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**EXPERIMENT DESIGNS OFFERED FOR DISCUSSION
PRELIMINARY TO AN LLNL FIELD SCALE
VALIDATION EXPERIMENT IN THE YUCCA
MOUNTAIN EXPLORATORY SHAFT FACILITY**

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December 7, 1988

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EXPERIMENT DESIGNS OFFERED FOR DISCUSSION PRELIMINARY
TO AN LLNL FIELD SCALE VALIDATION EXPERIMENT IN THE
YUCCA MOUNTAIN EXPLORATORY SHAFT FACILITY

by

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of

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for

Lawrence Livermore National Laboratory
under subcontract B055747

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I. INTRODUCTION

It has been proposed ("Progress Report on Experiment Rationale for Validation of LLNL Models of Ground Water Behavior Near Nuclear Waste Canisters", Keller and Lowry, Dec. 7, 1988) that a heat generating spent fuel canister emplaced in unsaturated tuff, in a ventilated hole, will cause a net flux of water into the borehole (as steam) during the heating cycle of the spent fuel. Accompanying this mass flux will be the formation of mineral deposits near the borehole wall as the water evaporates and leaves behind its dissolved solids. The net effect of this process upon the containment of radioactive wastes is a function of 1) where and how much solid material is deposited in the tuff matrix and cracks, and 2) the resultant effect on the medium flow characteristics.

Experimental concepts described in this report are designed to quantify the magnitude and relative location of solid mineral deposit formation due to a heated and vented borehole environment. The most simple tests address matrix effects only; after the process is understood in the homogeneous matrix, fracture effects would be investigated.

The basic scaling relationships are treated in the referenced progress report, as well as descriptions of the dominant processes. The major physical phenomena are:

- Conduction heat transport
- Liquid water, steam, and air transport in both simple porous media and fractures
- Energy transport due to convection
- Mineral solution and precipitation
- Thermal/mechanical effects on fracture and matrix flow characteristics, including creep
- Buoyancy (direction of gravity)

Material properties will be dependent on several parameters:

Property	Dependent on...
Permeability	Saturation
Matrix thermal conductivity	Temperature, saturation
Water viscosity	Temperature, composition
Capillary pressure	Saturation, temperature (temperature dependence of surface tension)
Solubility	Temperature, dissolved solids concentrations
pH	Temperature, dissolved solids concentrations

We suspect that the process has a strong rate dependence. If the thermal pulse is relatively strong and fast, the evaporation/condensation front will reach so far out from the borehole that precipitate formation will occur over too large an area to significantly impact flow properties. With a slow and weak thermal source, or high thermal conductivity of the medium, temperatures in the medium may not be sufficiently high to evaporate the liquid water at a rate needed to drive steam toward the borehole.

Scaling of the experiment will be dependent on relationships between the medium saturation and capillary pressure, saturation and permeability, and saturation and thermal conductivity. Positive control of thermal and flow boundary conditions, and initial conditions, is mandatory.

The ground rules and constraints that the proposed experiments must meet are as follows:

- They are relevant to the problem at hand. Process scaling is appropriate for the Yucca Mountain environment.
- They can be modeled to determine their relevance, using TOUGH or KRAK.
- The experiments must be of reasonable cost.
- Each experiment must require less than one year to complete.

II. CANDIDATE DESIGN CONCEPTS

Three conceptual designs are proposed. All are laboratory scale experiments, although several of them could be very large if scaling dictated (larger geometries, however, require longer times). A description of each concept, its merits, and its disadvantages are provided.

A. Cylindrical Configuration, Formed in Place

In this design the porous media is cast into a cylindrical volume, with a hole in the center representing the borehole (Figure 1). A resistance heater is located in the center of the hole. All boundaries of the test volume are sealed and insulated to prevent undesired flow of water and heat out of the system. Water vapor evolved during the heating process is, however, allowed to vent from the hole. Its rate of evolution is monitored by condensing and retaining in a container. The matrix material would be unconsolidated granular material. Ottawa sand, with well characterized flow and physical properties, could be prepared with a precise saturation content by drying completely and rewetting with a known amount of water. The characteristic curve of this material could be modified by grading the particle distribution. A relatively pure and inert sand would not tend to complicate the geochemistry by dissolving or reacting with the water.

Instrumentation would be located in the test volume and the sand cast in place (Figure 2). A very detailed temperature profile would be obtained by emplacing a grid of thermocouples. Since the process is essentially one dimensional (cylindrical), the sensors located on a radial path from the cylinder center would provide the primary temperature profile. The other sensors above and below the radial string would diagnose buoyancy and other two dimensional effects. Electrical power input to the heater would be measured. Condensed water from the center hole would be collected and weighed. The mass balance on the system could be confirmed by weighing the apparatus as the experiment progresses. The

Figure 1. Formed in place cylindrical test volume.

Figure 2. Instrument plan for formed-in-place experiment.

radial saturation profile would be best obtained by either a neutron activation measurement in an access tube placed on the radius (if a sufficiently small tube could be used) or attenuation measurements made through the thickness of the cylindrical volume at discrete points along the radius.

Electrical resistance measurements could be made between thermocouple leads or with discrete resistance probes, and electrical impedance tomography (EIT) techniques such as those used on core samples could be applied. If the initial dissolved solids concentration is extremely low (and contributes little to the conductivity of the water), these measurements would provide a good map of the saturation profile. An experiment designed specifically to do this would be useful. However, the electrical conductivity of a volume of the medium is a function of not only the water content, but also of the water temperature and dissolved solids concentration. This will confuse interpretation of the resistance measurements as an indication of saturation if sufficiently high dissolved solids concentrations are present. The resistance measurements could map another extremely useful property, namely the concentration of ions or dissolved solids. Electrical conductivity of a volume of fluid is roughly proportional to the number of mobile ions. If the fluid were distilled water laced with a small concentration of sodium chloride (several hundred parts per million), the region where evaporation is taking place would have a very high concentration (essentially saturated) of dissolved sodium chloride and a corresponding electrical conductivity several orders of magnitude higher than that farther out in the medium where evaporation is not taking place (see Figure 3). While temperature affects the conductivity of a solution at constant concentration, its impact is small over the range of 20 to 100°C (less than a factor of 3 for sodium chloride). Saturation will probably only vary from .2 to 1.0, so its effect is less than a factor of five. The saturation and temperature effects counteract each other. Consequently, the conductivity versus dissolved solids concentration relationship may provide a tool for inferring, at the least, the location of the vaporization front, and with other information (namely temperature and saturation) the spacial distribution of dissolved solids concentration.

Figure 3. Qualitative temperature, electrical conductance, and saturation distribution. (R_h = hole radius)

After the experiment is completed, the sand casting can be dissected for detailed mapping of precipitate formation.

A variation of this general design is to form the test volume of a cemented material. Casting the cylinder out of a grout would allow measurements in a range of flow characteristics more representative of the Yucca Mountain material. At the extreme, a cemented solid could be tailored to match the permeability, saturation/suction relationship, and porosity of Topopah Springs tuff (extensive matching may not be necessary, however, if the process scaling relationships are well thought out). Stress measurements could be cast in place (using, for example, the CALIP stress gauge) to measure the mechanical response of the matrix to thermal loading. All the measurements discussed for the sand experiment would be appropriate for a grout experiment. One complication the grout would cause is a relatively complex water chemistry (for conventional grouts anyway) and the possibility of grout dissolution. While this would impact diagnosis of chemical processes, it would not necessarily degrade the utility of the experiment with respect to the basic heat-driven flow process.

The advantages of a cast in place experiment (sand or grout) are:

- Detailed instrumentation could be cast in place.
- Initial material properties would be well known and tightly controlled.
- The physical size of the experiment is not a severe constraint (it could be large or small).
- Gravity effects could be studied by changing the orientation of the test volume.
- Sand would be very clean chemically, with easily controlled initial saturation.
- A sand test would run relatively fast.
- Grout would allow diagnosis of thermal/stress effects, and could attain material properties closer to those expected in Yucca Mountain.

Disadvantages of this experimental concept are:

- Sand would have a relatively high permeability and a much lower suction/saturation relationship. It would probably not be possible to come within a factor of a hundred to the values expected in the Topopah Springs material.
- Grout tests would have to accommodate a relatively complicated water chemistry.

The experiment ratio, ER, described by Keller and Lowry, may allow a relevant experiment under very different permeability conditions.

B. Block of Tuff

The second general design consists of a block of tuff with a heater hole bored in its center (Figure 4). The block's outer surface would be insulated and sealed to prevent flow out of the block (except for the borehole vent). While they would be more difficult to emplace, most of the measurements of the cast in place experiment could be used. Useful matrix suction measurements would be difficult with tensiometers, since the capillary tensions of interest for Topopah Springs tuff are in the range of 10 to 100 bars. A miniaturized version of the LLNL resonant cavity moisture sensor could be used here, or a thermocouple psychrometer, to infer matrix saturation. A significant feature of this test design is the ability to stress the test volume with an externally applied load (flatjacks or a triaxial testing machine). Thermal/structural effects on the matrix processes could be studied, and more importantly, fracture effects. Electrical impedance tomography would be valuable here because less intrusion is required for a saturation or concentration determination. The same reasoning applies to neutron attenuation measurements. The block could be dissected after the experiment to measure the concentration profile of precipitates.

Calculations are needed to verify this, but it is conceivable that using J-13 water may be sufficient to see the precipitation process. The heating rate would have to be scaled up, but resistance measurements and dissection of the block may be sufficient to observe precipitate deposit concentrations.

Figure 4. Tuff block experiment cross section.

An interesting technique for measuring capillary suction in fractures has been developed at the University of Arizona (Figure 5). A small hole (.5 in. diameter) is drilled through the rock block just to the fracture plane. A tensiometer constructed of a small porous cup covered with filter paper is pushed up against the wetted crack. They have successfully measured tensions as high as a bar with this device, which may be sufficient for the fracture. Holding filter paper against the rock has also allowed collection of a sample of the fluid, and calibration curves have been developed for chlorine concentration in the filter paper.

A variation on the intact block design that would enhance the diagnostics of the test would be to split the block in half along its axis (Figure 6). One half would be designated the test section, and the other a sort of "guard" section. In the test section sensors would be installed in the medium adjacent to the cut. Wires and tubes would be run out through drill holes in the guard block. The block halves would then be reassembled, glued together with a sealant that would preclude fracture flow in the cut plane, be resistant to heat, and would not penetrate so deep into the medium as to affect the measurements. RTV or silicone gasket sealant would probably do this very well. The salient features of this design are that 1) we have a whole block thermally, 2) we are looking at only half the block with the flow measurements but by sealing the cut plane the problem is still cylindrical, and 3) we have facilitated the emplacement of detailed instrumentation in the test section, using the guard section to pass wires and tubes out of the system.

Advantages of the tuff block experiment are:

- Precise match of the Yucca Mountain material.
- Thermal/structural and fracture effects would be diagnosed under loaded conditions.

Its disadvantages would be:

- Difficulty of instrument emplacement (except for the split block test).
- Relatively slow process rates.

Figure 5. Fracture capillary pressure tensiometer (developed at University of Arizona).

Figure 6. Split tuff block experiment.

It should be noted that a manufactured material (such as a refractory material) could be used in the place of tuff. The advantage would be in tight control over the material characteristics and homogeneity of the matrix, and perhaps easier installation of sensors.

C. Small Core Tests

The test bed for this concept is the Lin and Daily small core (8 cm. dia.) apparatus. A small hole is bored along the axis of the core, and a resistance heater is inserted (Figure 7). The core ends are sealed to prevent axial fluid flow and heat transfer. The heater hole is vented so vapor can be condensed and weighed. Around the circumference of the core is placed an array of electrodes for impedance tomography measurements. As the core center is heated, an annular cylinder of high electrical conductivity will form at the evaporation front, where a nearly saturated solution of water and dissolved solids exists. This should show as a circle growing outward from the core center as time progresses. The conductivity may be boosted, if necessary, by adding salt to the water. The thermal boundary of the core perimeter would be held at a constant temperature. Variations on this experiment would be application of different confining pressures and temperatures, and the inclusion of natural cracks in the core.

Major benefits of this concept are:

- Use of the actual tuff material.
- Use of an existing experimental apparatus that supplies precise control of confining pressure and temperature.
- Application of electrical impedance tomography to detect the location of the vaporization front, in a well-tested configuration and apparatus.

Disadvantages would be:

- A small size that constrains scaling.
- Limited options for intrusive instrumentation (due to small size and difficulty of locating sensors in rock).

Figure 7 . Small core experiment in apparatus of Lin and Daily

III. CALCULATIONAL NEEDS FOR EXPERIMENT DESIGNS

The major uncertainties in the process are the relations between all the following:

- Capillary suction as a function of saturation
- Matrix permeability as a function of saturation
- Heat conduction through the matrix (and matrix thermal properties as a function of saturation)
- Dissolved solids concentrations and precipitation rates

In order to design a credible experiment, parametric studies of the actual spent fuel emplacement in tuff, with best estimates of properties and dependencies, should be done with TOUGH and KRAK. Flow magnitudes and time scales need to be bounded. Different heater rates should be run to quantify the rate at which the precipitation process becomes significant. Since the thermal conductivity of tuff varies widely (due to both material variations and degree of saturation) its effects need to be bounded.

Once the in-situ case is understood, and its experiment ratio (ER) determined, analysis of the experiment designs will assess their relevance to the problem. Experiment ratios would be calculated for variations in geometries, properties, and heating rates. With this information, the detailed experiment designs would be possible.

IV. SUMMARY

Three experiment concepts have been proposed. Each has unique advantages and allows investigation of specific aspects of the precipitate formation process. Existing experimental methods and apparatus are incorporated to minimize leaps of faith. All could be done in reasonable time (less than a year) and none of them are extremely expensive (the most expensive is probably the structurally loaded block test). The calculational ability exists to analyze the "real" situation and each of the experiment designs, and produce a credible series of tests. None of the designs requires the acquisition of material property data beyond current capabilities. The tests could be extended, if our understanding is consistent with the data produced, to analyze fracture effects.