Baseline of Risk Insights

1. INTRODUCTION

As a part of the pre-licensing consultative process, the U.S. Nuclear Regulatory Commission (NRC) and the U.S. Department of Energy (DOE) have reached 293 agreements that define the information required from DOE to close NRC-identified key technical issues (KTIs). The nature of these NRC/DOE agreements varies from simply requiring DOE to document existing work to DOE conducting sophisticated technical investigations. Most of the agreements (more than 95 percent) relate to evaluation of post-closure safety, with the remainder addressing pre-closure safety. Each agreement relates to the contents for a license application defined in 10 CFR Part 63 and NRC staff guidance presented in the final draft Yucca Mountain Review Plan (YMRP). Although completion of each agreement will enhance the likelihood that the license application will be complete and of high quality, not all agreements are of equal importance. Some agreements pertain to information (data and/or analyses) that is critical to safety (or risk) evaluations, others are important but not critical, and there are some that request information that is primarily corroborative in nature. The guidance for risk-informed review documented in the YMRP stipulates that the depth of NRC review be based, in a large part, on the risk significance of a topic.

The objective of this paper is to synthesize existing information to categorize the agreements into (i) High-Risk Significance — the information requested has the potential to alter the risk estimates significantly; (ii) Medium-Risk Significance — the information requested has some influence on the risk estimates; and (iii) Low- Risk — the information requested is expected to have little effect on the risk estimates. Generally, the risk significance of an agreement is associated with the level of uncertainty addressed by the agreement and the relationship of the uncertainty to risk. For example, one might postulate a potentially risk-significant scenario involving the breaching of many waste packages, caused by large static loads of rock on the waste package, because of degradation and collapse of repository drifts. For this scenario, we could have agreements that require information to determine the extent of drift degradation and the strength of the waste package. The extent of the drift degradation is very uncertain and spans values that result in little, if any, damage to the waste package, to extensive damage to the majority of the waste packages. Consequently the information used to determine the extent of the drift degradation is considered to be of high-risk significance. The determination of the strength of the waste package is based on standard engineering principles and material measurement; thus, there is little uncertainty in the determination of the waste package strength and this information would be considered to be of low-risk significance. DOE needs to provide sufficient information to allow NRC to determine that the strength of the waste package is credible; however, this should be straightforward and would only be significant if the analysis is done incorrectly.

In practice, evaluating the agreements is not as simple as the above example, because many agreements are more complex and interrelated and thus are dependent on more than one agreement (e.g., corrosion processes for the waste package may be dependent on the chemistry of the water that contacts the waste package, which may be dependent on the estimates of deep percolation). Despite these complexities, the staff has used current understanding to classify the agreements by risk significance (i.e., understanding potential effect on the overall risk and the potential uncertainty of the risk estimate). In classifying agreements into the three categories (i.e., low-, medium-, and high-risk significant), risk information has been drawn and synthesized using many types of existing quantitative analyses, where each analysis has its own strengths and weaknesses. Evaluation of repository performance is complicated because of such things as the long compliance period, and reliance on computer models to extrapolate beyond laboratory and field information. Thus, staff judgment has been used, as needed, when combining information from different analyses.

Complementing the risk insights is the concept of multiple barriers (i.e., both engineered and natural barriers) in geologic disposal of high-level radioactive wastes. For example, the safety of geologic disposal is enhanced if the system includes: (1) a long-lived waste package that retains its integrity during the period of the highest thermal output of the waste when the waste form behavior is most uncertain, because of potentially high temperatures; (2) slow release rates of radionuclides from the engineered barrier system once the waste packages are breached; and (3) slow travel of released radionuclides from the engineered barrier system to the area where potential exposures might occur. Multiple barriers, as an element of a defense-in-depth approach, results in a robust repository system that is more tolerant of failures and external challenges (e.g., poor or highly degraded performance is necessary in multiple areas to have a significant effect on risk). The risk insights presented in Section 2 are developed within the multiple barrier context (i.e., understanding the safety significance of the long-lived waste package, release rates of radionuclides, and transport of radionuclides in the context of the effect on risk estimates). The chemical behavior and inventory of specific radionuclides, as well as the influence of the various barriers, requires that staff exercise care in developing the risk insights. For example, radionuclides that are very soluble [e.g., iodine-129 (I-129) and technetium-99 (Tc-99)] will not be sensitive to the amount of water contacting the waste form, whereas a solubility-limited radionuclide [e.g., neptunium-237 (Np-237)] will be sensitive to this factor. Additionally, radionuclides with relatively short half-lives [i.e., americium-241(Am-241) - 430 years and plutonium-240 (Pu-240) - 6500 years] are strongly affected by limited delay in the geosphere, whereas other long-lived radionuclides (e.g., Np-237 - 2 million years) would require substantially more delay to be as effective. Identification of risk-significance requires consideration of the risk potential of each radionuclide and the safety significance of the attributes of the repository system (i.e., engineered and natural barriers), including the uncertainties.

Development of the risk insights based on the performance assessment calculations includes all of the supporting evidence that is used to build confidence in the calculations and the safety attributes of the repository system. Such evidence may include information from laboratory and field experiments, natural or man-made analogs, sensitivity analyses, and other specialized analyses at a subsystem level. The risk insights are based on current information and understanding. The risk rankings may change as repository design evolves, site information improves, and performance analyses continue. Staff intends to update, as appropriate, the risk baseline and insights, and the risk rankings for the agreements.

The remaining sections of this report provide the risks insights used to rank the agreements and a summary of the high-risk significant agreements. Section 2 describes the repository system and identifies the risk insights according to the 14 post-closure model abstractions identified in the YMRP. Section 3 discusses the risk significance of the more generic review items in the YMRP, associated with the total system performance assessment. Section 4 provides a limited discussion of the risk significance of the pre-closure YMRP review items (the focus of the agreements has been on the post-closure performance). Section 5 presents a summary of the high-risk significant agreements.

2. RISK INSIGHTS RELATED TO POST-CLOSURE PERFORMANCE ASSESSMENT MODEL ABSTRACTIONS

Development of the risk insights is based on the estimated performance of the Yucca Mountain repository provided in the analyses of the staff and DOE, and includes the supporting evidence that is used to build confidence in the calculations. In this section, a general description of the repository system is provided as seven distinct discussions that separate the repository system by:

- Water infiltration, percolation, and seepage;
- Degradation of the engineered barrier system;
- Radionuclide release from the engineered barrier system;
- Flow and transport of radionuclides in the unsaturated zone below the repository;
- Flow and transport of radionuclides in the saturated zone;
- Biosphere and the reasonably maximally exposed individual (RMEI); and
- Igneous activity.

Risk insights, which are grouped according to the 14 model abstraction categories of the YMRP, are provided after each description [note: some minor variations from the exact format of the YMRP were made to aid the clarity of this section].

The risk insights discuss, as appropriate, three categories of risk significance (i.e., high, medium, and low) as defined in the previous section. The assignment of risk significance is somewhat subjective; however, the staff believes the three groupings provide a useful approach for prioritizing future efforts and activities with DOE. Further, the staff has attempted to provide a general identification of the risk-significant items; however, the staff has not attempted to identify <u>all</u> the low-risk-significant items. These risk insights are based on current understanding and are subject to change as new information is collected.

2.1 System Description: Infiltration, Percolation and Seepage

Yucca Mountain is located in an arid climate and currently receives an average of approximately 190 millimeters (mm) [7.5-inches] of precipitation per year. The current climate is expected to evolve according to anticipated glacial cycles. Evidence suggests at the last full glacial maximum, average annual precipitation may have been 1.5 to 2.5 times larger than current climatic conditions, whereas average annual temperatures may have been cooler by 5 to 10^{o}C. Approximately 95 percent of the precipitation currently falling onto Yucca Mountain is estimated to be removed by run-off, evaporation, and plant transpiration. The remainder infiltrates the surface and generally percolates vertically downward through the unsaturated tuff toward the proposed repository horizon. However, large-scale features (e.g., fault zones, hydraulic conductivity contrasts at the interfaces between tuff layers) and small-scale features (e.g., variability of hydraulic conductivity within a tuff layer) may complicate the flow paths and cause deep percolation to vary spatially. Additionally, several processes are likely to reduce the quantity of percolating water reaching the engineered components of the repository: (1) capillary forces in the unsaturated rock will tend to divert water through permeable rock around the drift opening; (2) a portion of the water entering the drift will tend to flow in a film down the drift walls rather than dripping from the ceiling; and (3) decaying radioactive waste emplaced in the drifts will heat the rock above boiling temperature during the first few thousand years, thereby driving liquid water away. However, processes controlling dripping are complex. For example, percolating water can be focused at sharp points of rock and avoid diversion by capillary forces. Water evaporated by repository heat will condense in cooler areas and flow back toward the drifts (refluxing), and infiltrating or refluxed water may penetrate back into thermally perturbed rock that has temperatures above boiling. Flow in fractures may be transient during episodes of high infiltration.

Deep percolation flux at the repository horizon directly influences the quantity and chemistry of water coming into contact with the drip shield and the waste package and, thus, directly influences the degradation of those engineered components through aqueous corrosion processes. Estimating the evolution of the near-field environment is complex because of coupled thermal-hydrological-chemical processes. Water and gas compositions will be influenced by the phases in the unsaturated fractured rock with which they react. Local changes in water and gas chemistry may result from interactions with engineered materials, corrosion products, or both. Major processes that will affect the evolution of the near-field environment include evaporative processes, mineral dissolution and precipitation, as well as aqueous- and gaseous-phase transport and chemical reactions. Deep percolation flux also directly influences the amount of water entering breached waste packages, which, in turn, facilitates the release of radionuclides from the waste form and into the unsaturated zone underlying the repository horizon. Deep percolation flux also directly influences the transport of radionuclides through the unsaturated zone to the saturated zone.

Model Abstraction: Climate and Infiltration

High-Risk Significance:

- None

Medium-Risk Significance:

- Estimates of current shallow infiltration rates are important for determining the deep percolation flux. The deep percolation flux has an effect on the release of Np-237, which is the radionuclide that most influences the peak estimated risk beyond 10,000 years (note: Np-237 exposure occurs beyond 10,000 years primarily because of retardation in the saturated alluvium).

- Surface soil thickness is an important parameter in determining shallow infiltration rates. Thin soil layers allow infiltration to enter fractures in the underlying bedrock more quickly and, thus, escape loss through evaporation.

Low-Risk Significance:

- Long-term climatic change, in terms of changes in precipitation and temperature, will directly affect the rate of shallow infiltration and, subsequently, deep percolation flux. However, models supported by available data indicate that climate change will be limited over the next 10,000 years and will not have a significant effect.

Model Abstraction: Flow Paths in the Unsaturated Zone

High-Risk Significance:

- None

Medium-Risk Significance:

- Seepage of water into the drifts determines the amount of water that comes into contact with the drip shields and waste packages and affects the release and transport of lower-solubility radionuclides (e.g., Np-237).

Low-Risk Significance:

- Short-term variation in precipitation does not significantly affect deep-percolation flux. After a precipitation event, infiltrating water moves in pulses vertically through the fractured rock unit and into the underlying rock units, where the pulses are variably damped in the Paintbrush non-welded unit into more steady vertical flow.

Model Abstraction: Quantity and Chemistry of Water Contacting Waste Packages and Waste Form

High-Risk Significance:

- Evaluating the evolution of the near-field water chemistry contacting the drip shield and waste package is important for determining corrosion rates. Evaporation can result in corrosive salt deposits on the surfaces of these barriers. Because of the concentrating effect of evaporation, small differences in water chemistry can result in large differences in the salt composition. Depending on the salt deposited, this process can lead to elevated concentrations of corrosive chemical species and high acidity (low pH) on the drip shield and/or waste package. Key constituents in salts include aggressive corrosive species such as fluoride and chloride and possible corrosion-inhibiting species such as nitrate.

- The temperature at which specific brine chemistries can develop on the drip shield and waste package may also be important for estimating uniform corrosion rates and evaluating the possibility of accelerated, localized corrosion. Evaporated salts can sorb water from the air in the repository to form a brine film on the surface. The temperature at which this occurs depends on the salt composition. In the case of some salts, the temperature of the brine could be higher than 100 °C. Because uniform corrosion rates increase exponentially as a function of temperature, and high temperatures could facilitate the chemical breakdown of the passive film and the occurrence of localized corrosion and accelerated uniform corrosion, it is important to establish the temperature ranges on the engineered barrier surfaces and the boundaries of this salt hydration process (i.e., possible salt mixtures and their deliquescence points, relative humidity, and temperature).

Medium-Risk Significance:

- The quantity and chemistry of water contacting the waste form can either enhance or limit the importance of certain radionuclide solubility limits (see Section 2.3). Both physical processes governing water movement and chemical processes governing mobilization of radionuclides could be important.

2.2 System Description: Degradation of the Engineered Barrier System

The current DOE design for the engineered components calls for 63,000-metric tons of commercial spent nuclear fuel as well as 7000-metric tons of DOE spent nuclear fuel and solidified high-level radioactive waste to be loaded into waste packages before placement in tunnels cut into the unsaturated tuff approximately 350-meters (1150 ft) below the surface. The commercial spent nuclear fuel generally is in the form of ceramic-like pellets of irradiated uranium-dioxide (UO_2) clad in approximately 0.6 to 0.9-mm (0.023 to 0.035-in.) thick corrosion-resistant Zircaloy tubes. The current waste package design for commercial spent nuclear fuel consists of a 20-mm [0.787- in.] thick Alloy 22 outer container surrounding a 50-mm [1.969-in.] thick type 316 nuclear-grade (NG) stainless steel inner container to provide structural strength during pre-closure operations. Our understanding is that after the spent nuclear fuel or other high-level waste is loaded, lids will be welded onto the waste packages before placing them in the repository; and before permanent closure of the repository, an inverted U-shaped metal drip shield, approximately 15-mm (0.6-in) thick, fabricated from Titanium Grade 7, will be installed over the emplaced waste packages. The bulk of the 7000 metric-tons of DOE waste will be in the form of borosilicate glass, poured into stainless steel canisters, and encased in waste packages of similar design to that used for commercial spent nuclear fuel.

The drip shield and waste package can protect the waste form from dripping water while they remain intact, thereby limiting both the timing and magnitude of radionuclide release. The drip shield may also limit the exposure of the waste package to aggressive chemical environments resulting from thermal-hydrological-chemical processes, as well as mitigate mechanical damage to the waste package from falling rocks. These engineered barriers may fail by various degradation processes, including corrosion and mechanical damage. The lifetime of the engineered barriers can be influenced by the environmental conditions to which they are exposed; rock-fall from drift degradation or seismicity; faulting; or ascending magma from volcanic activity.

The flow of water into a breached waste package will depend on the location and cross-sectional area of the breaches through the waste package. Four simplified categories of failure can facilitate understanding of the performance of the waste package in limiting radiological releases: (1) a limited number of waste packages with small cracks or perforations; (2) a small number of waste packages with large breaches; (3) a large number of waste packages with small cracks or perforations; and (4) a large number of waste packages with large breaches. A limited number of waste package breaches, either large or small, may result from aggressive and highly localized environments; isolated rock-fall from minor drift degradation or small seismic events; faulting; and manufacturing defects. Stress corrosion cracking is the main process by which frequent but small cracking of waste packages could occur. The likelihood of stress corrosion cracking can be promoted by aggressive environmental conditions combined with residual stresses resulting from fabrication and closure operations or applied stresses as a consequence of extensive rock-fall from widespread drift degradation or seismicity, as well as accidental internal overpressure. Large widespread failures of the waste packages may result from accelerated, localized corrosion because of pervasive aggressive environments or extensive rock-fall from large-scale drift degradation or large seismic events. In this context, the fabrication and closure processes may result in microstructural changes of the container material that can affect significantly the resistance to localized corrosion and mechanical damage, as well as the mode and extent of the resulting failure.

Model Abstraction: Degradation of Engineered Barriers

High-Risk Significance:

- The persistence of a passive film on the surface of the waste package ensures very slow corrosion rates of the waste package. High temperatures and aggressive water chemistry conditions have a potentially detrimental effect on the stability of the passive film and may accelerate corrosion over extended surface areas.

Medium-Risk Significance:

- The failure mode of the waste package (uniform corrosion, localized corrosion or stress corrosion cracking) and its morphology (e.g., pits, cracks, or large corrosion holes or patches) is important for determining the amount of water that can enter the waste package.

- The quantity and chemistry of the water that can develop on the waste package and their effects on corrosion modes and rates will depend on the integrity of the drip shield.

- Stress corrosion cracking of the drip shield or waste package is not necessarily significant because of the limited area affected by this corrosion process and thus is not expected to allow substantial amounts of water to enter the waste package. However, applied loads arising from accidental internal overpressure, rockfall, or seismic events may increase the failure area and facilitate the ingress of water through the extended opening of stress corrosion cracks.

Low-Risk Significance:

- Juvenile or early failures of the waste package (e.g., closure welding defects, such as flaws, which can promote other degradation processes) are expected to be limited to a small fraction of waste packages and not have a significant effect on waste package performance and hence on radionuclide release.

Model Abstraction: Mechanical Disruption of Engineered Barriers

High-Risk Significance:

- The accumulation of rocks falling into the tunneled drifts, because of such things as seismic events and natural degradation processes, has the potential to create large static loads on the barriers, which could damage the engineered barriers. A potentially beneficial effect is that the presence of a back-filled drift from natural rock fall would tend to decrease the dose contribution from volcanic disruption of waste packages by limiting the number of damaged waste packages. A possible detrimental effect may be the increase in the waste package and drip shield temperatures. The timing and extent of rock fall will determine the overall potential consequences to dose.

Medium-Risk Significance:

- The drip shield may be designed to limit the consequences of rockfall by diminishing the effect of static loads on the waste package.

Low-Risk Significance:

- Dynamic effects from rock falling onto engineered barriers, fault movement, and seismic events do not have a significant effect on overall dose when the probability of large or significant events is considered.

2.3 System Description: Radionuclide Release from the Engineered Barrier System

Once water enters into breached waste packages, the waste form can degrade and release radionuclides. Degradation of the waste form, release of radionuclides into the in-package water, and transport of the radionuclides out of the waste package and through the invert below affects the release of radionuclides to the unsaturated zone below the repository.

Before water can transport radionuclides, the waste forms must become exposed. Cladding encases the spent nuclear fuel waste form and protects it from water that has entered the waste package. Factors affecting the longevity of the cladding include the use of less-corrosion resistant materials (e.g., less-corrosion-resistant aluminum or stainless steel vs. more-corrosion-resistant Zircaloy); localized corrosion and stress corrosion cracking of Zircaloy cladding exposed to in-package water; hydride cracking, creep failure, or other mechanical failure processes of the thin clad because of seismicity, rockfall, faulting, shipping and handling; and swelling of exposed spent nuclear fuel pellets causing rapid “unzipping” of the cladding, in particular for high burn-up fuel. Similarly, in the case of reprocessing waste, the pour canister may provide protection beyond what is available from the waste package container.

After the spent nuclear fuel and other high-level radioactive waste are exposed to air and moisture, they must degrade before radionuclides bound in their ionic crystalline structure can become available for release. As the waste form degrades, radionuclides must dissolve in water for transport to occur. Dissolution of radionuclides, formation of or attachment to colloids, and incorporation into secondary minerals of uranium may influence the rates and amounts of radionuclides that are available for transport. A small percentage of the waste consists of radionuclides that are very soluble and are expected to release quickly, whereas the bulk of the radionuclide inventory consists of solubility-limited radionuclides that will require larger quantities of water in which to dissolve the available inventory. Some solubility-limited radionuclides (e.g., Pu), particularly those associated with the vitrified high-level radioactive waste forms, can form or attach to colloids. Association of radionuclides with colloids can increase their release from the degraded waste forms above that expected with dissolution alone.

Once radionuclides exit the waste package, they must migrate through the invert beneath the waste package to be released to the unsaturated zone beneath the repository. The current DOE design for the invert consists of a steel structure backfilled with compacted crushed tuff up to about one-half meter (1.64 ft) in thickness, through which water must migrate by advection and diffusion to the underlying rocks. The porous nature of the invert material may help retard the transport of radionuclides to the unsaturated zone, but may be too thin to have an appreciable effect.

Model Abstraction: Radionuclide Release Rates and Solubility Limits

High-Risk Significance:

- The dissolution rate of the waste form in an aqueous environment is important for all radionuclides. Uncertainty in the dissolution rate is large such that the time required to release radionuclides from the spent fuel matrix can vary from hundreds of years to hundreds of thousands of years. Water chemistry and temperature within the waste package could affect the degradation rate of the fuel. Oxidation of fuel and corrosion of internal metallic components of the waste package (e.g., fuel assembly baskets) could reduce pH, leading to higher dissolution rates.

Medium-Risk Significance:

- Zircaloy cladding is highly corrosion resistant, and could protect spent fuel for relatively long periods of time if undamaged. Performance assessment studies show a high correlation between dose and fraction of cladding that has failed. However, cladding is thin and not physically strong. It is subject to failure because of creep, hydride cracking, stress corrosion cracking, and localized corrosion, under adverse environmental and stress conditions.

- Solubility limits are effective for limiting the release of most radionuclides; however, I-129 and Tc-99 are not solubility limited. Because of its large inventory and long half-life, the solubility limit for Np-237 has the most significant affect on dose of any radionuclide, especially if Np-237 is incorporated in a secondary uranium mineral.

- The significance of diffusional release will depend on a number of assumptions such as water-film distances inside and outside the waste packages, unclogged openings, and a mechanism to sweep away contaminants in order to keep the concentration gradients high. Advective releases can be more significant after degradation processes cause openings in the waste package that are sufficiently large to allow dripping water to come into direct contact with fuel. These processes may lead to pathways for relatively large releases. These processes include localized corrosion and stress corrosion cracking coupled with mechanical loading events from dynamic and static rock-fall loads, and intrusive igneous activity.

- Colloids can form from the aqueous degradation of fuel and especially vitrified waste. For the degradation of fuel, dissolved radionuclides, in addition to colloids directly resulting from waste form degradation, can attach to natural or anthropogenic colloids, especially iron oxyhydroxides formed from corrosion of the steel in the waste package. In vitrified waste forms, degradation of glass can form clay colloids such as smectite and illite, which can also be the substrate for radionuclide attachment. Colloids can be transported out of the waste package primarily by advection in flowing water. However, colloids may be easily filtered once in a porous medium such as the invert.

Low-Risk Significance:

- The invert has a short travel pathway relative to the geologic barriers and is not expected to have a significant effect on radionuclide transport in the aqueous phase.

- The potential for criticality to occur either within the waste package or in the geosphere is considered unlikely; in addition, if it were to occur, the consequences would be limited (e.g., at most doubling of the inventory of fission products and locally increasing the temperature).

2.4 System Description: Flow and Transport of Radionuclides in the Unsaturated Zone below the Repository

The repository at Yucca Mountain will be underlain by approximately 300-meters (1000-ft) of unsaturated volcanic rock layers above the water table. The series of unsaturated layers below the repository is comprised of tuffaceous rock exhibiting varying degrees of welding, which affect both the fracture density and matrix conductivity. Densely welded tuffs are brittle and typically develop interconnected fractures, which may allow water to divert around areas of lower conductivity, whereas non-welded tuffs exhibit low fracture density and higher matrix conductivity.

Dissolved and suspended radionuclides released from the engineered components would be transported by water flowing through the unsaturated tuffs to the water table. Water typically moves vertically downward through the unsaturated tuffs below the repository through a combination of fracture and matrix flow. However, large-scale (e.g., fault zones or hydraulic conductivity contrasts at the interfaces between tuff layers) and small-scale (e.g., the variability of hydraulic conductivity within a tuff layer) features may add complexity to the flow paths. Water tends to move slowly [e.g., currently estimated at 1 meter (3.3 ft) per year and slower] through unsaturated tuff layers when flow occurs predominantly within the rock matrix. As the water flux exceeds the matrix saturated hydraulic conductivity, water will flow through fractures. Water tends to flow more swiftly (e.g., an estimated tens of meters per year and faster) through tuff layers when flow is predominantly through fractures. Current understanding suggests the Calico Hills non-welded vitric (CHnv) layer is the only unsaturated tuff layer below the repository with sufficient matrix saturated hydraulic conductivity to allow water to flow predominantly within the rock matrix. The thickness of the CHnv layer is spatially uncertain and may “pinch-out,” resulting in no CHnv layer beneath portions of the repository.

In addition to the advective transport process described above, transport of radionuclides in the unsaturated zone would be affected by molecular diffusion between fractures and the rock matrix, mechanical dispersion, and physico-chemical processes such as sorption and precipitation. Sorption of radionuclides onto mineral surfaces can be a significant retardation mechanism when radionuclides move through the rock matrix, because of the large surface area associated with the rock pores; conversely, fracture pathways have relatively limited surface area and thus exhibit limited if any sorption effects. Dissolved radionuclides transported by water within fractures may diffuse from the water within the fractures into the slow-moving water within the rock matrix, thereby limiting the transport of radionuclides in fractures. However, radionuclides transported by fracture flow could have limited time to diffuse from the fractures into the rock matrix because of the high velocity of water in the fractures (i.e., tens of meters per year).

Transport of radionuclides in colloidal form can limit the effectiveness of sorption processes; however, it can be expected that many colloids will be filtered out over long transport paths in geologic systems [see also Section 2.3].

Model Abstraction: Flow Paths in the Unsaturated Zone (below the Repository)

High-Risk Significance:

- None

Medium-Risk Significance:

- For units in which water flows wholly within the fractures, the small bulk porosities (0.001 to 0.0001) and low water contents of the fractures combine to yield ground-water travel times, from the repository horizon to the water table, that are estimated to be less than 100 years. Where the CHnv unit is present, the relatively large effective porosity (0.33) results in ground-water travel times that are estimated to exceed 1000 years. The areal extent and thickness of the CHnv unit are the most important aspects of unsaturated zone flow. Current information indicates that approximately half the repository footprint is underlain by a sufficient thickness of the CHnv unit to have a significant affect on travel times.

Model Abstraction: Radionuclide Transport in the Unsaturated Zone

High-Risk Significance:

- None

Medium-Risk Significance:

- Retardation in the CHnv unit has the potential to delay the movement of most radionuclides for very long time periods (e.g., thousands to tens of thousands of years and longer) for nuclides that tend to sorb onto rock surfaces [e.g., Np-237; Am-241; and Pu-240]. Certain nuclides do not readily sorb onto rock surfaces (i.e., I-129 and Tc-99). Where the CHnv unit is present below the repository, sorption of radionuclides may limit releases to the saturated zone, within the compliance period, to insignificant quantities for all radionuclides except I-129 and Tc-99. In this context, the retardation factor for Np-237 is the most significant, because of the large inventory and long half-life for this radionuclide.

- Matrix diffusion may have an effect on delaying radionuclide transport in the unsaturated units where the water flow is primarily in fractures.

- Transport of radionuclides attached to natural colloids may reduce the effectiveness of sorption properties of the CHnv unit.

2.5 System Description: Flow and Transport of Radionuclides in the Saturated Zone

The saturated zone in the vicinity of Yucca Mountain consists of a series of alternating volcanic aquifers and confining units above the regional carbonate aquifer. The volcanic rocks generally thin toward the south and become interspersed with valley-fill aquifers to the south and southeast of Yucca Mountain. The valley-fill aquifer is composed of alluvium derived from Fortymile Wash, and colluvium from the adjacent highlands to the east and west, as well as lacustrine deposits formed near the southern end of Jackass Flats. The effective porosities of the fractured rock are expected to be lower than the valley-fill alluvium, resulting in higher ground-water velocities in the fractured tuffaceous rocks.

Dissolved or suspended radionuclides released from the engineered components would be transported by water generally moving vertically downward through the unsaturated tuffs to the saturated zone. Ground-water flow, in the saturated zone immediately below the repository, is driven by a small hydraulic gradient, approximately 0.0001, and is directed to the east-southeast through the eastward dipping upper volcanic confining unit and upper volcanic aquifer. Approximately 2 to 4 kilometers (km) (1 to 3 mi.) east-southeast of Yucca Mountain, the hydraulic gradient is larger, approximately 0.001, and ground water is reoriented south through the tuff aquifer. South of Yucca Mountain, approximately 10 to 20 km (6 to 12 mi.), radionuclides would enter the highly porous valley-fill aquifer.

The transport of radionuclides in the saturated zone would be affected by molecular diffusion between fractures and the rock matrix, mechanical dispersion, as well as physico-chemical processes associated with sorption of radionuclides onto mineral surfaces. Many radionuclides will exhibit significant retardation when moving through the porous alluvium, because of the large surface area associated with porous media. Certain radionuclides, however, such as I-129 and Tc-99, are generally not retarded in geologic systems. Conversely, the fracture paths in the volcanic rock of the saturated zone are characterized by relatively limited surface areas and thus exhibit limited if any sorption effects within the fractures. However, dissolved radionuclides transported by water within fractures may diffuse from the water within the fractures into the slow-moving water within the rock matrix, thereby limiting the transport of radionuclides in fractures. Unlike the unsaturated zone fracture velocities, the saturated zone fracture velocities are smaller (because of the small gradients) and the flow path in the saturated zone is more than 10 times longer than the flow path in the unsaturated zone [i.e., km versus hundreds of m]. Therefore, there can be significant time for radionuclides to diffuse from the fractures into the rock matrix of the saturated zone.

Transport of radionuclides in colloidal form or attached to colloids can limit the effectiveness of sorption processes; however, it can be expected that many colloids will be filtered out over long transport paths in geologic systems [see also Section 2.3].

Model Abstraction: Flow Paths in the Saturated Zone

High-Risk Significance:

- None

Medium-Risk Significance:

- The saturated flow path is comprised of both fractured tufaceous rock and porous alluvium. The presence of a portion of the flow path to be comprised of alluvium is important because of the large capacity of the alluvium to retard a majority of the radionuclides. To have a significant influence on retarded radionuclides, the alluvium needs to comprise at least 500 m (1,640 ft) of the total flow path of 18 km (11.2 mi).

Low-Risk Significance:

- Hydrologic properties of the saturated zone tufaceous rock and alluvium have little effect on the capability of the saturated zone to limit radionuclide exposures. Representation of the saturated zone in performance assessments tends to be highly simplified (e.g., use of one dimensional stream-tube models) and could contribute to this limited effectiveness.

Model Abstraction: Radionuclide Transport in the Saturated Zone

High-Risk Significance:

- Retardation in the alluvium unit has the potential to delay the movement of most radionuclides for very long time periods (e.g., thousands to tens of thousands of years and longer) for nuclides that tend to sorb onto porous materials (e.g., Np-237, Am-241, Pu-240). In this context, Np-237 is the most significant radionuclide affected by retardation in the alluvium, because of the large inventory and long half-life for this radionuclide.

Medium-Risk Significance:

- Matrix diffusion is a somewhat effective process for delaying radionuclides, especially those radionuclides that are sorbed onto rock surfaces (e.g., Np-237, Pu-240, and Am-241). The extent of the rock volume that is available for matrix diffusion, and each radionuclide’s retardation factor, are the controlling factors.

- Transport of radionuclides attached to natural colloids may reduce the effectiveness of sorption properties of the alluvium.

Low-Risk Significance:

- Certain radionuclides do not readily sorb onto porous surfaces (i.e., I-129 and Tc-99). Information for sorption of this type of radionuclide is not important to performance because the sorption is very limited.

2.6 System Description: Biosphere and RMEI

Radionuclides reaching the accessible environment enter the biosphere. The biosphere is the environment that the RMEI inhabits. Characteristics of the biosphere and the RMEI are based on current human behavior and environmental conditions in the Yucca Mountain region. Ground water transporting released radionuclides to the biosphere may be used for drinking and agricultural purposes typical of current Amargosa Valley practices. Radionuclides entering the biosphere via ground water may reach the RMEI through some combination of three likely pathways: direct exposure from surface or suspended contamination; inhalation of suspended dust that has been contaminated; or ingestion of contaminated water, plants, or animal products. Biosphere dose conversion factors are used to convert exposures to contaminated materials to doses for the RMEI.

Model Abstraction: Concentration of Radionuclides in Ground Water

High-Risk Significance:

- None

Low-Risk Significance:

- In the current well pumping model, all radionuclides that enter the accessible environment are assumed to be captured in the volume of ground water projected to be withdrawn annually. This assumption limits the risk significance of modeling radionuclide concentrations in ground water.

Model Abstraction: Redistribution of Radionuclides in Soil

High-Risk Significance:

- None

Low-Risk Significance:

- Ground-water-based dose estimates are primarily influenced by the drinking water pathway, thereby limiting the importance of pathways related to radionuclides in soil. Igneous-activity-based dose estimates are dominated by inhalation of radionuclides that have low mobility in soil, so leaching processes do not significantly affect estimated doses (low soil leaching leads to higher crop ingestion doses).

Model Abstraction: Biosphere Characteristics

High-Risk Significance:

- None

Low-Risk Significance:

- The regulation specifies mean values to be used for many important biosphere parameters, which limits the consideration of uncertainties propagated in biosphere calculations. Uncertainties related to the biosphere calculations are low relative to other model abstractions in the performance assessment, thereby limiting the effect of biosphere modeling assumptions and parameters on total system risk estimates.

2.7 System Description: Igneous Activity

Basaltic igneous activity has occurred over the past 10 million years throughout the Yucca Mountain region. The probability of future igneous activity occurring directly at the proposed repository site is presently estimated at between 10^{-7} and 10^{-8} per year. Igneous activity can affect the repository through direct release or indirect release of radionuclides during extrusive or intrusive events, respectively. Although the likelihood of future igneous activity is very small, the potential radiological doses are sufficient to have igneous activity make a significant contribution to post-closure risk in current performance calculations.

If rising magma intersects repository drifts, the magma could flow into drift openings (intrusive event) or continue an upward ascent to the surface (extrusive event). During extrusive events, the magma reaches the surface and forms a volcanic eruption. Generally, a magma conduit to the surface gradually widens during an eruption. If this were to occur at Yucca Mountain, flowing magma could damage waste packages and potentially entrain radionuclides. These radionuclides would be transported downwind in the volcanic plume and deposited on the ground surface. Potential radiological dose from direct release results primarily from inhalation of contaminated ash. Ash deposits would be eroded and re-deposited through time by wind and water.

During an intrusive igneous event, ascending magma could flow into open or partially backfilled drifts in response to the pressure gradient between the confined magma and drift voids. The adverse thermal, physical, and chemical environment in magma could damage waste packages and alter the high-level waste form. After the magma cools, radionuclides are available for potential release from damaged waste package through the ground-water pathway.

Model Abstraction: Volcanic Disruption of Waste Packages

High-Risk Significance:

- The probability of igneous activity acts as a direct multiplier to the risk from igneous activity. Recent aeromagnetic surveys in the Yucca Mountain region have been conducted to improve estimates of the number of igneous events that have occurred in the past. The number, age, and location of past igneous features are used to constrain the estimates for the probability of future events.

Medium-Risk Significance:

- The consequences from direct release of radionuclides from igneous activity are directly proportional to the number of waste packages intersected in the eruption. At present, this is estimated based on observed conduit size at analog volcanoes. Alternative models of how a volcano interacts with a repository and develops the conduit could increase the number of affected waste packages and thus increase the concentration of radionuclides in erupted ash.

Model Abstraction: Airborne Transport of Radionuclides

High-Risk Significance:

- The concentration of radionuclides in ash is affected by the volume of ash released during an igneous event.   The number of waste packages affected during an igneous event is not related to the size of the event (i.e., volume of ash released during the event); however, when the volume of ash is small, the concentration of radionuclides will be larger and doses higher.

- Inhalation of resuspended volcanic ash dominates the total dose for the igneous scenario. Thus, assumptions regarding the amount of fine ash particles resuspended in the air significantly influence the calculated dose.

Medium-Risk Significance:

- Wind speed and direction affect the transport of contaminated ash from the eruption source to the location of the RMEI. Wind speed has been shown to be an influential parameter in the sensitivity studies conducted with performance assessment codes. Current performance assessments account for ash redistribution by fixing the wind direction toward the RMEI. A more realistic approach would be to account for the variations in wind direction and directly account for redistribution (see next bullet).

- After a potential eruption, contaminated ash could be deposited over hundreds to perhaps thousands of square kilometers (tens to perhaps hundreds of square miles). Some of this ash can be eroded and transported by wind and water, with later deposition at or near the RMEI. Consideration of remobilized ash could affect the levels of resuspended ash; however, processes influencing remobilization are not well-understood, and supporting data are sparse.

3. RISK SIGNIFICANCE OF GENERAL POST-CLOSURE PERFORMANCE ASSESSMENT REVIEW ITEMS

This section discusses the risk significance of more generic topics in YMRP Section 4.2.1, "Repository Safety After Permanent Closure - Performance Assessment." The section is divided into the four review areas that define an acceptable methodology for the performance assessment:

- System Description and Demonstration of Multiple Barriers;
- Scenario Analysis and Event Probability;
- Model Abstraction; and
- Demonstration of Compliance with the Post-closure Public Health and Environmental Standards.

These topics relate to post-closure performance objectives and to items needed to support confidence in the total system performance assessment risk calculations. For topics in this section, it is not easily determined how the information would change the risk. Thus, for these topics, the risk ranking also considers the significance of the information to build confidence in the calculations and the safety attributes of the repository system.

3.1 System Description and Demonstration of Multiple Barriers

Post-closure performance objectives specified in Part 63 require a system of multiple barriers (at least one engineered and one natural). As defined in the regulations, barriers are materials or structures that prevent or substantially delay movement of water or radionuclides. Thus, a key element of the safety case is the identification and description of the capabilities of the repository barriers. DOE must provide a description of the capabilities of each of the barriers and the technical basis for the capability of the barriers. The technical basis for the capability of the barriers needs to be consistent with the technical basis used to support the total system performance assessment abstractions.

High-Risk Significance:

- None

Low-Risk Significance:

- Capabilities of individual barriers, in light of existing parameter uncertainty (e.g., in barrier and system characteristics) and model uncertainty are needed.

3.2 Scenario Analysis and Event Probability

A complete safety evaluation of a geologic repository for high-level waste requires consideration of potential future conditions affecting its behavior during the period of regulatory concern. This safety evaluation may be accomplished through scenario analysis, which is the systematic enumeration of features, events, and processes that can reasonably occur in the repository system. Scenario analysis facilitates identifying the possible ways in which the geologic repository environment can evolve so a defensible representation of the system can be included in the total system performance assessment. A scenario is defined as the plausible future evolution of the repository system during the period of regulatory concern. A scenario includes a postulated sequence (or absence) of events and assumptions about initial and boundary conditions. A scenario analysis is composed of four steps: (i) identification of features, events, and processes relevant to the proposed high-level waste geologic repository; (ii) selection or screening of features, events, and processes important to estimating dose risk to an RMEI during the period of regulatory concern; (iii) formation of scenario classes from a screened or reduced collection of features, events, and processes; and (iv) selection or screening of the scenario classes for actual implementation into a total system performance assessment.

High-Risk Significance:

- Additional technical bases are needed for some features, events, and processes that may be risk-significant, but currently are not included in the performance assessment.

3.3 Model Abstraction

The 14 model abstractions are described individually in Section 2. The following are the generic topics that affect each of the abstractions and their integration in the total system performance assessment.

High-Risk Significance:

- Systematic process across the total system performance assessment model to ensure appropriate documentation and justification for (1) abstraction of models, (2) selection of conservatism in components, and (3) representation of uncertainty.

- The technical basis for the data distributions used in the total system performance assessment is needed to support mathematical representation of data uncertainty in the total system performance assessment.

3.4 Demonstration of Compliance with the Post-closure Public Health and Environmental Standards

High-Risk Significance:

- Development and implementation of a process for model confidence building and demonstrating compliance with model confidence criteria are needed.

4. RISK INSIGHTS RELATED TO PRE-CLOSURE REPOSITORY SAFETY

The assessment of repository safety during the pre-closure period is an important element in determining the overall safety/risk of the potential geologic repository. To evaluate pre-closure safety, 10 topics have been defined:

1. Site Description As It Pertains to Pre-closure Safety Analysis (PCSA);
2. Description of Structures, Systems, Components, Equipment, and Operational Process Activities;
3. Identification of Hazards and Initiating Events;
4. Identification of Event Sequences;
5. Consequence Analyses;
6. Identification of Structures, Systems, and Components Important to Safety; Safety Controls; and Measures to Ensure Availability of the Safety Systems;
7. Design of Structures, Systems, and Components Important to Safety and Safety Controls;
8. Meeting the 10 CFR Part 20 As Low As Is Reasonably Achievable Requirements for Normal Operations and Category 1 Event Sequences;
9. Plans for Retrieval and Alternate Storage of Radioactive Wastes; and
10. Plans for Permanent Closure and Decontamination, or Decontamination and Dismantlement of Surface Facilities.

The pre-closure safety section of the YMRP is organized around these 10 topics.

To date, NRC has developed agreements with DOE for three of these 10 topics:

- Identification of Hazards and Initiating Events;
- Identification of Structures, Systems, and Components Important to Safety;
- Safety Controls; and Measures to Ensure Availability of the Safety Systems; and
- Design of Structures, Systems, and Components Important to Safety and Safety Controls.

As DOE’s repository design matures, additional agreements related to these 10 pre-closure topics may be necessary.

As part of the license application for the proposed geologic repository, DOE will perform a PCSA to evaluate the risk associated with the pre-closure operational phase. The PCSA is performed to demonstrate compliance with the pre-closure performance objectives. The PCSA requires a systematic examination of the site, the design, and the potential hazards; initiating events; and event sequences and their dose consequences (e.g., radiological exposures to the public and workers). The PCSA includes an analysis of the structures, systems, and components, to identify those structures, systems, and components considered important to safety. The PCSA also identifies and describes the controls relied on to prevent potential event sequences from occurring or to mitigate their consequences, and identifies the measures necessary to ensure the availability of those structures, systems, and components. The PCSA requires a description and discussion of the design (both surface and subsurface facilities) of the proposed geologic operations area, including the relationship between the design criteria and the performance objectives and the design bases and their relationship to the design criteria.

4.1 Identification of Hazards and Initiating Events

High-Risk Significance:

- Current analyses indicate that risk associated with certain hazards and initiating events (e.g., accidental aircraft crashes) could be significant. However, these analyses are preliminary and further analysis is needed to evaluate the effect of further realism and to understand the uncertainties of the hazards.

4.2 Identification of Structures, Systems, and Components Important to Safety; Safety Controls; and Measures to Ensure Availability of the Safety Systems

High-Risk Significance:

- None

Medium-Risk Significance:

- Completion of a rigorous high-quality PCSA is critical to identifying structures, systems, and components important to safety, and measures to ensure the availability of these structures, systems, and components. DOE's PCSA methodology will identify structures, systems, and components important to safety and measures to ensure the availability of these structures, systems, and components.

4.3 Design of Structures, Systems, and Components Important to Safety and Safety Controls

High-Risk Significance:

- None

Medium-Risk Significance:

- Microstructural and compositional variations in waste package base metal and weld filler metals have the potential to degrade waste package mechanical properties. Substantial changes of the mechanical strength of the packages could lead to a much higher frequency of failure per waste package lift.

5. SUMMARY OF HIGH-RISK-SIGNIFICANT AGREEMENTS

Of the 293 agreements, 41 were judged to be of high-risk significance. These agreements can be grouped into the following 8 broad areas:

1. Corrosion of the Drip Shield and Waste Package
2. Mechanical Degradation of the Drip Shield and Waste Package
3. Effects of In-Package Chemistry on Dissolution of the Waste Form
4. Radionuclide Transport in the Saturated Zone
5. Probability of Volcanic Disruption of the Repository
6. Entrainment and Transport of Radionuclides in Volcanic Ash
7. Accidental Aircraft Crash During Operations
8. Performance Assessment Methods (model abstraction and confidence building)

Specifics of the high-risk-significant agreements within each of the 8 broad areas are summarized below:

- Corrosion of the Drip Shield and Waste Package

  Corrosion processes influence the lifetime of the engineered barriers. The effects of corrosion processes predominantly influence the lifetime of the waste package by breaking down the passive film on its surface. The passive film ensures a very slow corrosion rate for the waste package. Coupled thermal-hydrological-chemical processes can affect the chemical environment of the waste package and affect the stability of the passive film. Specifically, high temperatures and aggressive water chemistry conditions may have a potentially deleterious effect on the stability of the passive film.

  The chemistry of water contacting the engineered barriers is important for determining corrosion rates. Evaporative processes may result in potentially elevated concentrations of corrosive salt deposits and high acidity on the surfaces of the barriers. The evaporated salts can sorb water from the air to form a brine film on the surface, dependent on the temperature. The key chemical constituents that form these brines include both aggressive species such as chloride and possible corrosion-inhibiting species such as nitrate. Additionally, temperature affects the formation of the brine film and is dependent on the salt composition. Uniform corrosion rates increase exponentially as a function of temperature. Passive film breakdown, and the occurrence of localized corrosion and accelerated uniform corrosion, are facilitated by elevated temperature. Therefore, temperature ranges can significantly affect salt hydration processes and corrosion of the engineered barriers.

- Mechanical Degradation of the Drip Shield and Waste Package

  Large static loads, caused by mechanical processes such as seismic events and drift degradation, have the potential to damage the engineered barriers. Backfill from natural rock fall could beneficially limit the number of damaged waste packages during an igneous event. Conversely, backfill may increase waste package and drip shield temperatures. The timing and extent of the rock fall would determine the overall potential effects.

- Effects of In-Package Chemistry on Dissolution of the Waste Form

  The dissolution rate of the waste form in an aqueous environment is important for all radionuclides. Uncertainty in the dissolution rate results in radionuclide release times from the spent fuel matrix that vary from hundreds of years to hundreds of thousands of years. Water chemistry and temperature within the waste package could affect the degradation rate of the fuel. For instance, oxidation of fuel and corrosion of internal metallic components of the waste package could reduce pH, leading to conditions of high-dissolution rate.

- Radionuclide Transport in the Saturated Zone

  Retardation of radionuclides in the alluvium has the potential to delay the movement of most radionuclides for very long time periods, varying from thousands to tens of thousands of years for nuclides that tend to sorb onto porous materials. Key sorbing radionuclides include Np-237, Am-241, and Pu-240. Specifically, Np-237 is the most significant radionuclide affected by retardation in the alluvium, because of its large inventory and long half-life.

- Probability of Volcanic Disruption of the Repository

  The probability of igneous activity acts as a direct multiplier to the risk from igneous activity. Recent aeromagnetic surveys in the Yucca Mountain regions have been conducted to improve estimates of the number of igneous events that have occurred in the past. The number, age, and location of past igneous features are used to constrain the estimates for the probability of future events.

- Entrainment and Transport of Radionuclides in Volcanic Ash

  The inhalation of volcanic ash containing radionuclides strongly influences the dose for the igneous intrusion scenario. The volume of ash released during an igneous event and the assumptions regarding the resuspension of fine ash particles in the air both significantly affect the inhalation of contaminated ash and thus the dose for the igneous scenario. When the volume of ash is small, the concentration of radionuclides will be larger, resulting in a higher dose.

- Accidental Aircraft Crash During Operations

  Current analyses indicate that risk associated with certain hazards and initiating events (e.g., accidental aircraft crashes) could be significant. However, these analyses are preliminary and further analysis is needed to evaluate the effect of further realism and to understand the uncertainties of the hazards.

- Performance Assessment Methods

  The completeness of the set of features, events and processes considered and included in the total system performance assessment directly affects the resulting risk estimates. If features, events and processes are screened from the assessment without sufficient basis, the potential risks associated with these features, events and processes will not be evaluated. The goal for the performance assessment is that the potentially significant features, events, and processes are appropriately considered in the performance assessment.

  Inconsistencies in the development of model abstractions, the degree of realism and conservatism in the models, and the representation of uncertainty in the models could lead to erroneous risk estimates at the total system level. Guidance would ensure that the model abstraction process is systematic and consistent across the total system performance assessment model. Also, the selection of the data distributions used to represent parameter uncertainty in the total system performance assessment could also significantly affect the risk estimates. Therefore, the technical basis for assigning data distributions needs to be defensible and consistent across the total system performance assessment model.

  Development and implementation of a process for model confidence building and demonstrating compliance with model confidence criteria is needed.