Management and Technical Support Peak Dose Sensitivity Analysis

Presented to:
Nuclear Waste Technical Review Board

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February 01, 2006
Las Vegas, Nevada

Presentation Overview

- Objective and Limitations
- Overview of Model Approach
- Features, Events, and Processes (FEPs)
- Key Assumptions
- Modeling Approaches
- Results

Objective and Limitations

- Develop a scoping-level simplified model to evaluate those factors that influence the peak annual dose
- THIS IS NOT A COMPLIANCE MODEL
  - Results are informative in nature only and should not be compared to any proposed or final regulations
  - Initiated well in advance of the issuance of recently proposed revisions to regulations at 40 CFR 197 and 10 CFR 63 and no attempt was made to reconcile the methods, assumptions, and modeling approaches with proposed revisions
  - An assessment of post-closure repository performance for demonstrating compliance with 40 CFR 197 and 10 CFR 63 will be conducted in accordance with these regulations when final regulations are issued

Overview of Model Approach

- **Considered FEPs that were evaluated over a 10,000 year post-closure period**
- **Simplified model includes representative FEPs that could potentially affect the peak dose**
- **FEPs that have either a minor or no effect on the peak dose either were not included in the model or were included in a bounding representation**
  - **Although FEPs (or representations containing several FEPs) that were not included may have an effect on the maximum dose occurring during the first 10,000 years after repository closure, they could be excluded from the model because they have a less significant effect on repository performance over the period of peak dose**
  - **A bounding representation means that no performance credit was taken**

Overview of Model Approach

(Continued)

- Used documentation current as of early 2005 and historical Yucca Mountain Project information regarding post-closure repository performance
  - Recognize that several models that support the 10,000-year postclosure performance assessment used as input may be revised
- Similar to a performance assessment as defined in current 10 CFR Part 63
  - Fully integrated system-level model and analysis
  - Differs from the previous and ongoing total system performance assessment (TSPA) approach in that all processes that affect system performance over a 10,000 year postclosure period are not necessarily represented at a level of detail comparable to that found in a TSPA

Features, Events, and Processes Evaluation

- Evaluated FEP exclusion justifications over a 10,000 year period against a longer timeframe
- Slow and/or infrequent processes are of secondary importance to the primary degradation modes that are most significant to repository performance over the period of peak dose
  - Would tend to spread radionuclide release rates over time (i.e., due to earlier degradation of lesser consequence which tends to spread the resultant predicted dose over time) resulting in lower projections of the peak dose
  - Are not likely to occur even over longer time periods due to the cooling of the repository environment over time
  - Such processes can continue to be reasonably excluded from the post 10,000-year evaluations based on low consequence

Features, Events, and Processes Evaluation (Continued)

- **Slow degradation processes of engineered features – drip shield, waste package and pallet**
  - Types include, but are not limited to (1) creep, (2) thermal sensitization, (3) hydride cracking, (4) consolidation, and (5) non-seismic induced mechanical degradation
  - Very slow degradation processes that are accelerated at higher temperatures or require significantly higher temperatures to be initiated
  - Processes are either not initiated during the 10,000-year time period and/or they are of a sufficiently slow degradation rate that they have no significant effect during this time period
  - As the temperatures continue to decrease beyond 10,000 years, the rate will further reduce and there is no reason to expect these processes to significantly affect the degradation characteristics of the engineered features beyond 10,000 years
  - Even if the above processes did affect the degradation rate of the engineered features, the degradation mode of these processes generally leads to small holes or cracks in the engineered feature. Only slow diffusion of dissolved radionuclides would occur, rather than a significant advection of radionuclides as expected when the engineered features are "grossly breached" by corrosion processes that occur at the time of the peak dose

Features, Events, and Processes Evaluation (Continued)

- **Slow stress-induced degradation processes of emplacement drifts that affect engineered components**
  - **Processes include, but are not limited to, drift collapse and consolidation induced by drift collapse. Included in these processes is creep (e.g., static fatigue) of the rock mass**
  - **The rates of these processes decrease with lower temperatures and therefore become more stable with time in the repository environment**
  - **More significant at early times when the repository emplacement drifts are potentially affected by thermal and mechanical stress modifications**
  - **If these slow stress-induced processes can be reasonably excluded from assessments of 10,000-year performance, the decreased rate of deformation over longer time frames can also be reasonably excluded**

Features, Events, and Processes Evaluation (Continued)

- **Infrequent stress-induced degradation processes of emplacement drifts affected by seismic events**
  - The emplacement drifts are expected to be affected by seismic-induced stresses that can lead to deformation and degradation of the emplacement drifts
  - Because the most significant affect of seismic-induced drift degradation is drift collapse, this degradation should be considered and included in the seismic scenario evaluation
- **Degradation processes initiated by seismic and volcanic event sequences**
  - Evaluating long term risks associated with such events can be reasonably approximated by continuing the 10,000-year assessments to longer times
  - Extending the analysis in an uncoupled fashion would tend to minimize the likelihood of diluting the risk

Features, Events, and Processes Evaluation (Continued)

- **Results of FEP evaluation**
  - The vast majority of the FEP screening justifications applicable to a 10,000 year period are appropriate over a time period that covers the peak dose
    - Results from most screening justifications being time invariant, made on an annual probability basis, or on a low consequence basis that is not affected by time
    - Those that can be excluded from a 10,000-year postclosure performance assessment were excluded
    - Those that need to be included in a 10,000-year postclosure performance assessment were included, either explicitly or implicitly through a bounding approach

Features, Events, and Processes Evaluation (Continued)

- **Results of FEP evaluation**
  - **The remaining FEPs fall into three categories:**
    - **The screening justifications for several FEPs that can be excluded from the 10,000-year postclosure performance assessment were augmented to accommodate the time period of peak dose - These FEPs continued to be excluded**
    - **A few FEPs related to seismic effects that can be excluded from the 10,000-year postclosure performance assessment were considered appropriate for inclusion**
    - **Some FEPs that need to be included in a 10,000-year postclosure performance assessment can be excluded from an analysis conducted over the peak dose period based on low consequence because they have a negligible effect on the peak dose**

Key Assumptions

- **Constant climate state**
  - **Integrated long-term average**
  - **Slightly larger infiltration than Glacial Transition**
- **Repository average percolation flux equal to average infiltration**
- **Collapsed drift conditions for seepage**
  - **Assumed seismic activity will result in drift collapse over the period of peak dose**
- **Diffusive radionuclide transport neglected**
  - **Previous TSPA analyses have demonstrated that Engineered Barrier System (EBS) radionuclide releases via advection were several orders of magnitude larger than diffusive releases**
  - **Degradation mechanisms that result in diffusive releases were not considered – Stress Corrosion Cracking**
  - **This maximizes the inventory available when "gross breaching" and advective transport occurs**

Key Assumptions

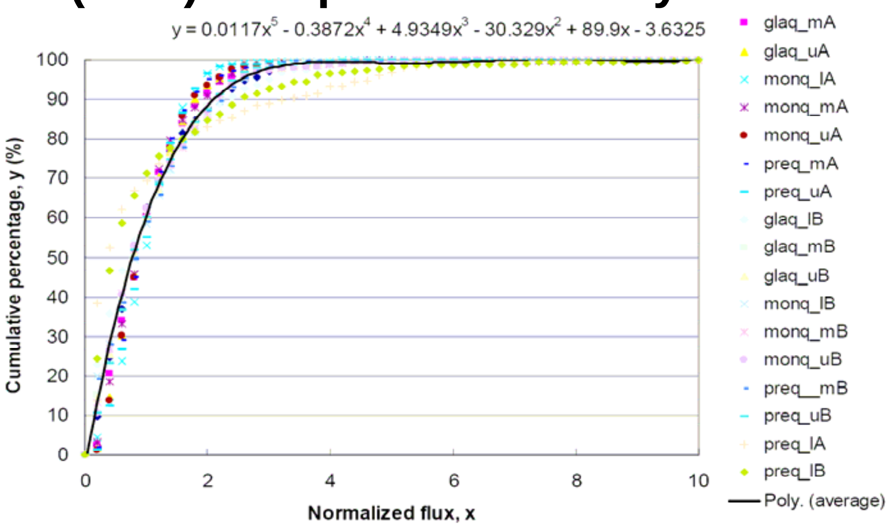
- **General corrosion is the only corrosion-related process considered**
  - Key aspect controlling peak dose is the formation of large openings in both the drip shield and waste package – advective transport
  - Not considering transport through other smaller breaches maximizes the inventory available when "gross breaching" occurs
- **Instantaneous degradation of waste forms**
  - Period over which waste forms degrade is small as compared to the timeframe of the peak dose
  - Seismic activity over the period of peak dose is likely to degrade the Commercial Spent Nuclear Fuel (CSNF) clad
- **For simplicity, assumed immediate radionuclide transport through the unsaturated zone and through the fractured-volcanic aquifer in the saturated zone**

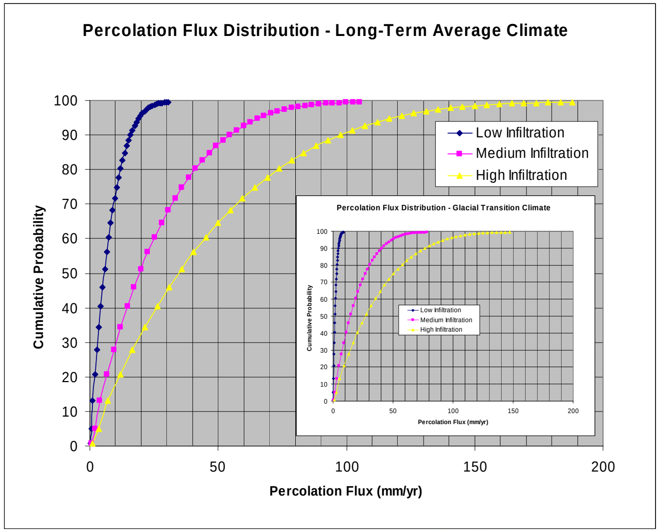
Model Approaches

- **Used average infiltration rates for various climate states to produce time-integrated average infiltration rate representative of long-term average climate**

Infiltration Case	Average Infiltration Rate
Low	7.7 mm/yr
Medium	26.6 mm/yr
High	47.6 mm/yr

- **Average percolation flux = average infiltration**
  - **Applied cumulative distribution function (CDF) for spatial variability**



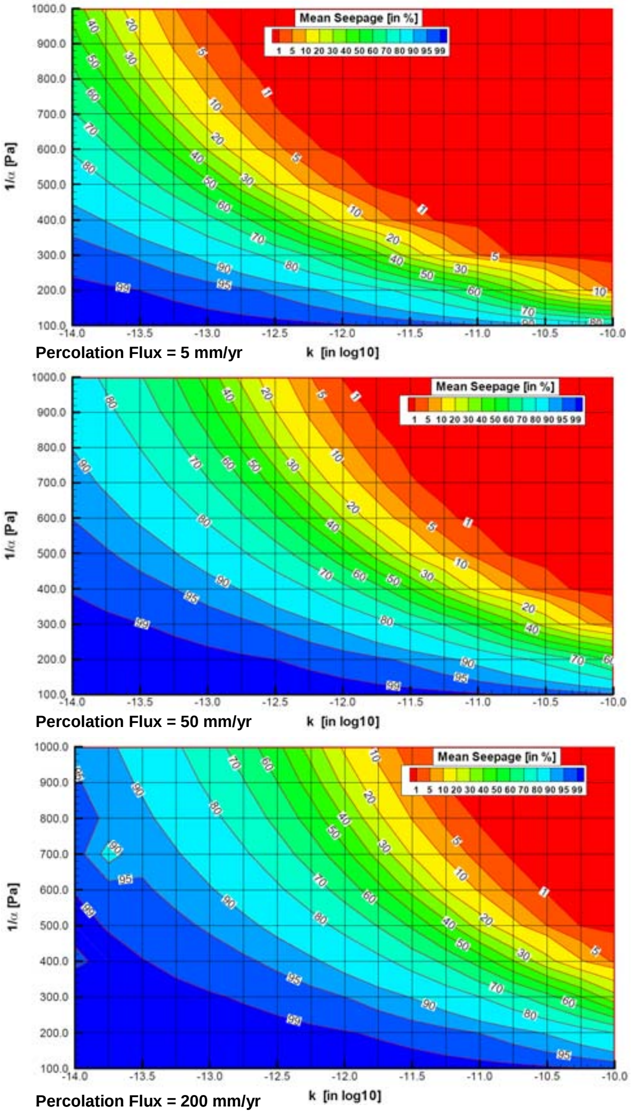


UZ Flow Models and Submodels, MDL-NBS-HS-000006 REV 02, Section 6.6.3

Model Approaches (Continued)

- **Emplacement drift seepage**
  - **Used response surface for collapsed drifts**
  - **Applied distribution of percolation flux to determine fraction of waste packages contacted by seepage and the average seepage rate**
  - **Accounted for spatial variability and flow focusing**

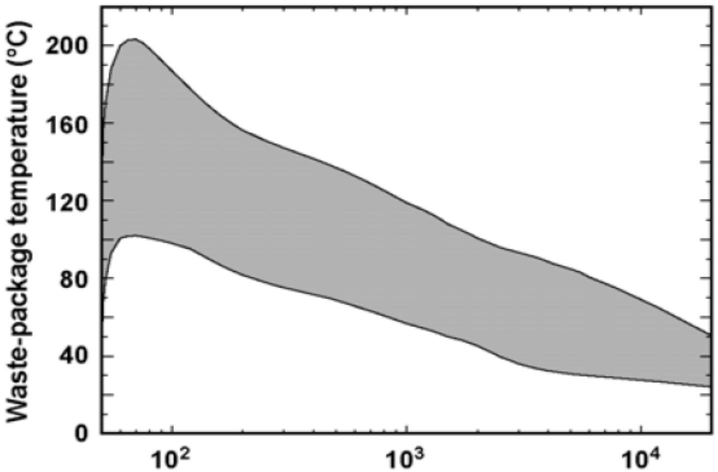
Climate State	Infiltration Case	Repository Average Seepage Rate (kg/yr per waste package)			Seepage Fraction (%)		
		Mean	Minimum	Maximum	Mean	Minimum	Maximum
Intact Drifts	Low	21	0	372	20.1	0	100
	Medium	79	0	898	39.3	0	100
	High	148	0	1163	48.3	0	100
Collapsed Drifts	Low	246	0	2651	74.0	0	100
	Medium	621	6	3244	87.9	4.5	100
	High	912	21	3580	88.1	15.9	100



Seepage Model for PA Including Drift Collapse, MDL-NBS-HS-000002 REV 03 **,** Section 6.6.3

Model Approaches (Continued)

- **In-drift environment**
  - **Multi-Scale Thermal Hydrology results, extrapolated to ambient (21º C) at 100,000 years, used to determine waste package surface temperature**



Multiscale Thermohydrologic Model, ANL-EBS-MD-000049 REV 02, Figure 6.3-53

Time (years)	Coolest Waste Package Surface Temperature (deg. C)	Hottest Waste Package Surface Temperature (deg. C)
50	70	160
60	100	200
70	102	205
80	101	200
90	99	190
100	95	185
200	82	160
400	75	147
500	72	142
1000	50	125
3000	40	95
5000	35	85
10000	33	70
20000	22	50
≥ 100000	21	21

  - **Chemical environment used long-term conditions (~100,000 years)**

Starting Water Chemistry	Partial Pressure CO_2 (bars) in the Emplacement Drift	Partial Pressure CO_2 (bars) in the Invert
HD-PERM	4.02E-3	2.02E-3
CS2000	8.19E-3	8.18E-3
CS1000	5.59E-3	5.54E-3
SD-9	3.88E-3	3.87E-3
CS500	5.91E-3	5.79E-3

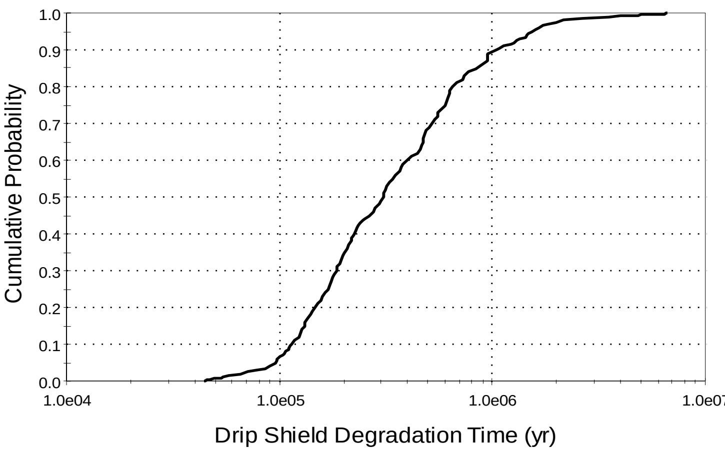
Engineered Barrier System: Physical and Chemical Environment, ANL-EBS-MD-000033 REV 03 ,Tables 6.7-1 through 6.7-5

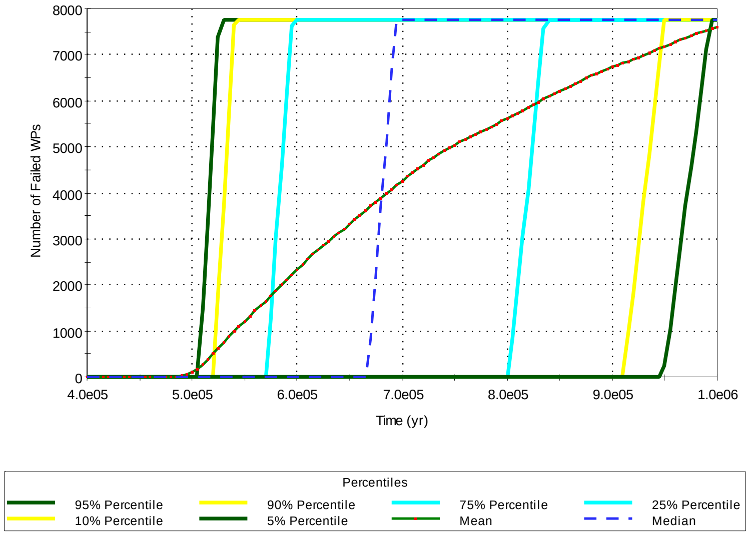
pCO_2	Invert pH
10^{-3} bar	8.579
10^{-2} bar	7.659

Engineered Barrier System: Physical and Chemical Environment, ANL-EBS-MD-000033 REV 03 ,Table 6.9-6

Model Approaches (Continued)

- **Drip shield and waste package degradation**
  - **Drip shield degradation due to general corrosion**
    - **Probability distributions of general corrosion rates from LTTF measurements– represents uncertainty**
    - **Weight-loss: Underside**
    - **Weigh-loss and crevice: Outer Surface**
  - **Waste package degradation due to general corrosion**
    - **Simplified approach to represent the results described in *WAPDEG Analysis of Waste Package and Drip Shield Degradation* AMR**
    - **Probability distributions of general corrosion rates from LTTF measurements – represents variability**
    - **Temperature dependence applied to 45 °C – coefficients are uncertain**
    - **Determined time for initial waste package general corrosion penetration for "coolest" and "hottest" waste package**
    - **Assumed uniform initial penetrated rate between "coolest" and "hottest" waste packages**
    - **Adjusted the average number of general corrosion breaches on penetrated packages to account for limited temperature dependence**





Model Approaches (Continued)

- **In-package chemistry**
  - **CSNF waste packages can initially fail due to stress corrosion cracking or general corrosion penetrations (50/50)**
    - **Late pH when cracks – Internals fully degraded when first general corrosion penetration occurs**
    - **Early pH when general corrosion – Internals degradation effects pH**
  - **CDSP in-package pH depends on volumetric water flow rate through the waste package**

WP Type	Period (years)	Log fCO2	Flow Rate (L/yr per WP)	Min pH	Max pH
CSNF	0 – 600 (*Applied in Peak Dose Model when waste packages fail by General Corrosion First*)	-5.0	N/A	4.5	8.1
		-4.5	N/A	4.5	8.1
		-4.0	N/A	4.5	8.0
		-3.5	N/A	4.5	7.9
		-3.0	N/A	4.5	7.7
		-2.5	N/A	4.5	7.5
		-2.0	N/A	4.5	7.3
		-1.5	N/A	4.5	7.0
	600 – 20,000 (*Applied in Peak Dose Model when waste packages fail by Stress Corrosion Cracking (SCC) First*)	N/A	N/A	4.5	7.0
CDSP	0 – 20,000	N/A	$Q \leq 150$	4.5	7.0
		N/A	$Q > 150$	4.5	8.0

In-Package Chemistry Abstraction, ANL-EBS-MD-000037, REV 03, Table 8-2

Model Approaches (Continued)

- **Radionuclide selection and initial radionuclide inventory**
  - **Results of past TSPAs and performance assessments conducted by EPRI to determine a limited sub-set**
    - **TSPA-FEIS: Np-237, Pa-231, Ac-227, Pu-239, and Pu-242**
    - **EPRI: Th-229 and U-233**
    - **Significant Daughter Radionuclides: Th-230, Th-232, Ra-226, and Ra-228**
    - **Additional Radionuclides In Decay Series**

Decay Chain	Cm-245	→	Pu-241	→	Am-241	→	Np-237	→	Pa-233	→	U-233	→	Th-229	→		
Half Life		8.50E+03		1.44E+01		4.33E+02		2.14E+06		Short		1.59E+05		7.30E+03		
CSNF Inventory	1.77E+01		2.69E+03		8.28E+03		4.63E+03				5.83E-02		0.00E+00			
CDSP Inventory	1.50E-01		3.01E+01		2.56E+02		1.88E+02				5.51E+02		3.23E-01			
Decay Chain	Am-242m	→	Am-242	→	Cm-242	→	Pu-238	→	U-234	→	Th-230					
Half Life				Short		Short		8.77E+01		2.46E+05	See Below					
CSNF Inventory	Negligible						1.54E+03									
CDSP Inventory	Negligible						5.47E+01									
Decay Chain	Am-243	→	Np-239	→	Pu-239	→	U-235	→	Th-231	→	Pa-231	→	Ac-227	→		
Half Life		7.37E+03		Short		2.41E+04		7.04E+08				3.28E+04		2.18E+01		
CSNF Inventory	1.26E+03				4.37E+04		6.34E+04			Short	9.28E-03		2.50E-06			
CDSP Inventory	7.25E+00				2.79E+03		2.62E+04				3.77E+00		1.41E-03			
Decay Chain	Cm-244	→	Pu-240	→	U-236	→	Th-232	→	Ra-228	→						
Half Life	Negligible			6.56E+03		2.34E+07		1.40E+10		5.76E+00						
CSNF Inventory			2.08E+04		3.89E+04		0.00E+00									
CDSP Inventory			4.78E+02		1.30E+03		5.37E+04									
Decay Chain	Cm-246	→	Pu-242	→	U-238	→	Th-234	→	Pa-234	→	U-234	→	Th-230	→	Ra-226	→
Half Life	Negligible			3.75E+05		4.47E+09		Short		Short		2.46E+05		7.54E+04		1.60E+03
CSNF Inventory			5.34E+03		7.92E+06						1.77E+03		1.54E-01			
CDSP Inventory			3.39E+01		9.31E+05						4.91E+02		1.17E-01			

Source: Initial Radionuclide Inventories, ANL-WIS-MD-000020 REV 01
Table 4-12 for half lives
Table 4-14 for decay chains
Table 7-1 for inventories

Model Approaches (Continued)

- **Radionuclide release from the Engineered Barrier System**
  - **Considered only radionuclide transport via advection**
  - **1-D transport using mixing cells (waste form, waste package internals, invert)**
  - **Solubility limits applied in each mixing cell**
    - **Solubility model from *Dissolved Concentration Limits of Radioactive Elements* AMR**
    - **Used NpO_2 as controlling phase because there is evidence that even NpO_2 solubility provides a reasonably bounding control (others in sensitivity analysis)**
    - **Function of in-package environment**
  - **Reversible sorption in waste package internals and invert**

Model Approaches (Continued)

- **Natural Barrier System Beneath the Repository**
  - For simplicity, assumed immediate radionuclide transport through the unsaturated zone and through the fractured-volcanic aquifer in the saturated zone
  - Considered radionuclide transport through the alluvium portion of the saturated zone flow system
    - For moderately-sorbing radionuclides UZ breakthrough is comparable to the period over which waste packages fail due to general corrosion (on the order of several tens to hundreds of thousands of years)
    - A steady state will ultimately be realized for moderately-sorbing radionuclides where the radionuclide mass flux out of the unsaturated zone will equal the radionuclide mass flux out of the EBS
    - SZ breakthrough on the order of several tens to hundreds of thousand of years for strongly-sorbing radionuclides, most delay in the alluvium
    - Significant retardation of Pa, Pu, and Th expected in UZ and fractured volcanic portion of SZ flow system
- **Biosphere dose conversion factors for Glacial Transition conditions**

Model Approaches (Continued)

- **Treatment of Seismic Disruptive Events**
  - Waste package damage from vibratory ground motion is expected to result in increased susceptibility to stress corrosion cracking
  - The waste package is protected by the drip shield from rockfall
    - The consequences of rockfall on the waste packages have not been analyzed
    - The expected consequences of rockfall on the drip shield is increased susceptibility to stress corrosion cracking
    - The likely consequence of rockfall on the waste package is increased susceptibility to stress corrosion cracking
  - Although stress corrosion cracking is likely to be the dominant failure mode, a sensitivity analysis was conducted assuming both vibratory ground motion and rockfall resulted in gross breaching of the waste package
    - Considered multiple seismic events over 1,000,000 years
    - Event magnitude sampled
    - Amount of gross breaching as a function of magnitude

Model Approaches (Continued)

- **Treatment of igneous disruptive events**
  - **Considered igneous intrusion and volcanic eruption cases**
  - **Simplified representations based on approaches described in the igneous consequence AMRs**
  - **Igneous Intrusion**
    - **Igneous events were assumed to occur every realization with the timing and magnitude of the event varying to account for uncertainty**
    - **Values for uncertain parameters were sampled over 1,000 realizations and repository performance was evaluated over a 1,000,000 year period based on the value of those sampled parameters**
  - **Volcanic Eruption**
    - **Generated 1,000 realizations with each realization producing an annual dose history associated with a series of eruptive events, one in each time step**

Results

- Discussion focuses on sensitivities and not the magnitude/timing of the peak annual dose
- The peak annual dose depends on nominal degradation processes
  - These processes are the gradual degradation of engineered barriers and subsequent release of radionuclides contained within them
  - In particular, the peak dose depends primarily on the timing and rate of waste package failure due to general corrosion processes and the rate that water transports radionuclides out of the EBS
- Seismic events will occur and although seismic-induced mechanical damage may influence the annual dose prior to the onset of significant waste package failure due to general corrosion, it is not expected to have a significant effect on the peak annual dose (mean or median)

Results (Continued)

- Although igneous intrusion may influence the dose prior to the onset of significant waste package failure due to general corrosion, it is not expected to have a significant effect on the peak annual dose (mean or median)
- The peak mean probability-weighted annual dose due to an igneous eruption scenario occurs within the first 10,000 years following closure of the repository and can be evaluated in the 10,000-year post-closure performance assessment

Results (Continued)

- **Sensitivity analyses**
  - Infiltration rates and percolation rates through the unsaturated zone have a minor effect on the magnitude of the peak dose
    - Over the range of repository average infiltration rates representative of a long-term average climate when considering collapsed drift conditions for estimating seepage
  - Emplacement drift seepage has a significant effect on the magnitude of the peak dose
  - Waste package performance, in particular general corrosion rates, have a significant effect on the peak dose estimate (magnitude and timing)

Results (Continued)

- Sensitivity analyses (continued)
  - The choice of controlling solid phase for determining neptunium dissolved concentration limits does not have a significant effect on the peak annual dose
    - For the range of parameters included in the model
    - Lower seepage rates increases the effect
  - Drip shield performance has a minor effect on the peak dose
    - The drip shield is likely to be completely degraded when gross breaches in the waste packages occur due to general corrosion and will not limit the advective release of radionuclides from the EBS
  - The natural barrier system below the repository, in particular the alluvial portion of the saturated zone, functions as an effective barrier for several key radionuclides over the period of peak dose
    - Strongly sorbing radionuclides will be significantly retarded

Conclusion

- Develop a scoping-level simplified model to evaluate those factors that influence the peak annual dose
- THIS IS NOT A COMPLIANCE MODEL
  - Results are informative in nature only and should not be compared to any proposed or final regulations
  - Initiated well in advance of the issuance of recently proposed revisions to regulations at 40 CFR 197 and 10 CFR 63 and no attempt was made to reconcile the methods, assumptions, and modeling approaches with proposed revisions
  - An assessment of post-closure repository performance for demonstrating compliance with 40 CFR 197 and 10 CFR 63 will be conducted in accordance with these regulations when final regulations are issued