METHODS AND SENSORS FOR MONITORING VARIABLY SATURATED FRACTURED ROCK AND THERMAL ENVIRONMENTS

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PREVIOUS REPORTS IN SERIES

Number	Title	Month Issued
CNWRA 2004-06 (ML043020389)	Performance Confirmation Activities under 10 CFR Part 63 with Emphasis on Activities Potentially Significant to Waste Isolation	September 2004
06002.01.191.610 (ML062060516)	Review of Vadose Zone Measurement and Monitoring Tools for Yucca Mountain Performance Confirmation Program	June 2006
06002.01.191.620 (ML061740535)	Review of Tools and Techniques to Monitor Repository Excavations	June 2006
06002.01.191.710 (ML071800385)	Sensor and Measurement Considerations for Long-Term Hydro-Environmental Monitoring of Vadose Zone Processes	June 2007

ABSTRACT

The U.S. Department of Energy (DOE) prepared a Performance Confirmation Plan to support its license application to construct a geologic repository for high-level radioactive waste and spent nuclear fuel at Yucca Mountain, Nevada. The plan identified a total of twenty performance confirmation activities to be undertaken by DOE. Eleven performance confirmation activities began during the Yucca Mountain site characterization phase and nine activities would commence should a construction authorization be granted. Performance confirmation activities are planned to continue during the construction and operation of the repository. This knowledge management report documents a review of information relevant to five selected performance confirmation activities that was performed in support of completing the U.S. Nuclear Regulatory Commission (NRC) Safety Evaluation Report (SER) for Yucca Mountain. This report focuses on literature that had been published or otherwise made available since the Center for Nuclear Waste Regulatory Analyses prepared a related report for NRC in 2007 on the topic of sensor and measurement considerations for long-term hydro-environmental monitoring of vadose zone processes, up until the SER was published in 2015. The five selected performance confirmation activities considered in this report have components related to monitoring methods and sensors for unsaturated-zone fractured rocks and thermal environments, such as would be anticipated within the proposed repository at Yucca Mountain during the preclosure period. Information contained in this report would be useful to assist NRC staff during review of evolving performance confirmation plans, should a construction authorization be granted.

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QUALITY OF DATA, ANALYSES, AND CODE DEVELOPMENT

DATA: All CNWRA-generated data contained in this report meet quality assurance requirements described in the CNWRA Quality Assurance Manual. Sources of other data should be consulted for determining the level of quality of those data. No original data were generated in this report.

ANALYSES AND CODES: No codes were used in the analyses contained in this report.

PRODUCT DESCRIPTION: Some methods discussed in this report are illustrated with an example to demonstrate how the method is implemented. There is no intent to provide an exhaustive catalog of manufacturers or products. Any use of trade, product, or firm names in this publication is for descriptive or illustrative purposes only and does not imply endorsement by CNWRA or NRC.

1 INTRODUCTION

In June 2008, the U.S. Department of Energy (DOE) submitted a license application (LA) (DOE, 2008) seeking authorization to construct a geologic repository for high-level radioactive waste and spent nuclear fuel at Yucca Mountain, Nevada, and in February 2009, DOE submitted an LA update (DOE, 2009a). As part of the LA, DOE described a Performance Confirmation Program in the Safety Analysis Report (SAR) (DOE, 2008, Section 4; 2009a), in references therein, as well as in its response to the U.S. Nuclear Regulatory Commission (NRC) staff's requests for additional information (DOE, 2009b, 2010). The NRC staff evaluation of the DOE plan for a Performance Confirmation Program was published in NRC (2014).

DOE's plan for the Performance Confirmation Program describes a set of measurements, experiments, and analyses that have been and would be conducted, where practicable, to evaluate the adequacy of the supporting assumptions, data, and analyses for the performance of the proposed repository. An objective of performance confirmation is to monitor key geotechnical and design parameters, including interactions between natural and engineered systems and components throughout repository construction and operation to identify any significant changes from conditions assumed in DOE's LA and evaluated by NRC in the Safety Evaluation Report (SER) that would affect postclosure safety. Changes in parameters and conditions during repository construction, operation, and through to closure would be identified by the Performance Confirmation Program by comparison with baseline and expected values. Baseline values were developed for the Performance Confirmation Program using assumptions, data, and analyses that DOE provided in the SAR (DOE, 2008, 2009a).

DOE's Performance Confirmation Plan (SNL, 2008) identified a total of twenty performance confirmation activities to be undertaken by DOE. Eleven performance confirmation activities began during the Yucca Mountain site characterization phase and nine additional activities would commence should a construction authorization be granted. Each activity would utilize a variety of measurement techniques and methodologies, some of which may overlap with those in other activities. The performance activities described in the Performance Confirmation Program will be periodically reassessed and updated by DOE to take advantage of new technology, or to respond to information that becomes available as a consequence of the activities. In several of the activities, DOE proposed methodologies or technologies for use in the unsaturated zone and thermal environment that did not yet exist. DOE stated that further development of specific monitoring devices or sensors would be needed, or that integration of specific technology not yet available would be needed to implement the measurements and inspections (e.g., DOE, 2008, Sections 4.2.1.2, 4.2.1.8, and 4.2.2.4). During the review, the NRC staff maintained an awareness and knowledge of relevant technological progress in the open literature to (i) provide context for the DOE proposed methods and techniques for measurements in the plan and (ii) better understand the gaps between existing technology and methodologies at the time of the SER and those that were proposed for use by DOE.

This Yucca Mountain knowledge management report documents a review of information relevant to five of 20 performance confirmation activities (Table 1-1). This report focuses on literature that had been published or otherwise made available since Or and Dinwiddie (2007) prepared a related performance confirmation report for the NRC, up until the SER was published in 2015. The five performance confirmation activities considered in this report have components related to monitoring methods and sensors for unsaturated-zone fractured rocks and thermal environments, such as those natural and thermally accelerated environments that would be anticipated within the proposed repository at Yucca Mountain during the preclosure period. Three of the five activities began during site characterization (i.e., subsurface water and rock testing, unsaturated zone testing, and seepage monitoring) and two would begin only after repository operations were underway (i.e., thermally accelerated drift near-field monitoring and in-drift environment monitoring). Information contained in this report would be useful to assist NRC staff during review of evolving performance confirmation plans, should a construction authorization be granted.

The organization of this Yucca Mountain knowledge management report is as follows. The second section of the report provides specific contextual information about DOE's five proposed unsaturated zone hydrology-related performance confirmation activities, for which potentially applicable monitoring sensors and methods are addressed throughout the remainder of the report. The third section of the report addresses geochemical monitoring methods pertinent to deep percolation, ambient and thermal seepage into the repository horizon, and radionuclide transport through the unsaturated zone. The fourth section of the report addresses methods and sensors for in-drift ambient and thermal seepage monitoring and the fifth section of the report addresses methods for near-field deep percolation monitoring. The sixth section provides a report summary.

Table 1-1. DOE-Proposed Performance Confirmation Hydrologic Monitoring and Testing Activities (SNL, 2008)

Activity	Description	Candidate Parameters	Purpose	Barrier	Proposed Tools and Techniques
General Requirements (NRC, 2014, Section 2.4.3.1.2)					
Subsurface water and rock testing	Laboratory analysis of chloride concentration and isotope chemistry based on collected water and rock samples	Chloride concentration; isotopic composition for U, Sr, O, ^{3}H, $^{36}Cl/Cl$, ^{99}Tc, and $^{129}I/^{127}I$	Confirm assumptions for fast paths used in unsaturated zone models	Upper and Lower Natural Barriers	Pore water chloride and rock/fracture coating isotope sampling from core, ion chromatography, isotope and dissolved ion analysis, bulk rock analyses, fracture coating analyses
Unsaturated zone testing	Testing of transport properties and field sorptive properties of the crystal-poor member of the Topopah Spring Tuff in ≥2 ambient seepage alcoves or drifts	Fracture density, apertures, coatings, fracture and matrix van Genuchten parameters, air permeability, deep percolation, air temperature and relative humidity, colloid/colloid-facilitated transport parameters, sorption parameters	Confirm transport properties and sorption coefficients used in unsaturated zone models	Lower Natural Barrier	Fracture mapping, single- and cross-hole air-injection and tracer-release testing, thermocouple psychrometers, relative humidity and temperature probes, geochemical analysis of water samples, derivation of water flow and radionuclide transport and sorption properties
Geotechnical and Design Parameters (NRC, 2014, Section 2.4.3.2)					
Thermally accelerated drift near-field monitoring	Monitoring of near-field coupled processes occurring around a thermally accelerated drift (i.e., thermal-hydrologic-mechanical*-chemical) properties and parameters	Fracture permeability, initial moisture content of retrieved core, evolving rock-mass moisture content, water chemistry, rock temperature and thermal gradients, mechanical deformation*, mechanical properties*	Confirm coupled process results from the thermal-hydrologic-chemical-mechanical* models	Upper Natural Barrier, Engineered Barrier System, Lower Natural Barrier	Borehole air injection testing and moisture monitoring (e.g., using neutron and induction logging, electrical resistivity tomography and crosshole radar tomography) via borehole arrays drilled from a lower observation drift upward toward the thermal drift; borehole-core testing for moisture and hydrochemical analyses; resistive temperature devices

Table 1-1. DOE-Proposed Performance Confirmation Hydrologic Monitoring and Testing Activities (SNL, 2008)

Activity	Description	Candidate Parameters	Purpose	Barrier	Proposed Tools and Techniques
Geotechnical and Design Parameter (NRC, 2014, Section 2.4.3.2)					
Thermally accelerated [drift] in-drift environment monitoring	Monitoring and laboratory testing of water quantities, composition, and ionic characteristics (including thin films); gas composition; microbial types and amounts; radiation* and radiolysis*; and microbial* types and amounts within a thermally accelerated drift	Thermal seepage, thin films, condensation water quantities, water composition, including microbes, and dissolved ionic species and ratio of aggressive to inhibitor ions; temperature, relative humidity, and barometric pressure; gaseous oxygen and carbon dioxide concentrations, radionuclides, radiolysis	Confirm assumptions used for in-drift physical and chemical environmental models	Upper Natural Barrier, Engineered Barrier System	Thermal seepage monitoring (video of locations and flowrate measurements), barometric pressure transducers wind speed sensors, thermocouple psychrometers, relative humidity and temperature probes, water sampling and chemical analysis (ionic species)
Thermal and ambient seepage monitoring	Seepage monitoring and laboratory analysis of water samples (from bulkheaded alcoves on the intake side of the repository and in a thermally accelerated drift)	Seepage rate, locations, quantity and chemical composition; ventilation air barometric pressure, temperature, and relative humidity	Confirm spatiotemporal seepage distribution results from seepage models and thermal loading effects	Upper Natural Barrier	Thermal and ambient seepage monitoring (video of locations and flowrate measurements), water sampling and chemical analysis; Barometric pressure transducers wind speed sensors, thermocouple psychrometers, relative humidity and temperature probes

*Consideration of performance confirmation of near-field mechanical properties, radiation, radiolysis, and microbial species is beyond the scope of this report

2 YUCCA MOUNTAIN UNSATURATED-ZONE-HYDROLOGY–FOCUSED PERFORMANCE CONFIRMATION ACTIVITIES

This section provides the context for the selection of five of DOE's twenty Performance Confirmation activities (Table 1-1) for which related monitoring methods are addressed throughout the remainder of this knowledge management report. A description of DOE's proposed Performance Confirmation activities provides context to better understand the potentially related monitoring methodologies and sensors that this report covers. The purpose of this Yucca Mountain knowledge management report is to document a review of advances in sensors and long-term monitoring methods that are relevant to the following five DOE-proposed Performance Confirmation activities. The five Performance Confirmation activities considered in this report, summarized next, have a significant focus on unsaturated zone hydrological and thermal processes of the Upper Natural Barrier, Engineered Barrier System, and Lower Natural Barrier at the proposed Yucca Mountain repository.

2.1 Subsurface Water and Rock Geochemical Testing

To confirm that the Upper Natural Barrier functions as anticipated and verify assumptions for fast flow pathways in unsaturated zone models, this activity would involve sampling and geochemical analyses of pore-water, rock, and low-temperature fracture minerals in the immediate vicinity of repository openings (DOE, 2009a). Laboratory analysis of isotope geochemistry {uranium [U], strontium [Sr], oxygen [O], hydrogen [H], chlorine-36/chlorine [$^{36}Cl/Cl$], tritium [^{3}H], technetium-99 [^{99}Tc], and iodine-129/iodine-127 [$^{129}I/^{127}I$] and ions (e.g., pore-water chloride [Cl^{-}] concentration/mass balance)} (SNL, 2008, Section 3.3.1.3; DOE, 2009a) would document actual subsurface conditions encountered and determine the water, rock, and fracture-filling chemistry of the Upper Natural Barrier in the zone where deep percolation may become seepage. Fracture minerals would be analyzed for ages and isotopic composition to confirm assumptions about the long-term percolation history of flow through the unsaturated zone (SNL, 2008, Section 3.3.1.3). Pore-water, rock, and fracture-filling sample collection and data analyses began during site characterization and would continue throughout repository construction as new drifts are excavated to extend the dataset for areas of the repository not previously sampled (SNL, 2008, Section 3.3.1.3). Two-meter-long boreholes would be dry drilled from drifts and retrieved cores would be carefully handled and preserved to avoid Cl^{-} contamination and drying (SNL, 2008, Section 3.3.1.3). Pore water would be extracted from the cores by centrifuge, and analyzed comprehensively by ion chromatography for dissolved ions and for isotopes. Fracture coatings would be collected from drift exposures where their high concentration at faults or other locations suggests relatively high percolation flux, and this material would be analyzed for U and Sr isotope geochemistry (SNL, 2008, Section 3.3.1.3). Bulk rock analyses of retrieved cores also would be undertaken for U and Sr isotope geochemistry (SNL, 2008, Section 3.3.1.3). DOE indicates it would publish the Subsurface Water and Rock Testing test plan before subsurface repository construction begins (DOE, 2009b). Results would be used to confirm the Cl^{-} concentration and isotopic information used in numerical models to describe the hydrologic conditions for flow in the unsaturated zone (SNL, 2008, Section 3.3.1.3). The state of the art for these geochemical measurement activities is summarized in Section 3 of this report.

2.2 Thermally Accelerated Drift Near-Field Monitoring

A goal of thermally accelerated drift near-field monitoring is to discern the postclosure response of the near-field environment to heat within emplacement drifts (SNL, 2008, Section 3.4.5). The near-field is the rock mass immediately surrounding repository drifts outward to a distance that encompasses significant and evolving thermal or excavation-induced changes in physical and chemical properties (DOE, 2009a). Near-field thermal testing in the crystal-poor middle nonlithophysal tuff began during site characterization with heaters rather than radioactive waste, including at the Single Heater Test and Drift Scale Test at the Thermal Test Alcove (i.e., Alcove 5) off the Exploratory Study Facility (ESF) and at the Large Block Test at an outcrop at Fran Ridge (SNL, 2008, Section 3.3.1.9; DOE, 2009a, Section 2.3.3.3.2).

Thermally accelerated drift near-field monitoring would be initiated during repository operations, with heat generated by emplaced waste packages, and would continue until closure (SNL, 2008, Section 3.3.1.9). DOE proposes to develop a thermally accelerated drift or test facility (Emplacement Drift 3) in the first panel of emplacement drifts (SNL, 2008, Figure 3-1). An observation drift would be excavated parallel to Emplacement Drift 3, but offset by 20 m (66 ft) to the north, beginning at Alcove 5 in the ESF, extending under the first panel, and ramping up to connect with the exhaust main on the opposite side of the panel (DOE, 2009a, Figures 1.3.3-18 and 1.3.3-19). Alcoves are small excavations, located off access mains away from significant traffic, for conducting testing and borehole monitoring operations and for housing monitoring instrumentation and associated electrical and communication equipment (DOE, 2009a, Section 1.3.3.1.7). A new monitoring alcove for the thermal test facility would connect at a right angle to the observation drift and pass below the thermally accelerated drift with a minimum of 10 m (33 ft) of tuff between the alcove ceiling and the drift invert (DOE, 2009a, Sections 1.3.3.1.6 and 1.3.3.1.7; Figures 1.3.3-18 and 1.3.3-19). The observation drift would enable monitoring of the near-field below and north of the axis of the thermally accelerated drift, whereas the alcove would enable monitoring of a cross-section of the near-field below and north and south of the thermally accelerated drift (DOE, 2009a, Section 1.3.3.1.6; Figure 1.3.3-19).

Mapping, instrumenting, and loading the thermally accelerated drift with waste packages is anticipated to take 1 to 2 years (SNL, 2008, Section 3.4.5). Then, ventilation would be gradually reduced to enable in-drift temperatures to increase during a 10–15-year period into the postclosure temperature range with the goal of achieving peak drift wall temperature {i.e., ≤150 °C [≤302 °F]} (SNL, 2008, Sections 3.3.1.11 and 3.4.5; DOE, 2009a,b). Sometime after attaining peak drift wall temperature, drift ventilation would be gradually increased or waste package removal would be initiated to enable the test drift to cool below boiling {<96 °C [204.8 °F]} to near ambient conditions before repository closure occurs (SNL, 2008, Section 3.4.5; DOE, 2009b). Near-field processes would be accelerated from occurring over a timespan of approximately 2,000 years to occurring over only approximately 100 years (SNL, 2008, Section 3.4.5).

Monitoring of near-field coupled thermal-hydrologic-mechanical-chemical processes and physical properties would be undertaken to confirm—in a surrogate environment for postclosure conditions—results obtained from the thermal-hydrologic-mechanical-chemical model, which are relevant to both the Upper and Lower Natural Barriers (DOE, 2009a), with regard to spatiotemporal distributions of drift seepage and deep percolation of radioactive waters. Important processes include evaporation, mineral dissolution and precipitation, and aqueous and gaseous-phase transport and chemical reactions (SNL, 2008, Section 3.3.1.9). DOE proposed ongoing, periodic measurement of geochemistry, porosity, and matrix and fracture permeability to monitor transient to permanent changes in these properties (i.e., evolution of the near-field environment) caused by thermal loading, and to thereby confirm thermal-hydrologic-mechanical-chemical modeling results that pertain to drift seepage and radionuclide transport (SNL, 2008, Section 3.3.1.9). Fracture permeability changes are anticipated to occur from a combination of moisture redistribution, mineral precipitation, and fracture aperture contraction/expansion from thermally induced stresses, and an ongoing series of periodic air injection tests would be undertaken in boreholes below (and possibly above) a thermally accelerated drift (SNL, 2008, Section 3.3.1.9) to measure evolving fracture permeability. Air injection boreholes may serve a dual purpose if they are also used to collect water samples for isotopic and ionic analyses to assess the water source (i.e., seepage vs. condensation) (SNL, 2008, Section 3.3.1.9). Near-field monitoring would employ borehole arrays drilled from underlying observation drifts or alcoves upward toward but not intersecting overlying waste emplacement drifts to monitor evolving properties of near-field rock (SNL, 2008, Sections 3.3.1.9 and 3.4.5; DOE, 2009a, Section 1.3.3.1.7). Boreholes would be dry drilled and retrieved cores would have their pore water extracted, measured for initial moisture content, and chemically analyzed as under the subsurface water and rock testing activity described in Section 2.1 (SNL, 2008, Section 3.3.1.9; DOE, 2009a).

Borehole geophysics, such as neutron and induction logging, electrical resistivity tomography, and cross-hole radar tomography would be used to monitor spatiotemporal distribution of moisture content as the boiling/condensation front traverses the rock mass in response to heating and cooling (SNL, 2008, Section 3.3.1.9). Borehole geophysical instrumentation may require hardening for use under high temperatures. DOE proposed to use commercially available resistive temperature devices installed in an array of vertically stacked, horizontal boreholes drilled orthogonal to the longitudinal axis of emplacement drifts to characterize the thermal property heterogeneity of the wall rock and for ease of comparison with model output (SNL, 2008, Section 3.3.1.9). DOE indicates this long-term monitoring would be conducted periodically around the thermally accelerated drift, but at a frequency yet to be determined (SNL, 2008, Sections 3.3.1.9 and 3.4.5; DOE, 2009b). DOE indicates it would publish the Thermally Accelerated Drift Near-Field Monitoring test plan during repository operations (DOE, 2009b). Development of heat- and radiation-hardened instrumentation, communication relays, and peripherals may be necessary to accomplish this performance confirmation activity. The state-of-the-art for borehole temperature monitoring is summarized in Section 5 of this report, and the reader is referred to Dinwiddie and Stothoff (2013) for their recent reviews of borehole geophysical methods proposed for use by DOE.

2.3 Thermally Accelerated Drift In-Drift Environment Monitoring

A goal of thermally accelerated drift in-drift monitoring is to discern the postclosure response of the repository environment to heat within emplacement drifts (SNL, 2008, Section 3.4.5). Monitoring the environment surrounding waste packages and drip shields would confirm assumptions used for in-drift physical and chemical environmental models of the performance lifetimes of EBS components that are at risk of corrosion (SNL, 2008, Section 3.3.1.11). Drift-scale testing of the anticipated emplacement environment and thermal-hydrologic-chemical coupled processes in the crystal-poor middle nonlithophysal Topopah Spring Tuff began during site characterization at the Drift Scale Test in Alcove 5 off the ESF (DOE, 2009a, Section 2.3.3.3) using heaters rather than radioactive waste.

Thermal management of the test facility using radioactive waste may be achieved by tailored waste package loading using less-than-full waste packages, waste of older-than-average age, increased spacing between waste packages, or scheduled relocation of waste packages, as well as ventilation (SNL, 2008, Section 3.4.5; DOE, 2009b). Because any artificial ventilation used during the thermally accelerated drift test (Section 2.2) would dominate in-drift hydrologic phenomena, such as seepage and condensation (SNL, 2008, Section 3.4.5), DOE may tend to rely more on scheduled movement of waste packages in and out of the test facility to manage the thermal environment (DOE, 2009b). Mapping, instrumenting, and loading the drift with waste packages is anticipated to take 1 to 2 years (SNL, 2008, Section 3.4.5). Ventilation may be terminated after 5 to 15 years to monitor in-drift thermal, hydrological, mechanical, and chemical effects in the absence of, and therefore unaffected by, ventilation (SNL, 2008, Section 3.4.5).

Thermally accelerated drift in-drift environment monitoring includes *in situ* seepage monitoring, as described in Section 2.4 (SNL, 2008, Section 3.3.1.2), and laboratory and field-testing that would be initiated during operations with heat generated by emplaced waste packages, and which would continue until repository closure (SNL, 2008, Section 3.3.1.11). Overall, this activity would monitor thermally accelerated drift in-drift physical and chemical conditions, including gas composition; in-drift water quantities, composition, and ionic characteristics (including thin films); microbial species; and radiation and radiolysis effects. A remote monitoring device could be used to collect water and microbial samples from drip shields for dissolved ionic species analyses and microbe species analyses (refer to Table 4-1 for technology development requirements), and stationary sensors would measure drift temperatures and relative humidity (SNL, 2008, Sections 3.3.1.11 and 3.4.5). Likewise, carbon dioxide (CO_2) and O_2 concentrations in the drift atmosphere would be measured by a remote monitoring device or stationary sensors (SNL, 2008, Section 3.3.1.11). Future DOE test plans would discuss how and how often remotely collected field samples would be removed from bulkheaded emplacement drifts or alcoves (SNL, 2008, Section 3.4.5) for laboratory analysis.

Technology exists for making measurements in bulkheaded, heated alcoves. During the Drift Scale Test, for example, approximately 1,750 thermal sensors collected temperature data in the vicinity of a 50-m-long drift segment (DOE, 2009a, Section 2.3.3.3.3.2). However, the combined high-temperature and high-radiation environments representative of post-emplacement conditions in a thermally accelerated drift require integration of specific technology applications to accomplish measurements and inspections (SNL, 2008, Section 3.3.1.11). DOE indicates this long-term monitoring of 1 or 2 thermally accelerated drifts would be conducted periodically, but at a frequency yet to be determined (SNL, 2008, Sections 3.3.1.11 and 3.4.5). DOE indicates it would publish the Thermally Accelerated Drift In-Drift Environment Monitoring test plan during repository operations (DOE, 2009b).

2.4 Thermal and Ambient Seepage Monitoring

Seepage represents the fraction of deep percolation from the Upper Natural Barrier that can enter drifts to contact the Engineered Barrier System (DOE, 2009a). Seepage does not include advective or diffusive vapor flow into drifts or condensation of water vapor on in-drift surfaces; only dripping water is considered seepage (DOE, 2009a; Section 2.3.3.2.1). Seepage monitoring in sealed (i.e., bulkheaded), unventilated (i.e., ambient) alcoves and in the Enhanced Characterization of the Repository Block (ECRB) Cross-Drift began during site characterization (DOE, 2009a; Section 2.3.3.2.2.1) and would continue under the Performance Confirmation Program in new repository areas until repository closure (SNL, 2008, Section 3.3.1.2). General observations for evidence of seepage also would be conducted in conjunction with drift inspections (SNL, 2008, Section 3.3.1.2). Seepage monitoring includes observations of seepage occurrences and quantities; geochemical analyses of seepage water samples collected from ambient alcoves (or boreholes) and from thermally accelerated test drift(s); and local monitoring of barometric pressure, temperature, and relative humidity within thermally accelerated test drift(s) to characterize moisture dynamics (SNL, 2008, Section 3.3.1.2; DOE, 2009a, Section 1.3.3.1.7). Relative humidity is the key factor affecting evaporation potential, which controls the amount of liquid water at drift walls that is available for drop formation and seepage into drifts (DOE, 2009a, Section 2.3.3.2.1.3). Whereas seepage into drifts is not anticipated during the operational period when repository drifts will be ventilated (SNL, 2008, Section 3.3.1.2), seepage monitoring inside thermally accelerated, unventilated, drifts (Section 2.3) may confirm thermal seepage modeling results (DOE, 2009a, Section 2.3.3.3). Remote video camera systems would make seepage observations in both ambient alcoves and thermally accelerated drift(s), necessitating heat- and radiation-hardened camera systems (addressed in Section 4.2.1). Video monitors would look for any dark spots on the rock wall ground support and wet spots on the drip shields (SNL, 2008, Section 3.3.1.2). Environmental sensors would be monitored for relative humidity spikes and abrupt decreases in air temperature as proxies for drift seepage (SNL, 2008, Section 3.3.1.2). Heat- and radiation-hardened in-drift environmental sensors and peripheral equipment would be required (addressed in Sections 4.2.2 through 4.2.4), such as barometric pressure transducers, relative humidity and temperature probes, wind speed sensors, data loggers, and fiber-optic network cables (cf. SNL, 2008, Section 3.3.1.2). DOE indicates it would publish the Seepage Monitoring test plan before subsurface repository construction begins (DOE, 2009b).

2.5 Unsaturated Zone Radionuclide Transport Testing

The geologic repository at Yucca Mountain would be constructed mainly in the crystal-poor lower lithophysal and the middle nonlithophysal units of the Topopah Spring Tuff (SNL, 2008, Figure 3-1). *In situ* unsaturated zone tests for radionuclide transport characteristics within ambient seepage alcoves or non-emplacement drifts would be performed at one or more excavations into each of these units to confirm that the Lower Natural Barrier functions as anticipated within the assumed range of behavior (DOE, 2009a). This type of activity began during site characterization; these new activities would begin during repository construction and continue through the early stages of waste emplacement (SNL, 2008, Section 3.3.1.4).

Unsaturated zone testing would involve fracture mapping and aperture measurement (see SNL, 2008, Section 3.3.2.1 on Subsurface Mapping), air injection testing, tracer release, and subsequent field measurement of water flow and radionuclide-specific transport and sorptive properties (i.e., van Genuchten parameters describing fractures and matrix, permeability, and effective sorption coefficient or K_d) based on test results and sampling and analysis of rock and tracer chemistry captured in ambient alcoves below repository drifts (SNL, 2008, Section 3.3.1.4; DOE, 2009a). Field results would be compared to laboratory batch test results and would confirm parameters used in DOE's numerical models to describe flow and colloid or colloid-facilitated transport in the unsaturated zone below the repository at Yucca Mountain (SNL, 2008, Section 3.3.1.4). DOE proposed to use a system of up to nine horizontal boreholes, up to 10 m long, stacked vertically from alcove floor to ceiling with which to conduct single-hole and cross-hole air injection tests and tracer release and capture tests at representatively fractured locations near mapped excavations (SNL, 2008, Section 3.3.1.4; DOE, 2009a). Selected tracers would satisfy the need for physically modeling both highly sorptive and poorly sorptive radionuclides (DOE, 2009a). K_d values would be computed based on the changes in tracer concentrations that occur between the upper release and lower capture boreholes. DOE indicates it would publish the Unsaturated Zone Testing test plan during subsurface repository construction (DOE, 2009b). The state of the art for these measurement activities is summarized in Section 3 of this report.

3 WATER CHEMISTRY AND CHEMICAL PRECIPITATE ANALYSIS

Yucca Mountain Performance Confirmation activities related to the Upper Natural Barrier and Lower Natural Barrier are intended to provide data to evaluate if these barriers would function as intended and anticipated. This section discusses geochemical measurements DOE proposed in its SAR (DOE, 2008, Section 4; 2009a), in references therein, and in its response to NRC staff's requests for additional information (DOE, 2009b, DOE, 2010) and reviews the state of the art for using geochemical indicators to address this goal. The review focuses on techniques and technologies considered in support of completing NRC's SER for Yucca Mountain that may have been developed since June 2007, when CNWRA transmitted a report to NRC related to sensor and measurement considerations for long-term monitoring of the vadose zone at Yucca Mountain (Or and Dinwiddie, 2007).

3.1 Upper Natural Barrier

The Upper Natural Barrier at Yucca Mountain consists of surface features that limit infiltration of meteoric precipitation into the shallow bedrock and properties and structures in the unsaturated bedrock above the proposed repository that limit percolation of water from reaching the Engineered Barrier System. These features of the Upper Natural Barrier are expected to greatly limit the rate and volume of percolating meteoric water that can enter the Engineered Barrier System. Thus, the performance confirmation activities that are based on geochemical indicators, in whole or in part, as proposed by DOE are intended to provide data to test this assumption. Specifically, geochemical sampling and analyses would be used to identify the chemical composition of deep percolation and confirm (i) assumptions about slow and fast flow pathways used in DOE's unsaturated zone flow models, (ii) thermal-hydrologic-chemical-mechanical near-field modeling results, and (iii) ambient and thermally accelerated seepage model results (see Table 1-1), as well as to specifically evaluate (SNL, 2008, Section 3.3.1.3):

- The percolation history of flow through the Upper Natural Barrier based on ages and isotopic composition of low-temperature fracture minerals
- Whether the fast pathway parameters used in the unsaturated zone flow models sufficiently represent subsurface conditions
- Upper Natural Barrier residence time based on the effects of water–rock interactions on the isotopic systems at the bulk-rock scale
- The potential percolation flux through the repository level

The DOE Performance Confirmation Plan (SNL, 2008) includes monitoring of precipitation and its chemical and isotopic composition, monitoring of seepage, if any, and its chemical and isotopic composition in unventilated alcoves and in a thermally accelerated test drift, collection and analysis of pore-water chemistry and isotopy in rock core samples, and analysis of fracture coating chemistry and isotopy (DOE, 2008, Section 4; 2009a). Specific chemical and isotopic constituents to be analyzed are Cl^-, U and Sr isotopes, O isotopes, Tritium (^3H), $^{36}Cl/Cl$ isotopic ratio, ^{99}Tc, and $^{129}I/^{127}I$ isotope ratio. According to the Performance Confirmation Plan (SNL, 2008), fracture coatings may suggest a high percolation flux. Fracture coating samples and bulk rock (from borehole core) would also be analyzed by DOE for isotope geochemistry (e.g., U and Sr isotopes).

Or and Dinwiddie (2007) proposed the potential use of artificial tracers applied at or near the land surface as indicators of deep percolation and seepage of meteoric water into the repository horizon. More recent geochemical indicators to elucidate the nature and extent of seepage into the repository horizon were reviewed in support of completion of NRC's SER for Yucca Mountain and may be potential considerations for inclusion in performance confirmation test plans should a construction authorization be granted (i.e., performance confirmation plans are likely to evolve during construction and operations). Potential considerations are:

- Are there any environmental tracers or other indicators associated with seepage of meteoric water that have been identified since development of the Performance Confirmation Plan?

- Are there any new methods for analyzing environmental tracers that would significantly contribute to performance confirmation?

- Are there any new methods for collecting water and tracer samples that would contribute to performance confirmation?

3.1.1 Indicators of Deep Percolation and Drift Seepage

The Performance Confirmation Plan (SNL, 2008) proposes the use of environmental tracers and analysis of fracture coatings as indicators of deep percolation and drift seepage, as addressed in the LA and considered by NRC staff during preparation of the SER. For the purposes of this report, environmental tracers are chemical or isotopic constituents of either natural or artificial origin that are present in meteoric water or the shallow vadose zone that can be used as indicators of deep percolation into the repository horizon. The environmental tracers identified in the Performance Confirmation Program (Cl, O isotopes, ^{3}H, and $^{36}Cl/Cl$) were used by DOE during Yucca Mountain site characterization (e.g., Flint et al., 2002) and at numerous other locations to estimate deep percolation and groundwater recharge rate (e.g., Phillips, 1994). Marshall et al. (2012) provide a summary of past applications of environmental tracers during Yucca Mountain site characterization.

Tritium and ^{36}Cl have particular utility as groundwater tracers because the discrete timing of their input to the atmosphere from above-ground nuclear bomb testing is well known (e.g., Fabryka-Martin et al., 1985). More recently, the Fukushima nuclear accident may have provided another pulse of radionuclides to the atmosphere (Xu et al., 2013) that may be useful for determination of flux rates. The Performance Confirmation Plan (SNL, 2008) also includes ^{99}Tc and $^{129}I/^{127}I$ in the Upper Natural Barrier analytical suite. Like tritium and ^{36}Cl, iodine is a non-sorbing tracer. ^{99}Tc may have been included by DOE in the analytical suite because it is a highly mobile radionuclide, and it might be feasible to release ^{99}Tc on a very limited scale during a performance confirmation activity to obtain related transport information (see Section 3.2).

Environmental tracers not included in the performance confirmation monitoring suite that have been used to study sources and ages of deep percolation include stable hydrogen and O isotopic ratios, Carbon-14 (^{14}C), noble gases, chlorofluorocarbon compounds (CFCs) and sulfur hexafluoride (SF_6). Stable hydrogen and O isotope ratios have primarily been used as source water indicators because they are sensitive to the temperature of recharge locations (e.g., Coplen et al., 2000).

Noble gases (helium, neon, argon, krypton, and xenon) also have been used as source water and water age indicators because their concentration in subsurface water is a function of recharge temperature (e.g., Aeschbach-Hertig et al., 1999; Stute and Schlosser, 2000). Their use in the vadose zone is limited, however, due to the interaction of pore water with pore gases. Because of barometric pumping and vapor-phase diffusion in Yucca Mountain (e.g., Ahlers et al., 1999; Flint et al., 2002), noble gas concentrations in pore water and seepage samples would be difficult to interpret. Marshall et al. (2012) summarized gas chemistry in the vadose zone at Yucca Mountain and concluded that (i) gas transport in the deep unsaturated zone was due to molecular diffusion and (ii) gas and pore water concentrations were not in equilibrium due to sample artifacts, thus complicating the interpretation of volatile environmental tracers, including ^{14}C ages. If the difficulties could be reconciled, vapor phase tracers have the potential to shed light on near-field conditions such as oxidation potential and temperature evolution associated with the thermal tests discussed in Section 4.

CFCs are chemical compounds introduced into the atmosphere and meteoric water from release of refrigerants (e.g., Plummer and Busenberg, 2000; Marshall el al., 2012). SF_6 was released into the atmosphere starting in the 1950s from electrical switch gear in which it was used as an insulator (e.g., Maiss and Brenninkmeijer, 1998). Both CFCs and SF_6 have been used as indicators of recent recharge to groundwater (e.g., Gooddy et al., 2006). As with noble gases, the use of both CFCs and SF_6 for age-dating deep percolation at Yucca Mountain would be complicated due to exchange between pore water and pore gas in the vadose zone. Marshall et al. (2012) reported that SF_6 samples had been collected and analyzed in conjunction with vadose zone gas sampling at Yucca Mountain, but did not provide interpretations based on SF_6 analyses.

3.1.2 Analytical Technologies

Analytical technologies that may be used to conduct Performance Confirmation activities, as were considered by NRC during preparation of the SER, are well established for the analytical suite proposed by DOE in the Performance Confirmation Plan (SNL, 2008) for monitoring seepage water and pore-water chemistry and isotopy. These include ion chromatography for Cl^-, mass spectroscopy for isotopes, and liquid scintillation spectroscopy (^3H). Although improvements in the accuracy and precision of analytical techniques are always possible, the state of the analytical art has not changed significantly since the Performance Confirmation Plan (SNL, 2008) was published.

Improvement in sample collection and processing may be possible, particularly in regard to collection and extraction of pore water from bulk rock and core specimens. For example, Cizdziel et al. (2008) compared the results of $^{36}Cl/Cl$ measurements on soil and rock samples using alternative leaching methods and bromide as opposed to Cl^- precipitation with the results of previous analyses reported by Los Alamos National Laboratory (LANL) (USGS, 2006). The $^{36}Cl/Cl$ ratios reported by Cizdziel et al. (2008) were generally lower than those reported by LANL.

Dinwiddie and Stothoff (2013; Section 4.3.1.5) provided a brief overview of a diverse family of fiber optic chemical sensors (Wang and Wolfbeis, 2013; references therein) that may be deployed downhole, and their potential advantages and disadvantages. Fiber optic chemical sensors enable optical spectroscopy from the infrared to the ultraviolet, and in absorption, emission, and plasmonic resonance modes (Dinwiddie and Stothoff, 2013). They may be coated with chemically responsive materials to permit an even more extensive range of chemical analyses (Dinwiddie and Stothoff, 2013). Changes in the optical response of such sensors enable detection of aqueous or gaseous concentrations, either for specific species (e.g., O, carbon dioxide, ions) or for classes of compounds (e.g., volatile organic compounds), as well as pH, salinity, and even relative humidity (Dinwiddie and Stothoff, 2013). Fiber optic chemical samplers do not disturb flow and enable chemical sampling when physical extraction of water samples is challenging (Dinwiddie and Stothoff, 2013).

3.1.3 Sample Collection Technologies

As addressed in the LA and considered by NRC during preparation of the SER, collection of pore-water samples from boreholes adjacent to test alcoves or drifts, or pore-water extraction from borehole cores (Table 1-1), would be necessary before geochemical laboratory techniques could be applied to characterize deep percolation at Yucca Mountain. Pore water from the unsaturated zone of Yucca Mountain has typically been extracted for geochemical analysis by uniaxial compression or ultracentrifugation of dry-drilled rock cores (Marshall et al., 2012). A wide range of techniques for collecting water samples were reviewed by Dinwiddie and Stothoff (2013), including experimental absorption samplers (see ASTM D4696-92, ASTM International, 2008). These samplers consist of an absorbent material (e.g., a cellulose-nylon sponge or unglazed, tapered ceramic rod) that collects pore-liquid continuously until the sampler is removed for liquid extraction. Sponge samplers can be installed against the ceiling of a cavity. Absorbent methods are most effective in nearly saturated soils, but McLin et al. (2005) reported using absorbent wicks to obtain small amounts of water from boreholes in sandstone with low water content. Another relatively new water sample collection technique that may be applicable to performance confirmation is the automated equilibrium tension lysimeter (AETL) described by Masarik et al. (2004). This device is a modification of the equilibrium tension lysimeter that automatically maintains equilibrium between the lysimeter and the matrix to collect a water sample. Although the instrument has been used in soils, its capability for extracting water from a rock matrix is untested.

3.2 Lower Natural Barrier

The unsaturated Lower Natural Barrier at Yucca Mountain is characterized by properties and structures that limit deep percolation through the unsaturated bedrock below the proposed repository and that limit radionuclide transport from the repository to the water table. *In situ* unsaturated zone tests for radionuclide transport characteristics (see Table 1-1 and Section 2.5) would be performed at one or more excavations within boreholes extending from ambient seepage alcoves or non-emplacement drifts to confirm modeling assumptions about radionuclide sorption coefficients of the unsaturated Lower Natural Barrier (crystal-poor member of the Topopah Spring Tuff, in particular), and to confirm that this barrier functions as anticipated within the assumed range of behavior (DOE, 2009a). This type of activity began during site characterization and new activities would begin during repository construction and continue through the early stages of waste emplacement (SNL, 2008, Section 3.3.1.4). These activities include:

- *In situ* transport, colloid transport, and colloid-facilitated transport and sorption testing to measure transport and field sorptive properties at an ambient seepage alcove or drift

- Laboratory analysis of water samples collected from an ambient seepage alcove or drift (see Section 3.2) to identify chemical composition of deeper percolation waters.

The Performance Confirmation Plan (SNL, 2008) mentions the use of tracer tests to confirm the transport properties of highly sorptive and poorly sorptive radionuclides. At least one test would be performed in the Topopah Spring Tuff middle nonlithophysal zone (Tptpmn) (SNL, 2008). The sorptive behavior of redox-sensitive radioelements americium (Am), neptunium (Np), protactinium (Pa), plutonium (Pu), U, and Tc can be affected by changes in the redox state within the flow zone. Tracer tests would be performed between horizontal boreholes drilled from the unventilated alcoves after unsaturated flow tests have been performed by saturating the upper boreholes (SNL, 2008). Tracers would be added in the liquid phase (SNL, 2008). DOE would use tracers that represent both highly sorptive [e.g., Am, Np, Pa, Pu, Th, U, cesium (Cs), Sr, and radium (Ra)] and poorly sorptive [e.g., Carbon (C), I, and Tc] radionuclides, and would identify them in a future test plan. The Performance Confirmation Plan (SNL, 2008) states that "K_d values derived from field tests will be compared to the laboratory batch tests and to the K_d values presented in Radionuclide Transport Models Under Ambient Conditions (BSC, 2003 [DIRS 163228])."

For the weakly or non-sorbing elements, diffusion from fractures into the tuff matrix (i.e., matrix diffusion) can complicate the interpretation of tracer test results. To investigate transport involving matrix diffusion, bromide and pentafluorobenzoic acid (PFBA) have been used by Reimus et al. (2003) as non-sorbing tracers in saturated tuffs near Yucca Mountain because of their differing aqueous diffusion coefficients. Carboxylate-modified latex (CML) microspheres of variable size also have been used to detect matrix diffusion effects and to study colloidal transport processes in fractured dual-porosity media (e.g., Mondal and Sleep, 2013). The use of microspheres as tracers capitalizes on differences in physical size between the tracers and pore space of the porous media, particularly between fracture apertures and matrix pores. The retarding effect of matrix diffusion may be ascertained by contrasting conservative tracer breakthrough times or very small microsphere transport times with the more rapid transport times of colloid-sized microspheres, which follow preferential flow paths like open fractures rather than diffuse into adjacent matrix (e.g., Mondal and Sleep, 2013, and references therein).

LiBr-traced well water was used during the excavation of the ESF and ECRB Cross Drift to repeatedly wash newly exposed tunnel walls; tagged well water like this also might be used, albeit at greater volumes, throughout repository construction should a construction authorization be granted. Marshall et al. (2012) confirmed previous assessments that the LiBr-traced construction water did not significantly affect the composition of pore-water samples collected and analyzed during Yucca Mountain site characterization; pore-water samples collected during unsaturated zone testing performance confirmation activities would likely be similarly unaffected.

4 IN-DRIFT AMBIENT AND THERMAL SEEPAGE MONITORING

Yucca Mountain Performance Confirmation activities related to the Upper Natural Barrier and Engineered Barrier System are intended to provide data to evaluate if these barriers would function as intended and anticipated. This section reviews evidence for ambient seepage flux into subterranean openings (Section 4.1) in addition to in-drift ambient and thermal seepage monitoring that DOE proposed in its SAR (DOE, 2008, Section 4; 2009a), in references therein, and in its response to NRC staff's requests for additional information (DOE, 2009b, DOE, 2010) and reviews the state-of-the-art for methods and technologies that could be used to address this goal (Section 4.2). The review focuses on techniques and technologies developed since June 2007 when CNWRA transmitted a report to NRC about sensor and measurement considerations for long-term monitoring of the vadose zone at Yucca Mountain (Or and Dinwiddie, 2007).

Seepage monitoring includes observations of seepage occurrence and quantity; geochemical analyses of seepage water samples collected from ambient alcoves (or boreholes) and from thermally accelerated test drift(s) (see Section 3); and local monitoring of barometric pressure, temperature, humidity, and wind speed within thermally accelerated test drift(s) (SNL, 2008, Section 3.3.1.2; DOE, 2009a) (see Section 2.4 for summary of thermally accelerated drift activity). Seepage monitoring in sealed (i.e., bulkheaded), unventilated (i.e., ambient) alcoves would be conducted in new repository areas until repository closure and general observations for evidence of seepage also would be conducted in conjunction with drift inspections (SNL, 2008, Section 3.3.1.2). Seepage monitoring would require remote video camera systems to make seepage observations in both ambient alcoves and thermally accelerated drift(s), necessitating heat- and radiation-hardened camera systems. Dark or light-reflecting spots on the rock wall ground support and light-reflecting spots on drip shields may indicate seepage (SNL, 2008, Section 3.3.1.2). Stationary environmental sensors would monitor for relative humidity spikes and abrupt decreases in air temperature as proxies for drift seepage (SNL, 2008, Section 3.3.1.2). Heat- and radiation-hardened in-drift environmental sensors and peripheral equipment would be required for use in thermally accelerated drifts, such as barometric pressure transducers, humidity and temperature probes, wind speed sensors, thermocouple psychrometers, data loggers, and fiber-optic network cables (cf. SNL, 2008, Section 3.3.1.2).

4.1 *In Situ* Seepage Monitoring Sensors and Enabling Technologies

Video cameras would monitor the in-drift environment for evidence of seepage, condensation waters, and thin films within drifts while stationary sensors would measure in-drift environmental parameters (e.g., temperature, barometric pressure, wind speed, and relative humidity). Data acquisition issues include the service life of instrumentation and sensor network systems; maintenance, replacement, and sensor calibration (Read and Ofoegbu, 2006). Measurements, sampling methods, and bulkhead-opening intervals would need to consider approaches that would not unduly disturb the in-drift environment. Any lighting used to illuminate ambient drifts would necessarily have to be cool lamps or the equivalent, with a narrow emission spectrum that does not provide an undue source of in-drift heat to drive moisture transport or support photosynthesis (Cigna, 1993).

4.1.1 Video Camera Monitoring Systems

For the seepage monitoring performance confirmation activity (Section 2.4), remote video camera systems would enable seepage observations in both ambient alcoves and thermally accelerated drift(s). Monitors would scan video for the presence of dark spots on the rock wall ground support and for wet spots on drip shields (SNL, 2008, Section 3.3.1.2). Nuclear-industry-based inspection cameras generally have been insufficiently radiation hardened to provide long service lives at in-drift dose rates of 200 rad/hr [2 Gy/hr]; prevailing industry trends are to dispose of and replace failed irradiated cameras after short lifecycles rather than hardening them for uninterrupted use (Burgess et al., 2005). For video cameras mounted inside thermally accelerated drifts, recent research has been conducted to improve camera radiation hardening against sensor degradation that occurs in low- to high-dose-rate gamma ray environments (e.g., Dodd et al., 2010; Armani et al., 2011; Bogue, 2013; Cho et al., 2014).

The tolerance of video cameras to total ionizing radiation can be enhanced by hardening individual susceptible components, such as the (i) image sensor [e.g., charge coupled device (CCD) or complementary metal-oxide semiconductor (CMOS)]; (ii) optical system of glass lenses that may undergo browning when irradiated; and (iii) illumination systems based on light emitting diodes (LED), superluminescent light emitting diodes (SLED), or lasers, as well as by testing cameras at the system level for irradiation susceptibility. Bayesian networks may be used to probe system sensitivities and quantitatively estimate the total ionizing dose (TID) response of sensor systems and system-level radiation hardness. As individual irradiated components degrade, the Bayesian network can track interactions between components that could cause overall system failure, even while individual degraded components remain within their specifications. The utility of Bayesian networks for estimating overall system health begins with system design decisions and continues through field deployments.

Sensor electronics comprised of semiconductor components associated with silicon oxides, such as CCD and CMOS, are particularly susceptible to irradiation effects. Two mechanisms are responsible for sensor degradation: (i) lattice displacement and (ii) ionization that causes voltage shifts (Bogue, 2013). Lattice displacement causes permanent, irreversible degradation, whereas ionization effects are often transient. Sensor parameters that may be adversely affected by irradiation include dark current; transistor gate threshold voltage; field/channel threshold voltage; and charge transfer efficiency (CTE) and linearity, causing hot pixels, image noise, decreased contrast, and diminished measurement accuracy (Marbs and Boochs, 2006; Bogue, 2013). Thin silicon oxide layers tend to be more radiation hard than thicker layers. Armani et al. (2011) demonstrated that exposure to temperatures of 200 °C [392 °F] may extend the lifespan of irradiated CMOS Active Pixel Sensors because heat serves to partially regenerate their functional behavior through the thermal annealing process after degradation has occurred. Lower temperatures were less effective at restoring lost functionality. Thermal regeneration of functional behavior was never complete, and it also became less effective with repeated irradiation and annealing. The thermal operating range of the CMOS sensor integrated circuits tested by Armani et al. (2011) {≤70 °C [≤158 °F]} were too low for use inside a thermally accelerated drift. Dodd et al. (2010) note that specialty radiation-hardened integrated circuits generally lag three generations behind state-of-the-art, high-volume production, commercially available integrated circuits. The TID radiation hardness of commercial CMOS microelectronics is rapidly improving, but is neither monitored nor guaranteed by commercial manufacturers (Dodd et al., 2010).

Beyond CCD and CMOS image sensors, carbon nanotube or graphene devices, having very thin oxides, are among the most favorable replacements for conventional technologies. Compound semiconductor devices are robust against TID damage because they have no associated transistor gate or field oxides that would trap and accumulate radiation-induced positive charges (Dodd et al., 2010; Bogue, 2013) and thereby distort the electrical characteristics of the sensor (Bogue, 2013). Silicon-carbide integrated circuits (Zetterling et al., 2012) and charge-injection devices (Bogue, 2013) may be potential solutions to the in-drift high-radiation, high-temperature working environment. Charge-injection devices by Thermo Fisher Scientific (Waltham, Massachusetts) are qualified to withstand 3×10^6 rad (Bogue, 2013), offering a lifetime of 600 days at 200 rad/hr.

4.1.2 Temperature Monitoring Systems

Air temperature is an environmental tracer for heat and mass transfer. For the seepage monitoring performance confirmation activity (Section 2.4), temperature sensors would be installed to monitor in-drift air temperatures within thermally accelerated test drift(s) as proxies for seepage and to characterize in-drift moisture dynamics (SNL, 2008, Section 3.3.1.2; DOE, 2009a, Section 1.3.3.1.7). Abrupt decreases in air temperature may be interpreted as evidence for drift seepage (SNL, 2008, Section 3.3.1.2). Long-lived heat- and radiation-hardened temperature sensors and peripheral equipment {i.e., able to withstand 203 °C [397.4 °F] and 200 rad/hr [2 Gy/hr]} would be required. Future seepage monitoring test plans may specify air temperature sensor types, their operating ranges, resolution, accuracy, precision, sampling rates, data acquisition rates, data filtering, compression and reduction, data storage requirements, data transmission, power requirements, and maintenance intervals, among other specifications (Allen et al., 2010; Schoellhammer, 2010). Temperature sensors used in nuclear power plants are often mineral-insulated, metal-sheathed thermocouples or resistance temperature detectors (RTDs), qualified to withstand radiation to 3×10^8 rad (Bogue, 2012; 2013), with a 170 yr life at 200 rad/hr. Non-contacting acoustic thermometry (de Podesta et al., 2010; see also http://projects.npl.co.uk/metrofission/wp1.html) and Johnson noise thermometry, both offering milli-Kelvin resolution, are newer methods being developed to improve temperature sensing in the nuclear industry (Bogue, 2012). Britton et al. (2014) began addressing the lack of telerobotic technologies and environmental sensors, such as temperature sensors, capable of functioning in high-radiation environments by developing radiation-hardened circuitry using mask-programmable analog arrays and specially selected sensors. Shortly thereafter, Britton et al. (2015) recommended the radiation-hardened Intersil Americas, LLC (Tokyo, Japan) ISL71590SEH transducer for temperature monitoring, which has a maximum operating temperature of 125 °C [257 °F], can withstand 300 krad total dose, and offers 1 °C [0.56 °F] accuracy. However, its operating temperature is not sufficiently high for use inside a thermally accelerated drift that may attain waste package temperatures of 203 °C [397.4 °F] within 10 years, nor does it offer a sufficiently long radiation-tolerant lifespan for long-term, uninterrupted use in performance confirmation seepage monitoring.

4.1.3 Relative Humidity Monitoring Systems

Relative humidity is the key factor affecting evaporation rate, which controls the amount of liquid water at drift walls that is available for drop formation and seepage into drifts (DOE, 2009a, Section 2.3.3.2.1.3). At high relative humidity, a very small temperature drop would cause vapor-phase water to condense. Relative humidity is an environmental tracer for mass transfer. For the seepage monitoring performance confirmation activity (Section 2.4), relative humidity sensors would be installed to monitor in-drift relative humidities within both ambient and thermally accelerated test drift(s) as proxies for seepage and to characterize in-drift moisture dynamics (SNL, 2008, Section 3.3.1.2; DOE, 2009a, Section 1.3.3.1.7). Relative humidity spikes may be interpreted as evidence for drift seepage (SNL, 2008, Section 3.3.1.2). Long-lived heat- and radiation-hardened relative humidity sensors {203 °C [397.4 °F] and 200 rad/hr [2 Gy/hr]} and peripheral equipment would be required. Future seepage monitoring test plans would specify relative humidity sensor types, their operating ranges, resolution, accuracy and precision (particularly at high values), sampling rates, data acquisition rates, data filtering, compression and reduction, data storage requirements, data transmission, power requirements, and maintenance intervals, among other specifications (Allen et al., 2010; Schoellhammer, 2010). As mentioned in Section 3.1.2, there are fiber optical chemical sensors that also are capable of measuring relative humidity.

4.1.4 Barometric Pressure Monitoring Systems

For the seepage monitoring performance confirmation activity (Section 2.4), gauge pressure sensors would be installed to monitor in-drift air pressures within ambient and thermally accelerated test drift(s) as proxies for seepage and to characterize in-drift moisture dynamics (SNL, 2008, Section 3.3.1.2; DOE, 2009a, Section 1.3.3.1.7). Long-lived heat- and radiation-hardened in-drift gauge pressure sensors {203 °C [397.4 °F] and 200 rad/hr [2 Gy/hr]} and peripheral equipment would be required (cf. SNL, 2008, Section 3.3.1.2). Future seepage monitoring test plans would specify gauge pressure sensor types, their operating ranges, resolution, accuracy, precision, sampling rates, data acquisition rates, data filtering, compression and reduction, data transmission, power requirements, and maintenance intervals, among other specifications (Allen et al., 2010; Schoellhammer, 2010). Pressure sensors used in nuclear power plants are typically long-established, inherently radiation-resistant electromechanical thin metal film strain gauges bonded to metal diaphragms and diaphragm-driven linear variable differential transformers that remain stable when exposed to between 10^6 and 10^{12} rad (Bogue, 2012), offering between 200 days and potentially 600,000 yrs of use before irradiation-induced failure in a 200 rad/hr environment. A fiber optic pressure sensor by Luna, Inc. (Roanoke, Virginia) remains stable when exposed to gamma radiation up to 10^{11} rad (Bogue, 2013), potentially offering on the order of 60,000 yrs of use before irradiation-induced failure. Britton et al. (2014, 2015), who also selected pressure sensors for use with their radiation-hardened circuitry, concluded that radiation-hardened pressure sensors were scarcely available. Potentially meeting their requirements was the Omni Instruments, LLC (Fort Wayne, Indiana) radiation “resistant” pressure sensor, yet it lacked test data to a specific radiation total-dose-tolerance level. A heat-resistant, piezoresistive silicon pressure sensing technology developed by Kulite® Semiconductor Products, Inc. (Leonia, New Jersey) is “dielectrically isolated” or “silicon-on-silicon,” featuring piezoresistors electrically insulated from *n*-type silicon diaphragm material by a silicon dioxide layer or that combined with a glass layer so that current does not leak at high temperatures, thereby extending the operating temperature of conventional piezoresistors from 150 to 540 °C [302 to 1,004 °F] (Bogue, 2012); the susceptibility of such sensors to irradiation, however, is unclear.

4.1.5 Enabling Technologies for In-Drift Monitoring

Suppliers of radiation-hardened components and systems greatly decreased after the early 1990s when the U.S. Government phased-out programs that required radiation-tolerant electronics; for this reason, commercial entities would not meet the robotic and sensor needs of the Yucca Mountain Performance Confirmation Program (Burgess et al., 2005). There are relatively few developers of radiation-hardened technology today, including military/space manufacturers, government laboratories, and universities (Burgess et al., 2005). Even the dose rate tolerances of components and subsystems developed for space applications are insufficient to withstand in-drift radiation levels of 200 rad/hr [2 Gy/hr] (Burgess et al., 2005). For example, microelectromechanical (MEMS) systems and sensors, widely used in space applications, are not used in the nuclear industry.

The U.S. DOE Office of Civilian Radioactive Waste Management, Office of Science and Technology International program (OCRWM/OSTI) asked Burgess et al. (2005) to evaluate a list of enabling technologies for Yucca Mountain operations that could be developed with funding provided by that program. Their initial list of candidate technologies provided a useful starting point for considering enabling technologies that would require development for use in Performance Confirmation. From their overall list, a subset of in-drift monitoring enabling technologies is provided in Table 4-1. For example, high temperatures in ambient and thermally accelerated drifts and near 100 percent relative humidities in ambient drifts make chemical batteries an unsuitable energy source for performance confirmation monitoring sensors (Burgess et al., 2005; Constantinou et al., 2010). Constantinou et al. (2010) instead proposed an electromechanical battery for powering wireless sensor networks and demonstrated the feasibility of their concept with a prototype system.

Iterative deployment of large-scale monitoring systems and sensor networks enables progressive refinement to more effectively meet application and end-user requirements [e.g., Allen et al. (2010)].

4.2 Integrated Measurements in Subterranean Openings

4.2.1 Collection and Analysis of Peña Blanca Nopal I Mine Seepage

DOE conducted a high-spatial-resolution unsaturated zone seepage study at the abandoned Sierra Peña Blanca Nopal I uranium mine, which is located ~50 km [~31 mi] northeast of Chihuahua, Chihuahua State, Mexico, to understand how seepage rates respond to precipitation and are affected by local fracture characteristics (Dobson et al., 2012). The final report on the Nopal I project of Dobson et al. (2012) is presented in Levy (2016). The Nopal I uranium ore body occurs primarily in unsaturated, fractured, and faulted rhyolitic welded ashflow tuffs of the Nopal and Coloradas Formations, such that it is a suitable analog for studies that evaluate the fate of spent nuclear fuel at Yucca Mountain (Simmons and Stuckless, 2010). Part of the ore body is exposed at the land surface with visible mineralization occurring over an elliptical area of 18 m × 30 m [59 ft × 98 ft] (Pearcy et al., 1995). During mining, which concluded in 1985, several surficial benches and subterranean adits were constructed (Simmons and Stuckless, 2010). The surface-exposed +10 level bench was mapped during a detailed fracture study by Pearcy et al. (1995) and Reyes-Cortés (1997). An adit had been constructed on the +00 level of the mine with its ceiling located 8 m [26 ft] below the exposed +10 level bench; the front adit intersects the ore body. Fractures and a fault in the adit ceiling were mapped in detail (Dobson et al., 2012).

Similar to a seepage capture system deployed at Yucca Mountain for use in a drift-scale seepage test (described by Trautz and Wang, 2002), DOE deployed four seepage collection frames, sized 1.5 m × 3.6 m [5 ft × 12 ft]; three frames were mounted near the ceiling in rear to middle adit zones (Frames 1–3), at locations 21 to 7 m [69 to 23 ft] from the margin of the ore body, and one frame (Frame 4) was mounted in the front adit only 2 to 5 m [6 to 16 ft] from the ore body; each frame contained 60 collection bottles, with one 125-mL bottle used to collect seepage from each 30 cm × 30 cm [12 in × 12 in] Lexan plastic compartment, with

Table 4-1. List of Enabling Technologies that Would Support In-Drift Performance Confirmation Activities at Yucca Mountain [Based on Burgess et al. (2005) and Expanded per SNL (2008)].			
Technology Candidates	**Reclassified Priority**	**Research & Development**	**Benefits**
Convert ambient gamma/neutron radiation to robot and or sensor power	High priority; high risk/ high reward	Define physics; conduct feasibility study of energy conversion process; calculate power that could be generated from radiation fields in loaded drifts; conduct experimental verification of physical prototypes	Extend operating life of robots, sensors, wireless sensor networks, and communication systems and reduce maintenance. Radiation cells would use ambient waste package radiation to supply long-term, in-drift power for monitoring
Radiation-hard, high-temperature electronics	High priority; high risk/ high reward	Develop a family of inherently tolerant electronics useful for a wide variety of applications, and guidelines for use given they may have radically different voltage ranges and levels of integration compared to COTS	Extend operating times and reduce maintenance costs and enable performance confirmation monitoring where rad levels are high and exposure times are long
Radiation-hard DC motors	Medium	Improve on existing technologies to undefined specifications	Extend operating life of in-drift robots and reduce maintenance
Non-contact, precision drift wall inspection system	High	Identify sensor technologies; sensor fusion; optimize scanning for in-drift conditions (i.e., lighting; resolution)	Enable fracture mapping and seepage monitoring (as in SNL, 2008, Section 3.3.1.2); decrease time to complete baseline drift inspection and periodic re-inspection activities to evaluate evolving structural integrity
In-drift moisture sensor and sampler	High	Develop radiation-hard {200 rad/hr [2 Gy/hr]}, high-temperature {203 °C [397.4 °F]} moisture sensors and samplers (direct/indirect)	Enable characterization and collection of thin films of moisture on in-drift surfaces for removal and water quality analysis
Robotic system to emplace/retrieve moisture samplers	High	Develop robotic system, including manipulators, to emplace/retrieve moisture samplers (e.g., water collectors/drip collection sheets/ drip cloths)	Enable collection of in-drift water and removal for chemical analysis
Radiation-hard, high-temperature radiation sensors to detect mobile radioactive gas and distinguish it from WP shine and radon	High	Develop radiation-hard {200 rad/hr [2 Gy/hr]}, high-temperature {203 °C [397.4 °F]} gas sensors to detect mobile radioactive gas and other gases important to performance confirmation	Ensure safety of subsurface operations staff and enable in-drift performance confirmation monitoring of gases

Table 4-1 (Cont'd). List of Enabling Technologies that Would Support In-Drift Performance Confirmation Activities at Yucca Mountain [Based on Burgess et al. (2005) and Expanded per SNL (2008)].			
Technology Candidates	**Reclassified Priority**	**Research & Development**	**Benefits**
Visualization without ambient light	Medium	Develop sensor systems to visualize in-drift environment without ambient light; data fusion	Enable seepage, condensation, and thin-film monitoring
Newly Defined Technology Items			
Radiation-hard, high temperature mechanical batteries for wireless sensor networks	Medium	Develop and optimize an operational electromechanical battery to store energy in a compressed magnetic spring until transferring it—by releasing the spring—to the electrical domain through electromagnetic induction (Constantinou et al., 2010)	Extend operating life of wireless sensor networks, and reduce in-drift sensor maintenance
Globally synchronized clocks	High	Design, develop, test, and operationally implement time synchronization protocols (Allen et al, 2010; Martinez and Hart, 2010)	Enable different yet related environmental data streams to be temporally matched
Software system to (i) identify impact of node faults on application (with uncertainty propagation), (ii) estimate missing data to fill gaps in temporal measurement sequences, and (iii) recommend prioritized list of maintenance actions	High	Design, develop, test and operationally implement a Vigilance-style software tool for Yucca Mountain performance confirmation applications, including sensor network deployment design (Schoellhammer, 2010)	Reduce maintenance activities that would perturb natural processes occurring in thermally accelerated drifts and ambient alcoves, preserving data quality of working sensor nodes Vigilance monitors wireless sensor network deployments and identifies the impact of missing data so that technicians have expert advice on whether maintenance is essential (Schoellhammer, 2010)

compartments arranged in a 12 × 5 array, for a total of 240 seepage collection bottles (see Dobson et al., 2012, for details). To improve temporal resolution, 6 seepage collection compartments (2 each in Frames 1–3; none in Frame 4) later had their bottles replaced by 340 mL columns that were monitored by pressure transducers every 2 hrs in both low and high seepage areas (Dobson et al., 2008, 2012). To complement the seepage collection systems, DOE installed Vaisala (Helsinki, Finland) temperature/relative humidity sensors and Setra (Boxborough, Massachusetts) absolute atmospheric pressure transducers [later replaced by GE Digital Solutions Druck (Pasadena, Texas) gauge pressure transducers] in the rear adit with a 2-hr recording interval (Dobson et al., 2012). At one point, DOE experienced environmental sensor failure when condensate water compromised sensor electronics; after this failure, condensate water was collected where it had been observed to form, using a roofed collector and collection bottle to prevent entry and mixing with seepage water (Dobson et al., 2012). Some fraction of collected “seepage” water may actually be local condensation dripping into collection compartments, but any condensation water probably originates as water vapor that enters the adit from net infiltration (Dobson et al., 2012), particularly in the rear adit far from the ventilated entrance.

DOE also deployed a Vantage Pro 2 (Davis Instruments Inc., Hayward, California) automated weather station on the +20 bench level ~60 m [~200 ft] west-southwest of the western margin of the ore deposit, enabling a precipitation and seepage flux study (Dobson et al., 2012). The weather station also recorded air temperature, barometric pressure, wind speed, and direction with a 2-hr recording interval.

The entire sequence of natural analog investigations conducted at Nopal I have shown that some of the fractures in the rear adit are highly transmissive and that residence times/water–rock interaction times are limited at distances far from the ore body above the adit; conversely, longer water–rock interaction times have been observed near the ore body. Pearcy et al. (1995) showed that fractures nearest the ore body are less continuous than those elsewhere in the surface unit and have undergone more extensive mineralization; thus, fractures nearest the ore body are less permeable, leading to long residence times. Consequently, Dobson et al. (2012) observed no fast flow pathways seeping into Frame 4. Due to a few highly transmissive fractures in the rear adit, Dobson et al. (2012) found residence times of less than 4 hours after large rainfall events; in the middle adit, they observed more typical 1–6-month lag times between the onset of monsoon season and the subsequent capture of seepage. Seepage data collected near the ore body are confounded by the close proximity of the front adit seepage collector frame to ventilation occurring through the adit entrance, which likely increased local evaporation of water from the adit ceiling before it could be captured (Dobson et al., 2012). The limited volumes of seepage collected from Frame 4 had higher salinities and $^{18}O/^{16}O$ and D/H ratios than the more significant volumes of seepage collected from Frames 1–3, consistent with higher evaporation rates occurring near the entrance (Dobson et al., 2012). Whereas Trautz and Wang (2002) adjusted their seepage results to account for potential seepage lost to evaporation that occurred inside a Yucca Mountain niche, Dobson et al. (2012) did not do so for their Nopal I seepage study.

4.2.2 Microclimate Studies inside Caves and Caverns

During a 2-year period at Kartchner Caverns, Arizona, Buecher (1999) conducted a microclimate study with 22 environmental monitoring stations, each consisting of a 23-cm [9-in]-diameter aluminum evaporation pan with drip shield (to preclude entry of seepage water), a dewpoint microvoltmeter soil psychrometer, and a polyvinyl chloride (PVC) pipe stand to contain air and soil temperature sensors. Dewpoint microvoltmeters were used by Buecher (1999) because they can be used to measure relative humidity with an accuracy of ±0.05 percent as well as dewpoint temperature. Accurate measurements of relative humidity are important because local relative humidity has a significant effect on local evaporation rate: at high relative humidity, a very small drop in temperature would cause vapor-phase water to condense. Additionally, eight drip monitoring stations at Kartchner Caverns were instrumented to measure the rate and volume of drips, and the electrical conductivity of the seepage water. An audible drip survey was conducted within each cave chamber to determine the “whole cave” drip rate over a fixed period of time; this whole cave drip rate was then converted to an average annual drip rate using data collected from the eight monitored drip locations. Seepage into the cave chambers also was estimated by measuring water collected in initially empty, unshielded evaporation pans that were located randomly throughout the caverns, and then by correcting the measured volume for evaporation losses. Buecher (1999) estimated evaporation within Kartchner Cavern by assuming zero evaporation occurs at the 100-percent-relative-humidity seeping ceiling and by assuming an effective evaporation area that is twice the area of the cavern floors to account for the irregular area of the floor and walls. Using site-appropriate geometrical factors, a similar approach could be used to further advance evaporation analyses for the Nopal I analog site and for ambient seepage tests conducted as Performance Confirmation activities at Yucca Mountain. Finally, Buecher estimated the rate of air exchange from the cave to the land surface by measuring airflow with a sensitive hotwire anemometer, and an airflow direction indicator, wet and dry bulb temperature sensors, and an atmospheric pressure sensor. He collected data that represent 1-min averages of each parameter intermittently over a 22-day period. He further estimated the air exchange rate between the cave and the surface by measuring changes in CO_2 gas concentrations inside the cave with Dräger (Lübeck, Germany) diffusion tubes, using the equation for the time-dependent concentration of a tracer that is removed at a constant rate. Likewise, he measured Radon Working Levels, the concentrations of ^{222}Rn gas and individual daughter products (i.e., ^{218}Po, ^{214}Pb, and ^{214}Bi) to understand the movement of cave air. Alpha track detectors, which offer high sensitivity at high relative humidities, were left inside the cave for 3 to 4 weeks before being read, to provide a long-term average for radon gas concentrations. To measure daughter products, Buecher (1999) used the modified Tsivoglou method (Harley, 1988; Nazaroff and Nero, 1988). The ratios of daughter products to each other and to their parent, if other than unity, may indicate that either air exchange with the surface is significant, or that attachment of daughter products to interior surfaces or aerosols is significant, with the latter being more likely except where air exchange rates are very fast (Buecher, 1999). Similarly, Fernández et al. (1986) performed radon and carbon dioxide surveys in Altamira Cave in northern Spain to quantify the seasonal natural ventilation rate inside that cavern.

Bourges et al. (2014) recorded cave and land surface environmental parameters within and outside of four caves to characterize their environmental stability. Environmental tracers were monitored at selected locations within the caves every 15 minutes, including relative humidity, air/wall temperature and pressure, CO_2, ^{222}Rn, and CH_4 concentrations. They employed a GE General Eastern (Boston, Massachusetts) HYGRO M4 chilled-mirror hygrometer with high-precision sensors with 1 percent accuracy and 0.01 percent resolution to measure relative humidity, GE Druck (Boston, Massachusetts) or Vaisala (Helsinki, Finland) sensors to measure barometric pressure, and platinum Pt100 sensors to measure air/wall temperatures (Bourges et al., 2014). Carbon dioxide concentrations were measured with a Dräger (Lübeck, Germany) Polytron IR CO_2 infrared sensor, and radon alpha radioactivity was determined with Algade (Bessines-sur-Gartempe, France) Barasol probes (Bourges et al., 2014). Evaporation and condensation processes may be inferred by comparing saturation vapor pressure near a wall and the water vapor partial pressure in air, computed with the air and wall temperatures and relative humidity (Bourges et al., 2014).

Altogether, these types of techniques and radiation- and temperature-hardened versions of such sensors could be deployed during performance confirmation seepage monitoring activities to monitor important processes occurring inside waste emplacement drifts at the proposed Yucca Mountain repository.

5 MONITORING EVOLUTION OF THE NEAR-FIELD ENVIRONMENT

Yucca Mountain Performance Confirmation activities related to the Upper and Lower Natural Barriers are intended to provide data to evaluate if these barriers would function as intended and anticipated. This section discusses borehole-based ambient and thermally accelerated near-field deep percolation monitoring that DOE proposed to conduct in its SAR (DOE, 2008, Section 4; 2009a), in references therein, and in its response to NRC staff's requests for additional information (DOE, 2009b; 2010), and the methods and technologies reviewed in support of completing NRC's Safety Evaluation Report for Yucca Mountain. The review focuses on techniques and technologies that may have been developed since Or and Dinwiddie (2007) completed their report for NRC related to sensor and measurement considerations for long-term monitoring of the vadose zone at Yucca Mountain.

Thermally accelerated drift near-field monitoring (see summary in Section 2.2) within boreholes would be initiated during repository operations, with heat generated by emplaced waste packages, and would continue until closure (SNL, 2008, Section 3.3.1.9). The goal of thermally accelerated drift near-field monitoring is to discern the postclosure response of the near-field environment to heat within emplacement drifts (SNL, 2008, Section 3.4.5). The near-field is the rock mass immediately surrounding repository drifts outward to a distance that encompasses significant and evolving thermal or excavation-induced changes in physical and chemical properties (DOE, 2009a). Near field thermal testing in the crystal-poor middle nonlithophysal tuff began during site characterization, including at the Single Heater Test and Drift Scale Test at Alcove 5 off the ESF and at the Large Block Test at an outcrop at Fran Ridge (SNL, 2008, Section 3.3.1.9; DOE, 2009a, Section 2.3.3.3.2). These three tests, particularly the Drift-Scale Test, provided the preliminary basis for the thermally accelerated drift near-field monitoring performance confirmation activity (Table 1-1), prior to the emplacement of radioactive waste that would occur should a construction authorization be granted. DOE proposed periodic measurement of geochemistry (see Sections 3.1.2 and 3.1.3), and periodic air injection testing to monitor the evolution of porosity and matrix and fracture permeability for transient, reversible to permanent changes in these properties (i.e., evolution of the near-field environment) caused by thermal loading and amorphous silica and calcite precipitation, and to thereby confirm thermal hydrologic-mechanical-chemical modeling results that pertain to drift seepage and radionuclide transport (SNL, 2008, Section 3.3.1.9; Simmons and Stuckless, 2010).
DOE indicates this long-term monitoring would be conducted periodically around the thermally accelerated drift, but at a frequency yet to be determined (SNL, 2008, Sections 3.3.1.9 and 3.4.5; DOE, 2009b). With the exception of developing adequately heat- and radiation-hardened instrumentation and equipment, including borehole geophysical equipment, technology development is generally unnecessary to accomplish this performance confirmation activity.

Distributed fiber optic temperature sensors, such as Bragg grating sensors and Raman and Brillouin time-domain reflectometry (TDR) sensors (Inaudi and Glisic, 2007a,b; O'Connor and Dowding, 1999) are amenable to borehole deployment for monitoring the thermal evolution of the near-field environment. Fiber optic TDR also enables seepage monitoring, where flowing water may be indicated by local temperature changes along a single instrument cable; seepage locations may be identified with an accuracy of 1–2 m [3.3–6.7 ft] along cables many kilometers long (Inaudi and Glisic, 2007b). Fiber optic TDR may be used to monitor thermal tracers (e.g., Tyler et al., 2009; Read et al., 2013) when temperatures change on time scales >1 hr (Vogt et al., 2010), with potential for use in monitoring the near-field environment surrounding waste emplacement drifts.

Freifeld and Tsang (2006) have proposed that thermal conductivity be measured in concert with such borehole temperature data, using constant wattage heat trace tubing. Because the thermal conductivity of rock is dependent on saturation and phase state, high-resolution inferences about moisture redistribution in the Yucca Mountain tuffs could be made based on the evolving thermal conductivity distributions of monitored rock volumes (e.g., von Herzen and Maxwell, 1959).

6 SUMMARY

DOE's Performance Confirmation Program is the set of measurements, experiments, and analyses that have been and would be conducted, where practicable, to evaluate the adequacy of the supporting assumptions, data, and analyses for the performance of the proposed repository at Yucca Mountain (SNL, 2008). An objective of performance confirmation is to monitor key geotechnical and design parameters, including interactions between natural and engineered systems and components throughout repository construction and operation to identify any significant changes from conditions assumed in DOE's LA, and evaluated by NRC in the SER, that would affect postclosure safety. Should a construction authorization be granted, differences in parameters and conditions observed during repository construction, operation, and through to closure would be identified by the Performance Confirmation Program when those parameters and conditions are compared against baseline and expected values.

This Performance Confirmation knowledge management report documents a review of information derived from literature that was published or otherwise made available since CNWRA prepared a related report in 2007 up until the time when the SER was published in 2015. This knowledge management report specifically addresses monitoring methodologies and sensors for unsaturated-zone fractured rocks and thermal environments, such as those environments that would be anticipated within the proposed repository at Yucca Mountain during the preclosure period. Three of the five performance confirmation activities considered in this report began during site characterization (i.e., subsurface water and rock testing, unsaturated zone testing, and seepage monitoring), and the other two activities would begin only after repository operations were underway (i.e., thermally accelerated drift near-field monitoring and in-drift environment monitoring) (see Table 1-1 and Section 2 for more information). Although relevant to in-drift environment monitoring, methods and sensors for monitoring mechanical properties, radiation, radiolysis, and microbial species were considered beyond the scope of this report. Instead, this review focused on methods for monitoring unsaturated zone hydrological processes of the fractured Upper Natural Barrier, Engineered Barrier System, and Lower Natural Barrier in and in proximity to the proposed repository horizon at Yucca Mountain. Information contained in this report may assist NRC staff during review of evolving Performance Confirmation plans, should a construction authorization be granted.

In summary, Section 1 of this knowledge management report introduced its topic. Section 2 provided specific contextual information about DOE's five proposed unsaturated zone hydrology-related performance confirmation activities for which potentially applicable monitoring sensors and methods were addressed throughout the remainder of the report. Section 3 addressed geochemical monitoring methods pertinent to deep percolation, ambient and thermal seepage into the repository horizon, and radionuclide transport through the unsaturated zone. Section 4 addressed methods and sensors for in-drift ambient and thermal seepage monitoring, as well as potential research and development efforts that may assist in-drift monitoring as Performance Confirmation plans evolve, should a construction authorization be granted. Section 5 provided a brief discussion of downhole methods for monitoring the evolving saturation and thermal conditions of the nearfield environment.

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