RISK INSIGHTS FOR USE IN THE U.S. NUCLEAR REGULATORY COMMISSION'S PROGRAM FOR THE POTENTIAL YUCCA MOUNTAIN REPOSITORY

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SUMMARY/ABSTRACT

The U.S. Nuclear Regulatory Commission (NRC) staff has completed the risk insights baseline in support of and in preparation for its regulatory review activities outlined in the Nuclear Waste Policy Act of 1982. The risk insights baseline provides a system-level perspective on the relative significance of features, events, and processes and associated uncertainties via their potential effect on the waste isolation capabilities of the repository system during the post-closure period, and the potential effect on public health and safety. The staff develops risk insights from experience gained through the development and exercise of its independent performance assessment; technical analyses to support pre-licensing interactions with the U.S. Department of Energy (DOE); and analyses conducted by the DOE and others. For the NRC high-level radioactive waste program, performance assessment is defined as the risk-assessment methodology used to assess risks associated with post-closure performance of a repository system.

The NRC staff has conducted further risk analyses in key areas identified in the risk insights baseline, including: (i) waste package corrosion and repository near-field chemical environment, (ii) radionuclide transport in the saturated zone, and (iii) inhalation of resuspended volcanic ash. The NRC staff uses the results of these analyses to risk-inform enhancements to its performance assessment..

The results of these analyses and subsequent enhancements to the performance assessment risk-inform ongoing pre-licensing activities and interactions with the DOE and other stakeholders. Performance assessment together with the risk insights baseline will complement information considered during a potential license application review. Independent analyses provide additional confidence for review of the strengths and limitations of a DOE demonstration of compliance with NRC regulations.

INTRODUCTION

The U.S. Nuclear Regulatory Commission (NRC) has published licensing criteria at Part 63 under Title 10 of the U.S. Code of Federal Regulations for disposal of high-level radioactive waste in a potential geologic repository at Yucca Mountain, Nevada [1]. In setting forth these criteria, the NRC sought to establish a coherent body of risk-informed, performance-based criteria for a Yucca Mountain facility that is compatible with the Commission's overall philosophy of risk-informed, performance-based regulation. Stated succinctly, risk-informed, performance-based regulation is an approach in which risk insights, engineering analysis and judgment, and performance history are used to i) focus attention on the most important activities, ii) establish objective criteria based on risk insights for evaluating performance, iii) develop measurable or calculable parameters for monitoring system performance, and iv) focus on the results of performance measures as a primary basis for regulatory decision-making.

Risk insights are drawn from risk assessments and help to convey the significance of specific features, events, and processes to the waste isolation capabilities of the potential repository system after closure as well as potential effects on public health and safety. Building on nearly twenty years of risk assessment activity, the NRC staff published a risk insights baseline documenting a set of system-level and detailed risk insights related to post-closure performance of a potential geologic repository system at Yucca Mountain [2]. The risk insights baseline documents an understanding and associated uncertainties of how a repository system at Yucca Mountain might function. The staff draws risk insights from experience gained through the development and exercise of its performance assessment [3]; technical analyses conducted to support pre-licensing interactions with the U.S. Department of Energy (DOE); and analyses conducted by the DOE and others.

RISK ANALYSES FOR RISK INSIGHTS

The NRC staff and the Center for Nuclear Waste Regulatory Analyses have conducted risk analyses to enhance understanding in key areas identified in the risk insights baseline [4]. These analyses provide insight on the impact of uncertainties associated with features, events, or processes expected to significantly affect the capability of the potential repository system to isolate waste following permanent closure. Areas analyzed included (i) waste package corrosion and repository near-field environment, (ii) radionuclide transport in the saturated zone, and (iii) inhalation of resuspended volcanic ash particles.

Waste Package Corrosion and Repository Near-field Environment

The current waste package design for high-level radioactive waste consists of 20 mm thick Alloy 22 outer containers surrounding 50 mm thick type 316 nuclear-grade stainless steel inner containers. In addition, DOE proposes installing mail-box shaped drip shields, fabricated from titanium alloys approximately 15 mm thick, above the emplaced waste packages at the time of permanent closure. The drip shields and waste packages are intended to protect 70,000 metric tons of high-level radioactive waste from dripping water and limit the radionuclide release to the geosphere. Various degradation processes, including corrosion, may compromise these engineered barriers. However, the presence of a thin, protective passive oxide film that restricts metal dissolution controls the corrosion rates of the alloys proposed for the engineered barrier system at Yucca Mountain, particularly for Alloy 22. Thus, the persistence of a passive film on the surface of the waste package should result in very low corrosion rates of the waste package. However, high temperature and aggressive chemistry conditions have a potentially detrimental effect on the stability of the passive film and may induce localized forms of corrosion. Therefore, evaluating the range in chemistry of water contacting the engineered barriers is important for estimating corrosion rates of the engineered barriers.

The range of expected chemical environments in the drifts for corrosion depends on variations in seepage water composition, condensate water composition, and the extent of interaction between these waters and the waste package. The NRC performance assessment considers the presence of highly concentrated solutions resulting from evaporation and the existence of salt systems of low deliquescence relative humidity. High temperatures, supported by deliquescence brines could activate enhanced corrosion rates, even in the absence of seepage water. However, there is currently no experimental support for sustaining enhanced corrosion rates in deliquescence solutions over extended periods.

This study investigates potential near-field environments contacting the waste package as functions of temperature and drip shield failure time, and their impact on the onset of localized corrosion. The analysis considers three representative chemical scenarios for potential impact on corrosion: i) seepage water not contacting the waste package, but humidity sufficiently high for the formation of deliquescence brines (Environment I); ii) seepage water contacting the waste package and evaporating (Environment II); and iii) seepage water contacting the waste package without significant evaporation (Environment III). Bechtel SAIC Company, LLC [5] evaluates the abundance of corrosion inhibiting species in dust potentially contacting the waste package surface during the dry period. Bechtel SAIC Company, LLC [5] also estimates the dependence of pH and concentration of corrosion-inducing (chloride) and -inhibiting species (oxyanions) as a function of relative humidity when seepage water contacts the waste package outer surface and evaporates producing brines. Since unsaturated seepage waters are diluted, waters in contact with the waste package should remain diluted when evaporation rates are much lower than seepage rates.

The analysis derives and calibrates an expression for the corrosion potential as a function of temperature and pH to experimental data over a range of temperatures and pH values [4]. An empirical relationship defines the critical potential for localized corrosion as a function of chloride, temperature, and the inhibiting oxyanion to chloride ratio [4]. This analysis assumes localized corrosion initiates in a given environment if the corrosion potential exceeds the critical potential. Dusts samples collected in the vicinity of the Yucca Mountain region indicate an abundance of inhibiting oxyanions. Thus, localized corrosion is unlikely during Environment I. During Environment II, localized corrosion is possible, therefore, the analysis evaluates the likelihood of localized corrosion based on the corrosion potential and critical potential expressions. Table 1 indicates the frequency of occurrence of various chemical environments resulting from evaporative brines on the waste package surface according to data in Bechtel SAIC Company, LLC [5]. According to Table 1, less than one percent of waste packages could experience localized corrosion on mill-annealed areas, whereas approximately 20 percent of waste packages may undergo localized corrosion on welded areas. These probabilities depend on the likelihood of seepage waters to come into contact with the waste package. If drip shields divert water during the thermal pulse, seepage would not contact the waste packages. During Environment III, waste packages are not expected to exhibit localized corrosion because of the diluted nature of seepage waters.

Table 1. Estimated Chemical Environment Composition, Frequency, and Likelihood of Localized Corrosion due to Evaporative Brines

Cl- [M]	NO_3^- [M]	pH	Frequency [%]	Bin	Localized Corrosion	
					Mill-Annealed	Weld
3.82	0.21	6.05	00.22	3	Unlikely	Likely
3.10	0.39	7.00	01.42	4	Unlikely	Unlikely
2.53	0.18	7.23	00.79	5	Unlikely	Unlikely
1.84	0.06	8.84	05.46	6	Unlikely	Likely
2.23	0.07	8.84	27.15	7	Unlikely	Likely
0.45	0.03	8.84	16.20	8	Unlikely	Unlikely
0.95	0.41	8.84	15.55	9	Unlikely	Unlikely
1.99	0.14	8.84	11.70	10	Unlikely	Unlikely
1.99	0.19	8.84	21.51	11	Unlikely	Unlikely

Radionuclide Transport in the Saturated Zone

Infiltrating water would transport dissolved or suspended radionuclides released from the engineered barrier system generally vertically downward through the unsaturated rock to the saturated rocks below the water table. The saturated zone in the vicinity of Yucca Mountain consists of a series of alternating volcanic aquifers and confining units above a regional carbonate aquifer that generally thin toward the south and become interspersed with valley-fill aquifers approximately 10 km to 20 km to the south and southeast of Yucca Mountain. The transport of radionuclides in the saturated zone may incorporate processes such as molecular diffusion between fractures and the rock matrix, mechanical dispersion, as well as sorption of radionuclides onto mineral surfaces. The saturated fracture paths in the volcanic rock are characterized by relatively limited surface areas, and thus could exhibit limited, if any, sorption effects within fractures. Conversely, retardation in the saturated alluvium could significantly delay the movement over very long time periods (e.g., thousands to tens of thousands of years and longer) of radionuclides (e.g., neptunium-237, americium-241, and plutonium-240) that tend to sorb onto porous materials.

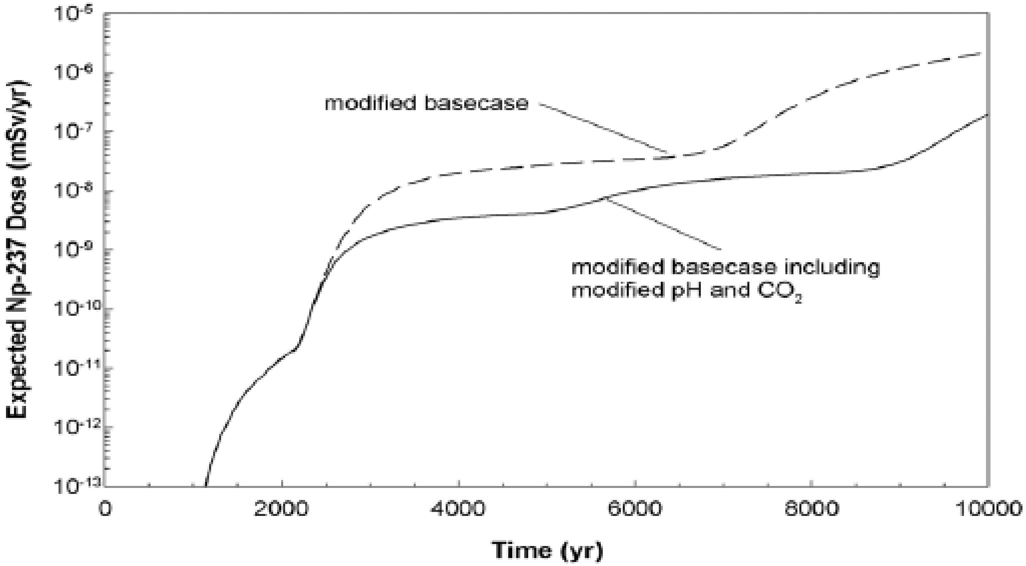

Figure 1. Comparison of Estimated Neptunium-237 Total Effective Dose Equivalent Derived from Surface Complexation Approach

The range of effective retardation factors for radionuclides that tend to sorb onto porous materials depends on the geochemistry and mineralogy of the saturated alluvium. Although the retardation factors currently used in the performance assessments likely provide a reasonable estimate of radionuclide sorption, the technical bases for these values are based on experiments with limited accounting of saturated zone chemistry or variation in alluvium mineralogy.

This study evaluates the capability of saturated alluvium to delay the movement of radionuclides that tend to sorb onto mineral surfaces (e.g., neptunium-237, americium-241, and plutonium-240). The assessment compares two sorption models, one considering a surface complexation description to define distribution coefficients as functions of pH and CO_2, and a second employing direct sampling from probability distributions of partition coefficients, K_d. The surface complexation model estimates the effective surface area normalized distribution coefficients ($K_a^{'}$) as functions of pH and partial pressure of carbon dioxide. The model estimates values of the distribution coefficient, $K_a^{'}$ from correlated ranges of pH and CO_2 representative of the saturated alluvium at Yucca Mountain. The surface complexation approach calculates a two-fold variation in neptunium-237 dose compared to the K_d approach. The analysis also updates groundwater chemistry data for pH and CO2. Sampled values are consistent with recent observations of groundwater chemistry and alluvium mineralogy. Figure 1 displays estimated groundwater doses for neptunium-237 in 10,000 years computed with the surface complexation approach (solid line) and for updated pH-CO_2 chemistry (dotted line). Updated chemistry results in approximately an order of magnitude variation in estimated dose for neptunium-237.

Inhalation of Resuspended Volcanic Ash Particles

Basaltic igneous events have occurred for over 10 million years in the vicinity of Yucca Mountain. Igneous activity can affect the potential repository through *extrusive* (i.e. conduits intercepting the repository footprint and directly releasing radionuclides in volcanic eruptions) or *intrusive* events (i.e., conduits damaging waste packages in a repository drift and radionuclides released via groundwater pathways). Although the likelihood of future igneous events is small, event consequences may be so important that igneous activity could be an important contributor to the overall risk after closure.

During an eruption at Yucca Mountain, flowing magma could entrain radionuclides from disrupted waste packages. The volcanic ash plume would transport entrained radionuclides released to the atmosphere downwind. and deposit them on the ground surface. Once deposited, surface disturbing activities may resuspend the small particles of high-level radioactive waste and volcanic ash potentially exposing the receptor via inhalation.

Inhalation of radionuclides dominates estimated doses in the extrusive igneous release scenario. Thus, the mass loading of ash particles in the air is a significant aspect influencing the magnitude of dose estimates.

Table 2. Estimated Daily Mass Inhaled from Outdoor and Indoor Exposures During Fresh Ash Conditions Assuming Peak Mass Loads Prevail for an Extended Portion of the Activity Duration

Activity	Outdoor Mass Inhaled (mg)	Indoor Mass Inhaled (mg)	Total Mass Inhaled (mg)
Sleeping	Not applicable	0.87	0.87
Sedentary	Not applicable	0.41	0.41
Light work	1.42	1.06	2.48
Moderate work	8.88	3.23	12.11
Hard work	3.44	3.44	6.88
All activities	13.74	9.01	22.75

The amount of fine ash particles resuspended above a deposit depends on the type and duration of surface-disturbing activities and the thickness of the deposit. The current NRC performance assessment includes a mass load factor for fresh ash (i.e., conditions soon after the occurrence of an eruptive event) and for soil (i.e., longer-term conditions for ash embedded in soil). However, the amount of ash in the air would be expected to vary as a function of human activities and characteristics of the exposure scenario.

This analysis compares the impact on dose estimates of the current ash condition mass loading approach to an alternative description evaluating various types of surface disturbing activities and dust levels possibly occurring shortly after an igneous event. The assessment estimates average inhalation volumes from breathing rates and durations of various indoor and outdoor activities including sleeping, sedentary, and work. The estimated mass loads available for inhalation from fresh ash for each of these activities are from measurements at Cerro Negro in Nicaragua and Montserrat in the West Indies. Measurement of the peak mass loads occurred over short intervals which are not expected to persist for the duration of the surface-disturbing activities. Therefore, the activity-specific description implements a stratified approach which considers that observed peak mass loads prevail for a short, an intermediate, and an extended portion of each activity's duration for both fresh ash and long-term soil conditions.

Table 2 indicates the estimated daily mass inhaled by an average receptor from outdoor and indoor exposures to fresh ash conditions assuming a peak mass load is generated for an extended portion of the activity duration. The analysis indicates that the daily mass load could vary by approximately two-fold when considering a range of the activity's duration over which the peak mass load prevails. Comparison of estimated dose from the median value of the activity-specific mass loading approach versus the ash-condition mass loading approach indicates a two-fold variation in estimated dose to the receptor.

CONCLUSIONS

Staff from the NRC and the Center for Nuclear Waste Regulatory Analyses conducted risk analyses to address uncertainties in key areas identified in the risk insights baseline. The areas analyzed include (i) waste package corrosion and repository near-field environment, (ii) radionuclide transport in the saturated zone, and (iii) inhalation of resuspended volcanic ash particles. The analysis of waste package corrosion and repository near-field environment evaluated the likelihood for waste packages to exhibit localized corrosion as function of chemical water compositions. Localized corrosion could only occur in concentrated solutions resulting from the evaporation of seepage waters. An approach to numerically evaluate the probability of localized corrosion was proposed which can be incorporated into the NRC performance assessment.

The extent of retardation in saturated alluvium of radionuclides that tend to sorb onto mineral surfaces was evaluated. A surface complexation model was used to define partition coefficients as functions of pH and CO_2. Correlated sampling of pH and CO_2 in the performance assessment model results in lower doses than directly sampling partition coefficients from predefined distribution functions. Future modifications to the performance assessment will consider incorporating a surface complexation model with updated geochemistry to estimate distribution coefficients.

The analysis of inhalation of resuspended volcanic ash evaluated the impact of stratified mass loads from a range of reasonable surface-disturbing human activities. The estimated dose to the receptor for the median value of the stratified mass load model is two-fold lower than the dose estimated simply for the age of the ash deposit. Future modifications to the NRC performance assessment may consider the impact of a range of surface-disturbing human activities on inhaled mass loads.

The results of these analyses and subsequent enhancements to the NRC performance assessment risk-inform ongoing pre-licensing activities and interactions with the DOE and other stakeholders. Performance assessment and risk insights will inform the staff's independent understanding during a potential license application review. Independent risk-informed analyses provide additional confidence for review of strengths and limitations of the DOE demonstration of compliance with NRC regulations.

ACKNOWLEDGMENTS

The NRC staff views expressed herein are preliminary and do not constitute a final judgment or determination of the matters addressed or of the acceptability for a geologic repository at Yucca Mountain.

This paper was prepared to document work performed by the Center for Nuclear Waste Regulatory Analyses (CNWRA) for the Nuclear Regulatory Commission (NRC) under Contract No. NRC-02-02-012. The activities reported here were performed on behalf of the NRC Office of Nuclear Material Safety and Safeguards, Division of High Level Waste Repository Safety. This paper is also an independent product of the CNWRA and does not necessarily reflect the view or regulatory position of the NRC.

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