A Mountain-Scale Monitoring Network for Yucca Mountain Performance Confirmation

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Abstract

Confirmation of the performance of Yucca Mountain is required by 10 CFR Part 63.131 to indicate, where practicable, that the natural system acts as a barrier, as intended. Hence, performance confirmation monitoring and testing would provide data for continued assessment during the pre-closure period. In general, to carry out testing at a relevant scale is always important, and in the case of performance confirmation, it is particularly important to be able to test at the scale of the repository. We view the large perturbation caused by construction of the repository at Yucca Mountain as a unique opportunity to study the large-scale behavior of the natural barrier system. Repository construction would necessarily introduce traced fluids and result in the creation of leachates. A program to monitor traced fluids and construction leachates permits evaluation of transport through the unsaturated zone and potentially downgradient through the saturated zone. A robust sampling and monitoring network for continuous measurement of important parameters, and for periodic collection of geochemical samples, is proposed to observe thermo-hydrogeochemical changes near the repository horizon and down to the water table. The sampling and monitoring network can be used to provide data to (1) assess subsurface conditions encountered and changes in those conditions during construction and waste emplacement operations; and (2) for modeling to determine that the natural system is functioning as intended.

Background

A *Performance Confirmation Plan*[1] has been prepared for the U. S. Department of Energy by Bechtel SAIC Company to meet the regulatory requirements specified in 10 CFR Part 63 Subpart F. The U.S. Nuclear Regulatory Commission requires that the performance confirmation program for the repository confirm that the actual subsurface conditions encountered and changes in these conditions during construction and waste emplacement operations are within the limits assumed in the licensing review (10 CFR 63.131(a)(1)). The performance confirmation program is also required to indicate, where practicable, whether the natural and engineered systems and components designed or assumed to operate as barriers after permanent closure are functioning as intended and anticipated (10 CFR 63.131(a)(2)). The purpose and objectives of the *Performance Confirmation Plan,* as quoted in regulation 10 CFR 63.102(m) is that:

> a performance confirmation program be conducted to evaluate the adequacy of assumptions, data, and analyses that led to the findings that permitted construction of the repository and subsequent emplacement of the wastes. Key geotechnical and design parameters, including any interactions between natural and engineered systems and components, will be monitored throughout site characterization, construction, emplacement, and operation to

> identify any significant changes in the conditions assumed in the license application that may affect compliance with the performance objectives specified at 63.113(b) and (c).

Hence, the *Performance Confirmation Plan* describes the U.S. Department of Energy strategy to collect, evaluate, and report on data used to confirm the basis for estimates of repository performance, and to increase confidence that performance objectives designed to protect public health and safety are satisfied. Direct observations and measurements during the preclosure period are planned to achieve these goals. The approach to the performance confirmation program is risk informed and performance based, focusing on parameters and processes important to evaluating assumptions, data, and analyses used in the licensing review. Generally, monitoring parameters important to either system performance or barrier capability, and have a relatively high degree of uncertainty, would be considered a valuable activity to be included in the performance confirmation program. This risk-informed, performance-based approach is used to select the set of activities for evaluating the postclosure performance. The *Performance Confirmation Plan* outlines, in high-level descriptions, 20 different activities, among which are:

- Unsaturated zone testing
- Saturated zone testing
- Construction effect monitoring

While the 20 activities are high-level descriptions, the *Performance Confirmation Plan* also states that the performance program of activities will be implemented through lower-level test planning and implementing documents. In this paper, we suggest a possible strategy, one that in our opinion would implement the above three bulleted activities.

Methodology

We present a methodology for implementing natural barrier monitoring activities under the umbrella of a mountain-scale monitoring network (MSMN). In concurrence with the approach laid out in the *Performance Confirmation Plan*, the MSMN will accomplish two distinct objectives: (1) monitoring the natural (undisturbed) conditions throughout Yucca Mountain and (2) assessing the response of the natural barrier system to the large perturbation created by repository construction. The MSMN will operate on the time scale of decades and will spatially encompass the entire repository.

The approach we suggest is based on the ability to relate observable parameters, such as temperature, to fundamental processes. This approach was taken during the Thermal Testing Program at Yucca Mountain on a drift scale (meters to tens of meters). A basis was established for relating monitored parameters to coupled thermal-mechanical-chemical-hydrologic processes. Measurements of pressure, temperature, strain, air permeability, and recovery of liquid and gaseous samples—conducted during the Large Block, Single Heater, and Drift Scale (Thermal) Tests—provided estimates of moisture and heat flux, geomechanical changes, and information on reactive geochemical processes. We propose to build on the experience of the thermal testing program and expand monitoring from the drift scale to the mountain scale (hundreds of meters to thousands of meters).

To effectively perform this task, innovative methods for subsurface monitoring are required. Distributed sensor networks permit acquiring measurements at a great number of locations along the entire length of a borehole. Similarly, new methods in performing geochemical sampling can be used to monitor transport processes by acquiring minimally perturbed gaseous and liquid samples. In addition, the MSMN should be designed to efficiently incorporate advancing technology, as well as to be safely terminated upon repository closure.

The Mountain-Scale Monitoring Network

Here we present a conceptual design for a MSMN that serves the dual purpose of observing changes induced by repository development and the long-term assessment of mountain-scale conditions. The MSMN is based on a series of instrumented boreholes that can be installed at a reasonable cost (so that a statistically significant number of locations may be instrumented), functions reliably for decades, and can be safely and inexpensively abandoned. The inadvertent creation of vertical conduits through the repository horizon to the water table during the postclosure period must be avoided, so abandonment procedures need to be incorporated in the initial design. Table 1, although not all-inclusive, presents a list of important parameters and the processes they monitor.

A network of multifunction borings, monitoring temperature and pressure, and facilitating periodic geochemical sampling serves as the backbone of the MSMN. Figure 1 shows a schematic of a monitoring boring incorporating an innovative geochemical sampling system, referred to as a U-tube[2], as well as distributed temperature and pressure measurement capabilities. Multilevel monitoring systems can be installed in each boring, and engineered backfill serves to isolate the measurement intervals. The use of distributed fiber-optic temperature and strain sensors permits data to be collected at 1-meter intervals, along the entire length of the borehole. This relatively new technology has recently seen increased use in dam monitoring projects to provide estimates of seepage rates and pinpoint localized deformation.[3,4,5] Based on life expectancies of fiber-optic communications cables, the design life for a fiber-optic sensor is estimated to be approximately 30 years. Because a fiber-optic cable can be removed, tested, and replaced within a small diameter sheath, a fiber-optic sensor installation will be viable for the entire duration of the pre-closure period. As technology advances, it will also be possible to install improved fiber-optic sensors without the need for drilling a new borehole and performing a new completion.

The U-tube sampling system, developed initially for monitoring CO_2 geosequestration by sampling multiphase fluids, was designed to provide high purity geochemical samples; owing to its simplicity, it can operate reliably for long-term monitoring.[2] The U-tube completion consists of a U-shaped loop of small diameter stainless steel tubing forming a drive and sample leg, and a check valve. The drive leg originates at land surface, extends to depth within the borehole to a screened or perforated zone of interest, and returns via the sampling leg to the surface. A check valve located downhole, at the bottom of the U between the drive and sampling legs, controls the movement of fluid from the region to be sampled into the U-tube. A secondary check valve, as shown in Figure 1, can permit "pumping" of the system by allowing repeated pressuring and depressuring of the drive leg, although that is not always required, depending on the location of the U-tube. A porous sintered stainless steel filter serves as the inlet to the U-tube and prevents particulates from clogging the check valve during sampling. Within the unsaturated zone, a stainless steel filter with a high air entry pressure permits the U-tube to act as a suction lysimeter. To recover the fluid in the tubing, compressed ultra-high-purity nitrogen is applied to the drive leg, causing the check valve closest to the inlet filter to close. Fluid is forced up the sample tube leg, which leads to an evacuated sampling vessel. The U-shaped tubing has the added benefit that it can be injected with chemical grouts for postclosure abandonment.

More specialized borings can be used to assess moisture potential, fluid flux, gas permeability, geomechanical conditions, and thermal conductivity. The distributed fiber-optic temperature and strain sensors can be incorporated into more complex distributed-parameter sensors. For example, a distributed fiber-optic temperature sensor can be used for measuring thermal conductivity at high spatial resolution (1 meter) by collocating it with constant-wattage heat trace tubing. Heat-trace tubing, utilizes a power bus running the length of the cable to energize short parallel heating circuits, maintaining a steady energy flux per unit cable length. Using the data inversion procedure established by Von Herzen and Maxwell, a fiber-optic distributed-temperature sensor run parallel to the heat trace can provide estimates of thermal properties along the entire length of a borehole.[6] Since thermal conductivity can be used as a proxy for saturation, moisture redistribution caused by repository heat loading can be observed with high spatial and temporal resolution. Similarly, below the water table, advective fluid flux acts to convectively transport heat, enabling a distributed thermal conductivity sensor to pinpoint location and magnitude of localized fluid flow. Previously, this technique has been employed by Ballard using his device, an *in situ* permeable flow sensor, which operates at a discrete location to measure flow velocity and direction.[7,8] A fiber-optic distributed-temperature sensor looped along the boreholebore axis, surrounding heat trace tubing, can function as an *in situ* permeable flow sensor to measure horizontal fluid velocity and direction along the entire length of a borehole.

Borehole placements and parameters to be measured are guided by Yucca Mountain unsaturated zone and saturated zone flow and transport models. Figure 2 shows a phased approach for developing the MSMN. The initial deployment of a monitoring network, shown in Figure 2 as Phase I, should be initiated prior to the excavation of emplacement drifts, so that baseline information can be obtained. Phase II borings will be completed during construction and emplacement of radioactive waste within the repository, focusing on the region immediately under the repository footprint down to the water table. As the perturbation to the mountain increases in lateral extent, post-emplacement Phase III monitoring outside of the repository footprint will focus on the interface between the unsaturated zone and water table towards the south, following the anticipated trajectory of solutes released from within the repository horizon. It is anticipated that monitoring will be continued up until the postclosure period, when sufficient confidence in the behavior of the natural system will permit cessation of monitoring activities.

One of the most important aspects of the MSMN will be monitoring tracers introduced during repository construction. This activity will be ongoing throughout the preclosure period. Arguably, direct observation of transport below the repository horizon provides the most unambiguous validation of performance assessment models and the assumptions inherent in the license application. Long-term geochemical sampling conducted under the *Performance Confirmation Plan* can increase confidence that the repository design achieves the necessary performance objectives required to protect public health and safety. In addition, near-field geochemical sampling provides data to understand the complex reactions between engineered materials and the natural barrier system.

The MSMN can be expanded from the natural barrier system to include monitoring the engineered barrier system and near field. This would include the following activities described in the *Performance Confirmation Plan*:

- Thermally accelerated drift near-field monitoring
- Thermally accelerated drift environment monitoring
- Thermally accelerated drift thermal mechanical effects monitoring
- Seal testing

Distributed fiber-optic networks can be embedded in the waste emplacement drift inverts and within backfill to provide temperature and strain information around the periphery of the drift and embedded within the concrete invert. Collocated U-tube samplers can provide gas and liquid samples at these same locations. Similarly, monitoring saturation around the drift periphery can quantify the extent of dryout and provide evidence of flow diversion. The U-tube samplers and suitable gas and liquid tracers can be used for active *in situ* testing of the integrity of grout seals. Throughout the preclosure period, tracers can be periodically injected on one side of a grout seal and can then be sampled for, from within and on the other side of the grout curtain, to provide information on grout seal integrity.

Summary

Seizing the opportunity presented by the perturbation at Yucca Mountain provided by repository construction, we present a plan for performance confirmation testing—that is, to deploy a Mountain-Scale Monitoring Network of multilevel monitoring stations designed to perform reliably for decades, and be safely abandoned with minimal added cost. The proposed MSMN takes advantage of recent technological innovations, in particular distributed fiber-optic sensors and novel geochemical sampling systems, for acquisition of data on the spatial and temporal scale necessary to increase confidence that the repository will perform as intended after closure of the repository.

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References:

[1] Bechtel SAIC Company, LLC, 2004. Performance Confirmation Plan, TDR-PCS-SE-000001 Rev 05, Las Vegas, Nevada
[2] Freifeld, B. M., R. C. Trautz, Y. K. Kharaka, T. J. Phelps, L. R. Myer, S. D. Hovorka, and D. J. Collins, 2005. The U-tube: A novel system for acquiring borehole fluid samples from a deep geologic CO_2 sequestration experiment, *J. Geophys. Res.*, 110, B10203, doi:10.1029/2005JB003735.
[3] Aufleger, M., Conrad, M., Perlzmaier, S., and Porras, P., September 2005. Improving Fiber Optic Tool for Monitoring Leakage. *HRW*, 13 (4).
[4] Johansson, S., Farhadiroushan, M., and Parker, T., 2000. “Application of fibre-optics systems in embankment dams for temperature, strain and pressure measurements – some comparisons and experiences”, ICOLD Congress, Beijing, China.
[5] Johansson, S., and Watley, D., 2005. Distributed Strain Measurements For Embankment Dams –Field tests at Ajaure Dam 2004-05, Elforsk rapport 05:32 (in press).
[6] Von Herzen, R.P., and Maxwell, A.E., 1959. The measurement of thermal conductivity of deep-sea sediments by a needle-probe method. *J. Geophys. Res.*, 64: 1557-1563.
[7] Ballard, S., 1996. The in situ permeable flow sensor: A ground water flow velocity meter. *Ground Water*, 34 (2): 231–240.
[8] Su, G. W., Freifeld, B. M., Oldenburg, C. M., Jordan, P. D. & Daley, P. F., 2005. Interpreting Velocities from Heat-Based Flow Sensors by Numerical Simulation. *Ground Water* **0** (0), ???-???.doi: 10.1111/j.1745-6584.2005.00147.x **[*in press*]**

Table 1.Mountain-Scale Monitoring Network Parameters.

Monitored Parameter	**Enabling Technology**	**Processes Investigated**
Temperature	Fiber-optic distributed temperature sensor	Heat flux Percolation flux
Gas-phase pressure	Gas sampling port	Gas flux Barometric Pumping
Thermal properties	Constant wattage heat trace tubing	Heat flux Matrix saturation/Moisture Redistribution
Air-permeability	Gas sampling port	Fracture saturation/Moisture redistribution
Pressure head	Gas sampling port	Percolation flux Saturated zone pressure gradients
Gas chemistry	Gas sampling port	Pore fluid pH Mineral Dissolution/Precipitation Transport rates
Aqueous Chemistry Environmental tracers Tracers introduced during construction	U-tube sampling system	Mineral Dissolution/Precipitation Percolation flux Transport rates
Strain	Fiber-optic distributed strain sensor	Mechanical deformation

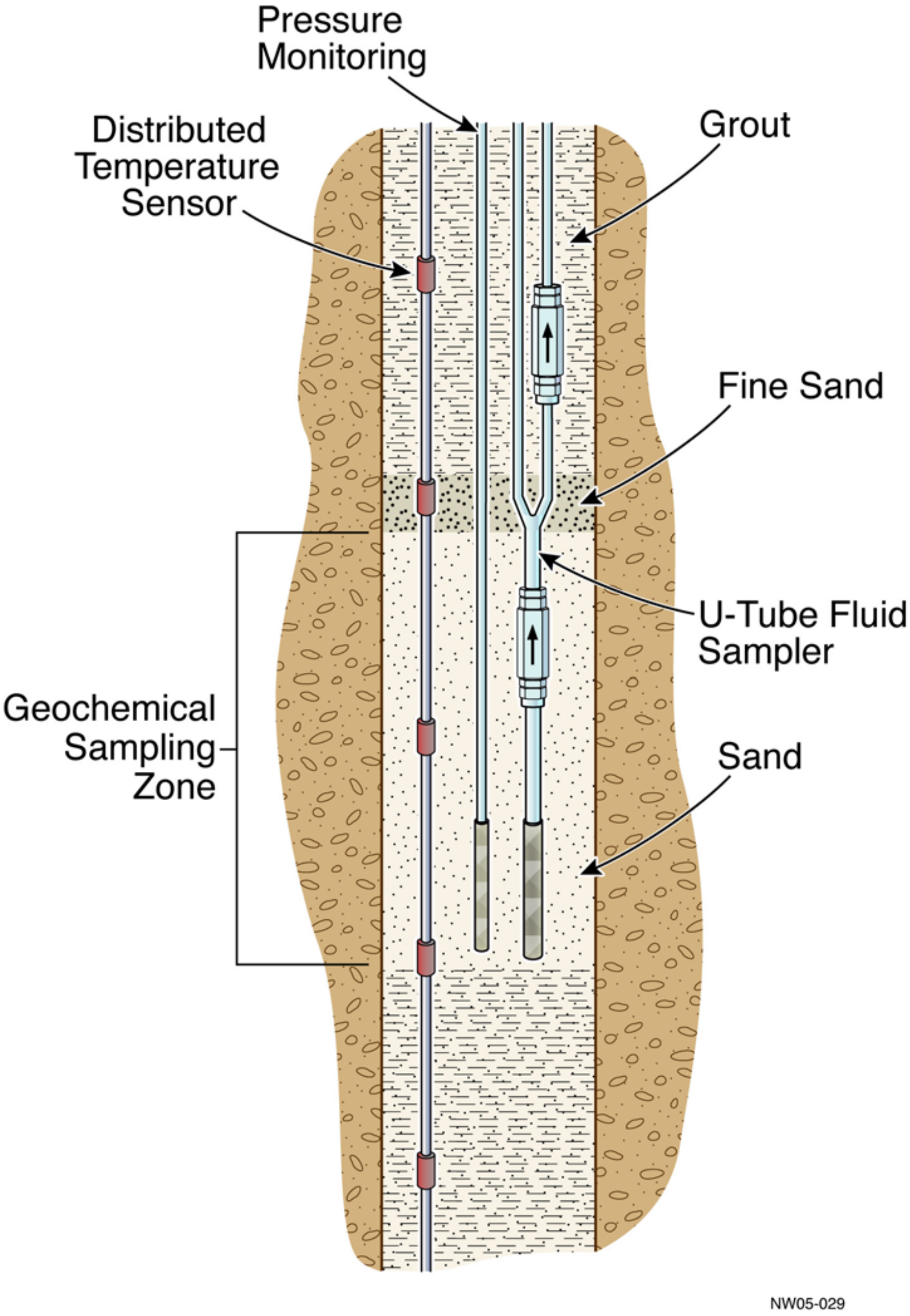

Figure 1. Conceptual layout of an instrumented interval in a Mountain-Scale Monitoring Network borehole. Important measured parameters include temperature and pressure, as well as collection of geochemical samples.

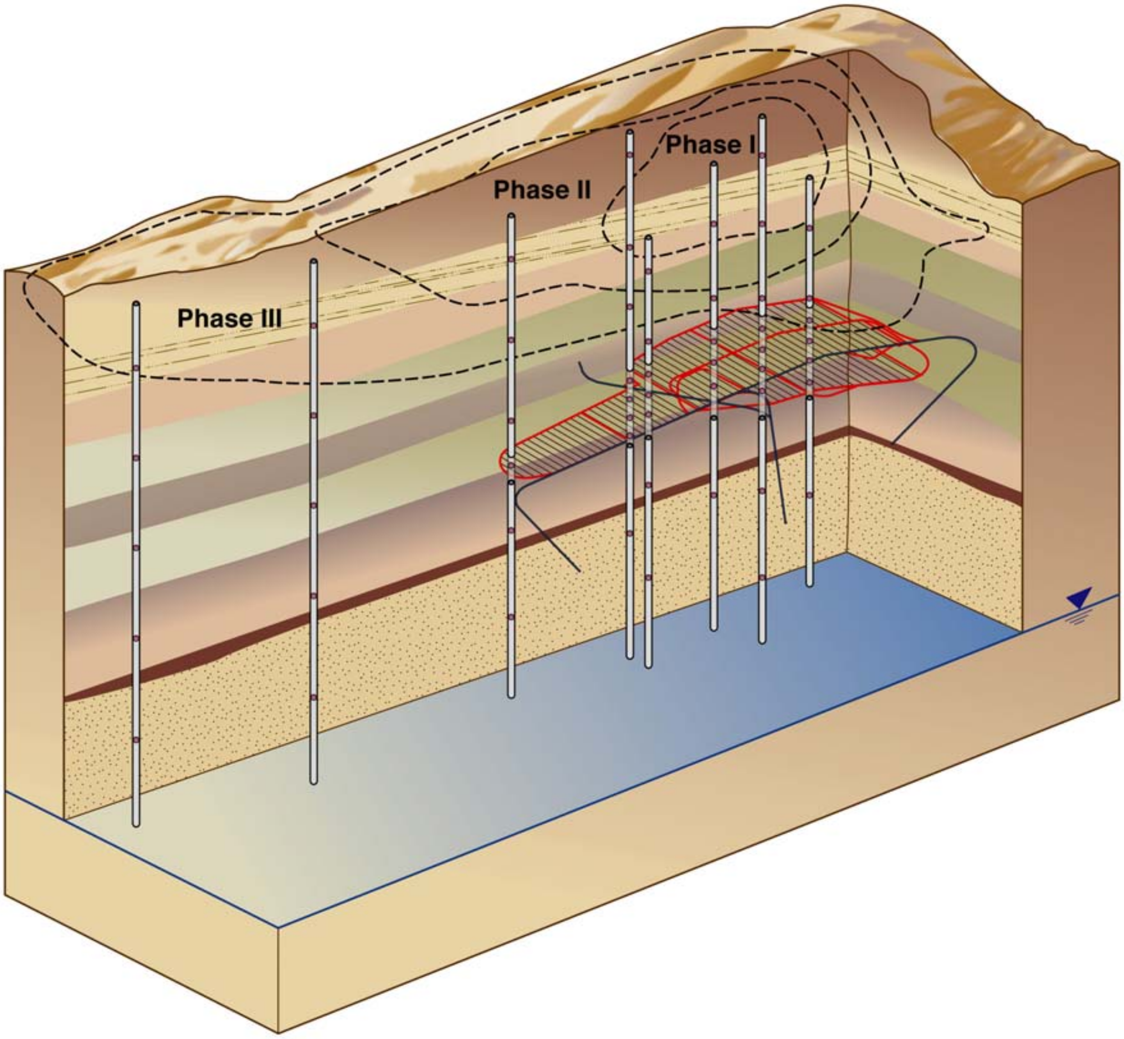

Figure 2. Schematic of a phased approach to the development of a Mountain-Scale Monitoring Network. Phase I monitoring boreholes are installed pre-emplacement, during initial repository construction. Phase II borings are installed during emplacement, and Phase III borings are constructed during the post-emplacement to closure time period.