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APPLICATION OF NATURAL ANALOGUES IN THE YUCCA MOUNTAIN PROJECT - OVERVIEW

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1. INTRODUCTION

The *Natural Analogue Synthesis Report (NASR)* [1] provides a compilation of information from analogues that test, corroborate, and add confidence to process models and model predictions pertinent to total system performance assessment (TSPA). The report updated previous work [2] with new literature examples and results of quantitative studies conducted by the Yucca Mountain Project (YMP). The intent of the natural analogue studies was to collect corroborative evidence from analogues to demonstrate greater understanding of processes expected to occur during postclosure of a proposed Yucca Mountain repository.

Natural analogues, as used here, refer to either natural or anthropogenic systems in which processes similar to those expected to occur in a nuclear waste repository are thought to have occurred over long time periods (decades to millenia) and large spatial scales (up to tens of kilometers).

In the past, the YMP has used analogues for testing and building confidence in conceptual and numerical process models in a number of ways. Yucca Mountain mineral alteration phases provided a self-analogue for postclosure alteration [3]. Thermodynamic parameters for silica minerals of the Wairakai, New Zealand geothermal field were added to databases used in geochemical modeling [4]. Scoping calculations of radionuclide transport using the Yucca Mountain TSPA numerical model were conducted for the Peña Blanca site [5]. Eruption parameters from the Cerro Negro volcano, Nicaragua, were used to verify codes that model ash plume dispersion [6]. Analogues have also been used in supplemental science and performance analyses to provide multiple lines of evidence in support of both analyses and model reports (AMRs) [7]; in screening arguments for inclusion or exclusion of features, events, and processes (FEP)s in TSPAs; in the quantification of uncertainties [7]; in expert elicitations of volcanic and seismic hazards [8, 9] and in peer reviews [10].

Natural analogues may be applied in a quantitative or a qualitative manner, depending upon the purpose to which they are applied and upon the specific analogue. They can provide descriptive information about the occurrence of various

processes, or they may be able to constrain the bounds of those processes. Analogue investigations may determine the conditions under which the processes occur, the effects of the processes, as well as the magnitude and duration of the processes.

Analogue information may also provide a body of data for testing codes and for validation of conceptual and numerical models. Natural analogue information may also be used to build confidence in databases themselves. Because natural analogues can be used to evaluate the validity of extrapolating from temporally limited field-scale experiments to longer time scales, or to add confidence when extrapolating from laboratory and intermediate-scale experiments to tests at larger spatial scales, they are uniquely suited to building confidence in process models. In this manner, they are used as a means of model validation, or confidence-building. Each of the Process Model Reports (PMRs) that support Site Recommendation (SR) includes a section on “validation” that in many cases utilizes natural analogue information.

Less commonly, natural analogues may be used to assist and support the selection of scenarios and to establish the probability of occurrence of selected scenarios. Because no single site will be a perfect analogue to all ongoing and anticipated processes at Yucca Mountain, focus is placed on identifying sites having analogous processes rather than total system analogues. Natural analogues do not reduce uncertainty *per se*; that is, the uncertainty bounds on a given parameter value may remain unchanged. However, natural analogues can build confidence that the bounds are set appropriately.

Comparison of model predictions with the results of natural analogue investigations will in general only permit confirmation that the model takes into account the relevant processes in appropriate ways. Validation of a predictive model by such comparison provides reasonable assurance that the model reflects future behavior. This is the level of confidence required by regulation 10 CFR 63, which states, in §63.101(a): “Demonstrating compliance will involve the use of complex predictive models that are supported by limited data from field and laboratory tests, site-specific monitoring, and natural analogue studies that may be supplemented by prevalent expert judgment.”

In addition to using natural analogues for long-term predictions, models must be able to explain and match the transport times and pathways from contaminated sites that provide anthropogenic analogues, such as Hanford, Washington; the Idaho National Engineering and Environmental Laboratory (INEEL); and the Nevada Test Site (NTS). Anthropogenic analogue sites are a challenge to constrain in models, because they often contain more than one source of contaminants, (sometimes with poorly identified source terms), have a complex mixture of radionuclides and other contaminants, and often occur in highly heterogeneous formations.

Natural analogues also have an important role, beyond their application to PA, in providing illustrative information to a broad range of audiences. Recognition of the important processes and events that control the repository behavior can be demonstrated from illustrative geological analogues. Public understanding of relevant timescales is important because the extended time periods of interest to disposal are generally longer than those within the normal range of experience.

2. SPECIFIC EXAMPLES AND APPLICATIONS IN THE NASR

Table 1 is a compilation of the ways in which analogues have been used in the NASR. The analogues are listed by section and are categorized as to their use in building conceptual models or understanding of processes, development of data parameters and their use in TSPA, or use for model validation. The majority of uses of analogues for YMP have been in the understanding of which processes to model and how to incorporate them into PA. Less frequent has been their use in model validation, and even more infrequent is their direct use in PA. This is not surprising because it corresponds to the frequency of application of analogues to these components of modeling in the international community [1, 11]. The most important insights from the NASR follow, along with suggestions for areas where analogues could increase needed confidence in process models. All of the subsequent examples are from the NASR; references to individual studies can be found within it.

Drift Stability

Radiometric dating of cave floor minerals at Carlsbad Caverns and Lechuguilla Cave indicates that natural openings larger than those proposed for repository drifts at Yucca Mountain have remained open for millions of years. Collapse of the roof of an

opening tends to occur where the fracture density is high and the overburden is thin, as is the case with some lava tubes. Factors that contribute to the size of a rockfall block are fracture spacing, which in turn depends on rock type and texture; and the size and shape of the opening. Paleolithic flint mines (~4,000 to 3,000 BC), Roman mines and aqueducts, and other anthropogenic examples demonstrate that man-made underground openings can also exist for thousands of years.

Waste Form Degradation

The reaction path of alteration of spent fuel at Yucca Mountain will be similar to that of geologically young, Pb-free uraninite, with schoepite and becquerelite forming as intermediate products, followed by uranyl silicates. The uraninite and its alteration products found at the Nopal I uranium deposit at Peña Blanca have these characteristics. Therefore, the uranium alteration paragenetic sequence at Nopal I is a good analogue for the alteration of uranium oxide spent fuel.

When uranium is incorporated into secondary minerals, it is effectively removed from the hydrologic system. Secondary mineral formation was responsible for incorporating uranium at Shinkolobwe, where fifty secondary uranium-bearing phases have been identified. Because of its great age, radiogenic lead-bearing phases played a role in sequestering uranium. At Okélobondo and Shinkolobwe, other secondary phases, particularly (U,Zr) silicates, formed stable phases. Secondary mineral phases could also play a role in retaining uranium within the waste form at Yucca Mountain.

Although natural glasses are somewhat different in composition from borosilicate nuclear waste glass, studies of natural glass alteration indicate that glass waste forms will be stable in a repository environment at Yucca Mountain. Higher stability is favored by higher silica and alumina content and by lower alkali and water content of the glass. Analogue studies have not considered radiation effects on glass over long time periods to confirm experimental results showing that radiation has little effect on glass waste stability.

Waste Package Degradation

The analogues to common metals serve mainly to demonstrate that under ambient to slightly elevated temperatures, the metals will be stable for thousands of years, even under oxidizing conditions. The survival of metal archaeological artifacts over

prolonged periods of time is related to the corrosion-resistant properties of metals and metal alloys, the development of protective passive film coatings with the onset of corrosion, and the location of artifacts in arid- to semi-arid environments. Such features have been used in the selection of materials and design configuration to enhance the durability of waste packages at Yucca Mountain.

The survival of the naturally occurring ordered Ni-Fe alloy in josephinite for millions of years (with only relatively minor amounts of surface oxidation) indicates that this material is highly resistant to oxidation and other forms of corrosion that occur in its geologic environment. While the composition of this metal differs from Alloy 22 (a key component of the waste package material proposed for Yucca Mountain), in that it does not contain Cr, Mo, or W, it does provide evidence that a similar alloy can remain passive over prolonged periods of time.

The potential instability of chromium-bearing materials is illustrated by the observed natural release of chromium from chromite in the Sierra de Guanajuato ultramafic rocks under ambient conditions. Corrosion appears to be concentrated along exsolution rims, analogous to structural defects on metal surfaces. However, although the chromite has undergone some alteration, it has survived for over 140 million years (since Jurassic time).

Engineered Barrier System Components

The highly corrosion-resistant nature of titanium has been demonstrated by long-term experiments conducted on a range of metal alloys in wells at the hypersaline Salton Sea geothermal field. This anthropogenic example supports the selection of titanium alloys for the construction of a corrosion-resistant drip shield for the Engineered Barrier System (EBS).

Because the proposed use of cementitious material in the EBS and its environs is restricted to grout for securing rock bolts in the emplacement drifts, hyperalkaline conditions are not expected to develop at Yucca Mountain. However, through reactive-transport modeling of the Maqarin site, it has now been demonstrated that coupled process models can reproduce the same suite of cement minerals, hyperalkaline water compositions, and pH that were found in the field. This builds confidence in use of such a model for analogous conditions at other sites.

Seepage

Natural analogues support the hypothesis that most of the infiltrating water in the unsaturated zone (UZ) is diverted around underground openings and does not become seepage. The analogues show that this is true even for areas with much greater precipitation rates than that at Yucca Mountain. Although examples exist where large amounts of seepage can be observed (e.g., the Mission Tunnel and Mitchell Caverns), the hydrogeologic setting is significantly different from that at Yucca Mountain, and thus these are not appropriate analogues. However, for all of the analogues that show some seepage, at least some of the seepage that enters underground openings does not drip, but rather flows down the walls. In the few instances where dripping has been noted in settings that are analogous to Yucca Mountain, the drips can be attributed to asperities in the surface of the roof and ceiling of the opening.

Unsaturated Zone Flow and Transport

Transport model calculations predicted retardation factors for neptunium and uranium that are orders of magnitude higher than retardation factors for the other radionuclides at the Radioactive Waste Management Complex (RWMC) of the INEEL. This result would indicate that very little movement of neptunium and uranium should be observed. However, detection of these radionuclides at depth was inconsistent with their predicted high retardation. Radionuclide transport in the surficial sediment zone at the RWMC could be interpreted as resulting from lateral flow or from a sudden surge of fluid that released a pulse of rapidly-downward propagating radionuclides, such that the peak concentration lies at a still greater depth below that at which the data were collected. Because the nonwelded Paintbrush Tuff (PTn) has somewhat of a damping effect on flow to the welded Topopah Spring Tuff (TSw), it is less likely that the enhanced transport scenario proposed in the INEEL modeling study would occur at Yucca Mountain, even though lateral flow in the PTn may be relevant locally.

At the Peña Blanca, Mexico, analogue site, the estimated transit time for flow from the surface to depths of ~10 m beneath the Nopal I deposit is on the order of a few weeks to a few months. Although the water transit time in the UZ at Peña Blanca is quite short, significant dissolution of uranium may have occurred in a low-water flux, high-uranium concentration setting near the Nopal I uranium deposit. The uranium dissolution rates at Nopal I are

about three times higher during the dry season than those in the wet season, possibly suggesting a favorable physiochemical condition (e.g., increased oxygenation) for uranium dissolution during dry periods. The low humidity during dry seasons may have also enhanced evaporation, causing higher uranium concentrations in the waters sampled. If analyses from future sampling campaigns confirm that transit time is short in the UZ at Nopal I, then the implications would need to be considered for the similar low-water flux environment at Yucca Mountain.

Coupled Processes

Yellowstone and other geothermal systems in welded ash flow tuffs or other low-permeability rocks indicate that fluid flow is controlled by interconnected fractures. Alteration in low-permeability rocks is typically focused along fracture flow pathways. Only a small portion of the fracture volume needs to be sealed by precipitated minerals to retard fluid flow effectively. The main minerals predicted to precipitate in the near field of the proposed Yucca Mountain repository are amorphous silica and calcite, which are also commonly found as sealing minerals in geothermal systems.

Thermohydrologic-chemical (THC) processes are expected to have a much smaller effect on hydrogeological properties at Yucca Mountain than what is observed at Yellowstone. THC simulations conducted to date for the proposed Yucca Mountain repository suggest that only small reductions in fracture porosity (1–3%) and permeability (< 1 order of magnitude) will occur in the near field as a result of amorphous silica and calcite precipitation. Changes in permeability, porosity, and sorptive capacity are expected to be relatively minor at the mountain scale, where thermal perturbations will be reduced; this also applies to the lower temperature (sub-boiling) operating mode. These predicted changes in hydrogeological properties should not significantly affect repository performance.

At the Paiute Ridge intrusive complex, the Papoose Lake Sill intruded into Rainier Mesa Tuff, and the resulting hydrothermal effects were characterized by low-temperature alteration of glass to clinoptilolite and opal, similar to the alteration assemblage present at Yucca Mountain. Hydrothermal alteration was confined to a narrow zone close to the sill-host rock contact. The pervasive opal veins and associated secondary minerals (e.g., clinoptilolite, calcite, cristobalite, etc.) appear to have reduced matrix or fracture permeability in the

immediate vicinity of the basaltic intrusion. Preliminary results of a one-dimensional THC dual-continuum model of the interaction of country rock with heat released from an intrusive complex emplaced above the water table demonstrated the possibility of forming opal-filled veins with the source of silica derived from the matrix of the host rock.

Saturated Zone Transport

At the Gunnison, Colorado, Uranium Mill Tailing Recovery Act (UMTRA) site, a fraction of the uranium originating at the site is transported in the alluvial aquifer at a rate similar to the rate at which a conservative constituent is transported and there is little evidence for lateral dispersion of contaminants in the downgradient direction. At the New Rifle site, dilution is a significant process in the downgradient direction and uranium is transported at almost the same rate as conservative constituents. The conclusions regarding uranium transport distances relative to conservative constituents must be tempered by uncertainties regarding the potential presence of unidentified complexing agents.

In most studies of natural systems, a proportion of the total uranium, thorium, and rare earth elements in the groundwater was associated with colloids. Unambiguous evidence from natural systems indicating colloidal transport over kilometer-scale distances is limited to a few reports. Observations from such places as Los Alamos and the NTS lend support to the concept that radionuclide transport in the saturated zone (SZ) can be facilitated by colloids, but so far no natural analogue studies have been able to quantify the importance of this process.

Biosphere

Results of the Chernobyl literature survey suggest that the increase in the concentration of radionuclides in soils during irrigation in the southern Ukraine, where environmental conditions are more similar to those at Yucca Mountain than are climatic conditions of Chernobyl, confirms the concept of a radionuclide buildup factor used in the Yucca Mountain biosphere conceptual model. Agricultural methods including irrigation, tillage, and types of crops play an important role in resuspension of radionuclides. Resuspended material is likely to increase the contamination of plant surfaces. Resuspended radionuclides would increase the inhalation dose for agricultural workers, which would be particularly significant for plutonium. Aspects of models of atmospheric contaminant dispersal,

radionuclide fallout, radionuclide resuspension, and particle size distributions may be relevant to constraining a model for radionuclide resuspension resulting from a volcanic eruption through a proposed Yucca Mountain repository.

Volcanic and Seismic Effects on Drifts

Use of natural analogues is a major investigative tool in Yucca Mountain volcanism studies. Analogues have been used to assess the probability of dike eruption, plausible eruptive styles, eruptive parameters, and magma compositions, and have also been used to increase confidence in use of the ASHPLUME codes for simulation of an eruption. For seismic effects, examples from observations of underground openings demonstrate that such openings are able to withstand ground shaking for a peak ground acceleration as high as 0.4 g. The bulk of evidence from analogue examples of underground openings, particularly in settings similar to Yucca Mountain (such as the Little Skull Mountain earthquake), demonstrates that damage to repository drifts by ground shaking during the postclosure period would be minimal or unlikely.

3. SUMMARY

The analogue examples and studies presented in this report provide varying degrees of confidence in the processes they are intended to support. The investigation of these analogues has helped to indicate the directions along which further analogue studies can best be focused to address processes that are not fully understood, to lend more realism to models, and to enhance confidence in performance of natural or engineered barriers. Key areas where analogues may assist in building more confident assessments of processes include the possibility of irreversible sorption, efficacy of the drift shadow zone, the manner of modeling plume dispersion, radionuclide behavior at the geosphere/biosphere interface, large-scale studies of colloid transport in relevant geological environments, and radionuclide transport along preferential pathways in unsaturated ash flow tuffs at sites in addition to Peña Blanca.

4. REFERENCES

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Table 1. Natural Analogues in the NASR and Their Potential Applications to PA Models

Section in Natural Analogue Synthesis Report	Conceptual Model Development	Direct Incorporation of Parameter Values into TSPA	Model Validation
3. Drift Stability	Variables that determine structural stability of underground openings		Existence and dimensions of caves and underground openings that have stood open for thousands of years
4. Waste Form	Retention of fission products at Oklo (Gabon) related to partitioning into uraninite; Importance of secondary phases at Shinkolobwe (Zaire) and Okelobondo (Gabon) in retaining U		Nopal I (Mexico) secondary uranium phases validated spent fuel dissolution experiments in which U-silicates are long-term solubility-limiting phases; Chemical and physical conditions required to reach criticality at Oklo used to estimate amount of spent fuel needed to create critical conditions at a repository; Qualitative validation from natural glass alteration studies indicating nuclear waste glass will be stable in repository environment
6. Waste Package	Enhanced preservation of objects stored in unsaturated conditions, as observed in Pintwater cave (NV); Vapor condensation resulting in corrosion, as observed in Altamira cave (Spain); Effects of hypersaline fluids on waste package materials, as observed in corrosion behavior of different metal compositions at Salton Sea (CA) geothermal field; Formation of protective passive film around metals, as observed in Delhi iron pillar (India); Long-term stability of Ni-Fe metals, as evidenced by occurrence of josephinite in 150 Ma ultramafic rocks (OR)	Evaporation experiments conducted to determine evolution of Yucca Mountain water compositions and corresponding mineral precipitates	
7. Engineered Barrier System	Hypersaline fluids have little effect on titanium, as observed in corrosion of titanium alloys at Salton Sea (CA) geothermal field; Zeolites and clay minerals retard radionuclides, as observed in tuffs at Yucca Mountain and Los Alamos (NM); Development of hyperalkaline plumes from cementitious materials, as observed at Maqarin (Jordan); Fe-bearing colloids may retard spent fuel components by forming colloids that are filtered from suspension at short distances, as observed at Poços de Caldas (Brazil)		Multicomponent reactive transport model used to compare simulated and observed fluid chemistry and rock alteration mineralogy at Maqarin (Jordan)

Table 1. Natural Analogues in the NASR and Their Potential Applications to PA Models (cont.)

Section in Natural Analogue Synthesis Report	Conceptual Model Development	Direct Incorporation of Parameter Values into TSPA	Model Validation
8. Seepage	<p>Flow diversion around openings in the UZ independent of climate demonstrated by cave paintings in southern Europe, Egyptian tombs, Buddhist temples;</p> <p>Decreases in seepage with decrease in infiltration demonstrated by preservation of fragile human artifacts and organic materials over thousands of years</p>		<p>Most infiltration does not become seepage, as observed at Kartchner Caverns (AZ) and Altamira (Spain)</p>
9. Unsaturated Zone Flow			<p>Calibration using ITOUGH2 to hydrographs at LPIT, INEEL yielded parameters consistent with measured data</p>
10. Unsaturated Zone Transport	<p>Significant dissolution of U may have occurred in groundwaters near Nopal I; also higher dissolution (or more U concentration) during dry season;</p> <p>Colloidal transport of U, Th in oxidizing UZ at Steenkampskraal (S. Africa) and Koongarra (Australia) (little at Koongarra)</p>		
11. Coupled Processes	<p>Fluid flow in fractures, as seen in Dixie Valley (USA), Siliangkitang (Indonesia) and Wairakei (NZ) geothermal fields;</p> <p>Numerical simulation of heat and fluid flow in numerous developed geothermal systems;</p> <p>Use of chemical tracers to constrain source of fluids, track movement of fluids, and identify high-permeability flow paths, as conducted at Bulalo (Philippines) geothermal field;</p> <p>Changes in water chemistry, precipitation of silica and calcite, and reductions in porosity and permeability, as observed at Cerro Prieto (Mexico), Yellowstone (WY), Otake (Japan), and various New Zealand geothermal fields;</p> <p>Precipitation of salts and silica associated with dryout, as observed in Karaha-Telaga Bodas (Indonesia) geothermal field;</p> <p>Mineral dissolution associated with condensation, as observed at The Geysers (CA) geothermal field;</p> <p>Localized U mobility in tuff at temperatures comparable to repository</p>		<p>Confirmation of TOUGH2-based thermal-hydrological reservoir simulations through post-audit history matching of Olkaria (Kenya) and Nesjavellir (Iceland) geothermal fields;</p> <p>Compared observed and simulated mineral assemblages calculated using EQ3/6 codes, measured geothermal fluid compositions, and observed reservoir conditions at Yellowstone (WY) and Wairakei (NZ) geothermal fields;</p> <p>Modeled formation of opal-filled veins with source of silica derived from host rock at Paiute Ridge (NV);</p> <p>Qualitative- Relative TM stability under sub-boiling conditions in heterogeneous host rock at K-26 (Russia)</p>

Table 1. Natural Analogues in the NASR and Their Potential Applications to PA Models (cont.)

Section in Natural Analogue Synthesis Report	Conceptual Model Development	Direct Incorporation of Parameter Values into TSPA	Model Validation
12. Saturated Zone	Various sites in UZ – some portion of U, Th, and REE transported as colloids		UMTRA plumes – weak to no uranium retardation in examples studied
13. Biosphere		Environmental ^{137}Cs in food 0.4–22 yrs (shorter than predicted), as observed at Chernobyl (Ukraine)	Resuspension of radionuclides in dust particles increases by an order of magnitude after soil tillage; Southern Ukraine – irrigation with contaminated water causes radionuclide buildup factor; Chernobyl – ingestion pathway constitutes small part of total dose; external pathway predominates, except for agricultural workers
14. Disruptive Events	Enhanced ability of underground structures to withstand damage from earthquakes demonstrated by lack of damage in underground facilities during major earthquakes	Intrusion/extrusion ratio near 1 supported by Paiute Ridge field studies and reexamination of dike systems at San Rafael volcanic field; Eruptive style and magmatic composition with combination of scoria cone, spatter cones and lava cones on the surface, and one or more dikes in the subsurface based on Lathrop Wells volcano	Cerro Negro (Nicaragua) used to validate the ASHPLUME code's ability to simulate an ash eruption; The DRKBA code used to model rockfall probabilities accounting for the seismic effect was verified based on test runs using natural analogues