. Additionally, the Topopah Spring vitrophyre shows dynamic alteration near fractures. The vitric-zeolitic transition in the Calico Hills formation is another area of hydrothermal alteration. Data suggest that mineral sealing of fractures in the vitrophyre with silica may occur and alter the hydrology. The goal of this study is to predict the effects of high temperature and water changes on mineral alteration for very long periods of time, beyond that which could be gathered in present day experiments. One of the complications of natural analogs is that Yucca Mountain is not presently an active system, and it is difficult to define past conditions. One interesting fact is that there would be a large release of water of hydration upon mineral alteration such as the degradation of clinoptilolite. This water might represent a significant source entering the hydrologic cycle within Yucca Mountain.

Bill Murphy from the CNWRA gave a presentation on the effects of heat on the gas-water-rock geochemistry. Some of the earliest effects of repository waste heat may be the effects on the rock of changes in the composition of circulating gases in Yucca Mountain in response to the increased gas circulation from thermal convection, and the adjustment in the carbon equilibrium. The model simulated changes in the geochemistry at a point 50 meters above the repository plane in response to the temperature, gas flux and gas composition. Gas flux, temperature and chemistry were calculated with the aid of the carbon flow and transport model developed previously by Murphy and Codell.

Geothermal Natural Analogs

There were several presentations concerned with whether heat pipes were possible at Yucca Mountain. Bo Bodvarsson and Karsten Preuss of Lawrence Berkeley Laboratories presented their field and mathematical modeling experiences with geothermal reservoirs, where heat pipes were a definite feature. Bodvarsson commented that mathematical modeling of geothermal reservoirs was in a high state of development, and rather successful despite incomplete descriptions of the underground chambers, magma sources and recharge. Success generally depends on developing a conceptual model based on as much physical and geochemical evidence as possible, and a long period of "history matching" where observed behavior of the reservoir in response to external stresses was matched by the computer model by the process of iterative adjustment of model parameters. Although these models are often successful for estimating yields of geothermal energy, predictions of chemical transport is much less certain because of a lack of understanding of processes.

In a related presentation Bodvarsson commented that, while the extended dry repository concept appears to offer significant advantages for waste isolation, it is an unproven hypothesis, based only on model calculations without significant history matching. Speculating on the possible down-side of the concept, he listed the possible failure modes as water flow in fractures because of heat pipe recirculation, increased surface temperature and gas outflow, and hydrothermal eruption. He did not believe however that any of these were very likely.

Multiphase thermal and flow analyses

Tom Buschak of LLNL presented results of modeling studies with the VTOUGH two phase flow program under a range of thermal loads. He emphasized several key issues about the effects of heat on the performance of the Yucca Mountain repository; (1) the critical concern is water contacting a waste package accelerating its failure rate, and transporting radionuclides to the water table, (2) the only credible means for liquid water circulation is by non-equilibrium fracture flow, originating from infiltration and condensation of water driven off of the hot rock. Water does not have to migrate from the surface to affect the repository.

Buschak presented a number of example calculations of thermally affected flow of vapor and liquid at Yucca Mountain. The model results generally demonstrate that large portions of the repository would remain dry for many thousands of years with sufficiently high thermal loads. Circulation of vapor might induce a net flow of liquid water to cooler parts of the repository. He recognized however that the conceptual models and their embodiment in VTOUGH have many simplifying assumptions, and will require model validation. Several hypotheses must be tested to support model validation, among which are (1) whether liquid water can flow in fractures in rock above the boiling point, (2) whether fracture density and connectivity are large enough to promote dry-out by permitting vapor pressure to dissipate (3) whether re-wetting of the dried rock lags the boiling period, and (4) whether large buoyant gas-phase convection will eventually dominate moisture movement in the unsaturated zone. Validation of the models will require large scale in situ heater tests conducted under both sub-boiling and boiling conditions.

Yucca Mountain would be classified as a vapor-dominated system, similar in some ways to geothermal systems. He believes that studies of geothermal systems may be the only way that the models of Yucca Mountain for the extended dry concept could be adequately tested with sufficient history matching. Heater experiments in the field are not likely to answer all questions about thermal effects because of their limited time and length scales.

First Day's Panel Discussion

The first day's round table panel discussion concerned geothermal analogues and modeling issues related to answering some of the questions of repository performance under differing thermal loading strategies.

Someone on the panel commented that geothermal reservoirs might not be an appropriate analog for the Yucca Mountain repository. Geothermal reservoirs differ from Yucca Mountain in several respects; (1) lower areal heat loading, (2) larger size. In addition, geothermal reservoirs almost always have impermeable cap rock above them which contains the pressure of the reservoir, and is usually a result of the circulation of water and precipitation of calcite and silica resulting directly from the geothermal heat over many thousands of years. Bodvarsson's comment was something to the effect that the geothermal reservoirs still allow validation of the models that would be useful for Yucca Mountain.

Bill Nelson, a volcanologist from the Smithsonian Institution representing the TRB, brought up the issue of phreatic steam explosions in volcanic terrain. A possible scenario would involve generation of steam pressure at depth and transfer of the overpressure to the surface through fractures. Preuss commented that the repository heat itself and the relatively shallow depth of the repository would make any phreatic explosion very unlikely. Bodvarsson commented that the pressure in the repository would be easily monitored, and any buildup of pressure could be relieved by drilling boreholes.

Jean Yonker from the M&O commented on why performance assessment results have not yet been factored into the site characterization activities. The abstracted performance assessment models to date lack a clear consensus, and the results cannot yet be relied on for directing the program.

Abe Van Luik from the M&O commented that all of the modeling studies should be put into perspective, since the biosphere and dose assessment models may be two orders of magnitude more uncertain than the models being used to evaluate the releases from the repository.

John Czarnecki from the USGS brought up an interesting possibility for the effects of heating of the saturated zone. He observed in an experiment on underground heat exchanger that the exchanger plugged quickly with precipitated calcite. He reasoned that repository heat would lead to precipitation of calcite in the saturated zone, thereby changing its permeability and perturbing the flow patterns and water levels. Tom Buschak has demonstrated that the increased temperature below the water table will likely lead to circulation of liquid water, in addition to the flux caused by the regional hydraulic gradient.

Corrosion Modeling

Daniel McCright of LLNL spoke about corrosion under various thermal options. Metal will oxidize, but not corrode until there is a transition at high-enough relative humidity. Steel will rust at relative humidity greater that 70%, but apparently not below. For wet conditions, corrosion will increase with temperature in response to the increased diffusion of oxygen to the surface, but will decrease above about 80 degrees C as the solubility of oxygen in water decreases. Some of the most corrosive natural conditions appear to be at the transition between the vadose and saturated zones. Recently, casing from the US WH-5 well was brought back up. Most of the casing was fairly clean, but the section straddling the water table showed significant corrosion over the 10 years it was in place. They are analyzing the corroded section now.

The emphasis in corrosion research is on multiple barrier packages; e.g., alloy 825 inner barrier, with a carbon steel outer barrier. The outer barrier would oxidize slowly and protect the inner barrier. There are many trade offs possible between material selection and performance. The extended dry thermal strategy appears to have fewer material performance considerations than strategies that allow a wetter environment.

Multi-Purpose Canisters

T. Doering of the M&O spoke of the compatibility of Multi-Purpose Canisters (MPC's) and Multi-Purpose Units (MPU's) with the thermal scenarios. The MPC with disposal overpack would hold up to 21 spent fuel assemblies, and be emplaced in drifts. Their output of heat would be much higher than the SCP container designs. Waste glass canisters might be placed between the MPC's in the drifts. The MPC's would be self shielding for worker safety since they would be loaded at the power plants. They might be filled with a buffering material, and would also contain neutron absorbers for criticality control. One of the scenarios for criticality is a water-drilled exploratory borehole that hits a container and fills it with the drilling fluid. If MPC/MPU designs are found to be incompatible with the repository design, they could be used for shipment only and repackaged into smaller containers at the site.

Decision on Thermal Loading

Larry Ramspott representing DOE commented that no decision on thermal loading is needed immediately for the conceptual design of the repository. However, there will be programmatic consequences of delaying the decision for the conceptual design such as having to accommodate waste packages with widely varying thermal loads.

Environmental Effects

Kent Ostler from EG&G spoke about the effects of repository heat on desert ecosystems. Under the SCP design thermal loading, temperature increases at the surface of the earth would probably be about 1 to 2 degrees C, and cover an area of 2 to 3 mi^2. Under higher heat loads in the extended dry concept, temperatures would be higher, but over a smaller surface area. The temperature peak at the surface would occur at about 2000 to 3000 years. Increased temperatures of less than 2 deg. C would have a minimum impact and would be within the range of year-to-year variations in soil temperature. Higher temperatures might have a moderate to large impact, according to some studies conducted in Yellowstone on the health of lodgepole pine trees. Increased temperatures might lead to higher evaporation, and timing of biological processes like seed dormancy, pollination and emergence from hibernation. He estimated that some of these processes would be speeded up about one week for each 1 degree increase.

Performance Assessment Modeling

Jerry Boak of DOE and Holly Dockery of SNL presented the plans for the DOE Total Systems Performance Assessment, Phase 2. The priorities of TSPA2 are to support ESF design and surface-based testing, alternative regulations, and the design of waste packages, waste emplacement and alternative thermal loads. They hope to incorporate new site information in their analyses, and conduct sensitivity and uncertainty analyses, including the effects of emplacement schemes and thermal loads. The DOE performance assessment will be more hierarchial than NRC's. They will have inputs on conceptual models for source term, hydrology, and geochemistry from LLNL, LANL, LBL and USGS. Sandia will perform the subsystem modeling on abstracted mechanistic models from the detailed models. The M&O will look at further abstracted models based on the Sandia results.

TSPA2 will differ from the 1991 TSPA in several important respects:

- It will consider the effects of increased areal thermal loading and the difference between the SCP layout for waste emplacement and the new concept of drift emplacement. They will also include glassified high-level waste which represents 10% of the total inventory. It does not appear that they will include very high burnup fuels in their considerations of inventory.

- It will consider conceptual models of thermal-hydrologic processes for aqueous flow. In particular, the weeps model for fracture flow will consider reflux of water evaporated from the rock by repository heat, and will exclude weep pathways in the rock that are hotter than the boiling point, so there can be no contact until the rock is cooler.

- the source term model will include solubility limited releases based on solubilities of pure species provided from LANL. There will be more radionuclides, and the source term and transport models will consider chain decay of actinides. The source term model will also consider coupled thermal and hydrological processes of a boiling front, dryout and reflux of condensed water. There will be consideration of pitting and general corrosion, dry oxidation of the waste form, aqueous alteration and congruent leaching. TSPA 1991 did not have a mechanistic model of waste package failure, but assumed only a statistical distribution of failure times, at which point the waste package was presumed to disappear. Most of these phenomena are included already in NRC's Phase 2 source term model.

- The C-14 transport model will be improved significantly to include geostatistical correlations of the spatially varying rock properties, replicated I believe for 10 realizations.

- They will consider correlations among variables for both the liquid and gas analyses, and will use geostatistics to correlate the hydraulic properties among the 9 vertical columns representing flow and transport in the unsaturated zone.

- They will include fracture-matrix coupling for fluid flow and transport.

- They will have a more mechanistic model for water contact with the waste form.

- They will consider multiple engineered barriers, especially related to the new container concepts.

- They will include individual and collective dose assessments as well as a calculations of cumulative releases. The model will consider a water well 5 kilometers from the edge of the repository block.

- They will have a 3-dimensional model of flow and transport in the saturated zone based on available USGS geohydrologic data.

They hope to have a complete summary document by early 1994.

Robert Andrews representing the M&O presented the performance assessment being conducted by the M&O using the Repository Integration Program (RIP). RIP represents the most abstracted level of the DOE performance assessment efforts. It apparently takes the results of the Sandia TSPA and empirical data to develop simpler models that can be used to evaluate sensitivity, uncertainty and effects of alternative designs and future states. The model has been successfully run to duplicate the results of the Sandia TSPA. Improved versions of RIP will continue to evolve along with the Sandia performance assessments.

James Duguid, also representing the M&O presented some calculations being done to help the National Academy of Sciences Committee on the Technical Bases for Yucca Mountain Standards. Duguid is calculating doses to a target population using groundwater contaminated at Yucca Mountain. The dose assessment was interesting to me because it involved some of the same estimations of populations and water use that we had to make for our Phase 2 IPA. Duguid's critical group size was based on available water, using water budget estimates from several regional basins in the general area. Available ground water was estimated between the "annual safe yield" of 300 acre-feet and the annual recharge of 2300 acre-feet. Household use was 150 gal/day per person. Farming required 20,000 square meters/person per year, and 150 liters/square meter per month, assuming a growing period of 6 months. This gave an estimated population of 1,800 to 13,000 persons, and a farming population of 21 to 160 persons. These estimates are similar in magnitude to those presently living in the region, and also similar to the populations chosen for our Phase 2 IPA. Duguid believes that the population supported is close to the maximum in terms of ground water resources. The highest individual dose calculated was less than 1 rem/year. The dose assessment was considerably simpler than the one performed in the NRC Phase 2 IPA. He chose what I consider to be an unreasonably thick screened interval for the aquifer of 2400 meters, which would tend to reduce concentration and therefore dose. The reason for this choice was apparently that the value was used in EPA's original analysis of doses for the HLW program.

Second Round Table Discussion

The second round table discussion was a wrap-up of thermal issues. Discussion started out with Rosa Yang from EPRI who is new to the Yucca Mountain project, but has worked for many years in the nuclear fuel business. She gave a resounding endorsement to the use of total system performance assessment for evaluating the repository and directing its programs. She said that they used performance assessment concepts in evaluating performance of reactor fuels.

Panel members seemed to recognize the importance of experiments that would determine the near field behavior, and in particular the possibility of thermally driven recirculation dripping onto the containers. Bill Halsey from LLNL commented that there were general plans to perform tests on this phenomenon, but no specific plans.

Conclusions

This meeting was very worthwhile from the point of view of performance assessment. Changes to thermal loading strategies, and the change from borehole emplacement to drift emplacement will have profound consequences in our iterative performance assessments. We got a glimpse of the next version of the DOE performance assessments, which should prove to be much more complete than the previous version.

DOE seems to be making a concerted effort to collect the kinds of data needed for performance assessments, particularly in the heater tests. Data on thermally driven water flux interacting with the waste packages is crucial for realistic performance assessments.

Sandia seemed anxious and willing to have technical exchanges so that the performance assessment teams can compare strategies. Holly Dockery commented that formal technical exchanges as we have had in the past have been very disruptive and time-consuming, so she would prefer a less formal setting. I would like to explore this possibility further.

/S/

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