Role of Different Barriers in Total System Performance Assessment - Examples from Nominal, Degraded, Neutralized and Early Waste Package Degradation Scenarios

Presented to:
Nuclear Waste Technical Review Board

Presented by:
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Outline

• NWTRB Question
• TSPA - the Tool
• Barriers in TSPA
• Approaches to Evaluating Barrier Contribution
  • Barrier Contribution Results
    – Nominal Waste Package Scenario Class
    – Early Waste Package Failure Scenario
    – Degraded and Neutralized Waste Package Failure Scenarios
    – Igneous Intrusion Waste Package Failure Scenario
• Unquantified Uncertainty Analyses
• Summary and Conclusions
NWTRB Question

• Clarify roles played by the different natural and engineered barriers in the total system performance assessment

• Address over reliance on the waste package in the safety case

• In answering these questions:
  – compare nominal case TSPA with more rapid waste package degradation scenarios
  – address the mode and extent of each waste package failure scenario, the mechanisms for release and the roles of the different barriers
    ◆ compare the dose due to a degraded and neutralized WP
    ◆ evaluate dose when completely neutralized
  – evaluate how robust are the conclusions on defense-in-depth
Total System Performance Assessment
The Tool

- TSPA is a tool which integrates all aspects of the system affecting postclosure performance
- Consequently, TSPA is both comprehensive and complex
- Some barriers can mask the performance contribution of other barriers
- Therefore, clearly evaluating the role of each barrier requires alternative methods
Barriers Evaluated in TSPA

- Surficial soils and topography
- Unsaturated rock layers overlying the repository
- Drip shield
- Waste Package
- Spent fuel cladding
- Waste form / concentration limits
- Drift invert
- Unsaturated rock layers below repository
- Tuff and alluvial aquifers
## Barriers Evaluated in TSPA-SR

<table>
<thead>
<tr>
<th>Key Attributes of System</th>
<th>Process Model Factor</th>
<th>Barrier</th>
<th>Barrier Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Limiting Water Contacting Waste Package</td>
<td>Climate</td>
<td>Surficial soils and topography</td>
<td>Reduce the amount of water entering the unsaturated zone by surficial processes (e.g., precipitation lost to runoff, evaporation, and plant uptake)</td>
</tr>
<tr>
<td></td>
<td>Net Infiltration</td>
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<td></td>
<td>Unsaturated Zone Flow</td>
<td>Unsaturated rock layers overlying the repository and host unit</td>
<td>Reduce the amount of water reaching the repository by subsurface processes (e.g., lateral diversion and flow around emplacement drifts)</td>
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<td>Coupled Effects on Unsaturated Zone Flow</td>
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<td>Seepage into Emplacement Drifts</td>
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<td>Coupled Effects on Seepage</td>
<td></td>
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</tr>
<tr>
<td>Prolonging Waste Package Lifetime</td>
<td>In-Drift Physical and Chemical Environments</td>
<td>N/A</td>
<td>These factors provide conditions that affect performance, but are not barriers per se in the TSPA-SR.</td>
</tr>
<tr>
<td></td>
<td>In-Drift Moisture Distribution</td>
<td></td>
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<tr>
<td></td>
<td>Drip Shield Degradation and Performance</td>
<td>Drip shield around the waste packages</td>
<td>Prevent water contacting the waste package and waste form by diverting water flow around the waste package; therefore limiting advective transport through the invert</td>
</tr>
<tr>
<td></td>
<td>Waste Package Degradation and Performance</td>
<td>Waste package</td>
<td>Prevent water from contacting the waste form</td>
</tr>
</tbody>
</table>
## Key Attributes of System

<table>
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<th>Barrier Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radionuclide Inventory</td>
<td></td>
<td>N/A</td>
<td>These factors provide conditions that affect performance, but are not barriers per se in the TSPA-SR.</td>
</tr>
<tr>
<td>In-Package Environments</td>
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<tr>
<td>Cladding Degradation and Performance</td>
<td></td>
<td>Spent fuel cladding</td>
<td>Delay and/or limit liquid water contacting spent nuclear fuel after waste packages have degraded</td>
</tr>
<tr>
<td>CSNF Degradation and Performance</td>
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<td>DSNF Degradation and Performance</td>
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<tr>
<td>DHLW Degradation and Performance</td>
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<tr>
<td>Dissolved Radionuclide Concentrations</td>
<td></td>
<td>Waste form</td>
<td>Limit radionuclide release rates as a result of low solubilities or low diffusion through degraded engineered barriers</td>
</tr>
<tr>
<td>Colloid-Associated Radionuclide Concentrations</td>
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<tr>
<td>In-Package Radionuclide Transport</td>
<td></td>
<td>Drift Invert</td>
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<tr>
<td>EBS (Invert) Degradation and Performance</td>
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</tbody>
</table>
# Key Attributes of System

<table>
<thead>
<tr>
<th>Barriers Evaluated in TSPA-SR</th>
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</thead>
<tbody>
<tr>
<td><strong>Key Attributes of System</strong></td>
</tr>
<tr>
<td>Slow Transport Away from the Engineered Barrier System</td>
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<tr>
<td>Addressing Effects of Potentially Disruptive Processes and Events</td>
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</tbody>
</table>
Barrier Conceptual Models

- Barrier conceptual models (including key assumptions and conservatisms) affect the significance of the barrier to system performance.

- Several key conceptual models have been presented in previous talks:
  - Waste package degradation models by Gerry Gordon
  - Unsaturated zone flow and transport conceptual models by Bo Bodvarsson
  - Saturated zone flow and transport conceptual models by Al Eddebarh

- EBS thermal-hydrologic and transport conceptual models are presented in the following slides to assist in explaining these barriers contribution to system performance.
Schematic of Conceptualizations for In-Drift Thermal-Hydrologic Processes - Dripping Environment

1. **Seepage into drift**
   - function of percolation and fracture characteristics

2. **Flux through drip shield**
   - function of drip shield failure fraction

3. **Flux into waste package**
   - function of waste package failure fraction

4. **Flux through waste package**
   - *assumed to contact all exposed waste*

5. **Flux out of waste package**
   - assume flux in = flux out (no “bathtub” effect)

6. **Flux through invert**
   - assume flux in = flux out

7. **Flux into rock**
   - assume flux into fractures
Schematic of Conceptualizations for In-Drift Thermal-Hydrologic Processes - Non-dripping Environment

1. **Humidity in drift**  
   - function of design and rock characteristics

2. **Salt/dust on drip shield and waste package surface** affect critical RH for corrosion initiation

3. **Moisture on waste package** controlled by humidity under drip shield

4. **Humidity inside and outside waste package** equilibrate after waste package fails

5. **Water film** assumed to develop on exposed waste form

6. **Cracks through failed waste packages assumed to be water saturated**

7. **Water content in invert**  
   - function of design and rock/invert characteristics
Schematic of Conceptualizations for In-Drift Chemical and Transport Processes - Dripping Environment

1. Flux contacts all exposed waste
2. Exposed waste alters
   - radionuclide concentration in liquid phase limited by solubility
   - radionuclides are released to liquid or colloid phase
3. Advective transport from waste package
   - function of flux and concentration (or alteration rate if very high solubility)
4. Advective transport starts as soon as waste package is breached
   - assume second breach is at bottom of waste package
5. Advective transport through invert
   - function of flux and concentration (solubility) in invert
6. Advective transport from EBS enters fractures in rock
Schematic of Conceptualizations for In-Drift Chemical and Transport Processes - Non-dripping Environment

1. Exposed waste form alters in humid air
2. Radionuclide concentrations in water film on altered waste form limited by solubility
3. Dissolved radionuclides diffuse through water film
   - *assume waste form is at base of waste package, i.e., no diffusion time to inner waste package barrier*
4. Diffusive transport through degraded waste package
   - *assume opening is in contact with invert*
   - diffusive transport a function of concentration/gradient, breach size, and diffusion characteristics
5. Diffusive transport through invert function of water content
6. *Diffusive flux through invert assumed to enter fractures of host rock*
Waste Package Breach Scenarios Considered - Key Assumptions

• **Nominal (base case) scenario class**
  - uses nominal models, analyses and parameters (and associated uncertainty) to develop “expected” waste package failure rate and amount
  - rate and amount of waste package and drip shield failure vary with time and from realization to realization due to uncertainty
  - 1% probability of first waste package breach at about 11,000 years

• **Early waste package breach scenario**
  - assumes a breached waste package at emplacement
  - assumes one breach of one waste package (300 cm²)
  - waste package randomly located in dripping or non-dripping environments
  - drip shield assumes nominal performance
Waste Package Breach Scenarios Considered - Key Assumptions

(Continued)

- **Neutralized waste package breach scenario**
  - assumes all (~12,000) waste packages are breached at emplacement
  - assumes the breached area remains constant
  - assumes one breach of each waste packages (300 cm²)
  - drip shield assumes nominal performance

- **Degraded waste package barrier analysis**
  - fixes several key waste package degradation parameters at the near maximum (5th or 95th percentile) of their expected range within the nominal scenario
  - rate and amount of waste package degradation vary with time, but at a higher rate than nominal scenario class
Waste Package Breach Scenarios Considered - Key Assumptions

(Continued)

- Igneous intrusion waste package breach scenario
  - assumes mean initiation probability of $1.6 \times 10^{-8}$ year$^{-1}$
  - assumes ~200 packages are completely neutralized (~400 breaches each ~300 cm$^2$)
  - assumes ~200 dripshields and cladding also completely neutralized
  - assumes solubility controlled by in-rock chemistry

**NOTE:** All other components of the TSPA are treated assuming the nominal performance scenario models and parameters (with their quantified uncertainty)

**NOTE:** Results presented illustrate quantified uncertainty in performance and statistical measures of that performance (i.e., mean, median, and 5th and 95th percentile)
Different Approaches to Quantifying Barrier Contributions

• Subsystem performance for nominal scenario class
  – key radionuclides
  – fluxes across different barriers
  – different release modes from EBS
    ◦ diffusion
    ◦ advection

• Subsystem performance for early waste package failure scenario
  – key radionuclides
  – fluxes across different barriers
  – different release modes from EBS

• Degraded and neutralized waste package scenarios

NOTE: Other degraded/enhanced barrier importance analyses are presented in TSPA-SR Rev 0, ICN 01. Other neutralized barrier importance analyses are presented in RSS Rev 4, ICN 01.
Subsystem Performance Results Used to Clarify Role of Different Barriers

- Individual radionuclide dose rates (mrem/yr)
  - high solubility radionuclides ($^{99}$Tc)
  - low solubility radionuclides ($^{237}$Np)
- Waste package and drip shield degradation
- Individual radionuclide release rates
  - across EBS (base of invert)
  - across base of Unsaturated Zone
  - across 20 km boundary of Saturated Zone
- Advective vs. diffusive release rates from EBS

NOTE: Release rates are in mass release rates (gm/yr)
Nominal Performance Scenario Class
Total Dose Rate and Key Radionuclides

- Total dose rate during the first 100,000 years is controlled primarily by $^{99}$Tc, $^{237}$Np, and $^{239}$Pu

- Doses to ~40,000 years dominated by $^{99}$Tc diffusive release through SCC cracks in the lid welds

- Doses of time greater than 40,000 years dominated by $^{237}$Np diffusive and advective releases, with a small contribution from $^{239}$Pu
Nominal Performance Scenario Class
Waste Package Failure Rate versus $^{99}$Tc Dose Rate

- $^{99}$Tc dose rate mirrors the mean waste package failure rate
  - NOTE: when the waste package failure rate becomes constant (~ 70,000 years) the $^{99}$Tc release (and dose) rate becomes constant also

- This applies to high solubility radionuclides which are assumed to diffuse through thin films

- This was also noted in TSPA-VA
Nominal Performance Scenario Class
Cumulative WP Opening Area versus $^{237}$Np Dose Rate

- Doses (and releases) of solubility-limited radionuclides, such as $^{237}$Np, mirror the cumulative waste package breach area (over all packages)
- Advective and diffusive releases from the waste package are both linearly proportional to the breach opening area for solubility limited radionuclides
- Small breach areas correspond to small crack penetrations (primarily stress corrosion cracks)
- Larger breach areas correspond to “patch” failures caused by general corrosion (times $> 40,000$ years)
- $^{237}$Np and $^{99}$Tc behave differently, primarily because of their different solubilities
Nominal Performance Scenario Class

$^{237}$Np Release Rate From Various Barriers

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Time (years)</th>
<th>237Np</th>
<th>95th Percentile</th>
<th>Mean</th>
<th>Median</th>
<th>5th Percentile</th>
</tr>
</thead>
<tbody>
<tr>
<td>EBS</td>
<td>1000</td>
<td>$10^{-5}$</td>
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<td></td>
<td></td>
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</tr>
<tr>
<td></td>
<td>10000</td>
<td>$10^{-4}$</td>
<td></td>
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<tr>
<td></td>
<td>100000</td>
<td>$10^{-3}$</td>
<td></td>
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<td></td>
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<tr>
<td>UZ</td>
<td>1000</td>
<td>$10^{-5}$</td>
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<tr>
<td>SZ</td>
<td>1000</td>
<td>$10^{-5}$</td>
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<td></td>
<td>10000</td>
<td>$10^{-4}$</td>
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</tbody>
</table>
Nominal Performance Scenario Class Comparison of $^{237}$Np Release Rate From Various Barriers

$^{237}$Np Mean Release Rate

$^{237}$Np Median Release Rate

- **EBS**
- **UZ**
- **SZ**

- **~1,000 years**
- **~2,000 years**
- **~10,000 years**
$^{237}$Np EBS Release Rates - Advection vs Diffusion

- **EBS diffusive releases** dominate to ~40,000 years
  - < 40,000 years “patch” area is very small and drip shields are intact (see following slide)

- **EBS advection ~ EBS diffusion** after 40,000 years
  - 15% of WPs have advection
Nominal Performance Scenario Results Waste Package and Drip Shield Failures

- Most drip shields fail by 30,000 - 40,000 years
- “Patch” area dominates crack area at ~40,000 years
Summary of Nominal Performance Scenario Results

- Waste package failure dominates time of occurrence of EBS release
- Waste package failure uncertainty and variability dominates spread of dose rates
- EBS releases are dominated by diffusion until “patches” form on the waste package (due to general corrosion) and drip shields fail
- Delay of transport in UZ and SZ is several thousand years
Degraded Waste Package Scenario Results

- Degraded scenario assumed several waste package degradation model parameters simultaneously set at near maximum (95% percentile)
  - this sequence of events has a very low probability (<<10^-4) of occurring

- Initial failures occur before 10,000 years

- Uncertainty in waste package failure rate (and dose rates) reduced
Early Waste Package Failure Scenario

- Single CSNF waste package failure
- Impose 300 cm² breach 100 years after emplacement
- Assume package randomly located
  - ~15% in dripping environment
  - ~85% in non dripping environment
- Drip shield performs as in nominal case
Early Waste Package Failure Scenario Dose Rate

- Total dose rate during the first 100,000 years is controlled primarily by $^{99}$Tc, $^{237}$Np, and $^{239}$Pu.

- $^{99}$Tc is less important for the early waste package failure scenario because the relatively large area of a juvenile patch failure (300 cm$^2$ at 100 years) releases the $^{99}$Tc inventory very rapidly.
Early Waste Package Failure Scenario

$^{237}$Np Release Rate From Various Barriers

- **EBS**
  - Time (years): 100, 1000, 10000, 100000
  - $^{237}$Np EBS Release Rate (g/yr):
    - $10^{-5}$
    - $10^{-4}$
    - $10^{-3}$
    - $10^{-2}$
    - $10^{-1}$
    - $10^0$
    - $10^1$
    - $10^2$
    - $10^3$
    - $10^4$
  - 95th Percentile, Mean, Median, 5th Percentile

- **UZ**
  - Time (years): 100, 1000, 10000, 100000
  - $^{237}$Np UZ Release Rate (g/yr):
    - $10^{-5}$
    - $10^{-4}$
    - $10^{-3}$
    - $10^{-2}$
    - $10^{-1}$
    - $10^0$
    - $10^1$
    - $10^2$
    - $10^3$
    - $10^4$
  - 95th Percentile, Mean, Median, 5th Percentile

- **SZ**
  - Time (years): 100, 1000, 10000, 100000
  - $^{237}$Np SZ Release Rate (g/yr):
    - $10^{-5}$
    - $10^{-4}$
    - $10^{-3}$
    - $10^{-2}$
    - $10^{-1}$
    - $10^0$
    - $10^1$
    - $10^2$
    - $10^3$
    - $10^4$
  - 95th Percentile, Mean, Median, 5th Percentile
Early Waste Package Failure Scenario
Comparison of $^{237}$Np Release Rate for Various Barriers

- Delay in mean (and median) breakthrough time across UZ ~ 1,000 years
- Delay in mean breakthrough time across SZ to 20 km ~ 1,000 years
  - median breakthrough time (~5,000 yrs) difficult to discern due to dispersive effects in SZ
Early Waste Package Failure Scenario

$^{237}$Np Adveective vs. Diffusive EBS Release Rate

- **EBS diffusion dominates until drip shield failure at ~ 30,000 years**
- **Initial peak caused by high solubility (low pH) pulse inside the package during basket degradation**

![Graphs showing EBS total, advection, and diffusion release rates over time](image_url)
Summary of Early Waste Package Failure Scenario Results

- A single waste package failure results in ~ 0.01 mrem/yr, based on conservative assumptions of in-package and EBS transport
- Subsystem results show significance of drip shield performance and limited seepage (i.e., limited advective release)
- Results corroborate observations about subsystem performance in the nominal scenario
- Several unquantified uncertainties need to be addressed
Neutralized Waste-Package Scenario Results

- Assumes all waste packages are breached at emplacement
- One breach of all waste packages (300 cm²) occurs at emplacement
- Drip shield and all other barriers perform as in the nominal scenario
- Dose response is approximately equal to 11,770 (i.e., the total number of emplaced packages) times the CSNF early waste package failure scenario dose response
Comparison of Nominal, Degraded, and Neutralized Waste Package Scenarios

- The cumulative waste package breach area is linearly proportional to the release rate and dose rate for solubility-limited radionuclides.

- The cumulative breach area increases with time for the degraded and nominal ("base") cases, while it is fixed for the neutralized case.
Igneous Intrusion Waste Package Breach Scenario

- Probability - weighted doses include probability of occurrence
  - \( \sim 1.6 \times 10^{-8} \text{ yr}^{-1} \)
  - \( \sim 8 \times 10^{-4} \) over 50,000 year simulation

- Unweighted doses remove the probability
  - i.e., assume event occurs within 50,000 year simulation

- Unweighted dose peaks at \( \sim 500 \text{ mrem/yr} \)

- \( \sim 200 \) waste packages completely neutralized
Igneous Intrusion Waste Package Breach Scenario - Comparison to Early Waste Package Breach Scenario

- Unweighted igneous intrusion doses normalized to one package by dividing total dose rate by ~200

Normalized igneous intrusion peak dose rate (~3 mrem/yr) is ~300 x the peak from early waste package breach scenarios because:
  - area exposed is greater
  - drip shield is removed

Conclusion: Differences in "completely neutralized" and early waste package breach explainable primarily by breach area difference
Unquantified Uncertainties

- Results and conclusions are predicated on considered models and their uncertainty
- Unquantified uncertainty exists in:
  - Diffusive release mechanism from waste package
  - Diffusive release across invert
  - Diffusive release from invert to fractured rock
  - Solubility of key radionuclides
- Ongoing efforts are evaluating the potential significance of these unquantified uncertainties (an example follows for the diffusive release from the waste package)
Comparison of Early Waste Package Failure Scenario with Preliminary Unquantified Uncertainties - In-Package and Ex-Package Diffusion Model

- Use a more realistic conceptual model for diffusive transport along the pathway from the waste package interior, out through the SCC cracks, along the waste package surface, down the pedestal, and to the invert

- Relative humidity and temperature used to determine the in-package and ex-package diffusion coefficient, based on water film adsorption

- Corrosion product assumed to be Fe$_2$O$_3$ (adsorption isotherm for Fe$_2$O$_3$ used)

- Probability distribution used for the waste form basket lifetime (uniform distribution from 4,300 to 18,000 years)
Summary and Conclusions

- Detailed explanation of results provided insights to barrier importance
  - insights are enhanced by conducting multiple analyses
- Interpretations require consideration of assumptions
- Additional insights possible for barrier importance and neutralization analyses
- On-going work to address unquantified uncertainties should provide additional perspectives
Backup Slides
Early Waste Package Failure Scenario **Realization 63**

Dose Rate of Various Radionuclides

- Direct causal relationship between mean histories, e.g., between mean dose rate and mean EBS release rate, is not rigorous
- Need to look at individual realizations to more rigorously trace cause-effect relationships
- Use realization 63 (always drip) to examine relative contribution of advection/diffusion and the effect of in-drift chemistry on releases
Early Waste Package Failure Scenario Realization 63

$^{237}$Np Release Rate from Various Barriers

- Indicates delay in the natural system
- Shows $^{237}$Np advective release when the drip shields begin to fail at about 30,000 years
Early Waste Package Failure Scenario Realization 63

Effect of EBS Chemical Environment

- In-package pH and invert pH have opposite trends over early times; similarly for in-package Np solubility and in-drift Np solubility
- Low in-package pH during the first 1000 years causes high in-package Np solubility during this time
- High in-package Np solubility during the first 1000 years causes a large release of Np to the invert where it precipitates because of low in-drift Np solubility
Early Waste Package Failure Scenario Realization 63
Effect of EBS Chemical Environment

- Initially high Np release rate from the EBS decreases when the precipitated mass of Np in the invert is depleted at about 2500 years
- Afterwards the invert pH and in-package pH remain approximately equal and the waste-package and EBS release rates reach a steady state with equal release rates
## Summary of Key Thermal Hydrologic Assumptions Affecting EBS Release Rates

<table>
<thead>
<tr>
<th>COMPONENT</th>
<th>CURRENT TREATMENT</th>
<th>KEY UNQUANTIFIED UNCERTAINTY</th>
<th>ADDRESSING SIGNIFICANCE</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Thermal-Hydrologic Environment</strong></td>
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<tr>
<td>▪ Above drip shield</td>
<td>▪ Thermally - perturbed seepage                                                   ▪ Effect of &quot;dry out&quot; zone</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>▪ Humidity and temperature spatial distribution                                    ▪ Effect of rock heterogeneity and uncertainty</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>▪ On drip shield</td>
<td>▪ Hydroscopic salts control corrosion                                              ▪ Salt/dust characteristics</td>
<td></td>
<td></td>
</tr>
<tr>
<td>▪ Under drip shield</td>
<td>▪ Humidity and temperature spatial distribution                                    ▪ Convection cells and condensation</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>▪ On waste package</td>
<td>▪ Hydroscopic salts control corrosion                                              ▪ Salt/dust characteristics</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>▪ In waste package</td>
<td>▪ Humidity and flux equilibrate                                                   ▪ Local chemical conditions</td>
<td>4</td>
<td></td>
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<tr>
<td></td>
<td>▪ Moisture film continuous on waste form                                            ▪ Moisture removed by evaporation</td>
<td>4</td>
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</tr>
<tr>
<td></td>
<td>▪ Moisture contacts all waste                                                     ▪ Flux does not contact all exposed waste</td>
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</tr>
<tr>
<td></td>
<td>▪ Flux in = flux out                                                               ▪ Time delay before flux in = flux out (i.e., &quot;bathtub&quot; effect)</td>
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<td></td>
</tr>
<tr>
<td>▪ Invert</td>
<td>▪ Saturation depends on design and rock/invert characteristics                    ▪ Uncertainty in water/invert characteristics</td>
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<tr>
<td></td>
<td>▪ Flux considers: 2-d effects                                                     ▪ Uncertainty in moisture removal</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>▪ Rock</td>
<td>▪ Advevctive flux go rates fractures                                              ▪ Drift &quot;shadow&quot; effect</td>
<td>4</td>
<td></td>
</tr>
</tbody>
</table>
## Summary of Key Chemical and Transport Assumptions Affecting EBS Release Rates

<table>
<thead>
<tr>
<th>Component</th>
<th>Current Treatment</th>
<th>Key Unquantified Uncertainty</th>
<th>Addressing Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waste form alteration</td>
<td>* Cladding degradation rate varies with initial state and localized zircaloy corrosion</td>
<td>* Alternative degradation modes and rates of Zircaloy</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>* Cladding degraded by seismic effects</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>* Alteration rate considers environment (pH)</td>
<td></td>
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<tr>
<td>Radionuclide concentration</td>
<td>* Solubility a function of environment for single controlling phase</td>
<td>* Uncertainty in controlling phases</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>* Colloids fraction and amount</td>
<td>* Uncertainty in colloid stability and transport characteristic</td>
<td>4</td>
</tr>
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<td></td>
<td>* Secondary phases considered as sensitivity</td>
<td></td>
<td></td>
</tr>
<tr>
<td>In-Waste package transport</td>
<td>* Once waste package degrades, environments equilibrate</td>
<td>* Consider in waste package dry out</td>
<td>4</td>
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<tr>
<td></td>
<td>* Water contacts all exposed waste</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>* For diffusion, waste is placed at bottom of waste package</td>
<td>* Time delay for in-waste package diffusion</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>* Water film is continuous</td>
<td>* Water film is discontinuous</td>
<td>4</td>
</tr>
<tr>
<td>Through waste package transport</td>
<td>* Advection occurs instantly with first breach</td>
<td>* Consider &quot;bathtub effect&quot;</td>
<td></td>
</tr>
<tr>
<td></td>
<td>* Advection and diffusion considers area of waste package degraded</td>
<td>* Limit area to thickness of film</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>* Diffusion length limited to 2 cm to invert</td>
<td>* Use diffusion length considering varying lengths to invert</td>
<td>4</td>
</tr>
<tr>
<td>Through invert transport</td>
<td>* Advection considers through waste package flux</td>
<td>* Consider 3-d effects</td>
<td>4</td>
</tr>
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<td></td>
<td>* Diffusive coefficient a function of saturation</td>
<td>* Diffusion coefficient uncertainty</td>
<td></td>
</tr>
<tr>
<td></td>
<td>* Diffusive transport released to host rock fractures</td>
<td>* Diffusive transport released to rock matrix</td>
<td>4</td>
</tr>
</tbody>
</table>