U.S. Department of Energy
Office of Civilian Radioactive Waste Management

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Total System Performance Assessment Results

Presented to:
NRC/DOE Technical Exchange on Total System Performance Assessment (TSPA) for Yucca Mountain

Presented by:
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Sandia National Laboratories

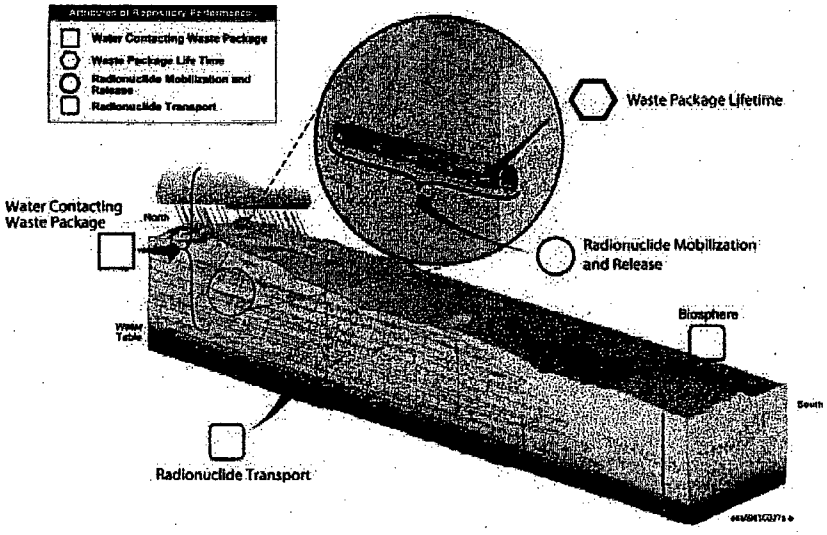
April 03, 2008
Las Vegas, Nevada

Outline

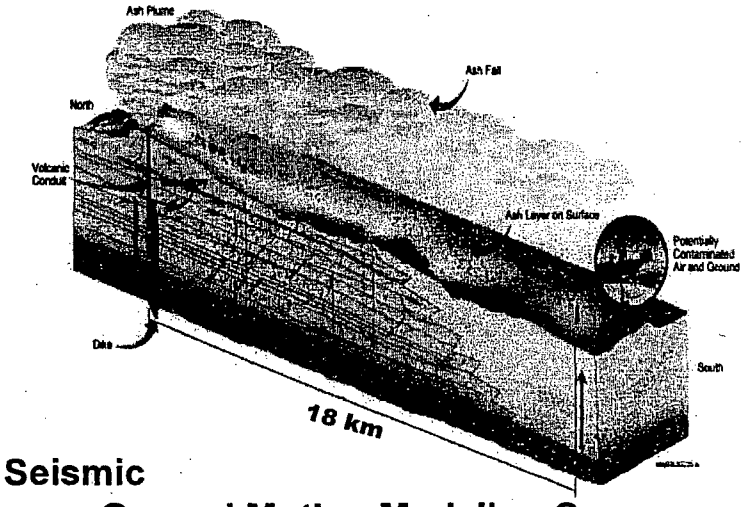
- Scenarios and Modeling Cases
- Overview of Total System Performance Assessment- License Application (TSPA-LA) results
  - Total Dose (summed over scenarios)
  - Important Scenarios and Radionuclides
  - What determines
    - Shape of expected dose history
    - Magnitude of expected dose
    - Uncertainty in expected dose
  - Stability of total dose results
- Results are from TSPA AMR (MDL-WIS-PA-000005) Rev00 AD01

Future Scenarios for Yucca Mountain

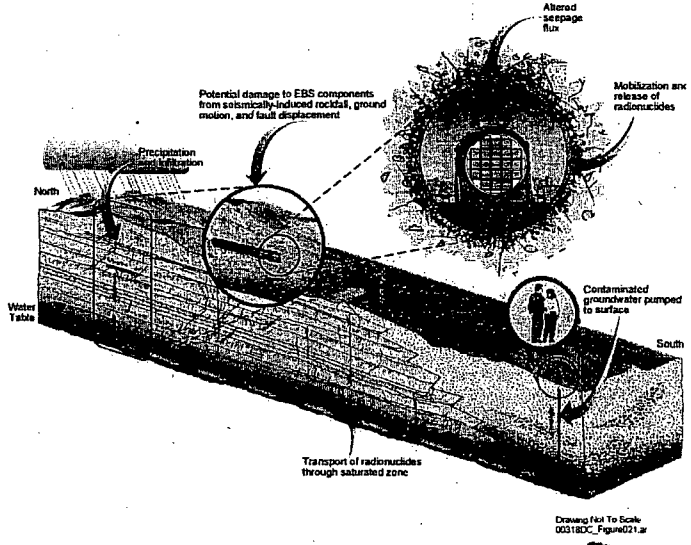
- Nominal Scenario
  - Nominal Modeling Case
- Early Failure Scenario
  - Waste Package Modeling Case
  - Drip Shield Modeling Case



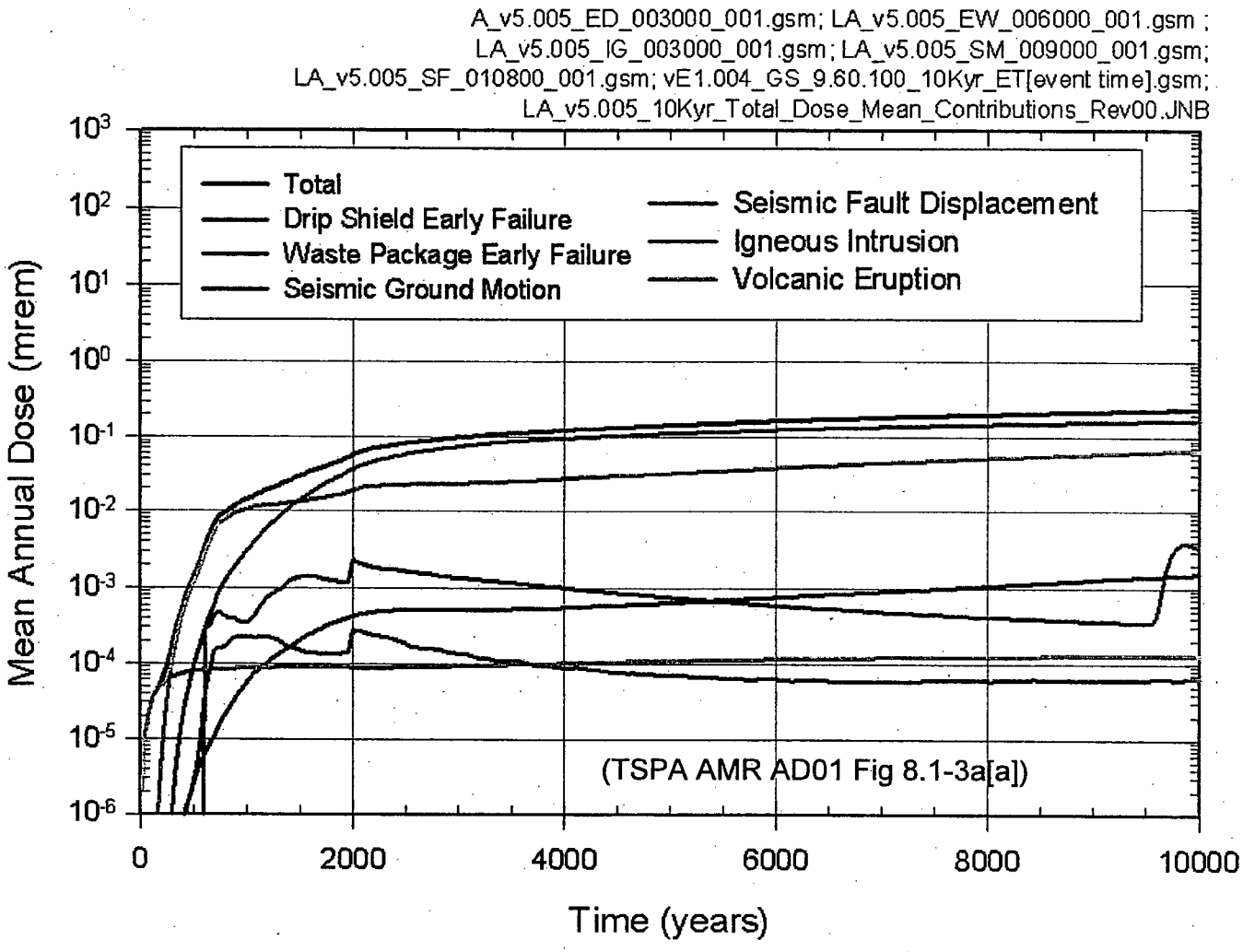
- Igneous Scenario
  - Intrusion Modeling Case
  - Eruption Modeling Case



- Seismic
  - Ground Motion Modeling Case
  - Fault Displacement Modeling Case



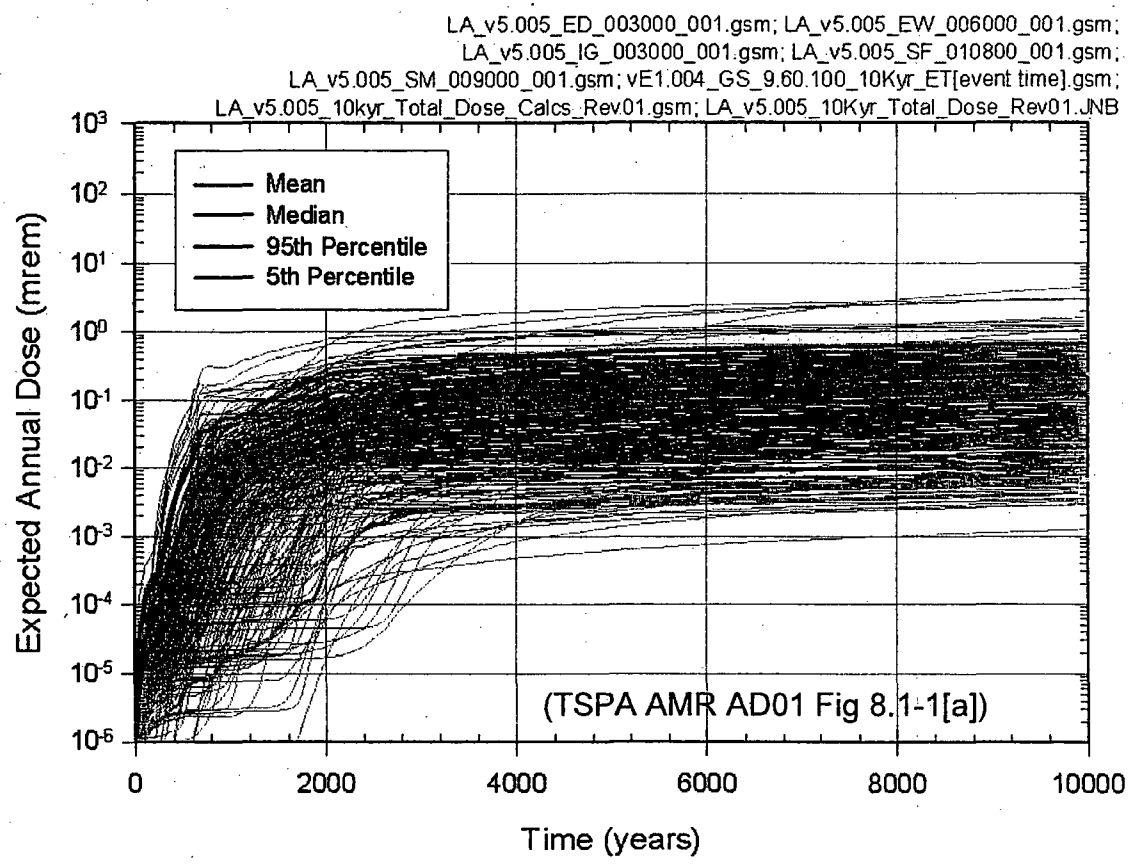
Total Mean Dose Contributions By Modeling Case



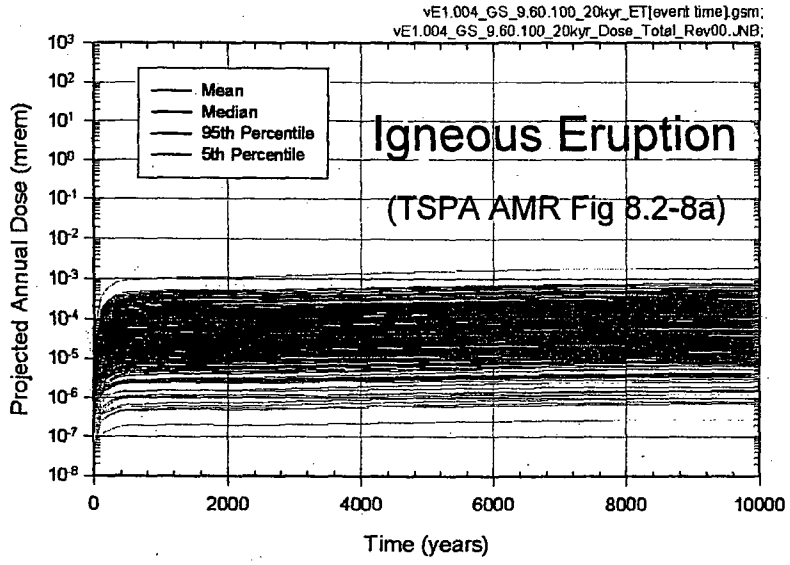
Uncertainty in Total Expected Dose (Summed over Modeling Cases)

Four questions:

1. What determines the <u>shape</u> of these curves?
2. What determines the <u>magnitude</u> of total mean dose?
3. What determines the <u>uncertainty</u> in total expected dose?
4. Are these results <u>stable</u>?



Shape of Total Expected Dose



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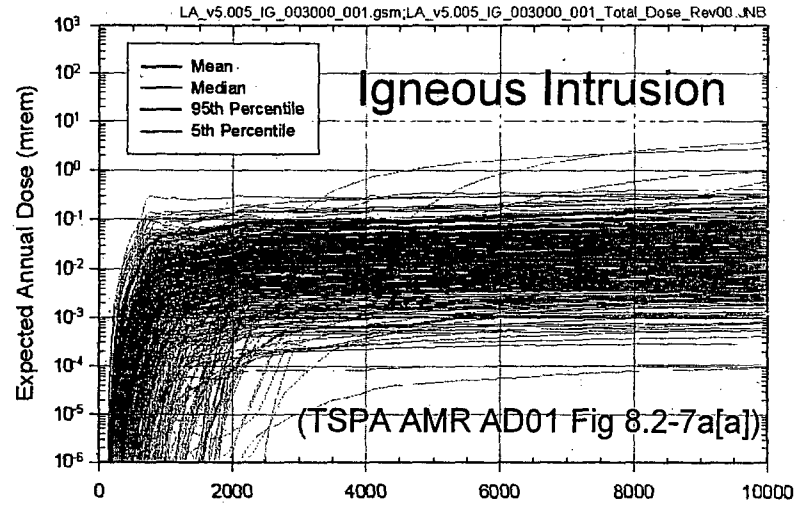

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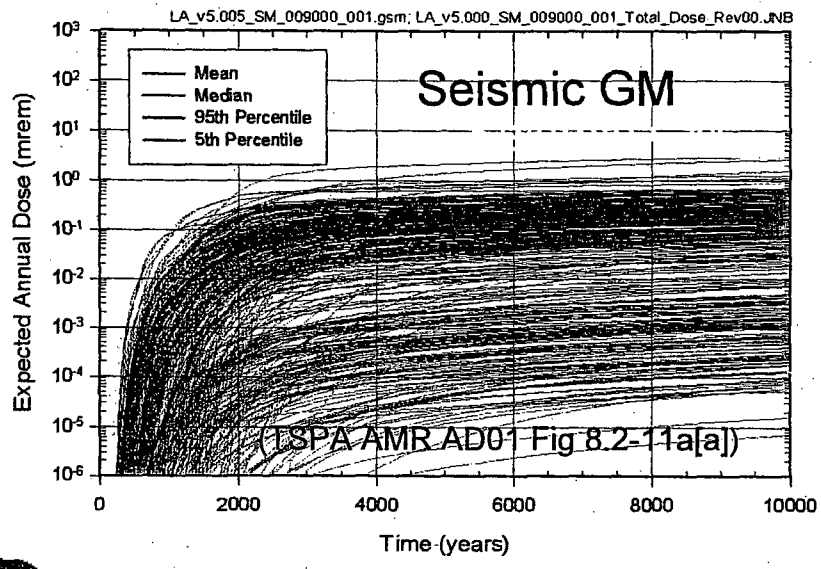

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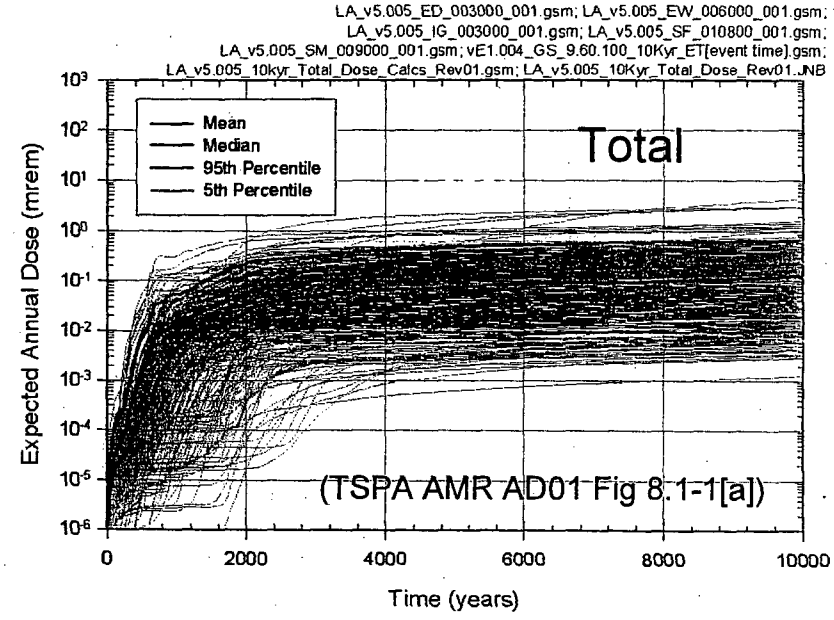
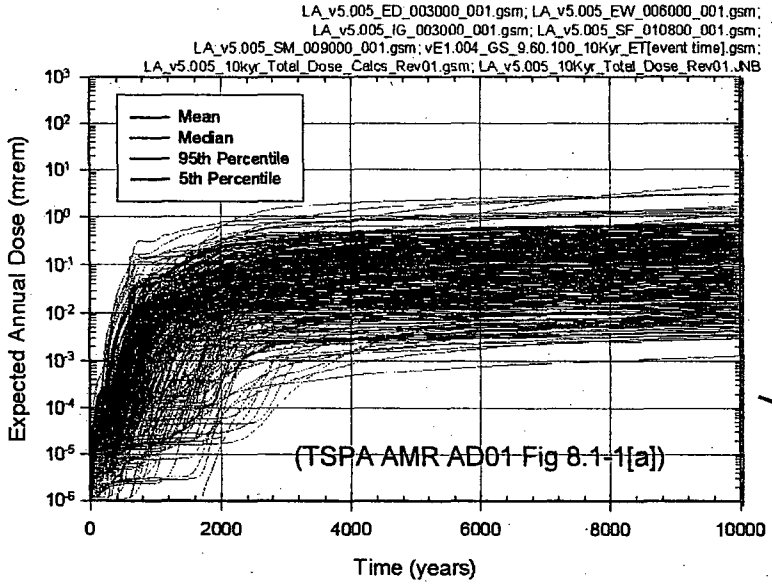
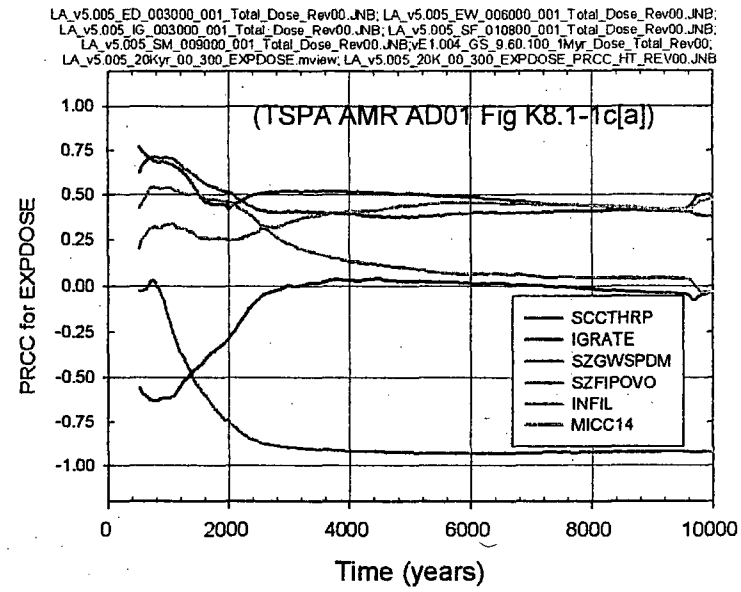
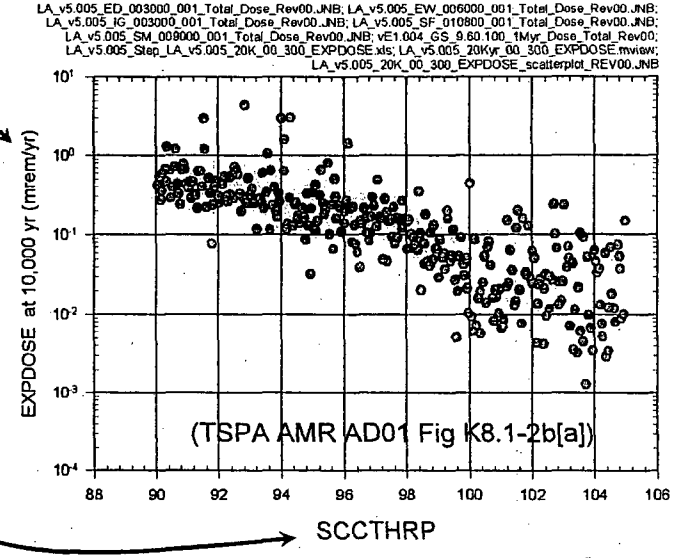


Uncertainty in Total Expected Dose

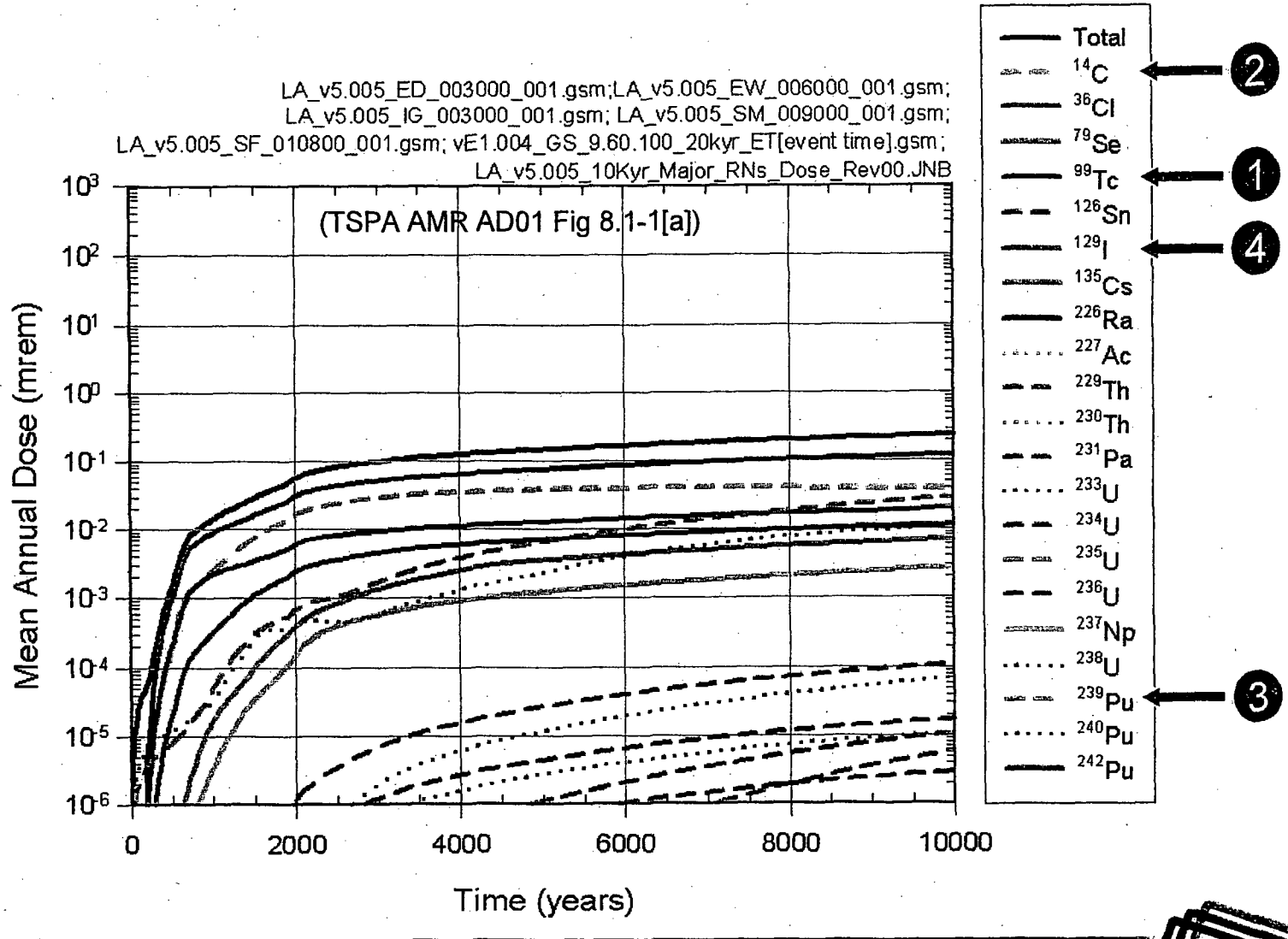




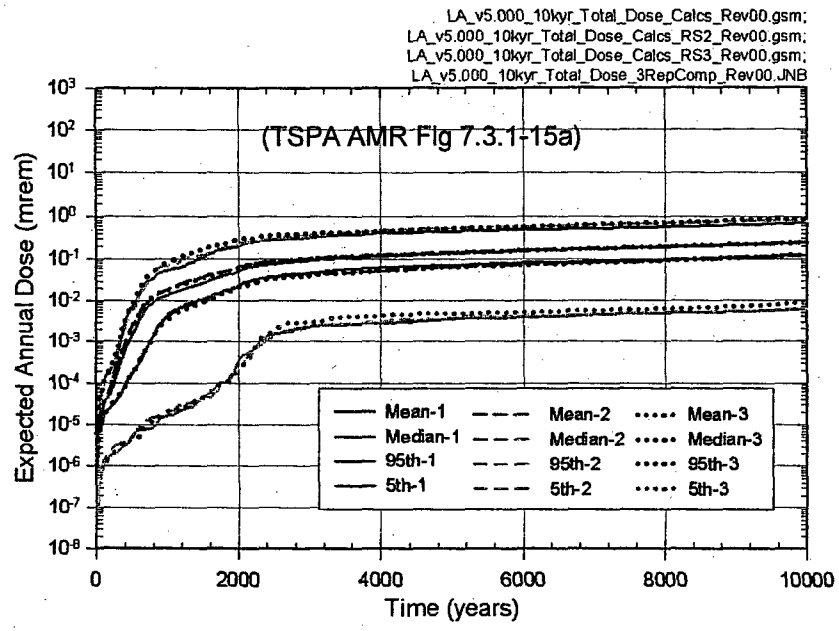


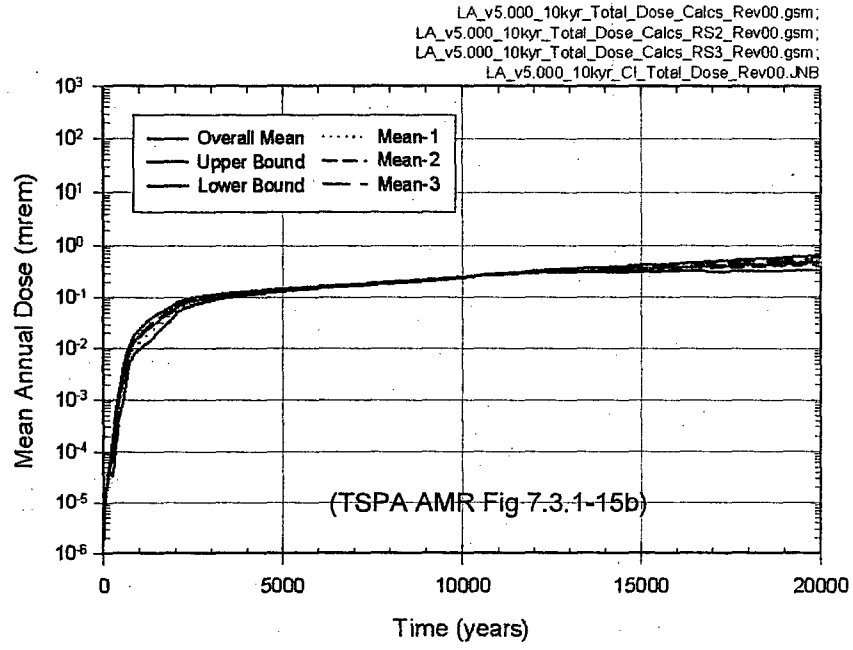
SCCTHRP – stress threshold for SCC initiation (90 to 105, % of yield strength)
IGRATE – frequency of igneous events
SZGWSPDM – logarithm of uncertainty factor in groundwater specific discharge
SZFIPOVO – flowing interval porosity in volcanic units
INFIL – infiltration case
MICC14 – biosphere dose conversion factor for C14

Radionuclides Contributing to Total Mean Dose at 10,000 Years



Stability of Total Dose





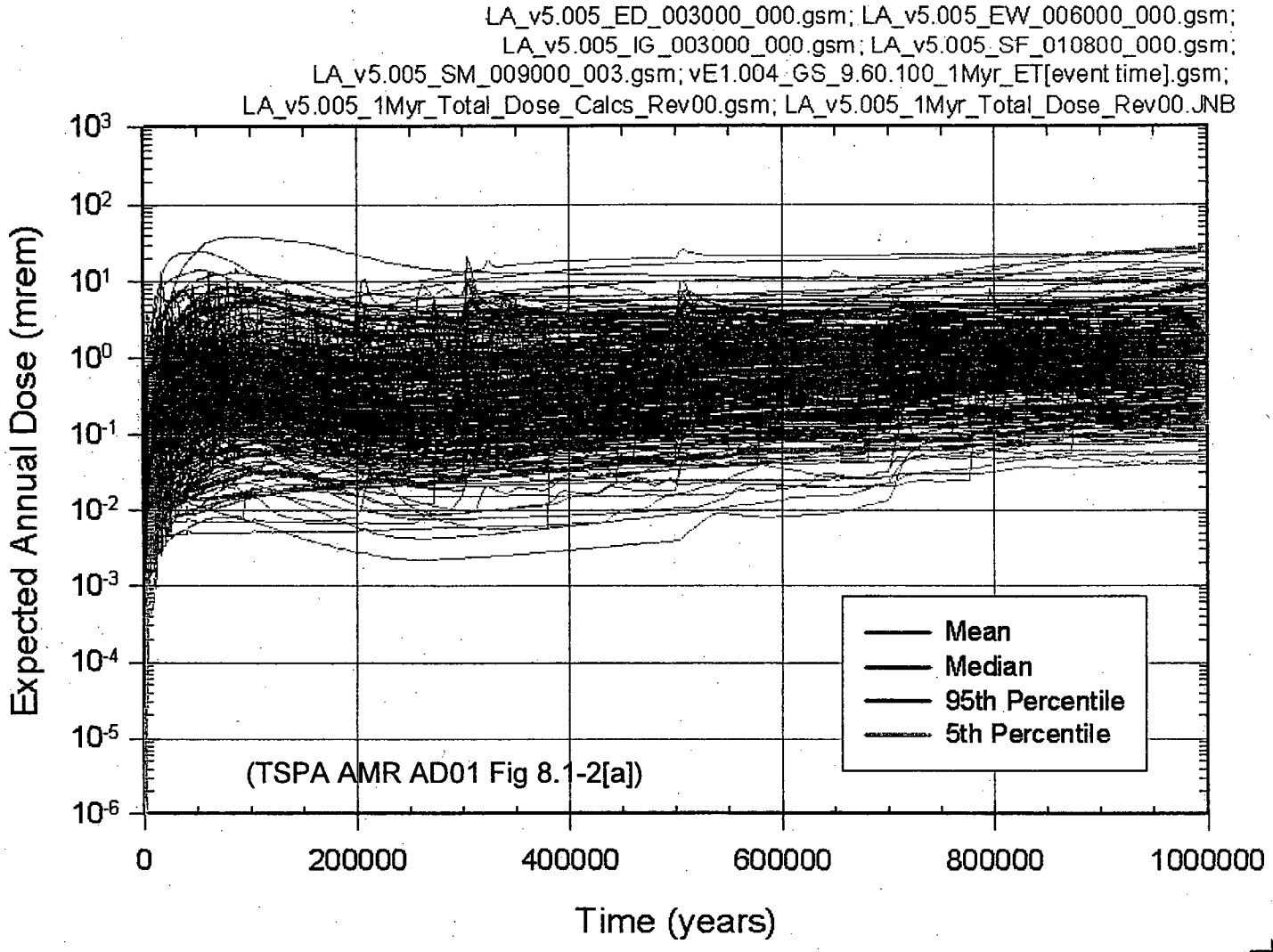
Replicated sampling demonstrates that sample size is sufficient

Confidence interval illustrates precision of estimate of total mean dose

Summary of 10,000 Year Results

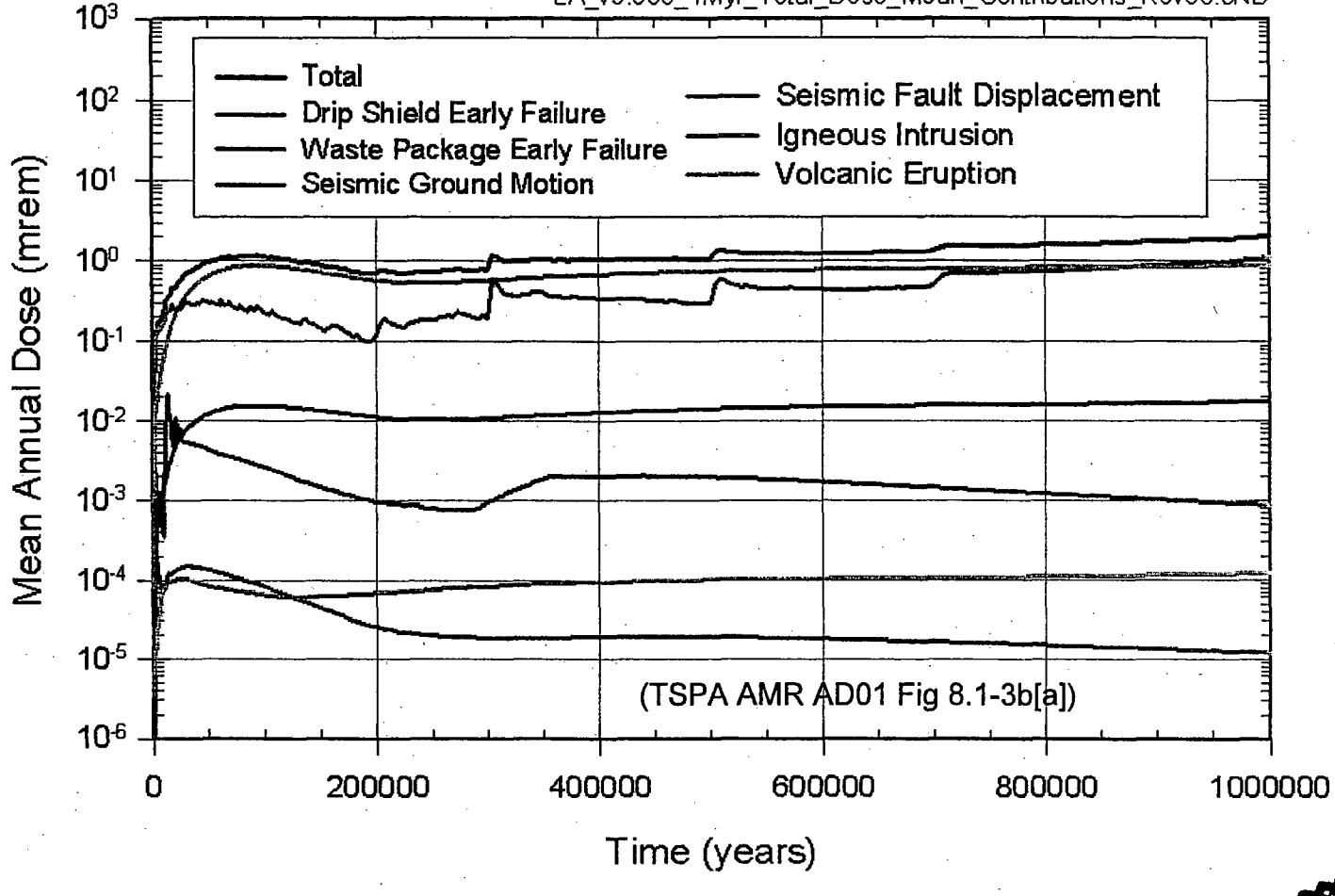
- Total mean dose determined by contribution from seismic scenario class
  - Probability of damage to co-disposed waste packages within 10,000 yr < 0.2
- Largest contribution to mean dose from ^{99}Tc
- Magnitude of mean dose determined by
  - Probability of events (seismic, igneous)
  - Diffusion of radionuclides through cracks in waste package outer barrier

Uncertainty in Total Expected Dose (post-10,000-year period)

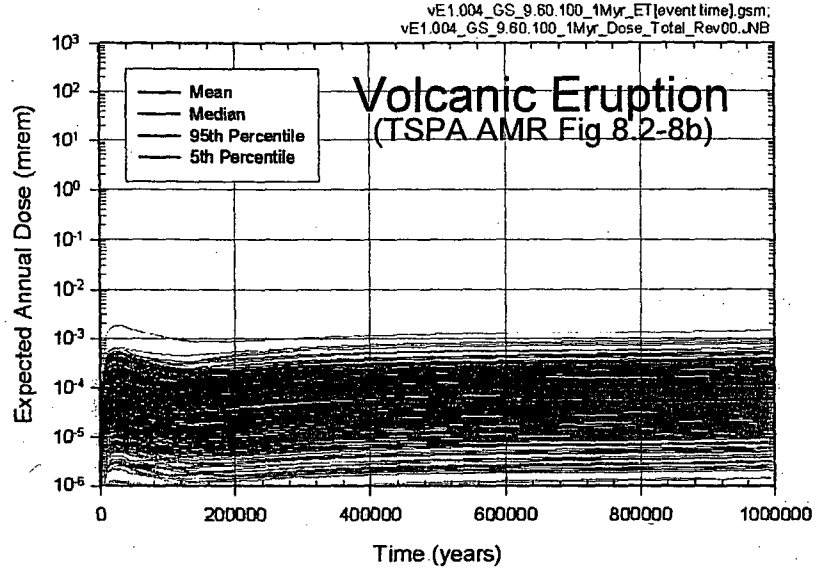


Total Mean Dose Contribution By Modeling Case

LA_v5.005_ED_003000_000.gsm; LA_v5.005_EW_006000_000.gsm ;
LA_v5.005_IG_003000_000.gsm; LA_v5.005_SM_009000_003.gsm;
LA_v5.005_SF_010800_000.gsm; vE1.004_GS_9.60.100_1Myr_ET[event time].gsm;
LA_v5.005_1Myr_Total_Dose_Mean_Contributions_Rev00.JNB



Construction of Total Dose



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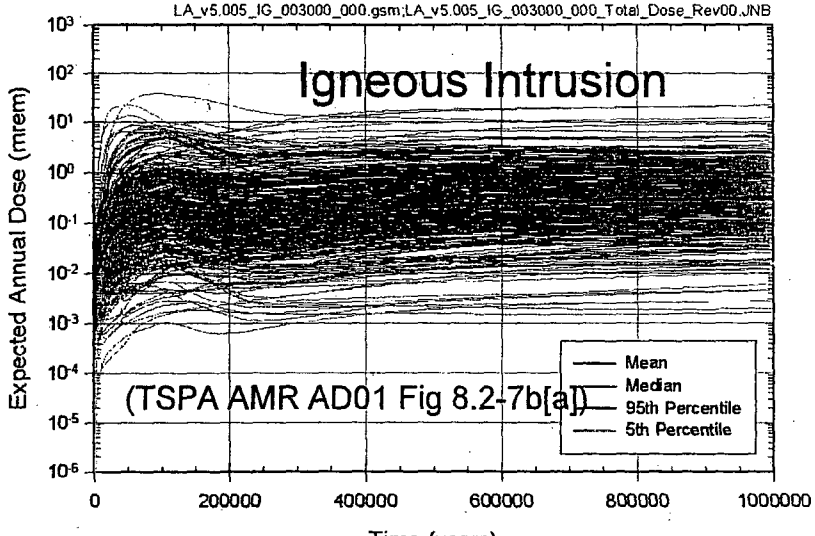

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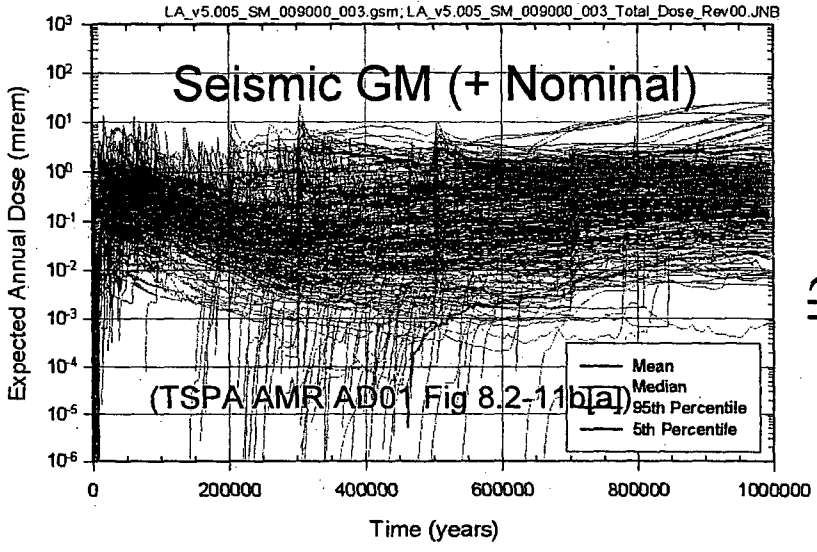

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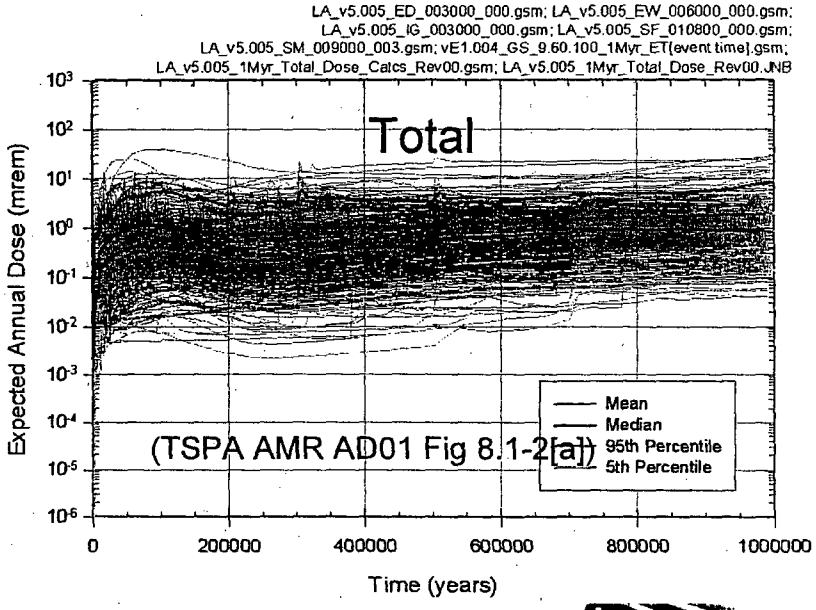
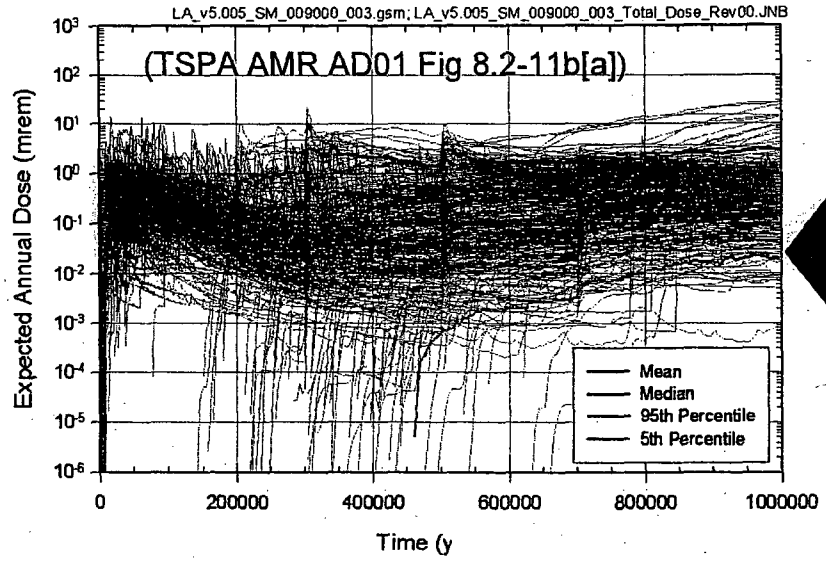


Composition of Dose from Seismic GM



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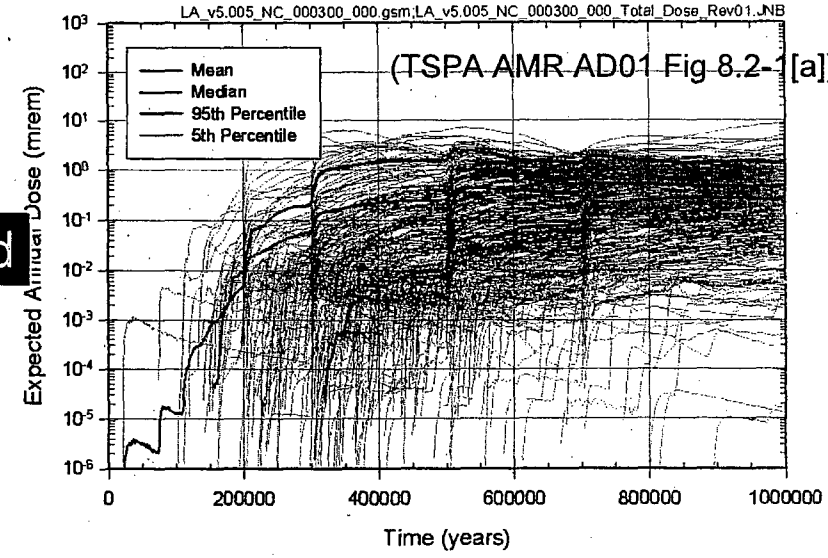
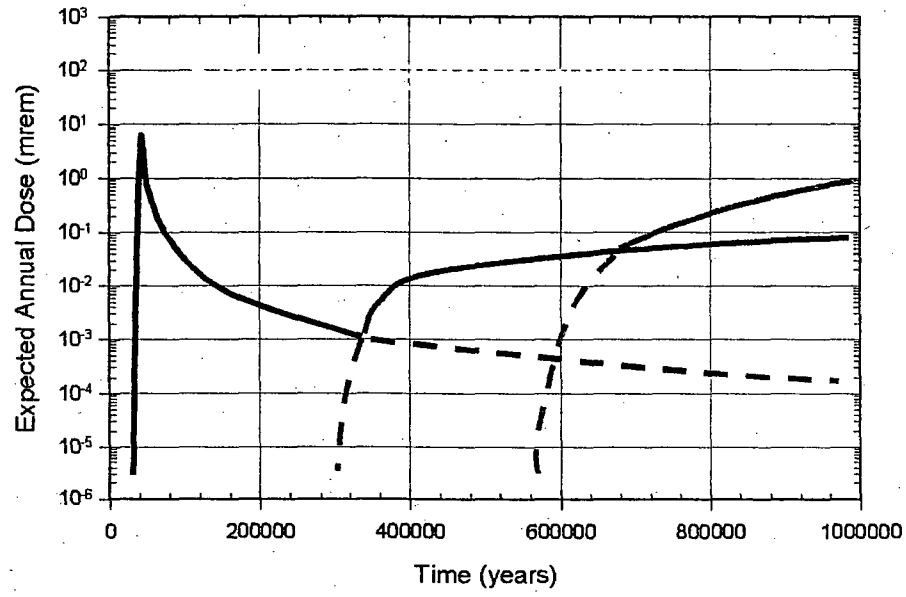
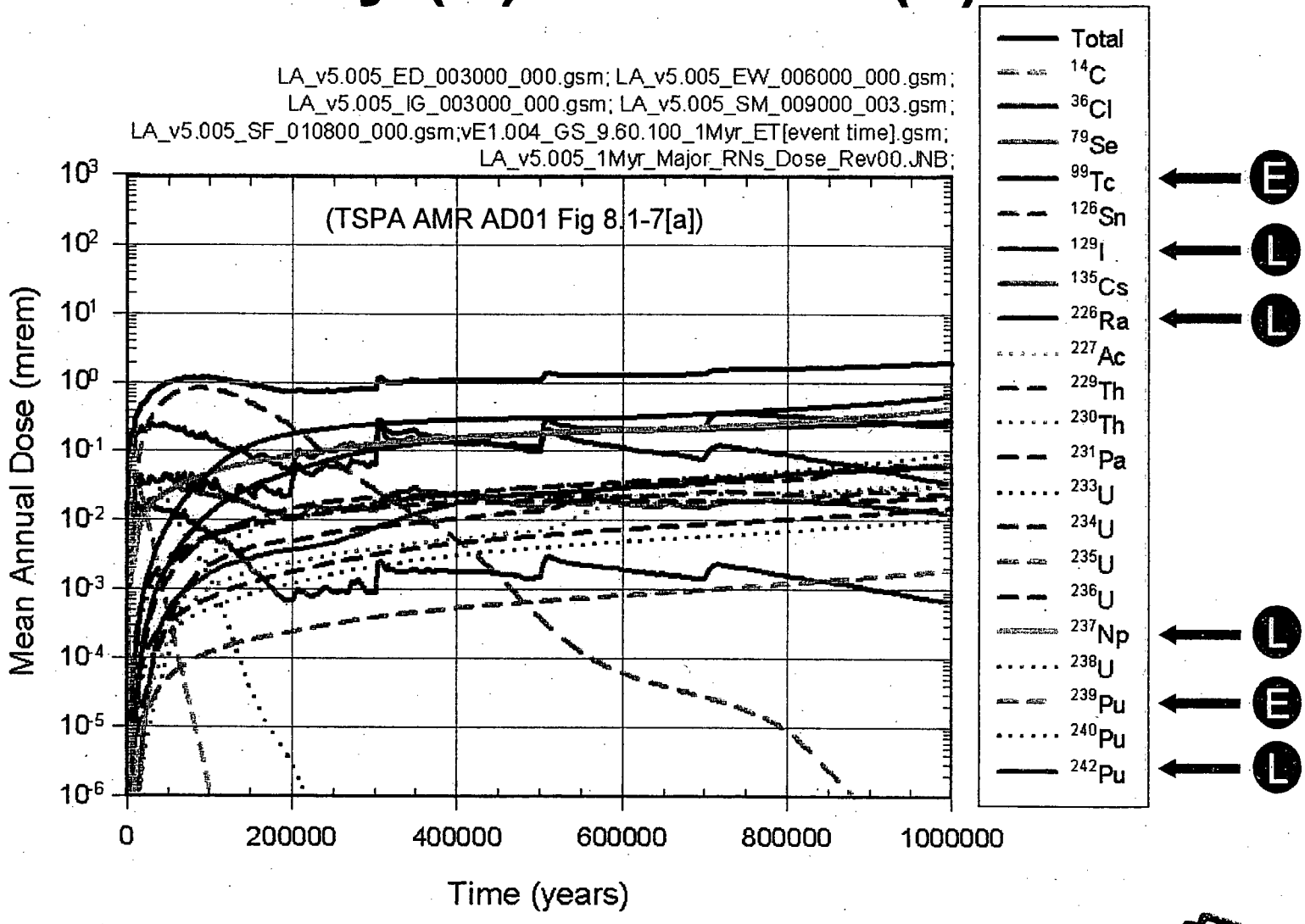


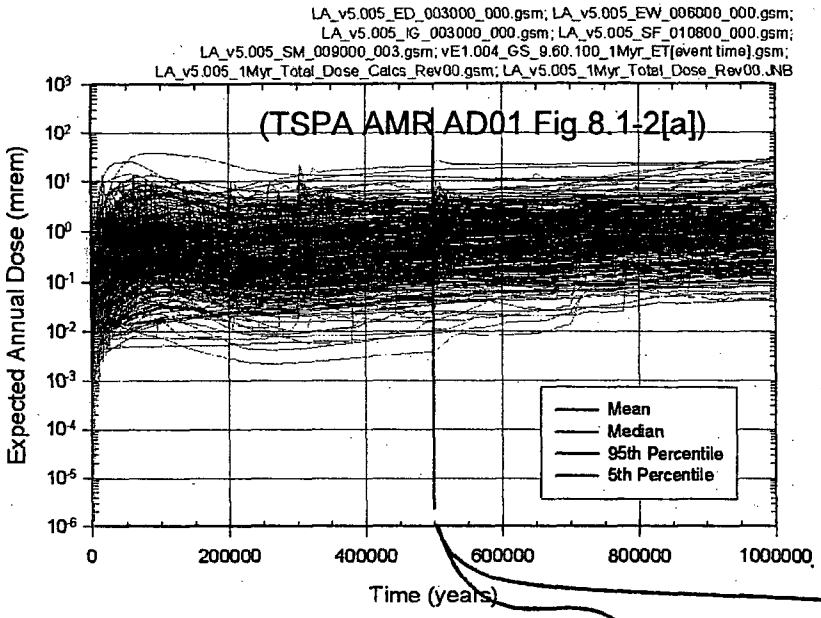


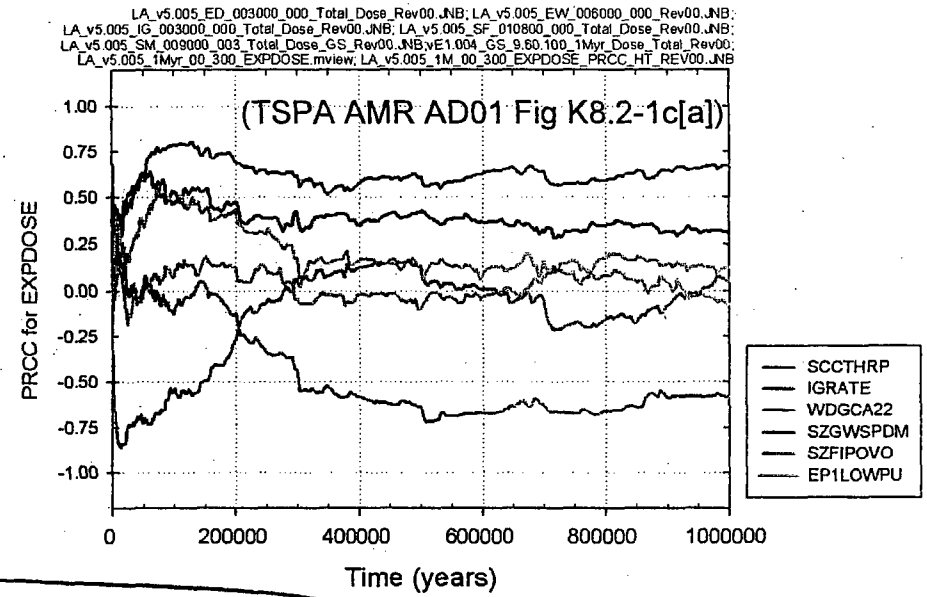
- From Seismic Damage to CDSP WP
- From SCC failure of CSNF WP
- From GC failure of both WPs (advection)

Radionuclides Important to Mean Dose Early (E) and Late (L)



Uncertainty in Total Expected Dose

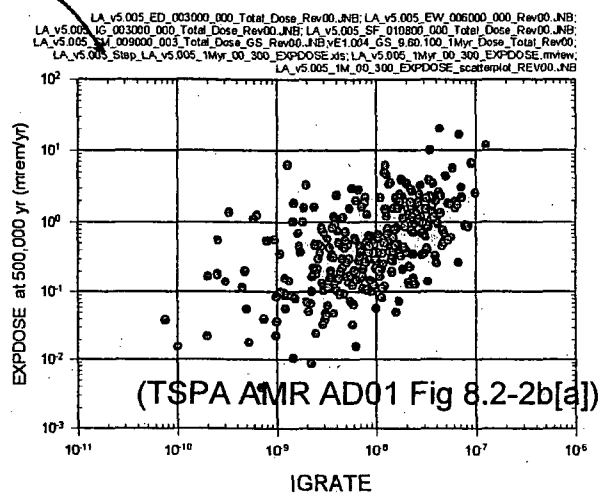


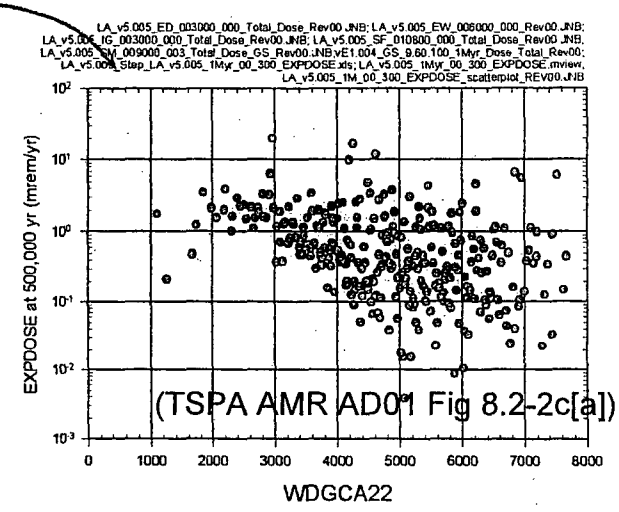


SCCTHRP – stress threshold for SCC initiation

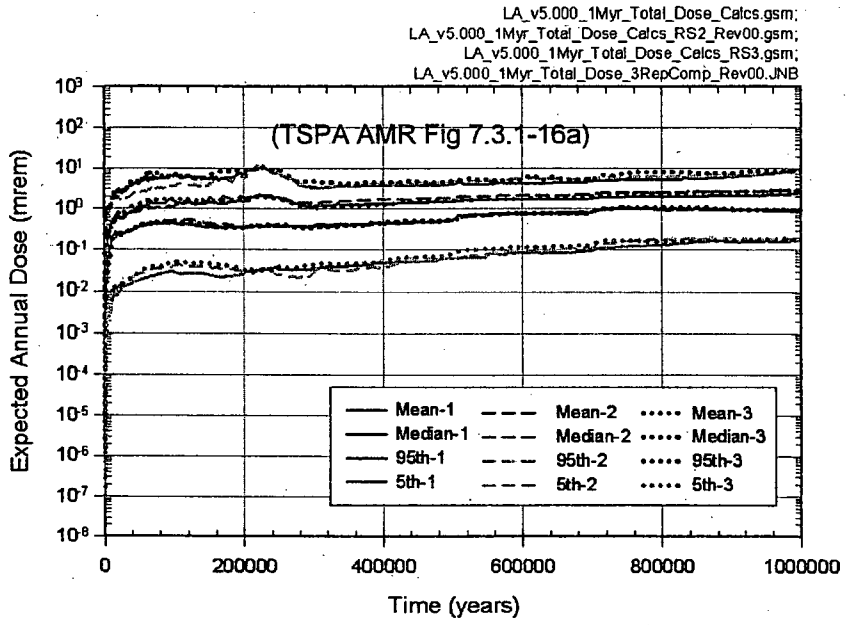
IGRATE – frequency of igneous events

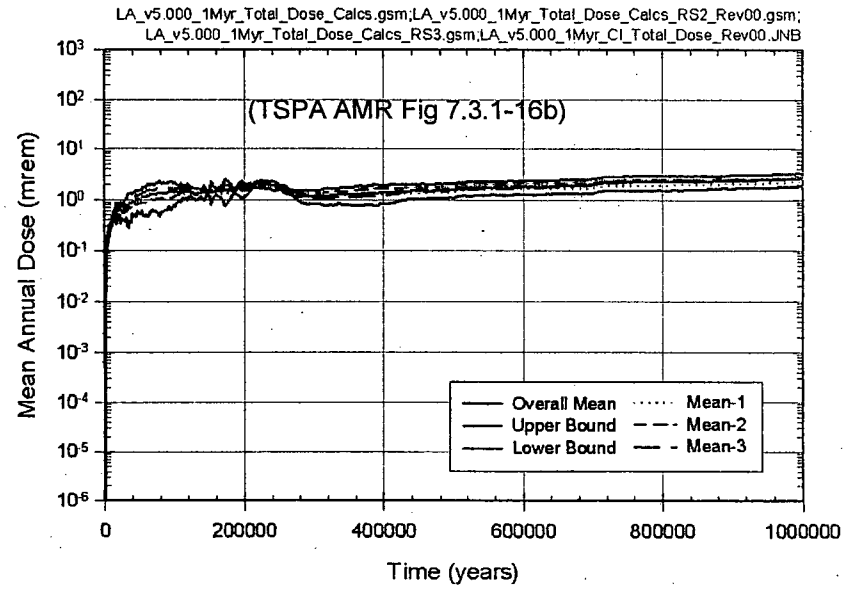
WDGCA22 – Temperature dependence in A22 corrosion rate





Stability of Total Dose





Replicated sampling demonstrates that sample size is sufficient

Confidence interval illustrates precision of estimate of total mean dose

Summary of 1 Million Year Results

- Total mean dose determined by occurrence of igneous events, seismic damage and general corrosion
- Major contributors to dose are technetium, iodine, plutonium, neptunium, radium
- Waste package outer barrier governs releases of technetium and iodine
- Chemistry governs release of plutonium from waste package

U.S. Department of Energy
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Repository Barrier Capability

Presented to:
NRC/DOE Technical Exchange on Total System Performance Assessment for Yucca Mountain

Presented by:
Robert J. MacKinnon
Sandia National Laboratories

April 03, 2008
Las Vegas, Nevada

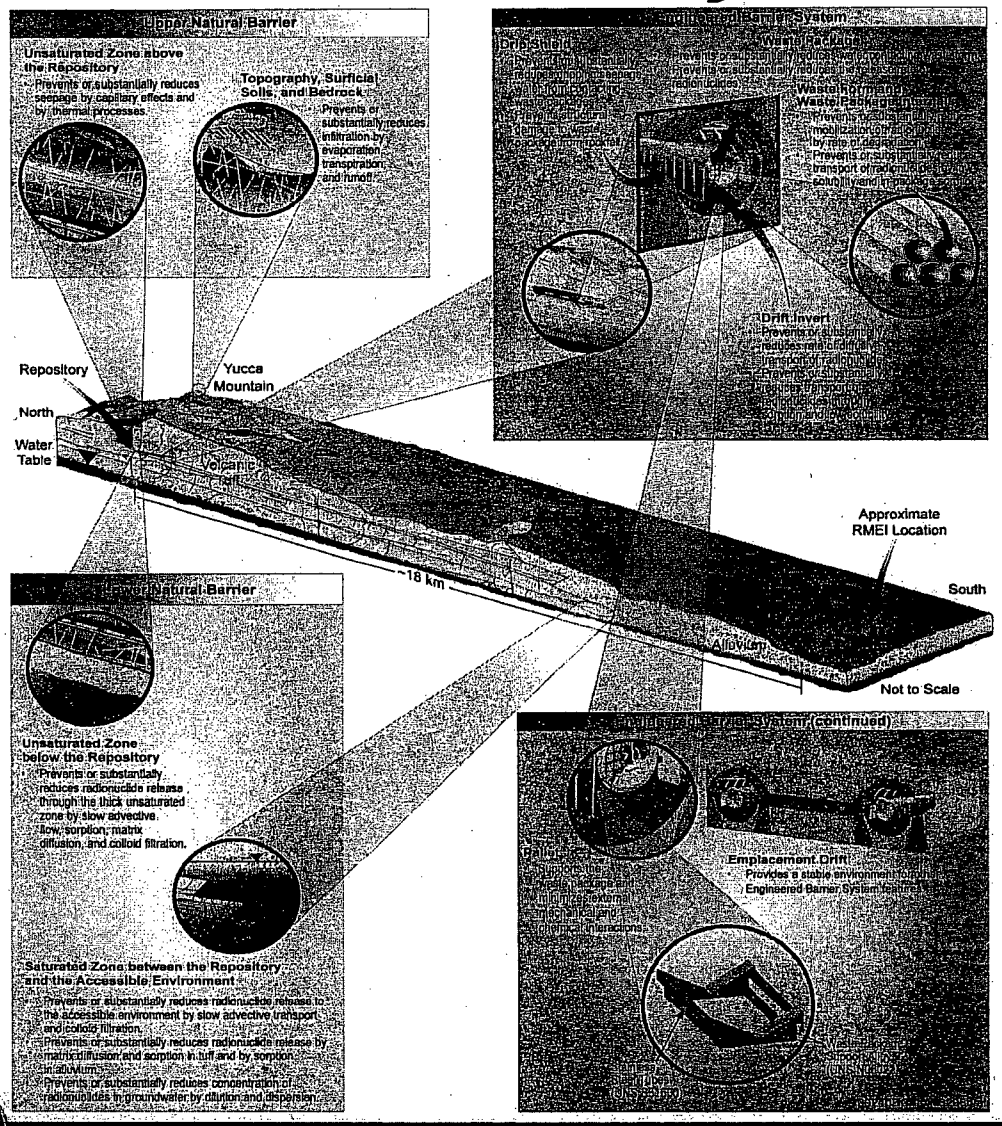
Presentation Outline

- Introduction
- Multiple barrier repository system
- Quantification of barrier capability
  - Upper Natural Barrier (UNB)
  - Engineered Barrier System (EBS)
  - Lower Natural Barrier (LNB)
- Summary
- Supporting documentation

Introduction

- The repository system is composed of natural and engineered features that function together as two natural barriers and an engineered barrier system
- A barrier is defined in 10 CFR 63.2 as any material, structure, or feature that, for a period to be determined by the NRC, prevents or substantially reduces the rate of movement of water or radionuclides from the Yucca Mountain Repository to the accessible environment, or prevents the release or substantially reduces the release rate of radionuclides from the waste
- As defined by 10 CFR 63.2, important to waste isolation (ITWI), with reference to design of the EBS and characterization of natural barriers, means those engineered and natural barriers whose function is to provide a reasonable expectation that HLW can be disposed of without exceeding the requirements of 63.113(b) & (c)

Schematic of the Multiple Barrier Repository System

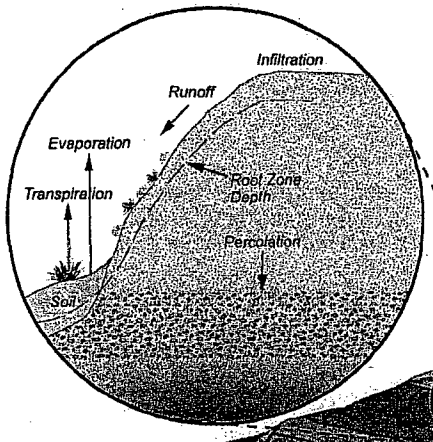


- The technical bases for the assessment of the capability of the three barriers are the same as the bases used for the compliance of the repository system with the postclosure performance assessment objectives and requirements
- Barrier capability is based on the abstraction models of processes included in the performance assessment as well as an evaluation of FEPs that have been excluded from the performance assessment

Quantification of Barrier Capability

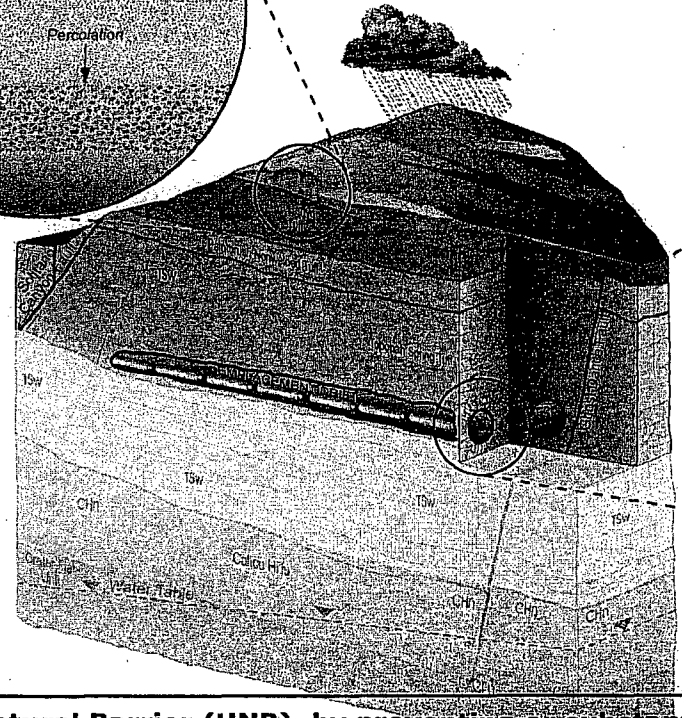
- Two modeling cases considered for demonstrating barrier capability
  - Combined nominal/early failure modeling case
    - Drip shield and waste package early failure modeling cases and the nominal modeling case are combined into one modeling case
    - Representation of repository futures in which disruptive events do not occur
    - Provides a projection of a reference capability
  - Seismic ground motion modeling case
    - Addresses barrier capability as a function of disruptive conditions
    - Important to demonstration of compliance with the regulatory standards

Upper Natural Barrier

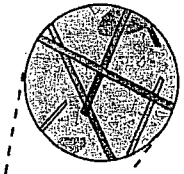


Topography and Surficial Soils

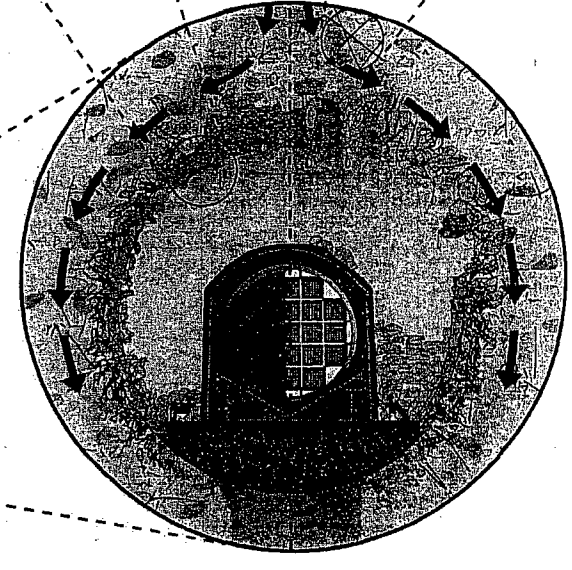
- Low precipitation
- Runoff
- Evapotranspiration
- Infiltration



Drift Surface
- Capillary Barrier
- Dripping
- Evaporation
- Roughness



Unsaturated Zone Flow
- Flow Focusing
- Percolation
- Dryout Zone



Intact Drift **Degraded Drift**

Unsaturated Zone above Repository

- Percolation
- Capillarity
- Flow Diversion around Emplacement Drifts

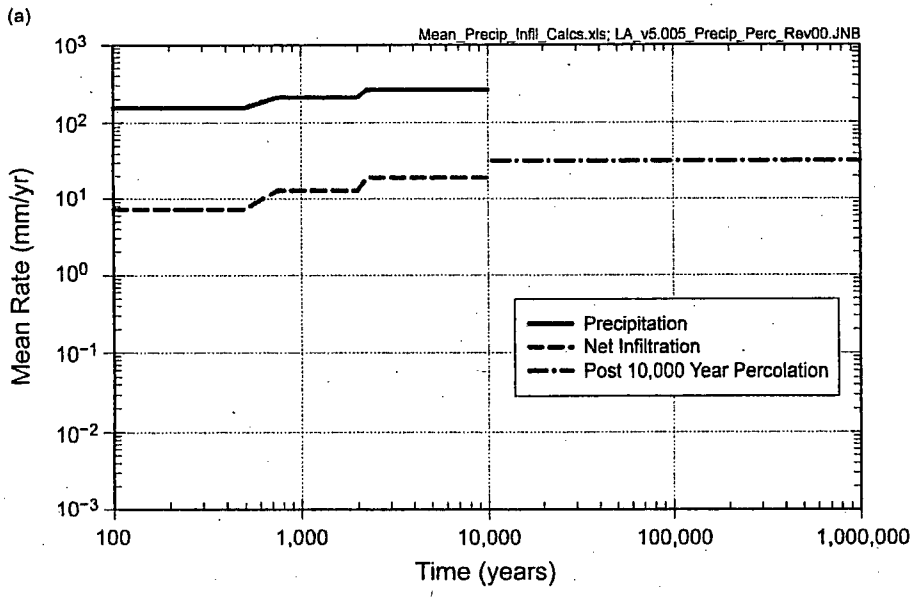
The Upper Natural Barrier (UNB), by preventing or substantially reducing the rate of movement of water into the repository, prevents or substantially reduces the rate of movement of radionuclides from the repository to the accessible environment

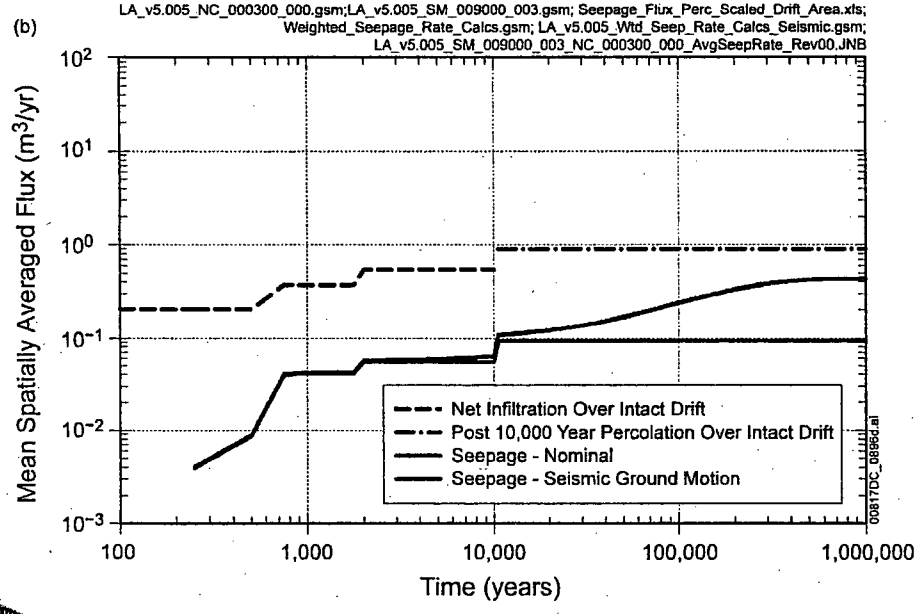
Quantification of UNB Capability

- Topography and surficial soils
  - Run-on and runoff, evaporation, and transpiration combine to divert water and permit only a small fraction of the precipitation at the site to infiltrate into the unsaturated zone (*Simulation of Net Infiltration For Present-Day And Potential Future Climates*, SNL 2008)
- Unsaturated zone above the repository
  - Damping of episodic pulses of precipitation and infiltration (*UZ Flow Models and Submodels*, SNL 2007)
  - Capillary forces in rock adjacent to emplacement drifts limit seepage into drifts (*Abstraction of Drift Seepage,* SNL 2007)
  - Elevated temperatures in the rock during thermal period limit seepage into the drifts (*Abstraction of Drift Seepage,* SNL 2007)

Quantification of UNB Capability (continued)

- Characteristics and properties of the topography and surficial soils are not expected to change in the 10,000 years after closure (YMP 1993, Topical Report YMP/92-41-TPR, Section 3.4)
- Drift collapse caused by seismic ground motion may reduce effectiveness of capillary barrier
  - Increase in seepage rates
  - Increase in seepage fraction
- Metrics: Net infiltration, drift seepage rate, seepage fraction





Key Points:

Mean Net Infiltration (I) as % of Precipitation rate:

- Ranges ~5% during present-day climate to 7% during glacial-transition climate
- ET accounts for 85 to 88% of reduction in net infiltration

Mean Drift Seepage (S) as % of ambient seepage flux (first 10K yrs)

- S ~ 2 to 11%
- Nominal & Seismic GM almost identical

Mean Drift Seepage as % of Post-10K Percolation

- Nominal, S ~ 11%
- Seismic GM, S ~ 12 to 48% (drift-degradation reduces effectiveness of capillary barrier effect)

(Ref: SNL 2008 MDL-WIS-PA-000005 REV 00 AD 01, Section 8.3.3.1.1[a])

Nominal/Early Failure Modeling Case for 10,000-year Period (Glacial-transition)

Percolation Subregion		Seepage Fraction for CSNF Waste Packages		
Subregion Index	Quantile Range	5th Percentile	Mean	95th Percentile
1	$p < 0.05$	0.0020	0.0887	0.2823
2	$0.05 \le p < 0.30$	0.0217	0.2308	0.5780
3	$0.30 \le p < 0.70$	0.0455	0.3294	0.7439
4	$0.70 \le p < 0.95$	0.0431	0.3848	0.7998
5	$p \ge 0.95$	0.0870	0.4666	0.8386
Repository Average		0.0424	0.3134	0.6950

Nominal/Early Failure Modeling Case for Post-10,000-year Period

Percolation Subregion		Seepage Fraction for CSNF Waste Packages		
Subregion Index	Quantile Range	5th Percentile	Mean	95th Percentile
1	$p < 0.05$	0.0082	0.1251	0.3121
2	$0.05 \le p < 0.30$	0.0617	0.3402	0.6555
3	$0.30 \le p < 0.70$	0.0949	0.4369	0.7943
4	$0.70 \le p < 0.95$	0.0606	0.4364	0.8439
5	$p \ge 0.95$	0.0934	0.4944	0.8802
Repository Average		0.0784	0.3999	0.7449

Seepage Fractions* (SF)

Key Points:

- Nominal & Seismic GM SF identical for 10K yrs (on average 70% of WPs experience non-seep environments for 10K yrs)
- Nominal & Seismic GM SF increase with drift degradation for post-10K

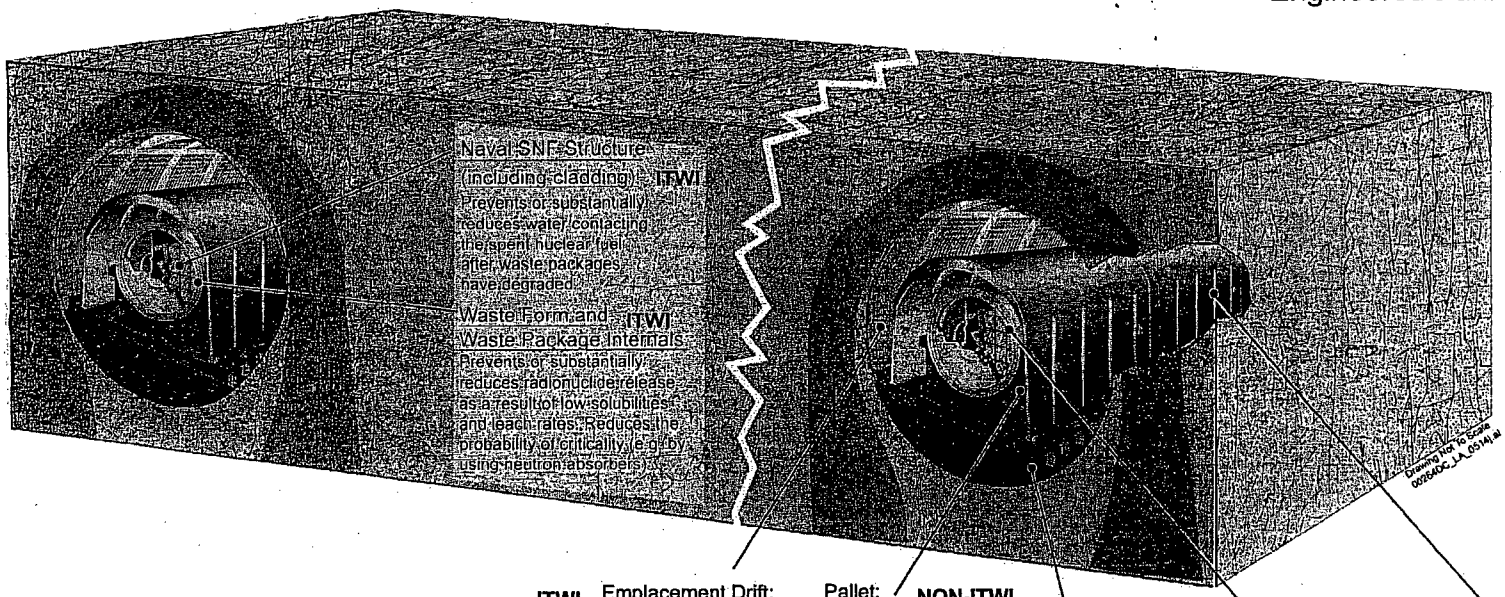
(*Defined as ratio WPs experiencing seepage to all WPs in repository)

Seismic Ground Motion Modeling Case for Post-10,000-year Period

Percolation Subregion		Seepage Fraction for CSNF Waste Packages		
Subregion Index	Quantile Range	5th Percentile	Mean	95th Percentile
1	$p < 0.05$	0.3231	0.4673	0.6923
2	$0.05 \le p < 0.30$	0.3089	0.6491	0.9173
3	$0.30 \le p < 0.70$	0.3114	0.7193	0.975
4	$0.70 \le p < 0.95$	0.226	0.7041	0.9803
5	$p \ge 0.95$	0.3107	0.7518	0.9869
Repository Average		0.2912	0.6870	0.9465

Engineered Barrier System

Engineered Barrier System



ITWI Emplacement Drift: Provides a stable environment for other Engineered Barrier System features

Pallet: **NON-ITWI** Supports the waste package and minimizes external mechanical and chemical interactions

Invert below the Waste Packages: **NON-ITWI** Reduces transport of radionuclides out of the Engineered Barrier System

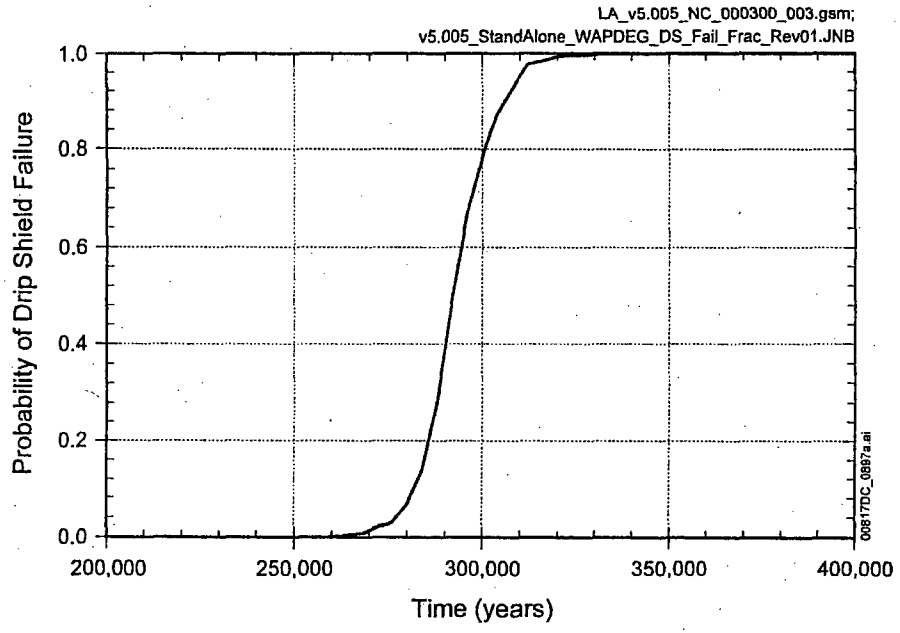
Titanium Drip Shield above the Waste Packages: **ITWI** Prevents or substantially reduces water from contacting the waste package

Waste Package: **ITWI** Prevents or substantially reduces water from contacting the waste form

The Engineered Barrier System (EBS) prevents or substantially reduces the rate of movement of water to the waste, prevents or substantially reduces the release rate of radionuclides from the waste, and prevents or substantially reduces the rate of movement of radionuclides from the repository to the accessible environment.

Quantification of EBS Capability: Drip Shield

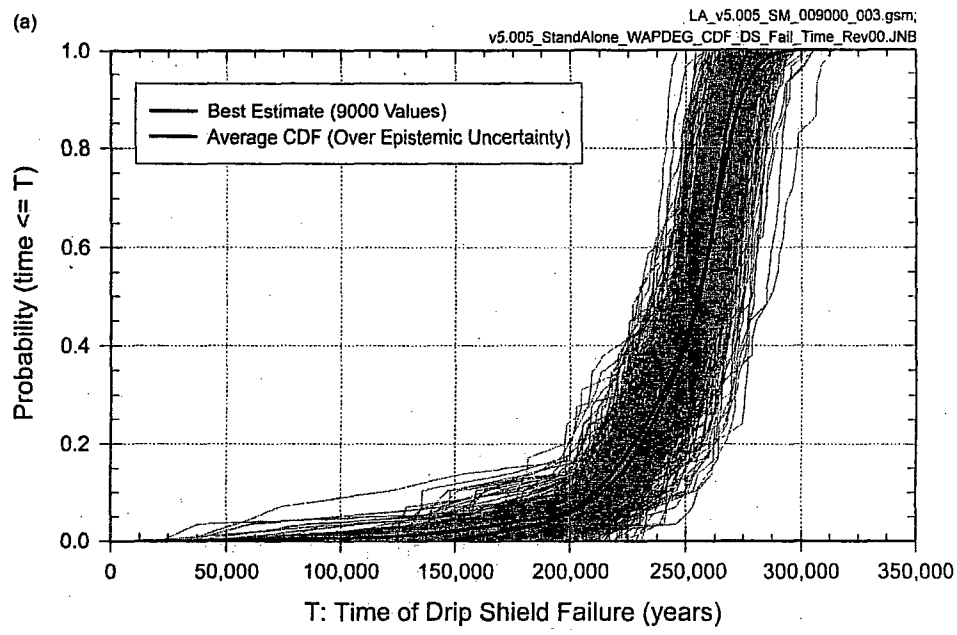
Nominal/Early Failure



Key Points:

- **DS failure under nominal conditions by general corrosion (GC) of Titanium Grade 7 plate**
- **Failure times from about 270,000 to 340,000 yrs**

Seismic Ground Motion



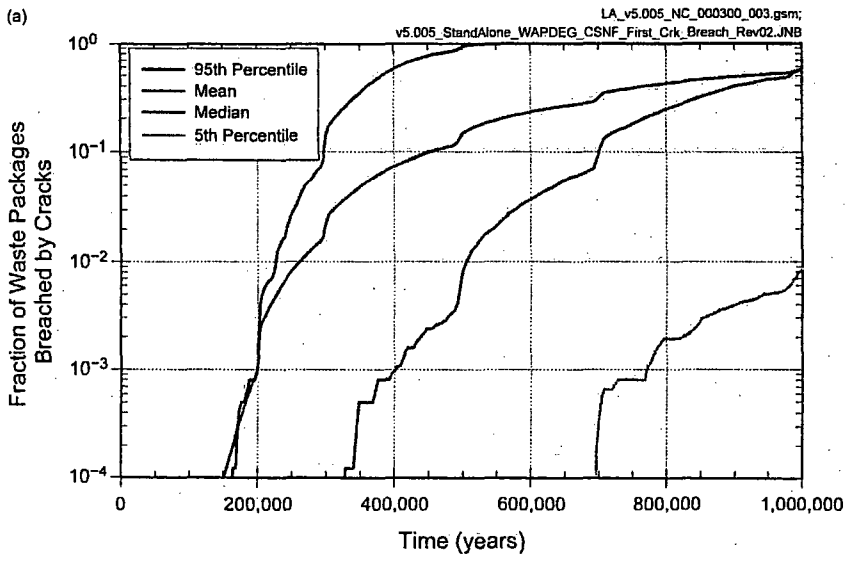
Key Points:

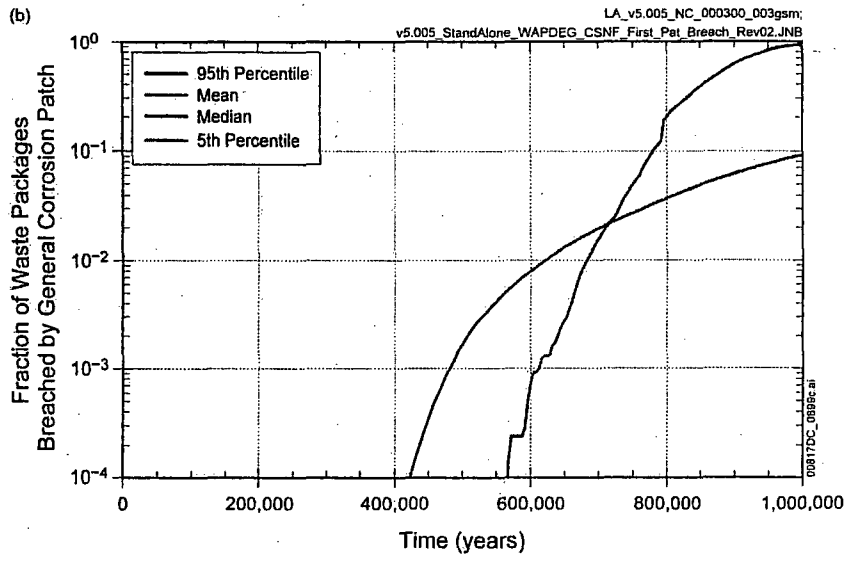
- **DS failure under seismic conditions by rubble accumulation and plate thinning by GC**
- **Probability of DS failure before 100,000 years is 0.0055**

(Note: The TSPA model does not include spatial variability in drip shield failure)

Quantification of EBS Capability: Waste Package

CSNF WP Breach for Nominal Conditions





Stress Corrosion Cracking
(of closure-lid welds)

Key Points:

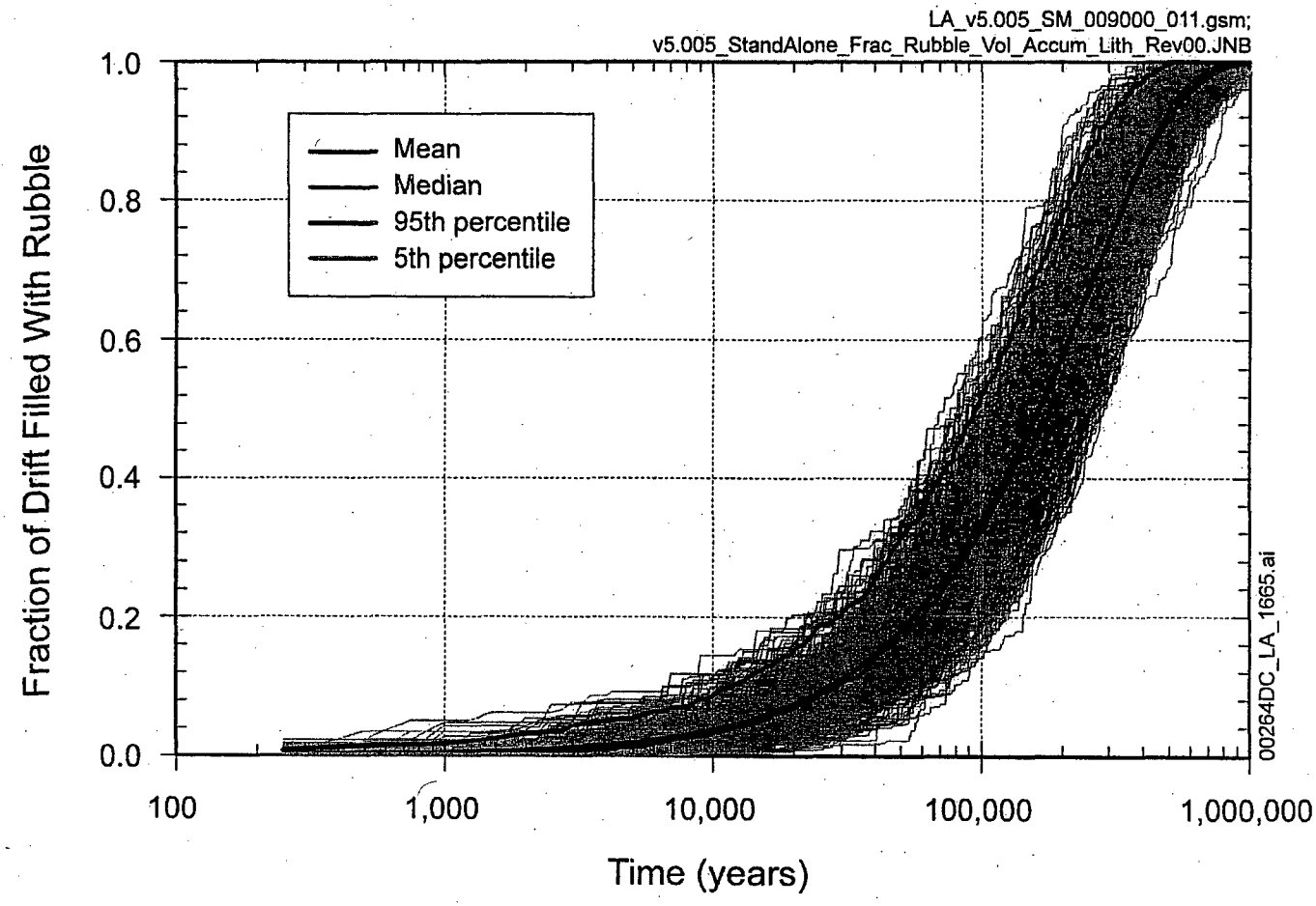
- **SCC breaches of CSNF WPs becomes more likely to occur after 170,000 yrs (based on 95th percentile curve)**
- **By 10^6 yrs, mean fraction of CSNF WPs breached by SCC is ~ 54%**

General Corrosion
(of Alloy 22 outer barrier)

Key Points:

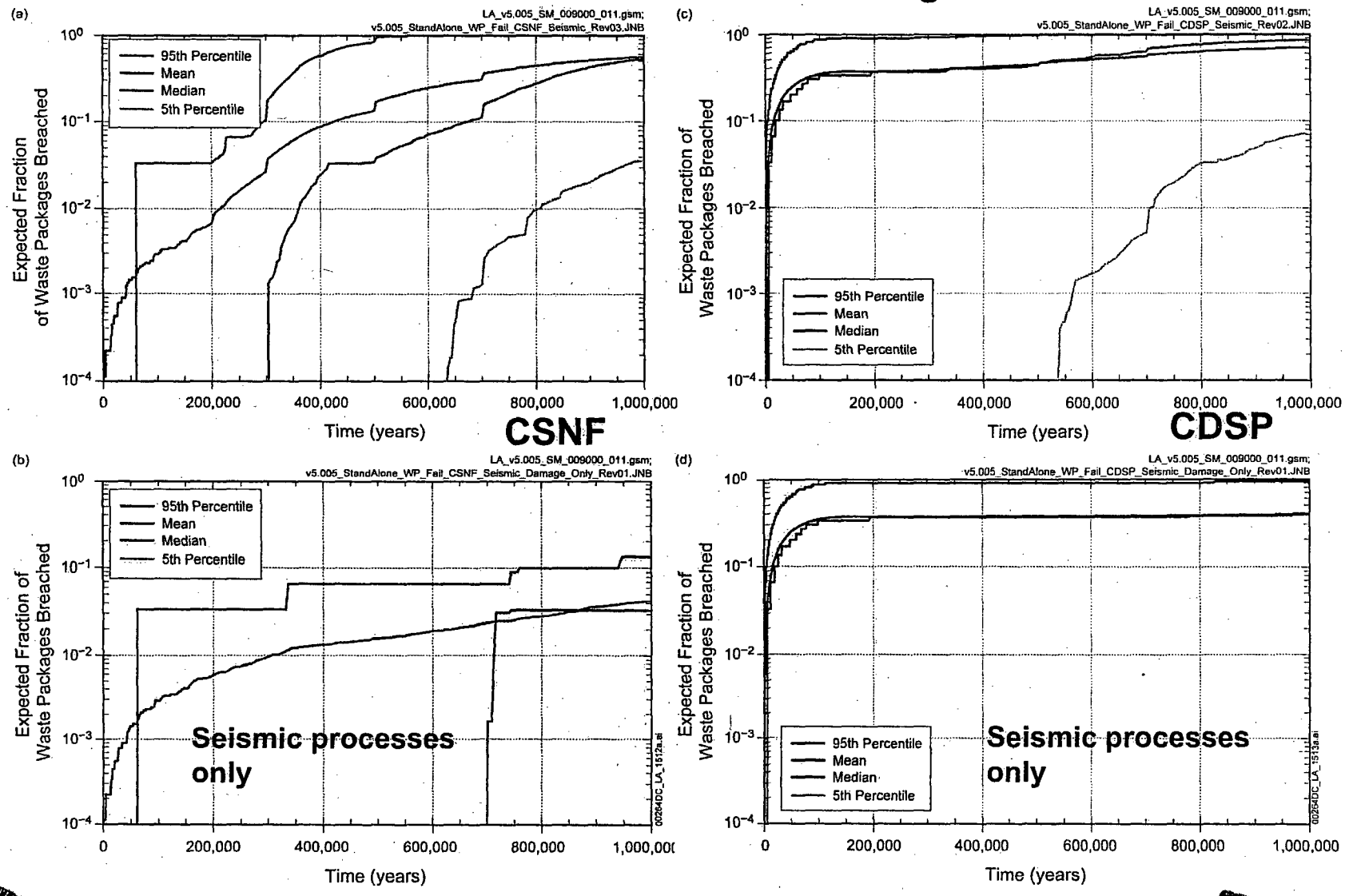
- **GC patch penetrations of CSNF WPs becomes more likely after 560,000 yrs (based on 95th percentile curve)**
- **By 10^6 yrs, mean fraction of WP penetrated by GC is ~ 9%**

Lithophysal Rubble Accumulation

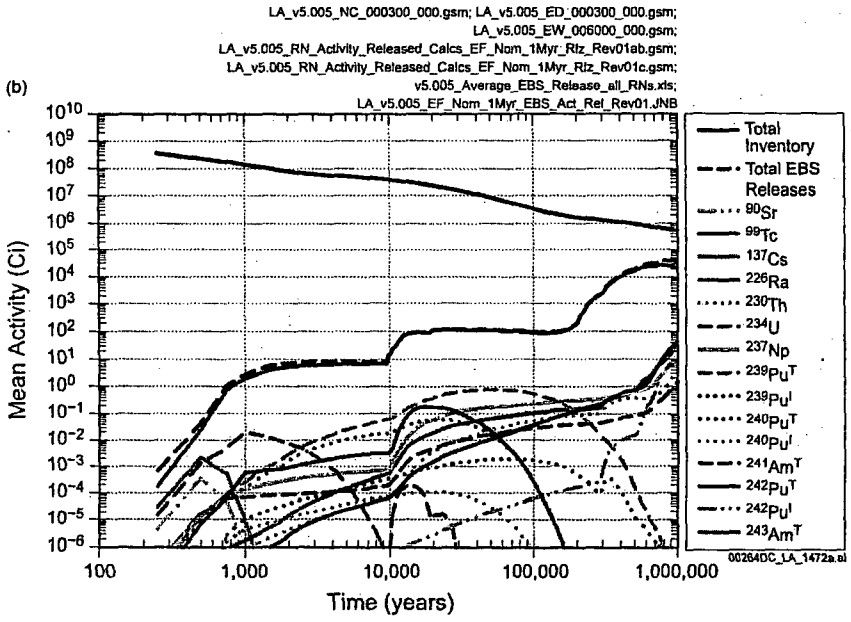


Quantification of EBS Capability: Waste Package

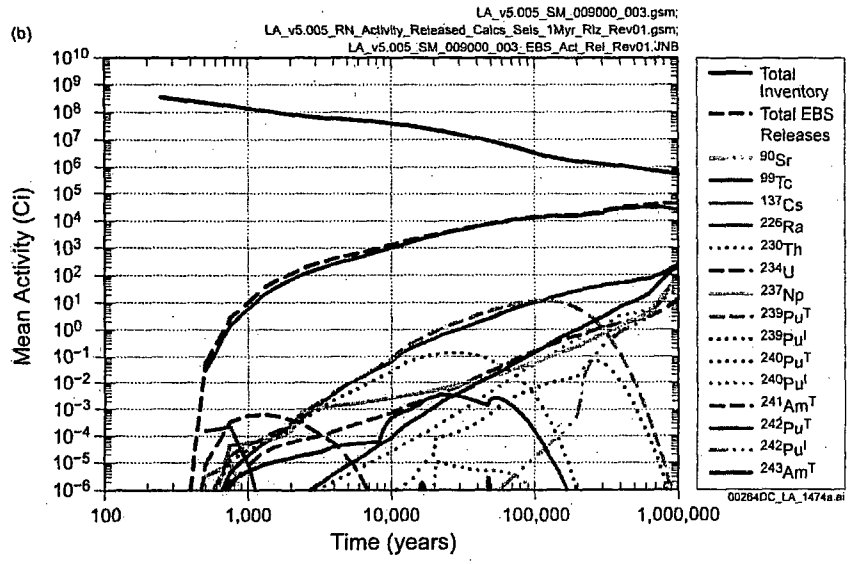
Seismic Ground Motion Modeling Case



Mean Activity Released from the EBS



Combined Nominal/EF



Seismic Ground Motion

Key Points:

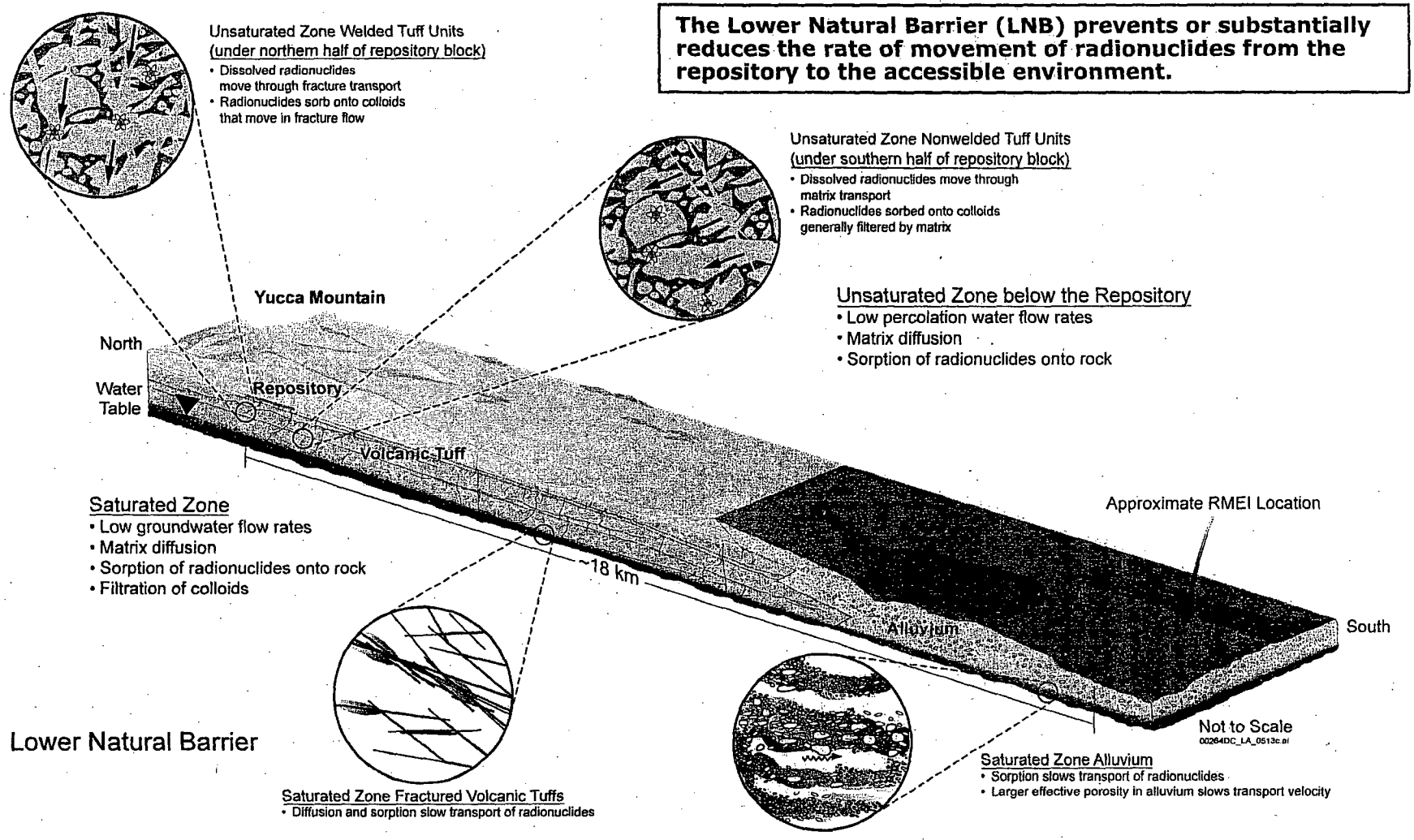
- **At 10^4 yrs, mean activity released from EBS is less than 4 x 10^{-5} % of the inventory**
- **By 10^6 yrs, mean activity released from EBS is about 7% of total inventory**

Key Points:

- **At 10^4 yrs, mean activity released from EBS is about a factor of 100 higher than Nominal/EF**
- **By 10^6 yrs, mean activity released from EBS is about the same as Nominal/EF**

Lower Natural Barrier

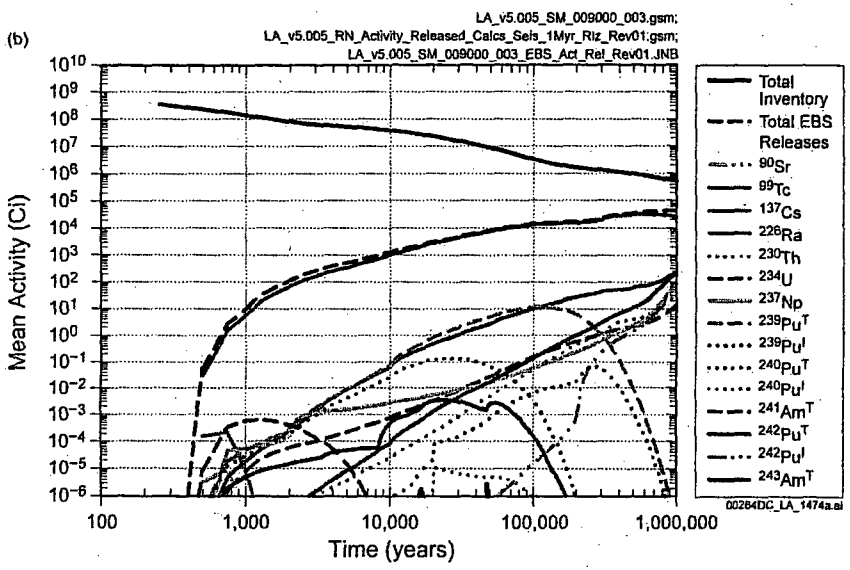
The Lower Natural Barrier (LNB) prevents or substantially reduces the rate of movement of radionuclides from the repository to the accessible environment.



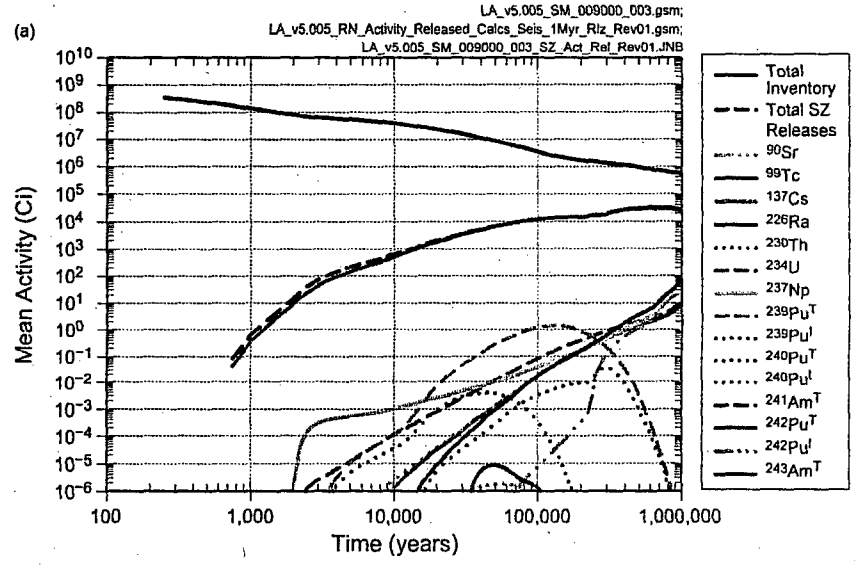
Lower Natural Barrier

Mean Activity Released for the Seismic Ground Motion Modeling Case

EBS to UZ



SZ to Accessible Environment



Key Points:

- At 10^4 yrs, total mean activity released from SZ is about 50% of activity released from EBS
- By 10^6 yrs, total mean activity released from SZ is about 5 % of total inventory (vs 7% from EBS)
- Mean activity releases from SZ dominated by ^{99}Tc

- ^{90}Sr & ^{137}Cs from EBS confined to LNB
- Reduction in activity released from LNB (10^4 yrs and 10^6 yrs): ^{241}Am (100%), ^{239}Pu (99% and 90%), ^{242}Pu (99% and 66%), ^{237}Np (78% and 23%), ^{234}U (89% and 32%)
- Mean activity releases of ^{230}Th & ^{226}Ra from SZ determined by precursor ^{234}U release

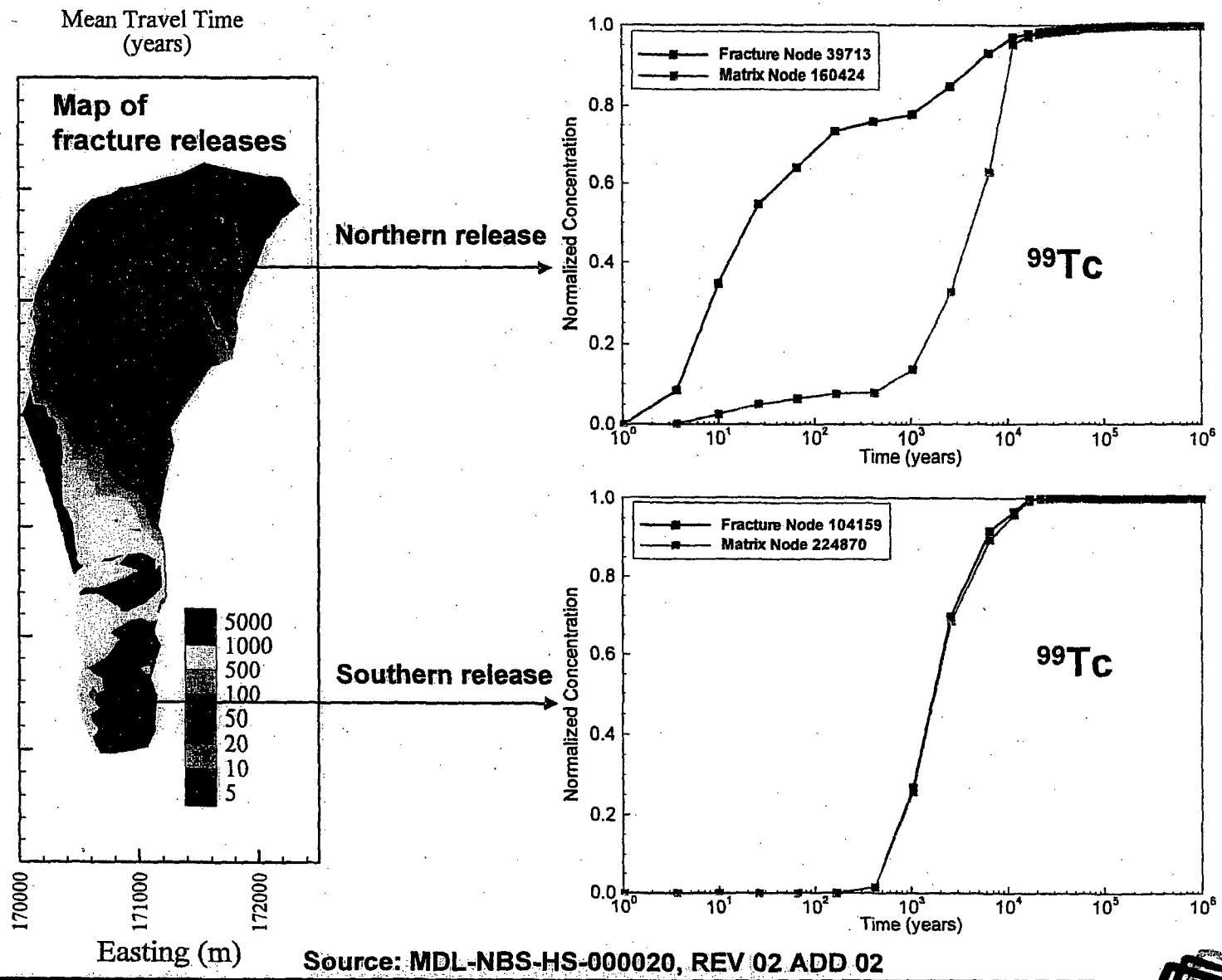
Summary

- The Yucca Mountain repository system is comprised of three barriers, the UNB, EBS, and LNB
- These barriers have the functions of (1) preventing or substantially reducing the rate of movement of water to the waste, (2) preventing or substantially reducing the release rate of radionuclides from the waste, and (3) preventing or substantially reducing the rate of movement of radionuclides from the repository to the accessible environment
- Barriers include multiple features that have processes and events that may act on or within the features to affect the capability of the performance of the barrier
- Rationale and basis for ITWI classification and qualitative demonstration of barrier capability is provided in *Postclosure Nuclear Safety Design Bases* (SNL 2008)
- A complete evaluation of all potential FEPs, including the technical basis for their inclusion or exclusion in the performance assessment, is presented in *Features, Events, and Processes for the Total System Performance Assessment: Analyses* (SNL 2008)

Supporting Documentation

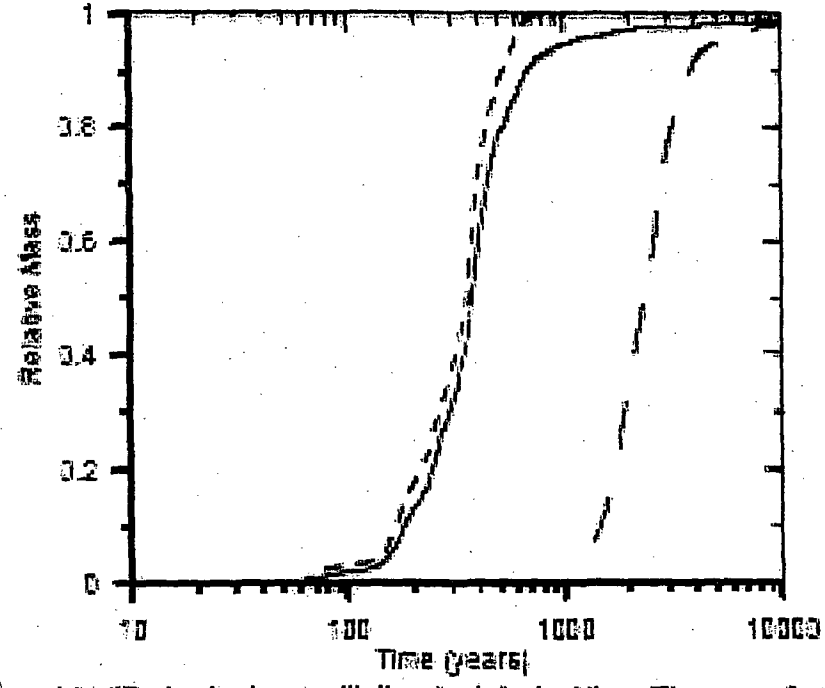
- **Postclosure Nuclear Safety Design Bases (SNL 2008) provides**
  - Rationale and basis for ITWI classification
  - Provides qualitative description of barrier capability
- **Total System Performance Assessment Model / Analysis for the License Application (SNL 2008, Section 8.3[a])**
  - Provides quantitative assessment of barrier capability
- **Technical bases for barrier capability are contained in**
  - *Features, Events, and Processes for the Total System Performance Assessment: Analyses* (SNL 2008)
  - Performance Assessment analysis and modeling reports
- **All barrier capability identified as important to waste isolation is included in the TSPA model**

Fracture vs. Matrix Releases



Source: MDL-NBS-HS-000020, REV 02 ADD 02

Mass Breakthrough Curves at 18-km Distance Showing Sensitivity to Matrix Diffusion for a Nonsorbing Radionuclide



NOTE: The case of no matrix diffusion is shown with the short-dashed line. The case of maximum matrix diffusion is shown with the long-dashed line. The case for which flowing interval spacing is set to its 95th percentile value (79.4 m) is shown with the solid line. Mass breakthrough curves are for present climate and do not include radionuclide decay.

MDL-NBS-HS-000021 REV 03 ADD 02 , Figure 6-3

Summary of Simulated Transport Times in the SZ Under Glacial-Transition Climatic Conditions

Species	Range of Median Transport Time (years)	Median Transport Time Among All Realizations (years)
Carbon Technetium Iodine	10 – 22190	230
Reversible Colloids: Americium Thorium Protactinium	1,000 - >1,000,000	>1,000,000
Reversible Colloids: Cesium	42,000 to >1,000,000	>1,000,000
Reversible Colloids: Plutonium	3,000 to >1,000,000	95,000
Neptunium	100 to 455,300	3,700
Irreversible Colloids: Plutonium Americium	100 to 501,900	4,500
Radium	18,000 to >1,000,000	731,000
Strontium	9,000 to >1,000,000	286,000
Uranium	200 –to 931,200	8,900
Fast Fraction of Irreversible Colloids: Plutonium Americium	10 to 1,790	60
Selenium	200 to >1,000,000	14,900
Reversible Colloids: Tin	3,000 to >1,000,000	>1,000,000
MDL-NBS-HS-000021 REV 03 ADD 02 , Table 6-10[a].		

U.S. Department of Energy
Office of Civilian Radioactive Waste Management

www.ocrwm.doe.gov

Total System Performance Assessment Model Support and Confidence

Presented to:
NRC/DOE Technical Exchange on Total System Performance Assessment for Yucca Mountain

Presented by:
S. David Sevougian
Sandia National Laboratories

April 03, 2008
Las Vegas, Nevada

Presentation Outline

- Regulatory drivers for TSPA model development
- TSPA Model and Code Verification, Validation, and Confidence-Building
  - TSPA Model Information Flow and Data Transfer
  - During-Development Model Validation Activities
    - Verification of inputs and software
    - Model stability testing: statistical stability, temporal stability, spatial stability
    - Uncertainty characterization reviews
    - Surrogate waste form analyses for DOE-owned and naval SNF
  - Post-Development Model Validation Activities
    - Corroboration of abstraction models with results of process-level models
    - Corroboration with auxiliary analyses
    - Corroboration with natural analogue information
    - Technical review

Links to 10 CFR 63 and NUREG-1804

- **Proposed 10 CFR 63.114. Requirements for Performance Assessment**
  - 10 CFR 63.114(a)(7). "Provide the technical basis for the models used to represent the 10,000 years after disposal...such as comparisons made with outputs of detailed process-level models..."
- **NUREG-1804, Section 2.2.1.4.1.3 Acceptance Criterion 3: "The Total System Performance Assessment Code Provides a Credible Representation of Repository Performance"**
  - (1) Assumptions made within the total system performance assessment code are consistent among different modules of the code. The use of assumptions and parameter values that differ among modules of the code is adequately documented
  - (2) The total system performance assessment code is properly verified, such that there is confidence that the code is modeling the physical processes in the repository system in the manner that was intended. The transfer of data between modules of the code is conducted properly
  - (3) The estimate of the uncertainty in the performance assessment results is consistent with the model and parameter uncertainty; and
  - (4) The total system performance assessment sampling method ensures that sampled parameters have been sampled across their ranges of uncertainty

TSPA Model and Code Verification, Validation, and Confidence-Building, (including Proper Data Transfer)

[Acceptance Criterion 3(2) of NUREG-1804, Section 2.2.1.4.1.3]

Model Validation Approach

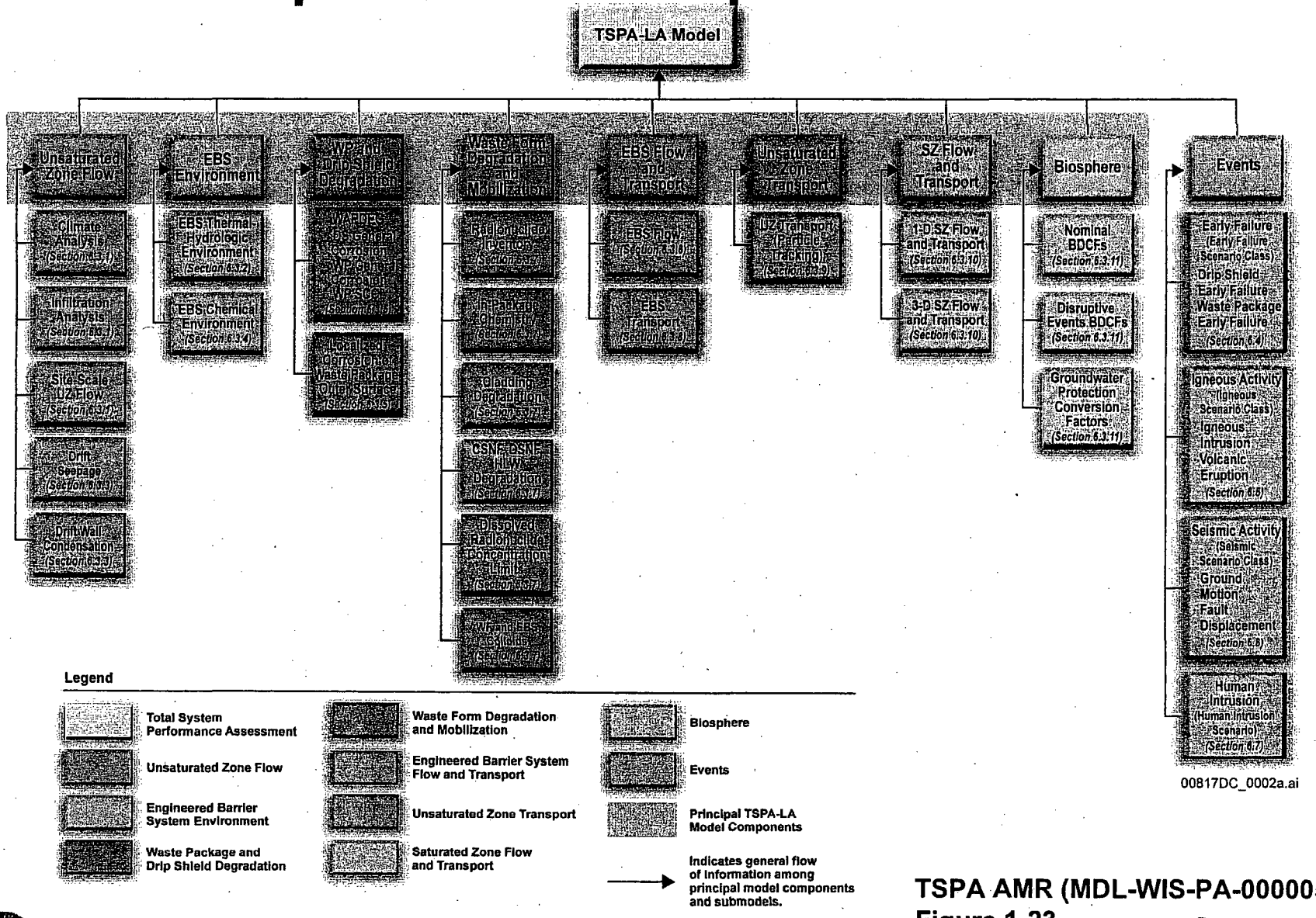
- **During-Development Confidence-Building Activities**
  - Verification of inputs, software, submodel implementation, and submodel coupling
  - Model stability testing: statistical stability, numerical accuracy, temporal stability, spatial stability
  - Uncertainty characterization reviews
  - Surrogate waste form analyses for DOE-owned and naval SNF
- **Post-development Confidence-Building Activities**
  - Corroboration of abstraction model results with the results of process-level models
  - Corroboration with auxiliary analyses
    - Deterministic single realization analyses
    - Comparison of TSPA Model results to Simplified TSPA Analysis
    - Comparison of TSPA Model results to EPRI PA results
    - Performance Margin Analysis (PMA): remove key conservatisms
  - Corroboration with natural analogue information
  - Technical review

During-Development Model Validation Activities

During-Development Model Validation Activities

- Computer code and input verification
  - Verify GoldSim & EXDOC_LA software and Dynamically Linked Libraries (DLLs)
    - Qualification of Software, IM-PRO-004
    - Supplemental verification tests are performed on the DLLs within the TSPA model framework
  - Verify input parameters
    - Input parameter values in the TSPA Input Parameter Database are verified against the source information in a DTN or AMR
  - Verify submodels, model components and coupling among submodels and model components
    - When applied in the TSPA model, specified inputs produce expected results

TSPA Principal Model Components & Submodels

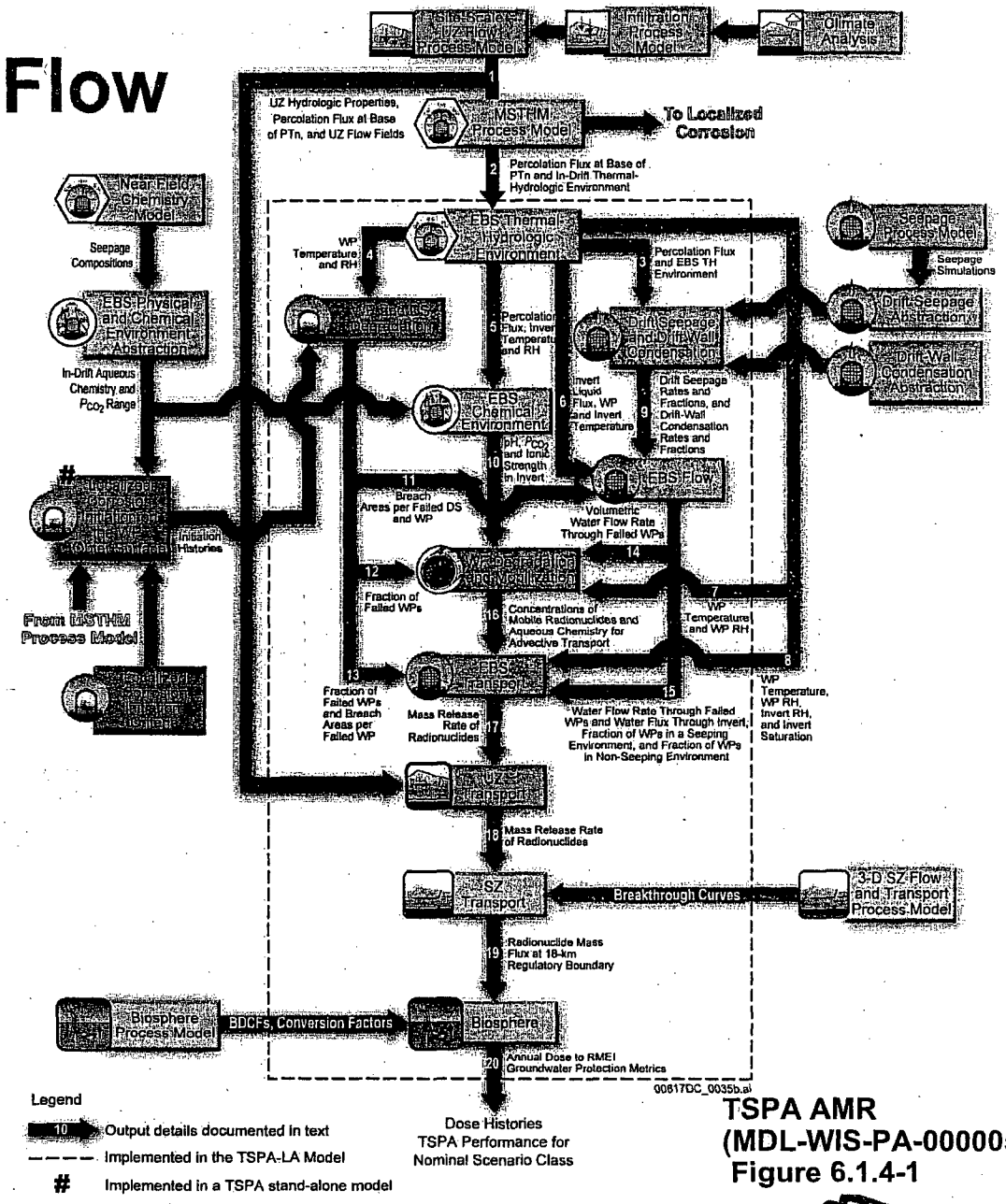


00817DC_0002a.ai

TSPA AMR (MDL-WIS-PA-000005)
Figure 1-23

TSPA Information Flow

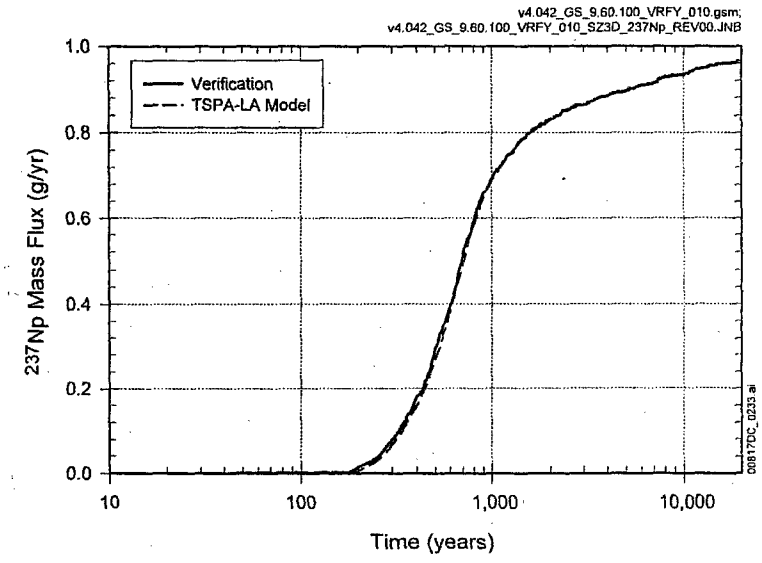
- Nominal scenario class
- Shows primary types of information passed from process models to TSPA abstractions, and among TSPA abstractions and submodels
- Other diagrams are applicable to early failure, seismic, and igneous scenario classes
- TSPA AMR Sections 6.1.4 and 6.3.X



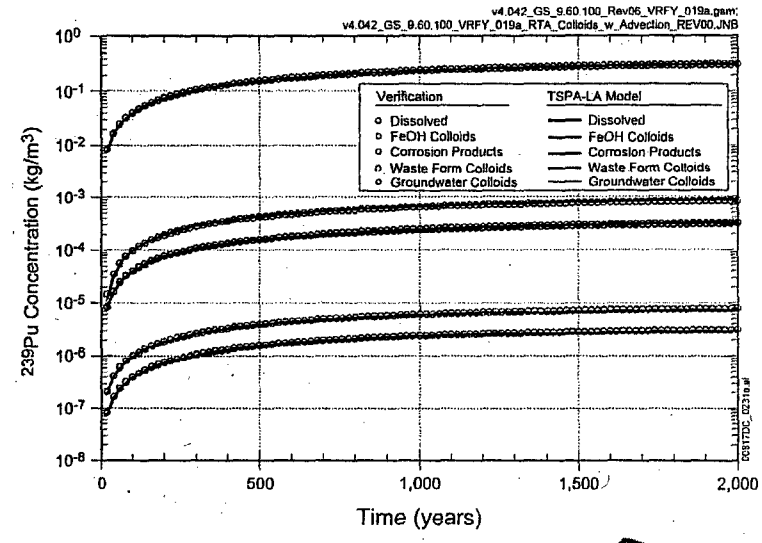
TSPA AMR (MDL-WIS-PA-000005) Figure 6.1.4-1

Examples of Verification

- **DLL Verification: Comparison of the ^{237}Np breakthrough curve generated by the SZ_Convolute DLL in the TSPA model with the DTN source data**



- **Verification of the EBS Transport Submodel: Comparison of ^{239}Pu concentrations generated by the TSPA model with those generated by an Excel spreadsheet (as provided in Appendix B of ANL-WIS-PA-000001, the EBS RTA model report)**



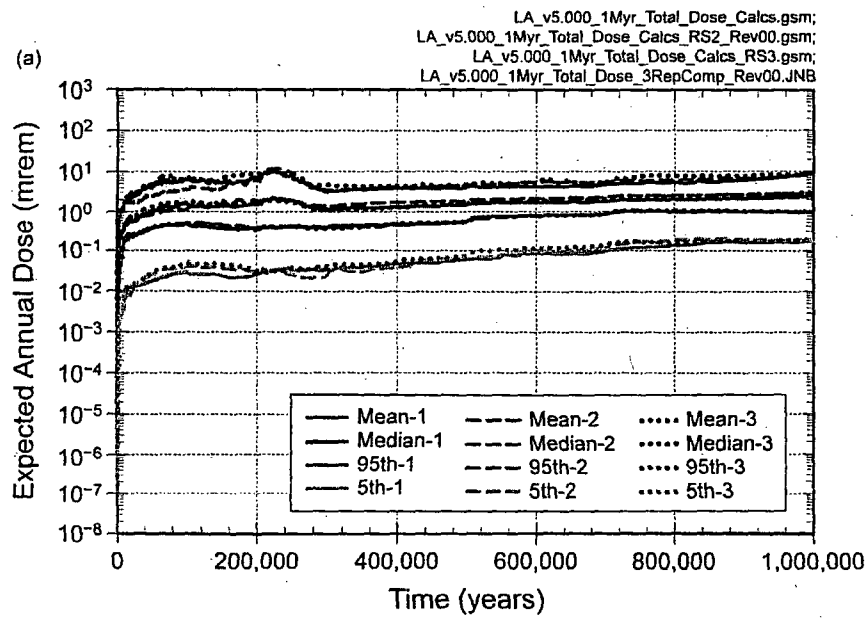
Illustrative figures from TSPA AMR (MDL-WIS-PA-000005) Figures 7.2-12 and 7.2-9

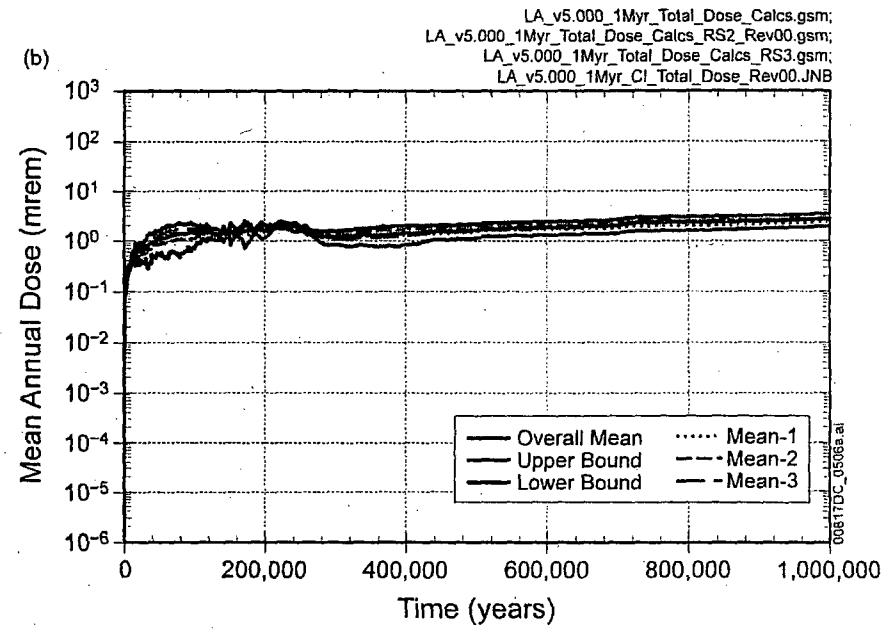
During-Development Model Validation Activities

- **Model stability testing**
  - Statistical stability
  - Numerical accuracy
  - Temporal stability
  - Spatial stability

Statistical Stability for the Epistemic Uncertainty:
1,000,000-Year Total Dose (over all modeling cases)

- **Replicate testing**
  - 3 different random seeds
  - Visual test
- **95% Confidence Intervals for Mean**
  - Assume *t*-distribution
  - Use the 3 replicates

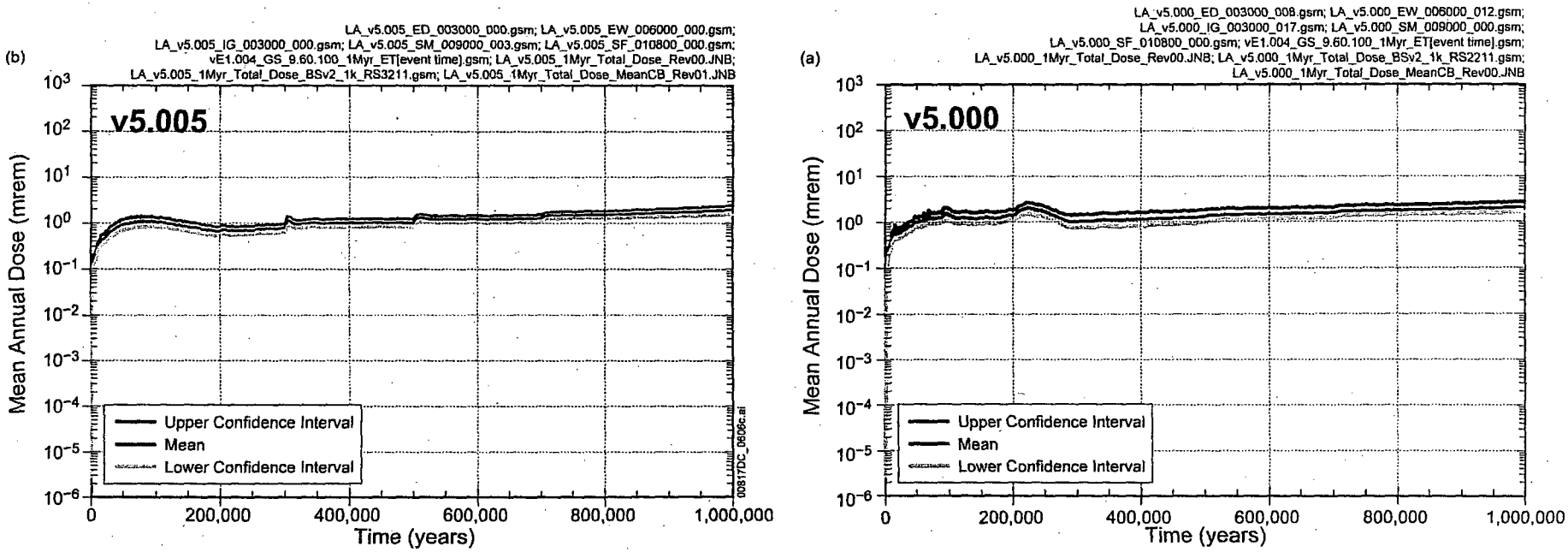




Illustrative figure from TSPA AMR (MDL-WIS-PA-000005) Figure 7.3.1-16 (a and b)

Statistical Stability for the Epistemic Uncertainty:
1,000,000-Year Total Dose

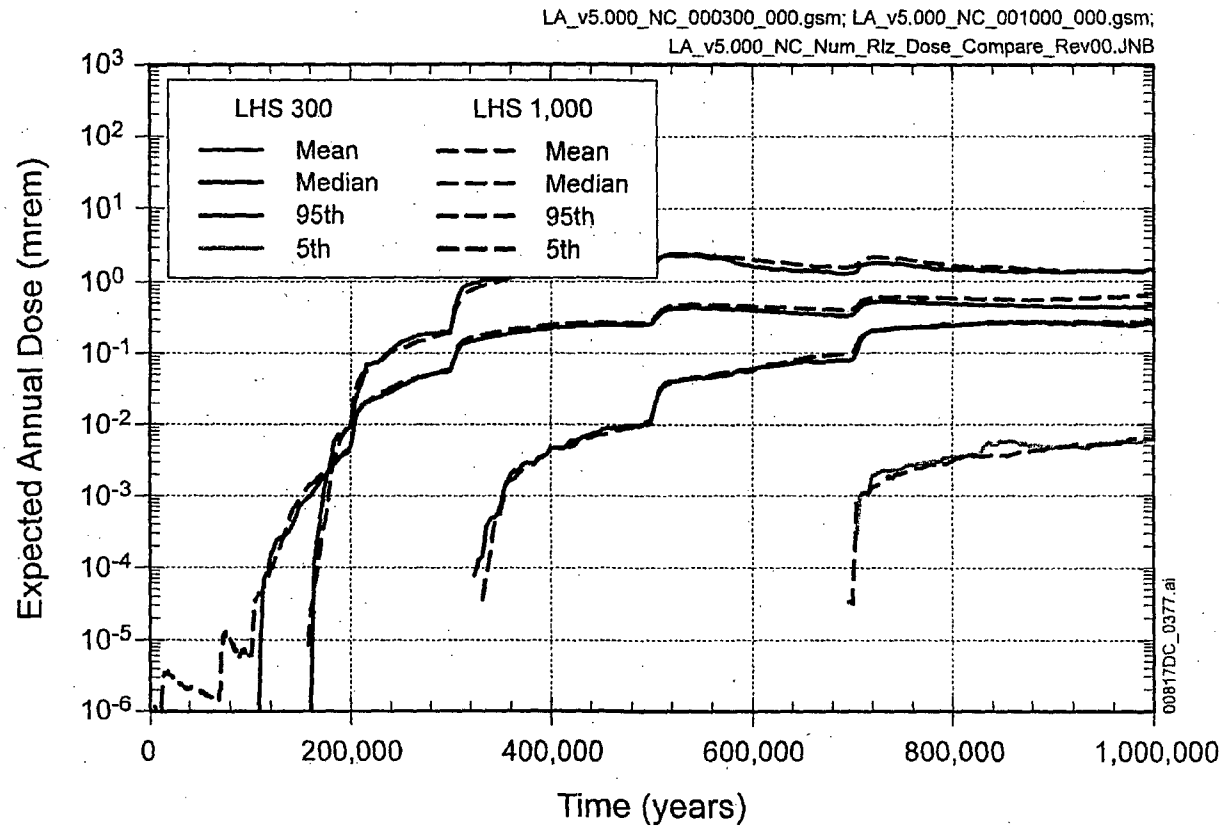
- **Bootstrap simulation (re-sampling)**
- **Gives sampling distribution and confidence intervals of mean for a single L.H.S. sample**



Illustrative figure from TSPA AMR (MDL-WIS-PA-000005) Figure 7.3.1-48[a] (a and b)

Numerical Accuracy
1,000,000-Year Nominal Modeling Case

- **Effect of number of realizations**

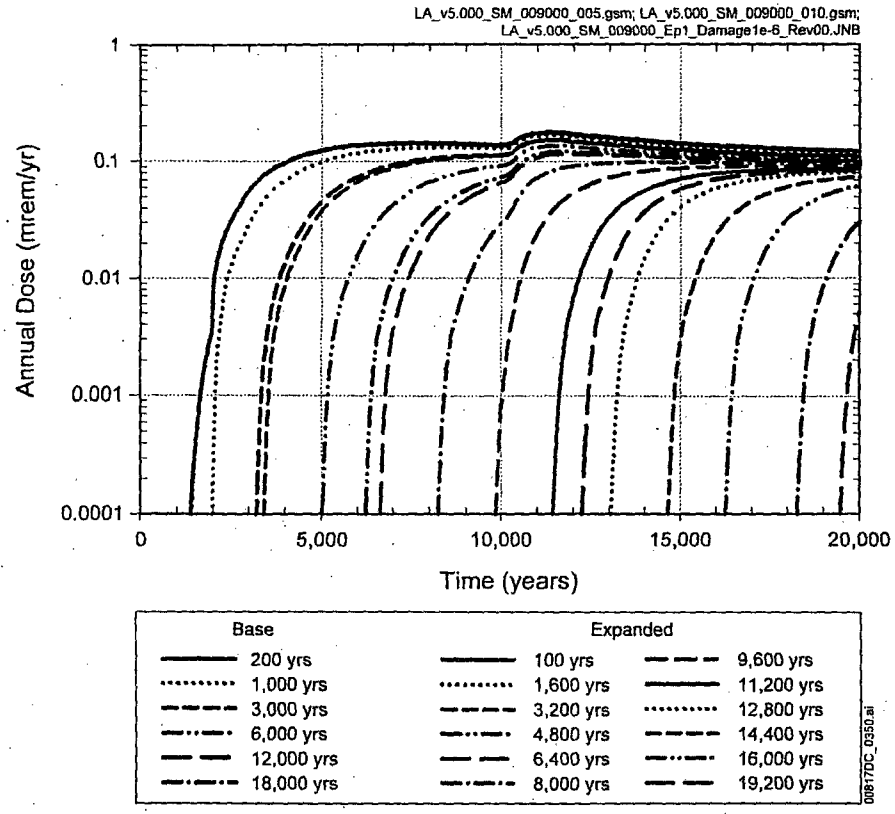


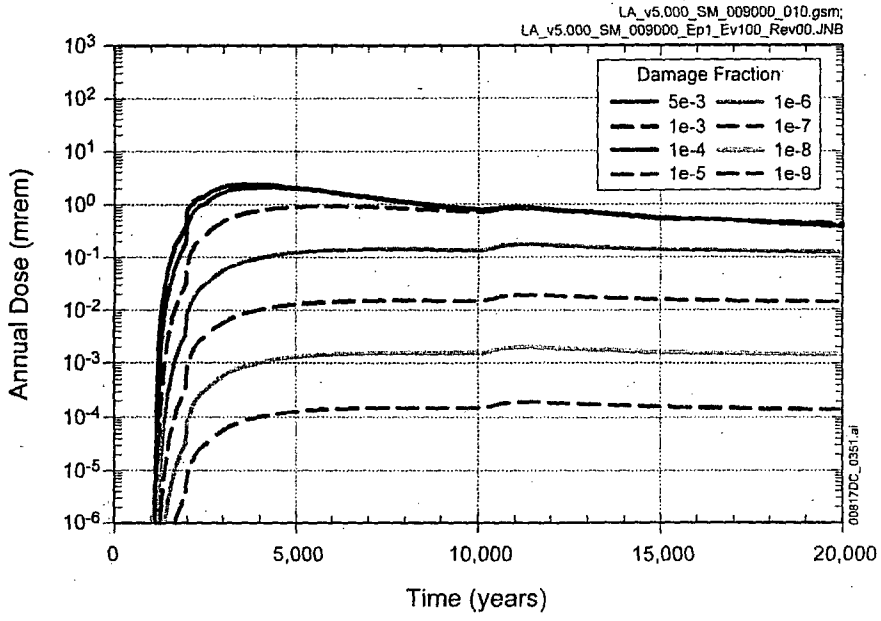
Illustrative figure from TSPA AMR (MDL-WIS-PA-000005) Figure 7.3.2-2

Numerical Accuracy of the Aleatory Integration:

10,000-Year Seismic Ground Motion Modeling Case

- **Expanded set of aleatory futures**
  - Base case: 6 event times, 5 damage fractions
  - Expanded case: 12 event times, 8 damage fractions



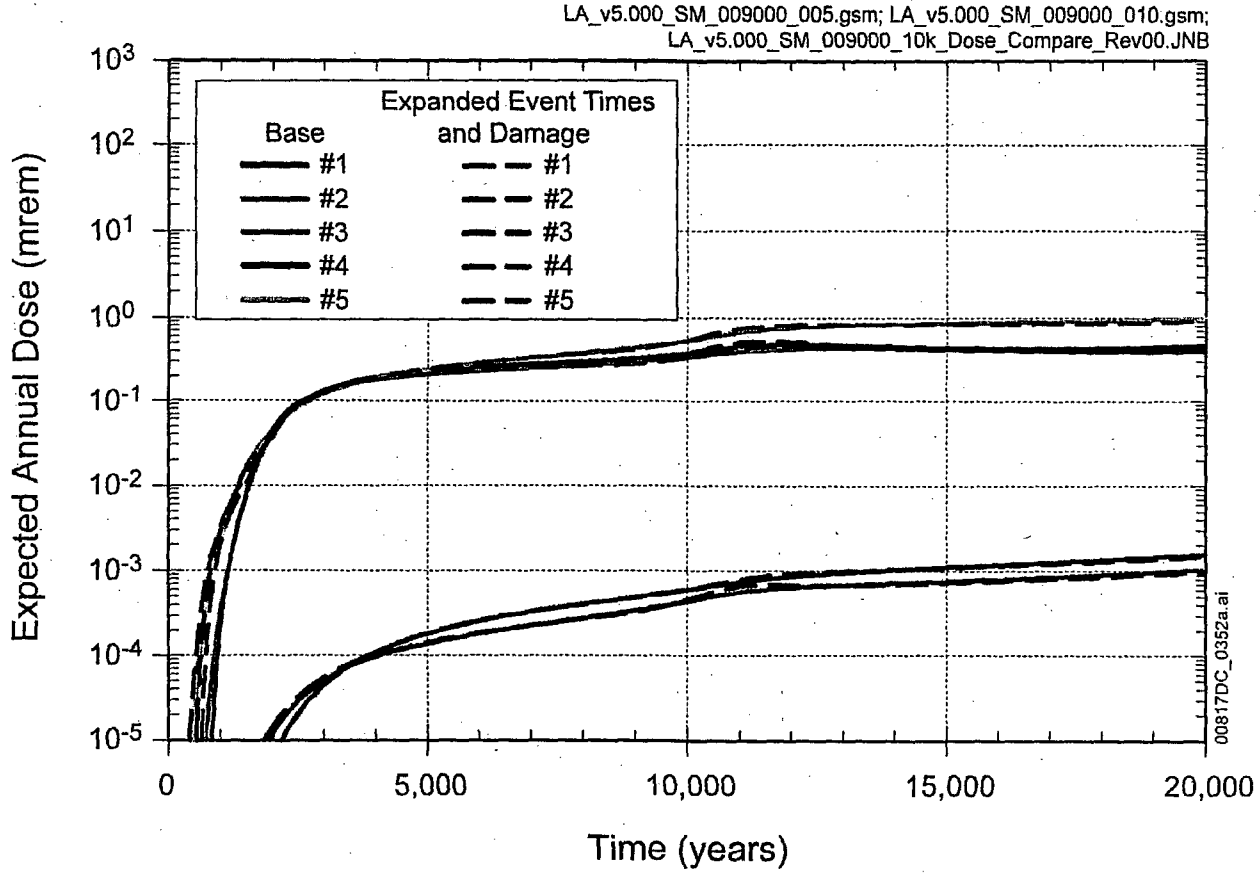


Illustrative figures from TSPA AMR (MDL-WIS-PA-000005) Figures 7.3.2-8 and 7.3.2-9

Numerical Accuracy of the Aleatory Integration:

10,000-Year Seismic Ground Motion Modeling Case

- **Expected dose for five different epistemic realizations: base case vs. expanded case**

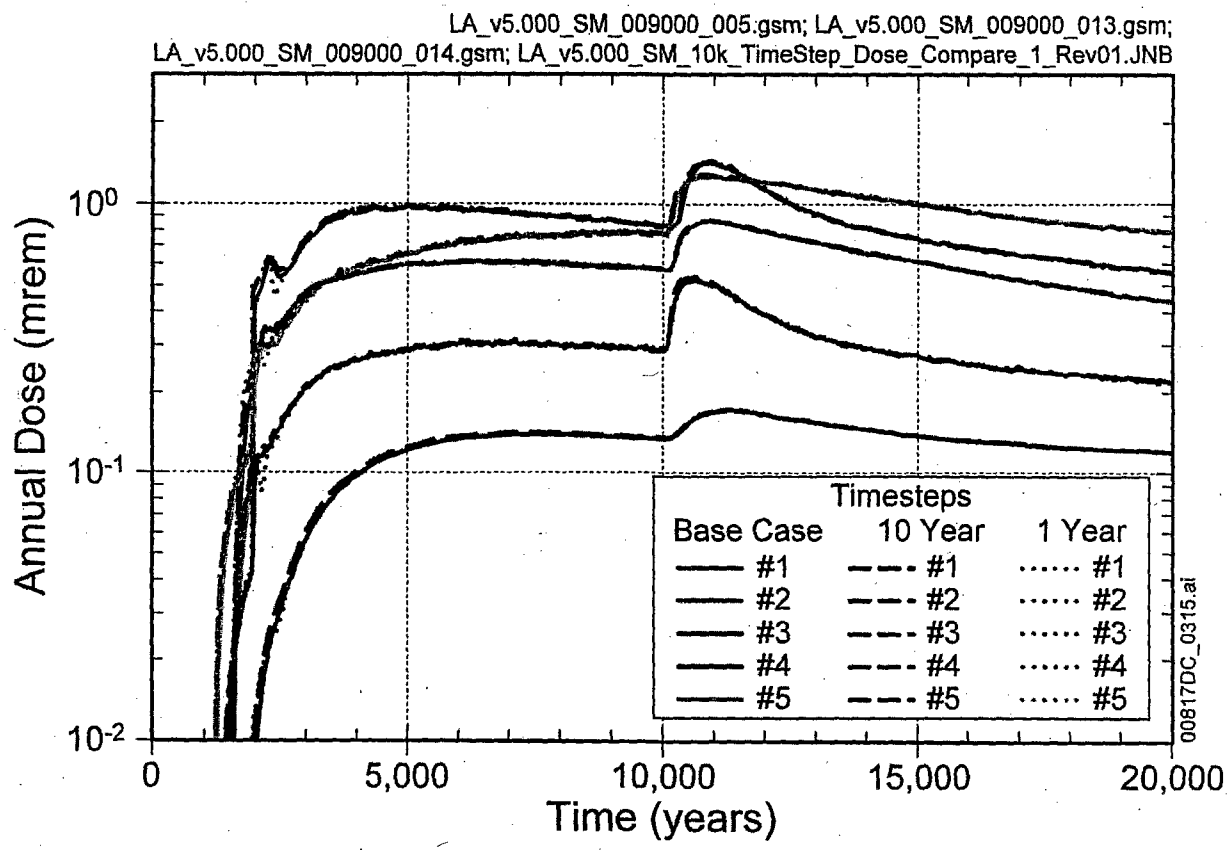


Illustrative figure from TSPA AMR (MDL-WIS-PA-000005) Figure 7.3.2-11

Temporal Stability:

10,000-Year Seismic Ground Motion Modeling Case

- **Two different timestep schemes for a given repository future**

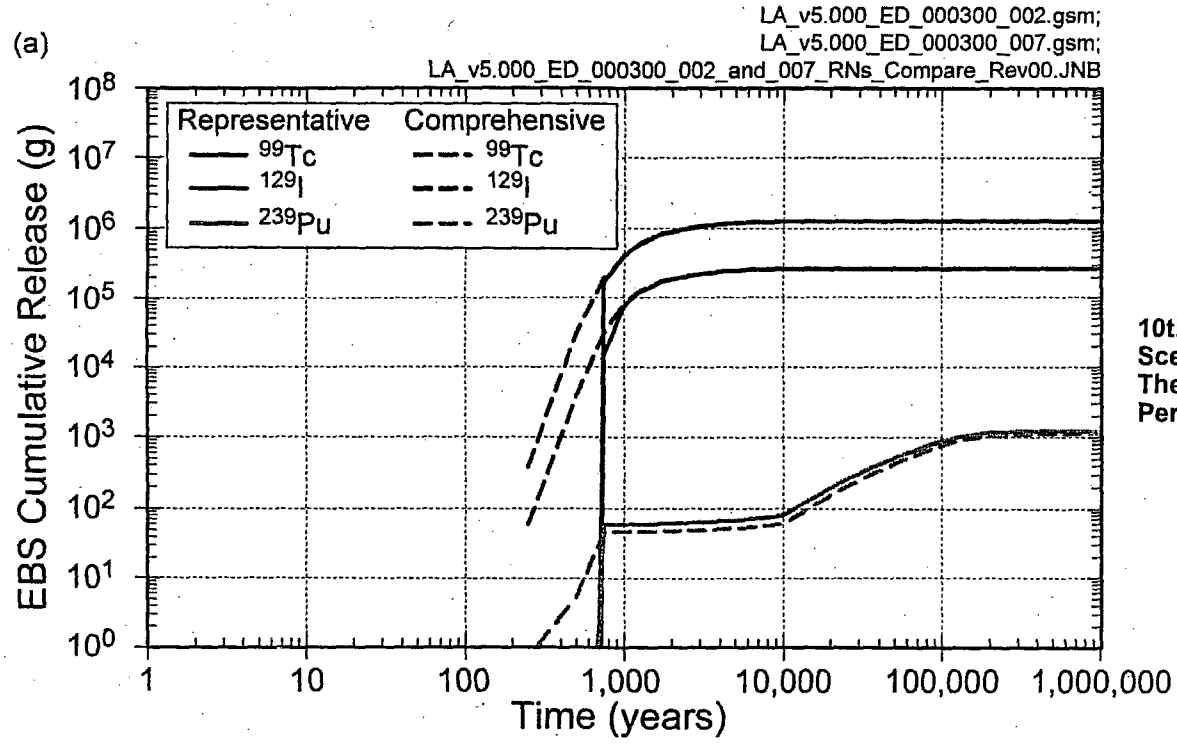


Illustrative figure from TSPA AMR (MDL-WIS-PA-000005) Figure 7.3.3-8

Spatial Stability:

10,000-Year Drip Shield Early Failure Modeling Case

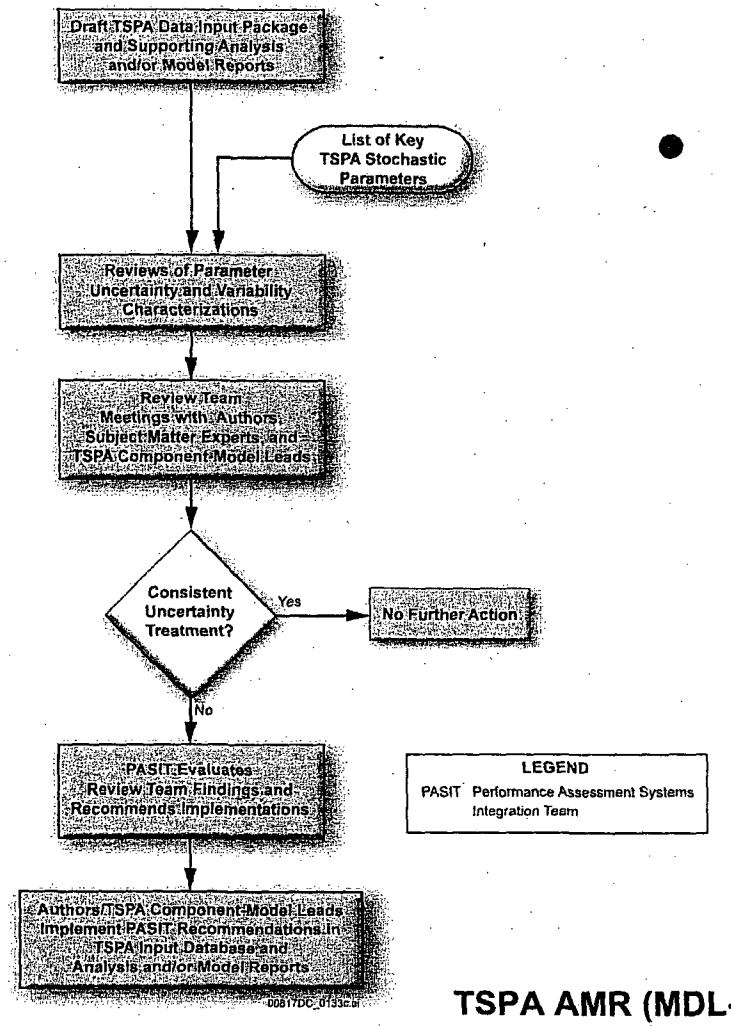
- **Comparison of the Effect on EBS Release of the Representative versus the Comprehensive Thermal-Hydrologic Data Sets for ^{99}Tc, ^{129}I, and ^{239}Pu**



10th Percentile Infiltration Scenario, Low Host-Rock Thermal Conductivity, Percolation Subregion 1

Illustrative figure from TSPA AMR (MDL-WIS-PA-000005) Figure 7.3.4-1(a)

During-Development Model Validation Activities

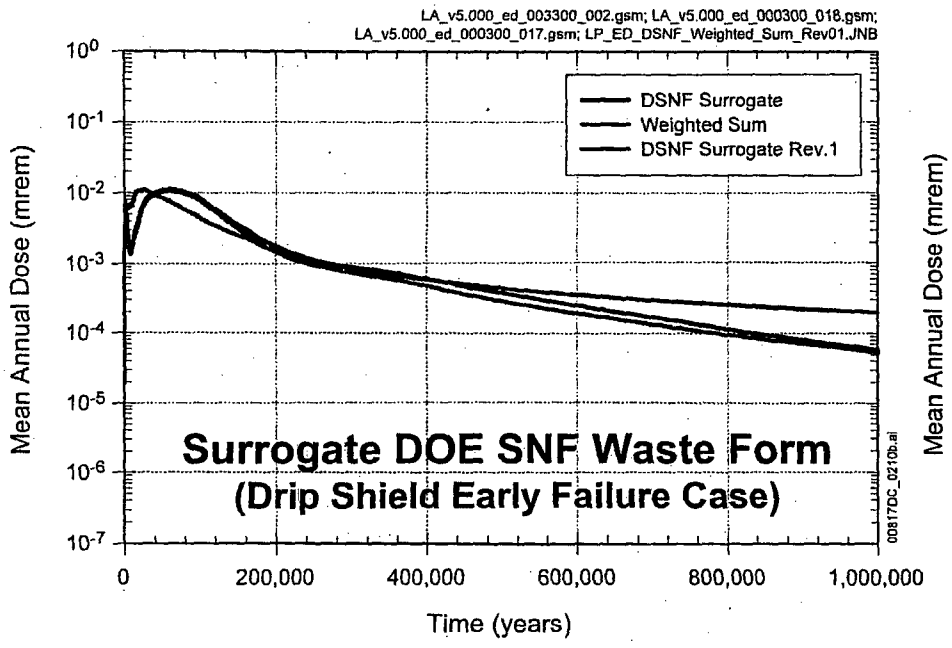


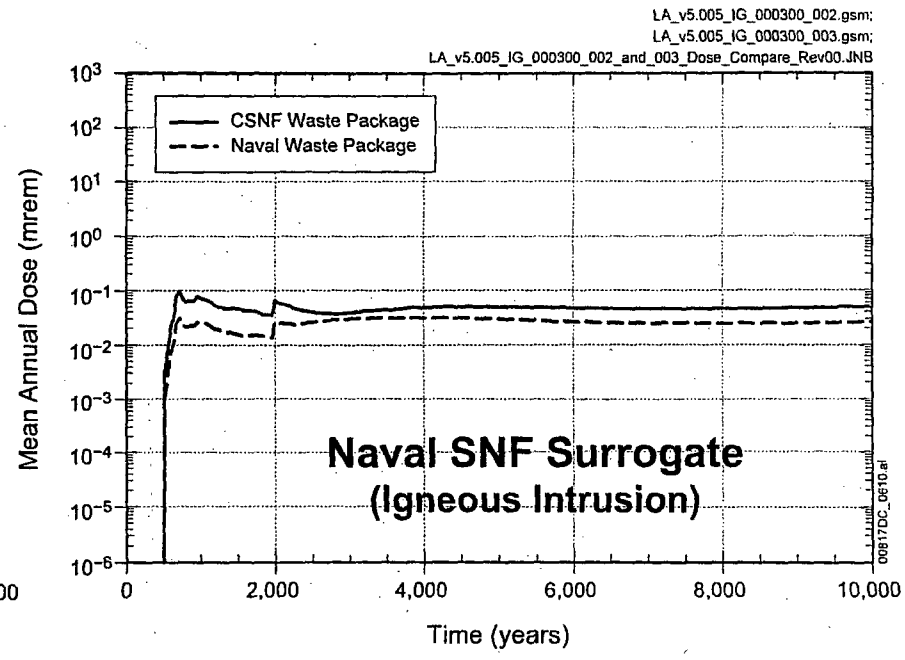
TSPA AMR (MDL-WIS-PA-000005)
Figure 7.4-1

- **Uncertainty characterization reviews**
  - Confirm parameter representations reflect the major sources of uncertainty and/or variability
  - Verify that probability distributions were derived using sound statistical methods and interpretations
  - Ensure parameter representations are reasonable and defensible
  - Uncertainty and sensitivity analyses

During-Development Model Validation Activities

- **Surrogate waste form validation**
  - N-Reactor fuel as a surrogate for DOE SNF (excluding naval SNF)
  - CSNF as a surrogate for naval SNF





Illustrative figures from TSPA AMR (MDL-WIS-PA-000005) Figures 7.5-20 and 7.5-5[a]

Post-Development Model Validation Activities

Post-Development Model Validation Activities

- Corroboration of direct input abstraction results with validated process models
  - TSPA model is an integration of abstractions and process models
  - Abstractions provided to the TSPA code are corroborated with their underlying process models during their individual development and post-development validation phases

Post-Development Model Validation Activities

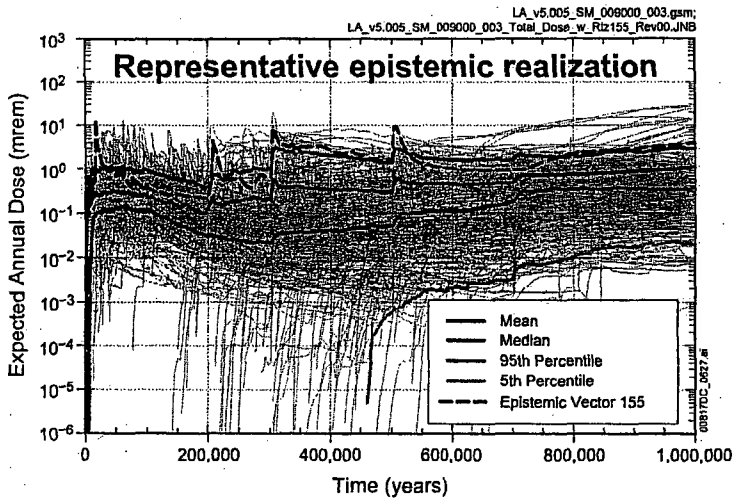
- Corroboration of results with auxiliary analyses
  - Single realization analysis
  - Comparison to independently developed Simplified TSPA analysis
  - Comparison to EPRI IMARC analysis
  - Performance Margin Analysis (PMA)—effect of key conservatisms

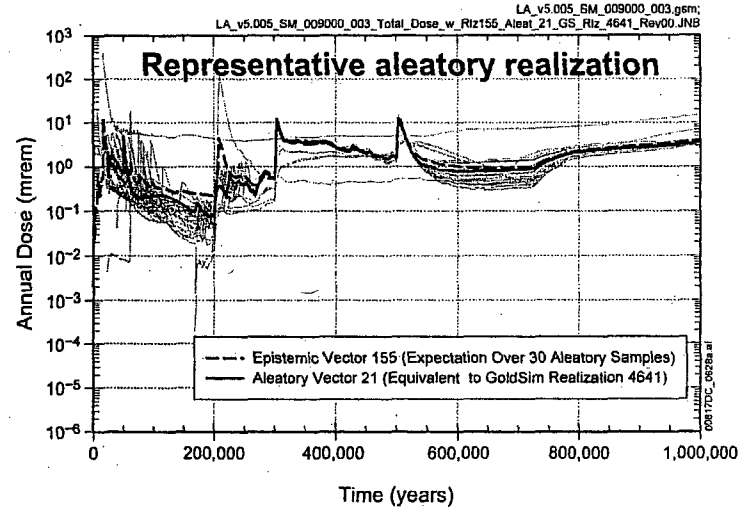
Single Realization Analysis

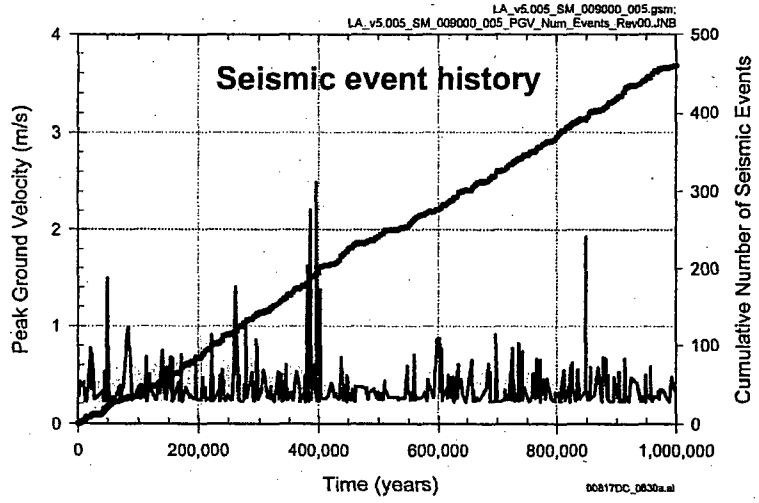
- Provide insight into submodel coupling
- Investigates the interactions and cause-effect relationships between model components
- Comprehensive understanding of the performance of the system
- Error-checking and model verification

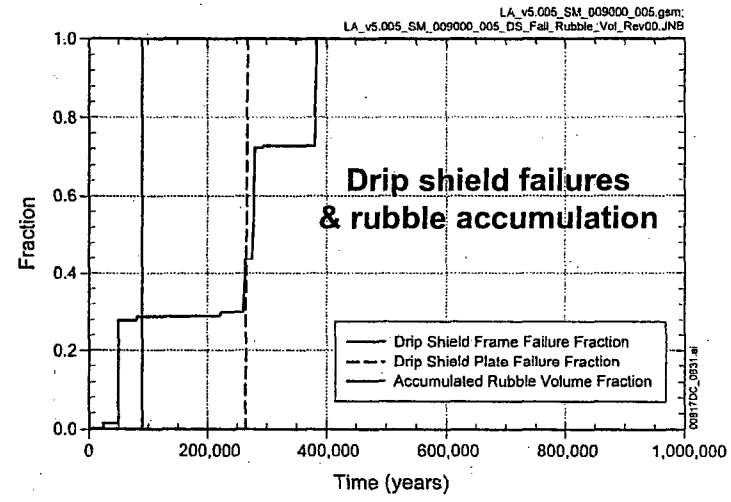
Single Realization Analysis:

1,000,000-Year Seismic Ground Motion Modeling Case





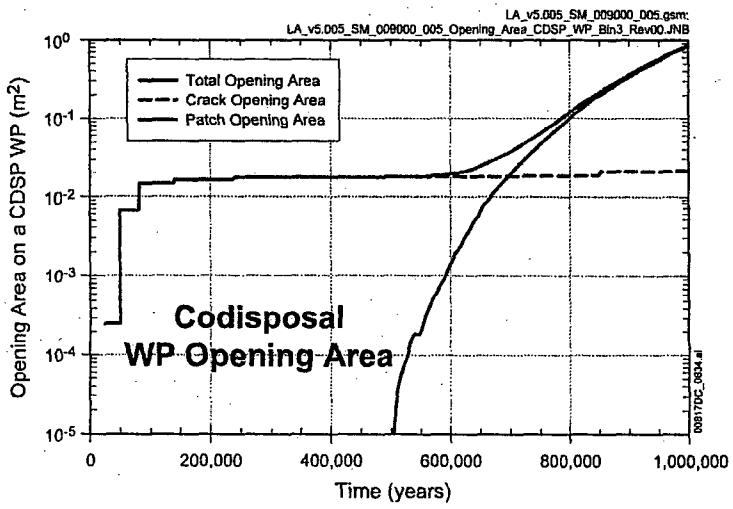


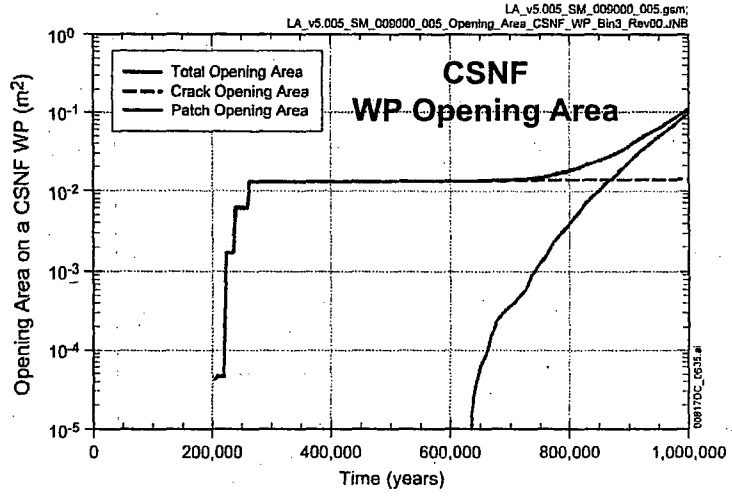


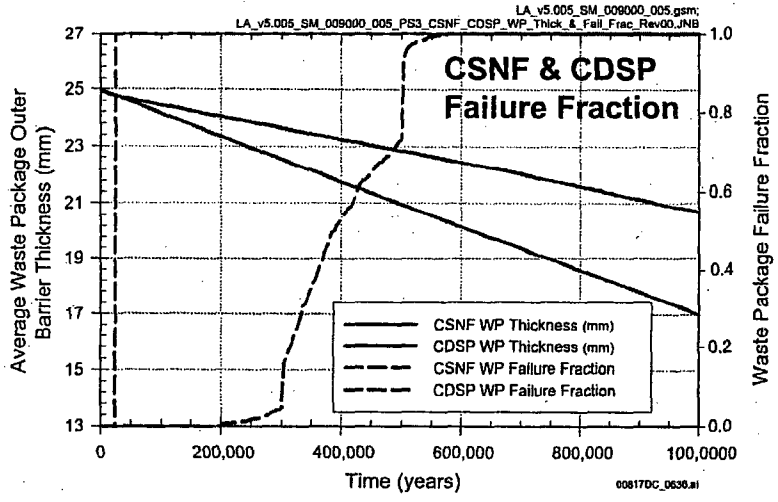
Illustrative figures from TSPA AMR (MDL-WIS-PA-000005), Figures 7.7.1-52[a], 53[a], 55[a], and 56[a]

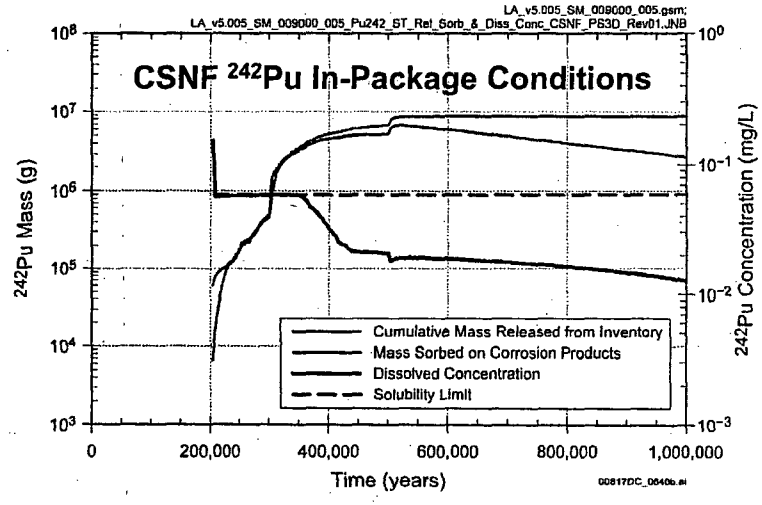
Single Realization Analysis:

1,000,000-Year Seismic Ground Motion Modeling Case







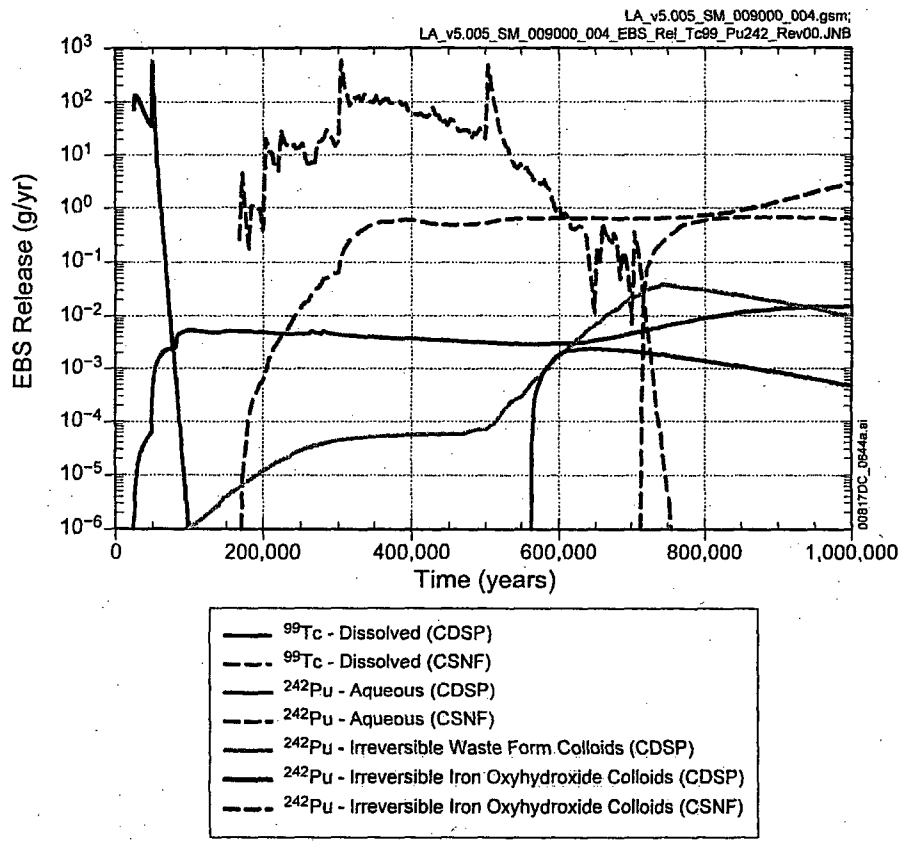


Illustrative figures from TSPA AMR (MDL-WIS-PA-000005), Figures 7.7.1-59[a], 60[a], 61[a], and 65[a]

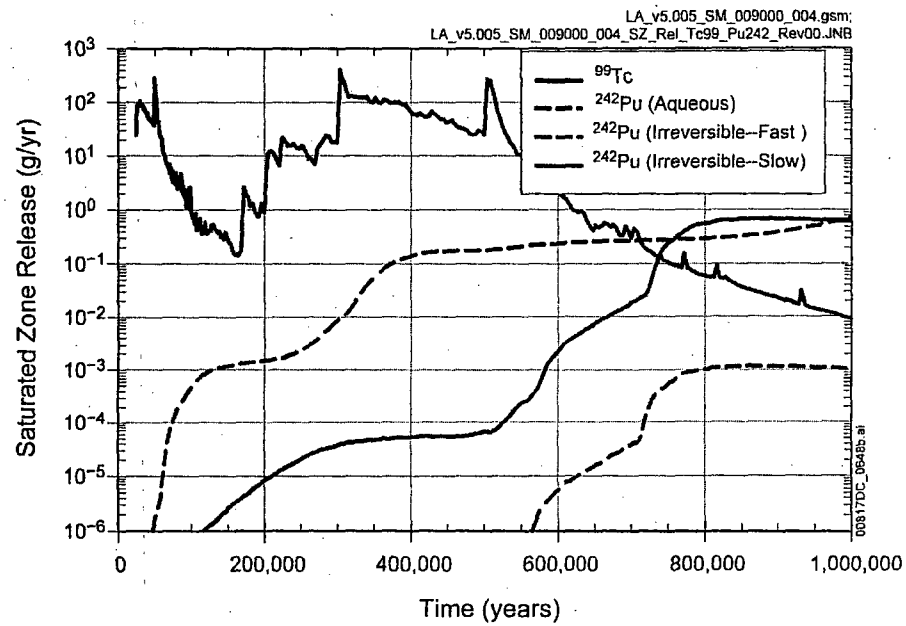
Single Realization Analysis:

1,000,000-Year Seismic Ground Motion Modeling Case

EBS Releases



Lower Natural Barrier Releases

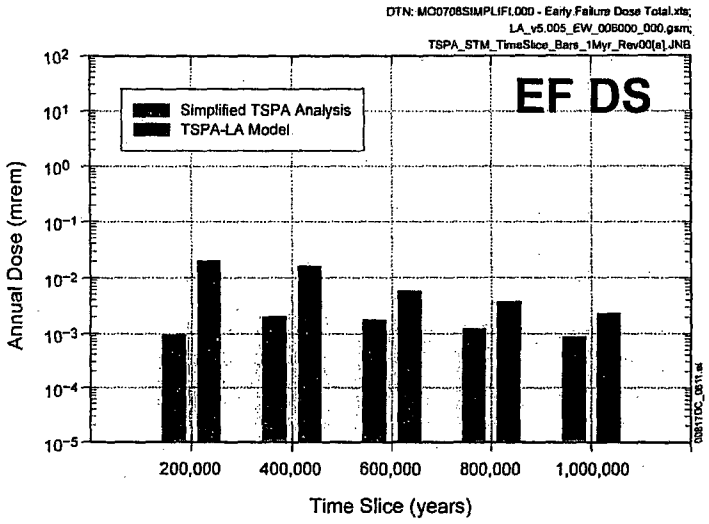


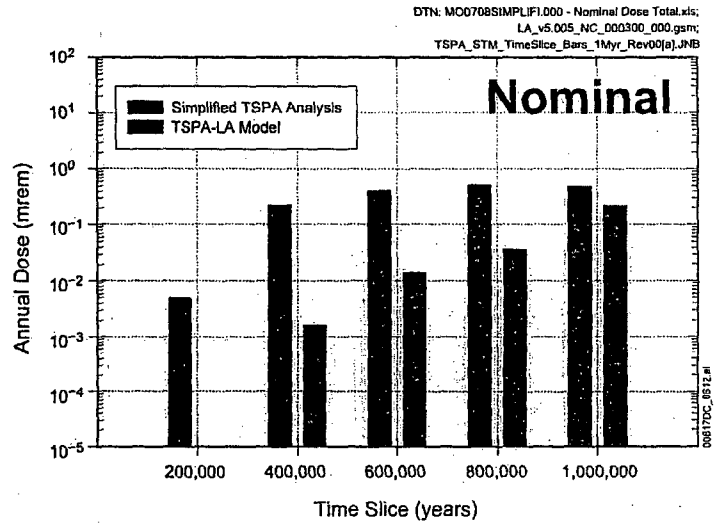
Illustrative figures from TSPA AMR (MDL-WIS-PA-000005) Figures 7.7.1-69[a] and 7.7.1-73[a]

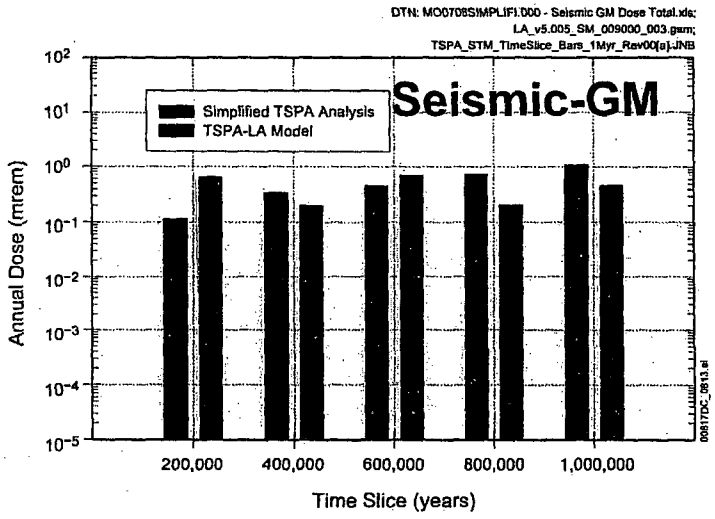
Simplified TSPA Analysis

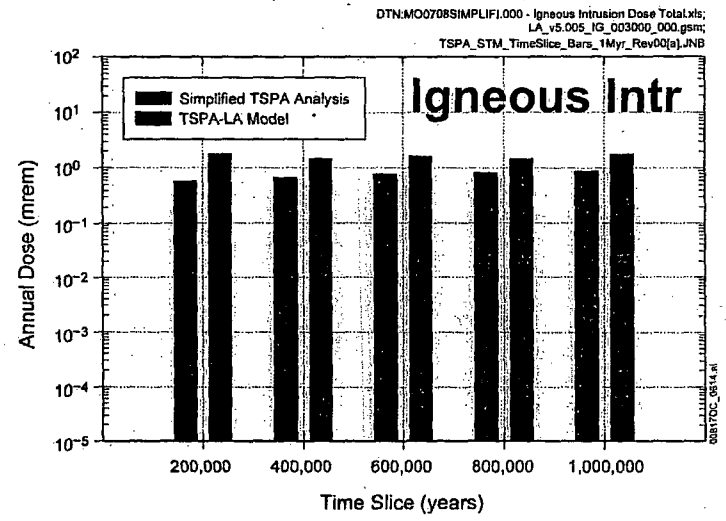
- Simplified representations of mathematical equations that describe many degradation, release, and transport processes
- Stand-alone FORTRAN 90 computer program
- Higher level abstraction of the same TSPA FEPs; reduction in spatial and temporal variability
- Simplified UZ and SZ transport models

Simplified TSPA Analysis







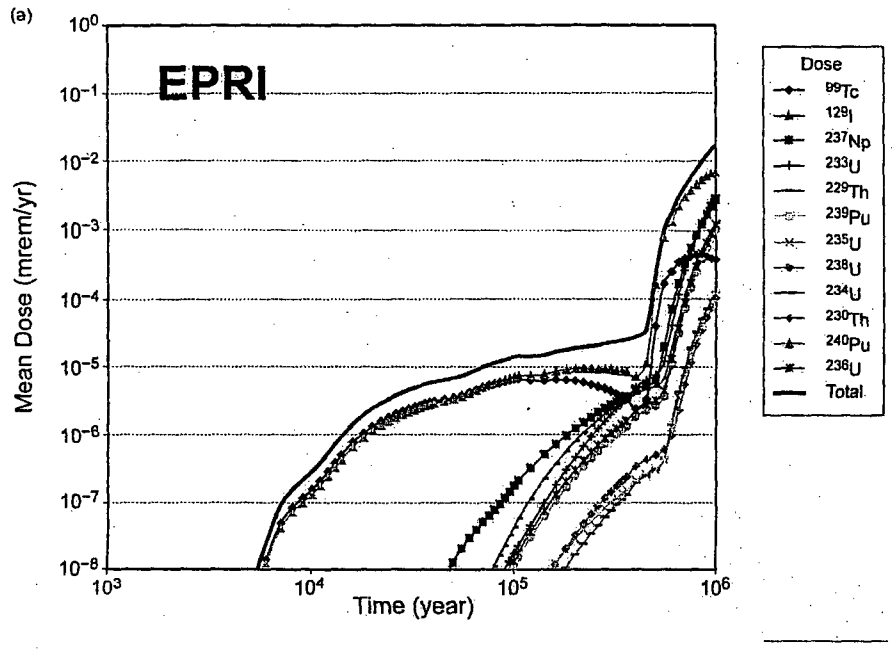


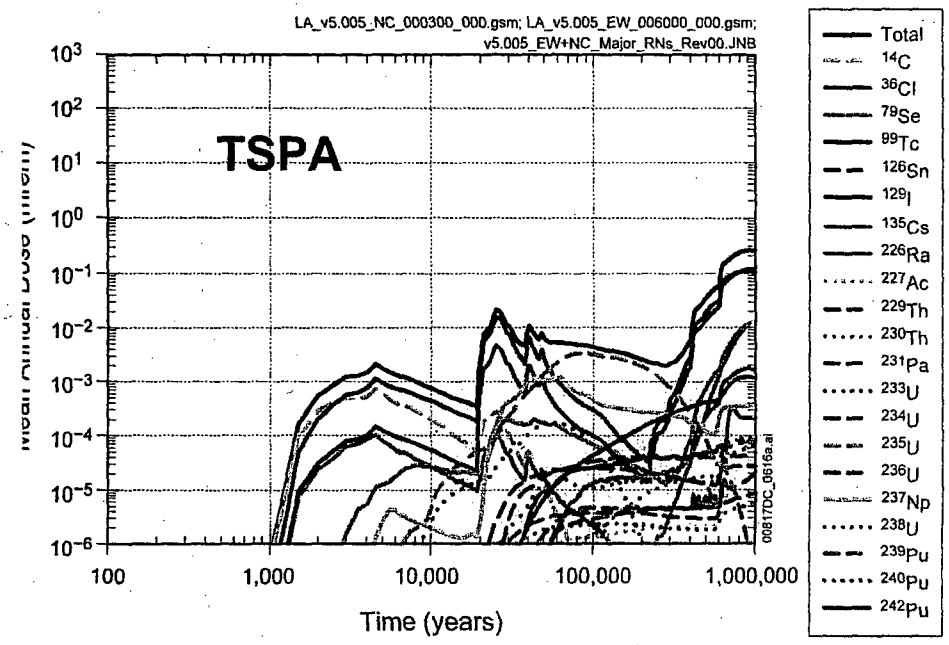
Illustrative figures from TSPA AMR (MDL-WIS-PA-000005), Figures 7.7.2-3[a], 6[a], 9[a], and 12[a]

EPRI Analysis

- Independent third-party assessment of key technical and scientific issues
- Logic-tree vs. Monte Carlo sampling-based
- Same model components and FEPs
- Differences in the results can be explained by differences between the two models: (DOE TSPA uses the most recent submodel updates)

Comparison to EPRI Analysis





- **Nominal Plus Early Failure Waste Packages**
- **At 1,000,000-yrs dose results are comparable**
- **^{129}I and ^{99}Tc are significant dose contributors in both PAs**

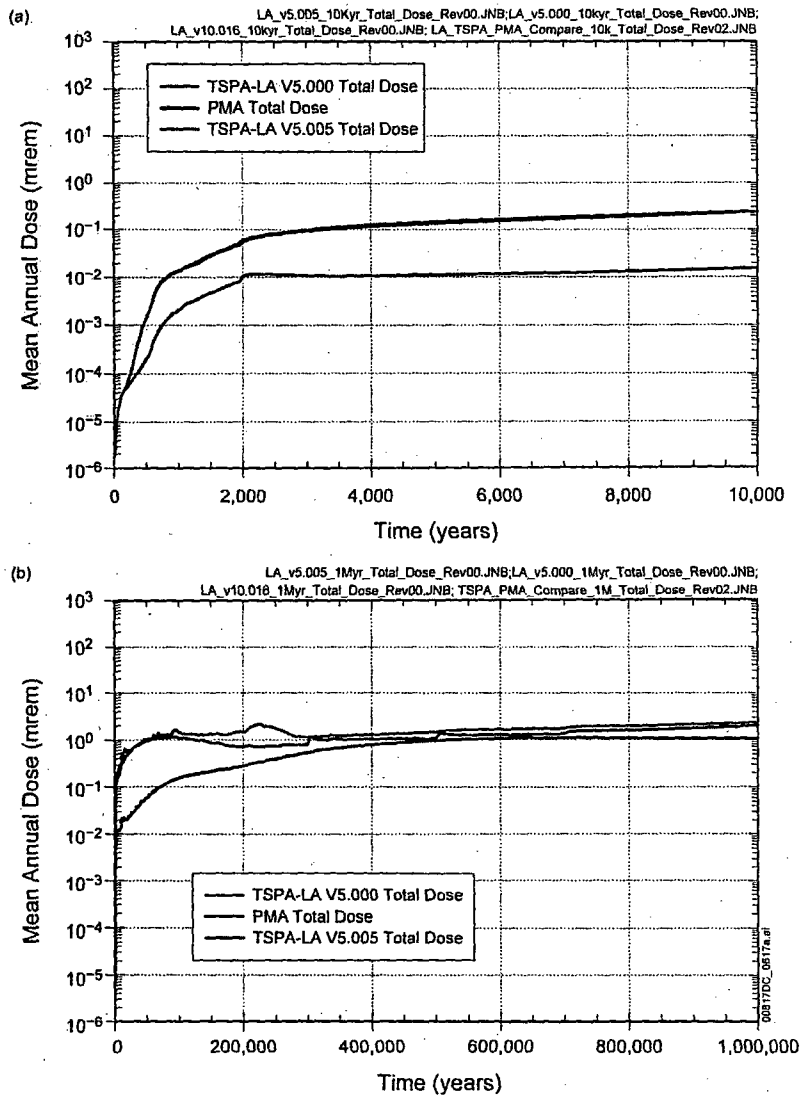
Illustrative figure on the right from TSPA AMR (MDL-WIS-PA-000005), Figures 7.7.3-3[a]

Performance Margin Analysis

- Include less conservative alternative conceptual models
- Narrower parameter uncertainty distributions in cases where conservative bounding values were assumed
- Includes additional coupling among different physical and chemical processes

Performance Margin Analysis

- Submodel conservatisms propagated through the total system do not underestimate the total mean annual dose
- PMA dose is more than a factor of 10 lower at 10,000 years and a factor of 2 lower at 1,000,000 years
- The evaluated conservatisms do not introduce any risk dilution in TSPA results



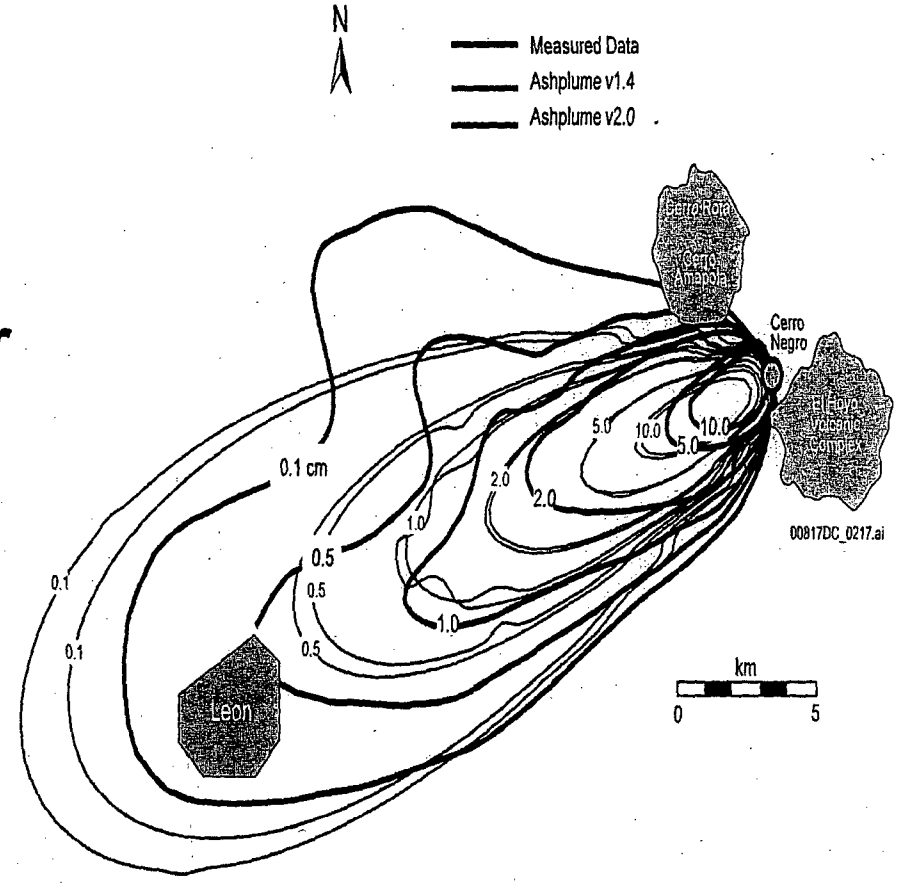
Illustrative figure from TSPA AMR (MDL-WIS-PA-000005) Figure 7.7.4-7[a] (a and b)

Natural Analogues

- Compare repository conditions and materials to observed conditions and materials for time periods relevant to the lifetime of the repository
- Provide insights and build confidence in the conceptual and numerical models used to represent processes and events
- TSPA analogues
  - 1995 volcanic eruption at Cerro Negro, Nicaragua
  - Radionuclide transport at the Nopal I uranium deposit in the Sierra Peña Blanca in Chihuahua, Mexico

Natural Analogues - Cerro Negro

- Confirm ASHPLUME software code is capable of calculating ash deposition from an eruption that could occur at Yucca Mountain
- ASHPLUME calculation for ash deposition around Cerro Negro compares well with observed data



TSPA AMR (MDL-WIS-PA-000005)
Figure 7.8-1

Natural Analogues – Peña Blanca

- Analogue for the evolution, fate, dissolution and transport of SNF placed in the repository
- Uranium deposit is geologically, climatically, geochemically, and hydrologically analogous to Yucca Mountain
- Hydrogeologic and geochemical investigations at Nopal I indicate that there has been relatively little transport of the radionuclides from the ore deposit and that few radionuclides have traveled very far from their sources

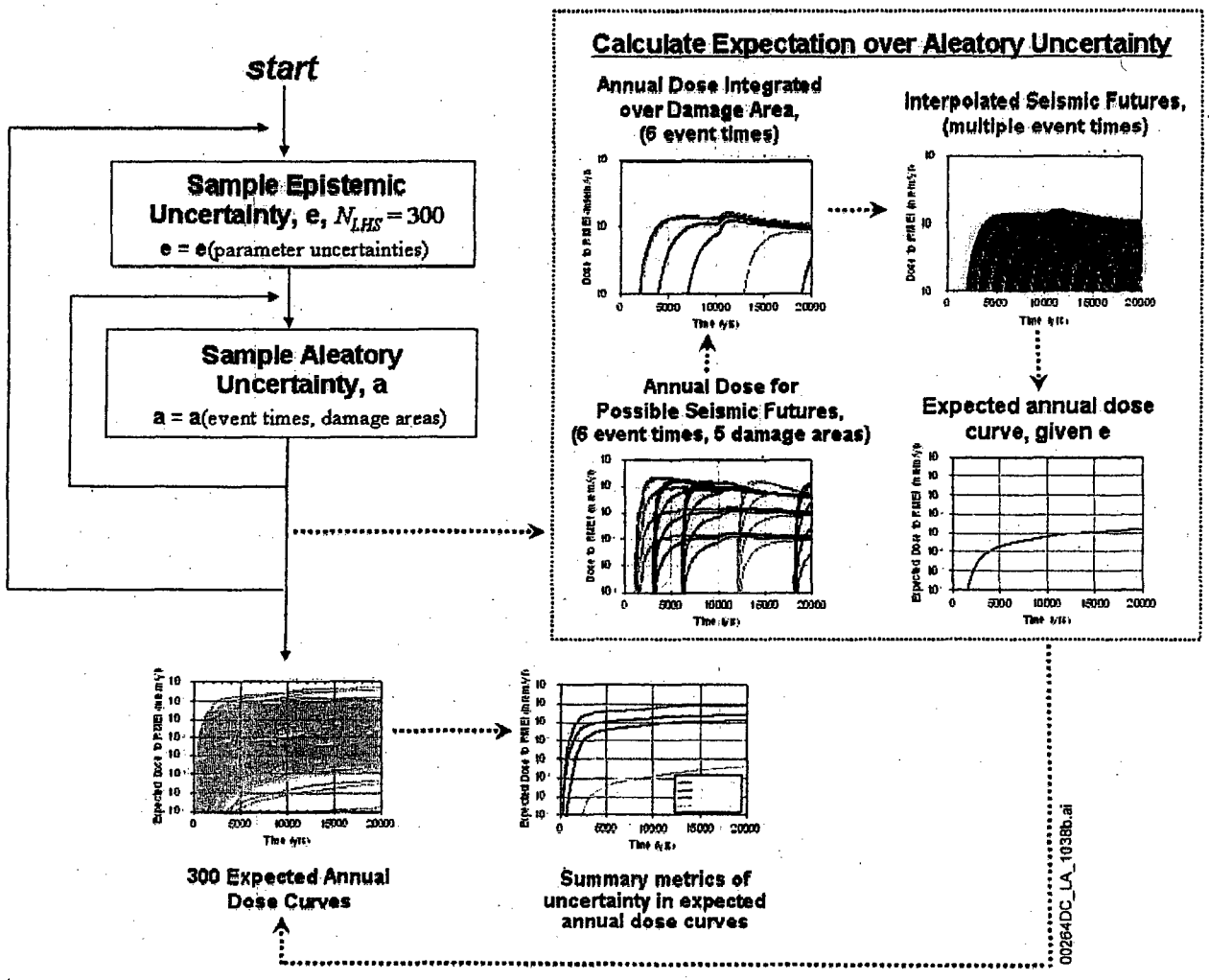
Independent Technical Review

- Successive iterations of the TSPA model have been subject to independent reviews by technical staff and various external organizations
- During the development of subsequent iterations of the TSPA model, recommendations from the technical review of the preceding iterations are considered
- In addition to routine NWTRB reviews, three recent technical reviews include
  - TSPA-VA model peer review conducted in 1999
  - TSPA-SR model review by an international review team in 2002
  - TSPA-LA draft model review by an independent validation review team completed in 2006

References

- SNL 2008. *Total System Performance Assessment Model/Analysis for the License Application*, MDL-WIS-PA-000005 REV 00 AD 01.

Computational Strategy for 10,000-year Seismic Ground Motion Modeling Case



U.S. Department of Energy
Office of Civilian Radioactive Waste Management

www.ocrwm.doe.gov

Nominal Scenario: Model Abstractions of Waste Package Corrosion Mechanisms

Presented to:
NRC/DOE Technical Exchange on Total Systems Performance Assessment for Yucca Mountain

Presented by:
Neil R. Brown, Ph.D.
Los Alamos National Laboratory

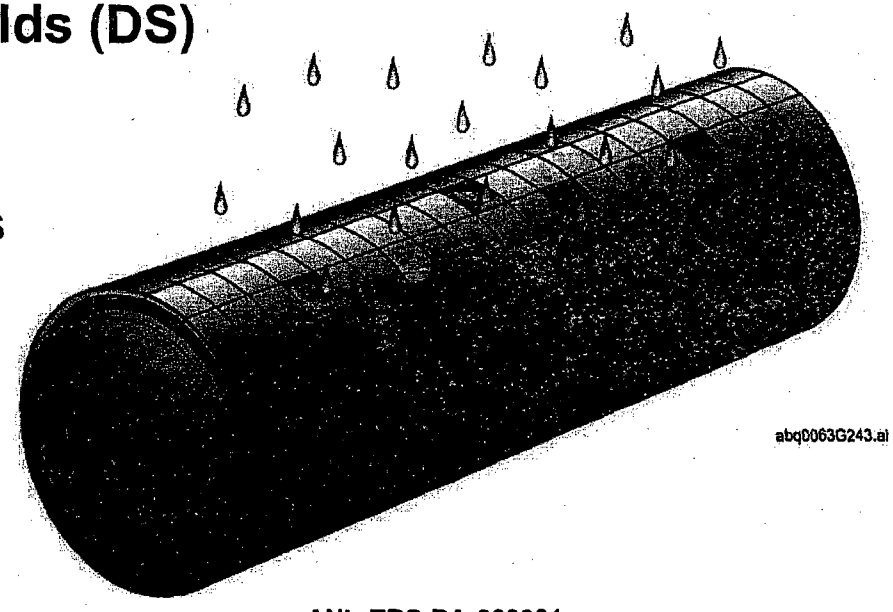
April 04, 2008
Las Vegas, Nevada

Outline

- **Waste Package Corrosion Mechanisms**
  - **General Corrosion (GC)** (ANL-EBS-MD-000003)
  - **Microbially Influenced Corrosion** (ANL-EBS-000003)
  - **Localized Corrosion (LC)** (ANL-EBS-000003)
  - **Stress Corrosion Cracking** (ANL-EBS-000005)
  - **Waste Package Crack and Patch Failures vs. Time**
- **Drip Shield Corrosion Mechanisms**
  - **General Corrosion** (ANL-EBS-MD-000004)
  - **Drip Shield Failures vs. Time**
- **Nominal Scenario Dose Curves**

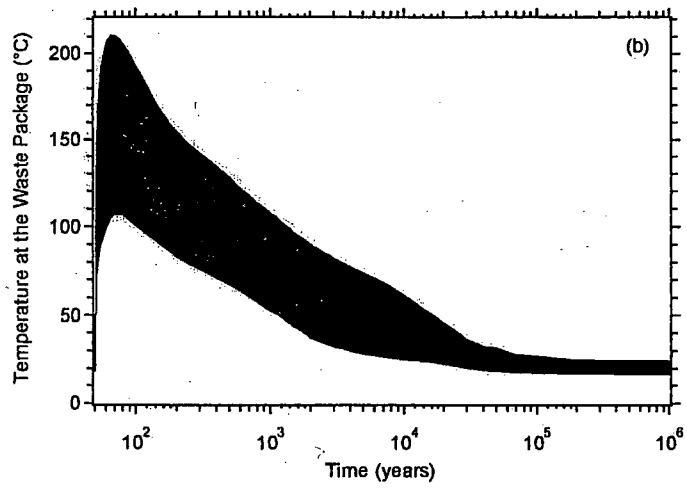
Objectives of Waste Package and Drip Shield Degradation Abstraction

- Provide the Engineered Barrier System (EBS) flow and transport model and waste form degradation and mobilization model:
  - Number of patch and crack breaches per failed waste package (WP)
  - Number of failed drip shields (DS)
  - Waste package and drip shield thinning for seismic consequences

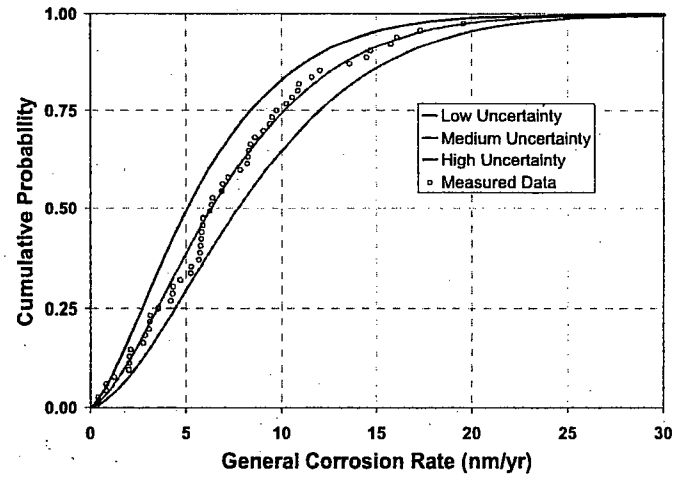


ANL-EBS-PA-000001

Waste Package General Corrosion



ANL-EBS-MD-000049 fig 6.3-76[a]



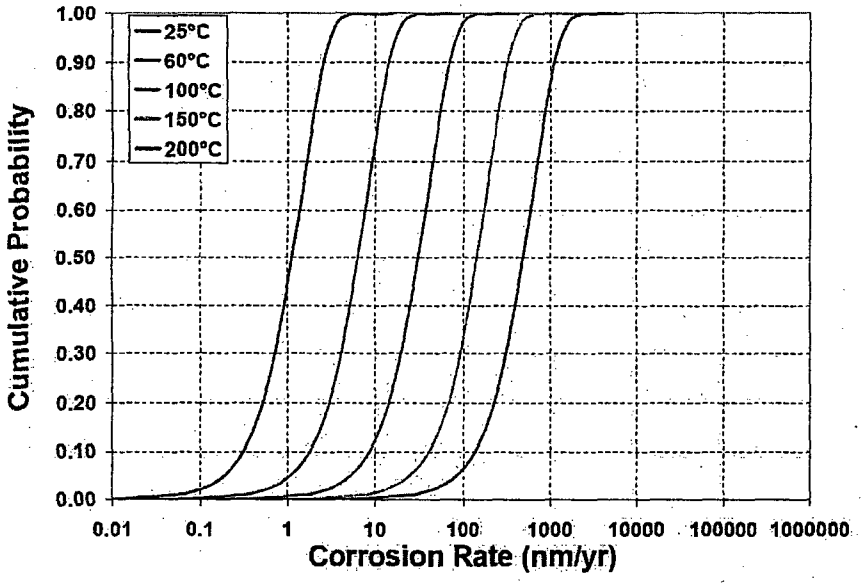
ANL-EBS-MD-000003 fig 6-23

$$\text{Rate} = f_{MIC}\exp\left(C_o - \frac{C_1}{T}\right)$$

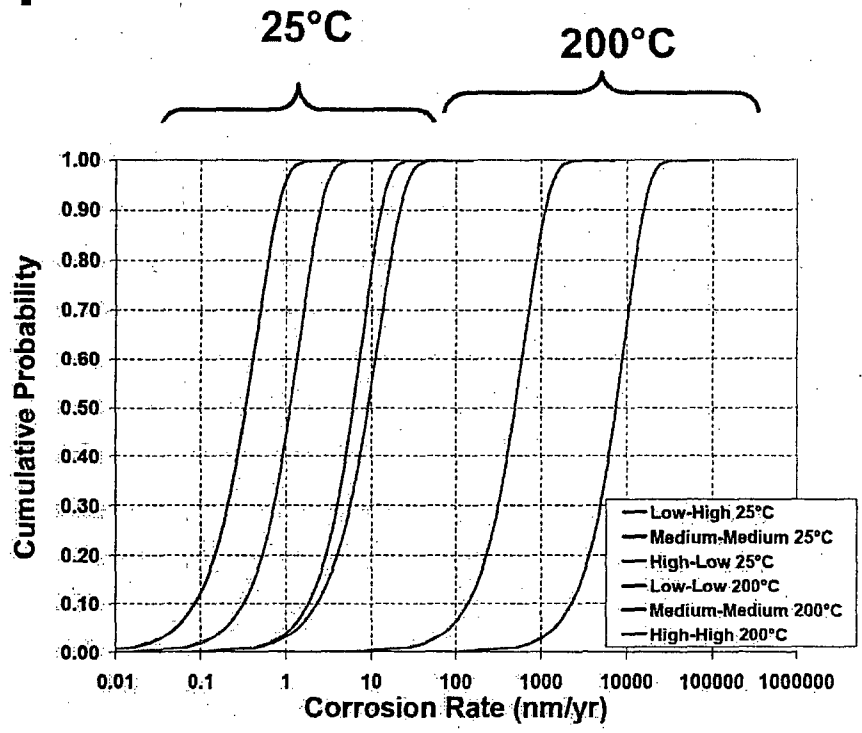
- **Temperature profiles**
  - **Spatial variability (WP-to-WP)**
- **C_o, pre-exponent corrosion rate at 60°C, based on Weibull distribution fit to weight-loss data**
  - **Spatial variability (patch-to-patch)**
- **C_1, temperature dependence, based on normal distribution from polarization data**
  - **Uncertainty**
- **f_{MIC}, Microbially Influenced Corrosion multiplier**
  - **Spatial variability (patch to patch)**

General Corrosion of the Waste Package

- 5-yr crevice geometry specimen weight-loss
- Activation energy from polarization resistance



Corrosion Rate Range for Median Activation Energy
ANL-EBS-MD-000003 fig 6-26

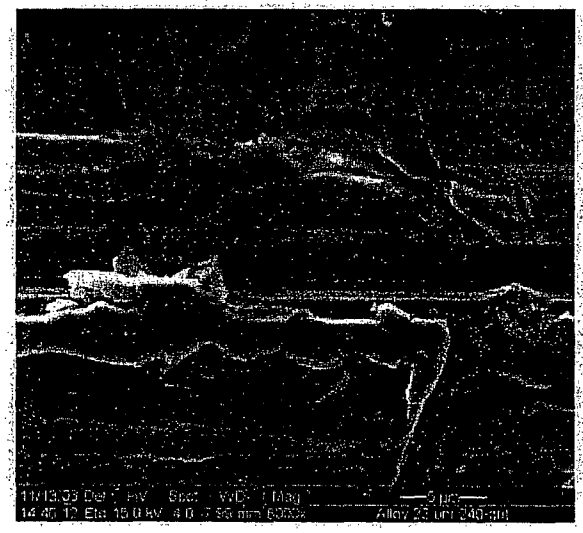


Corrosion Rate Range for 25°C and 200°C
ANL-EBS-MD-000003 fig 6-27

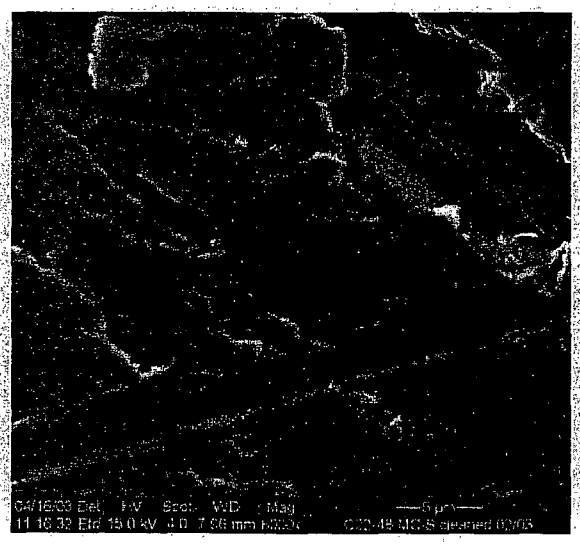
Microbially Influenced Corrosion

- **Alloy 22 incubated with sterile or nonsterilized YM rock**
  - F_{MIC} 1-2x multiplier on GC rate, no localized corrosion effect
  - Concentrated (10×) groundwater with 0.1% glucose ~ 5 years
  - Applied at a relative humidity threshold of 75-90% (uniform)

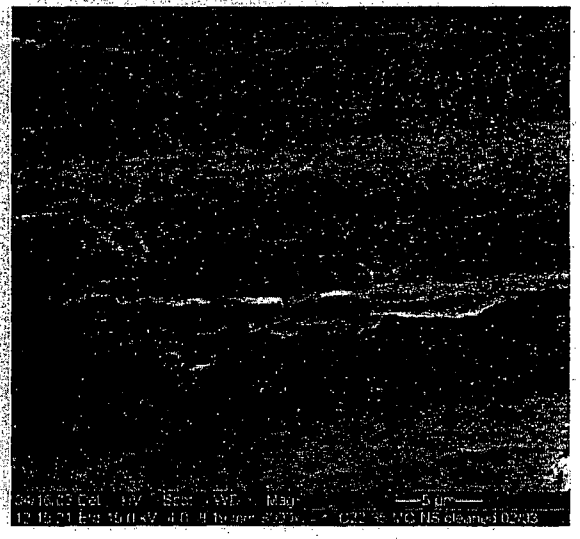
Non-reacted



43 months sterile microcosm



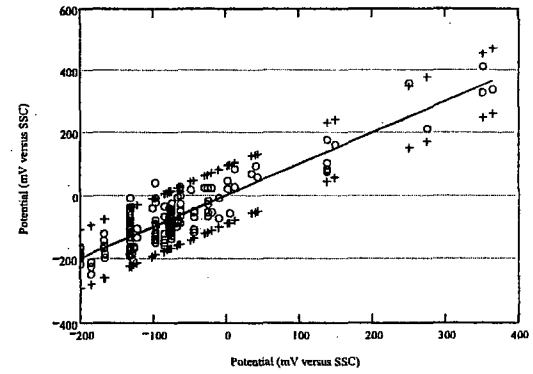
57 months non-sterile microcosm



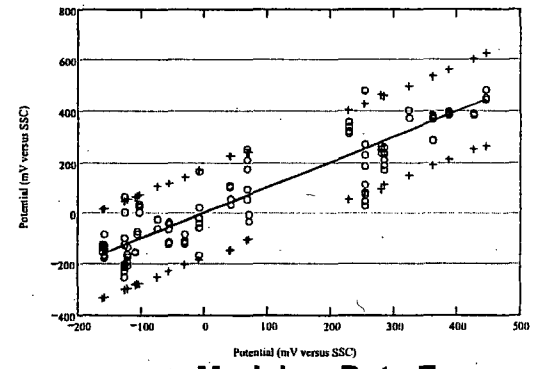
ANL-EBS-MD-000003 fig. 6-55

Waste Package Localized Corrosion

- Waste package areas contacted by seepage may be subject to LC
- If seepage occurs at relative humidity (RH) < ~70% model initiates LC – salt separation
- If seepage occurs at RH > ~70%
  - Compare
    - E_{corr}, long-term corrosion potential, to
    - E_{rcrev}, crevice repassivation potential
  - If $E_{corr} \geq E_{rcrev}$ model initiates LC
    - E_{corr} and E_{rcrev} functions of T, pH, [Cl^-], [NO_3^-]
      - » Uncertainty in fitting parameters
      - » Spatial variability from thermal and chemical variations
- LC corrosion rates result in rapid penetration of WP



Model vs Data E_{rcrev}

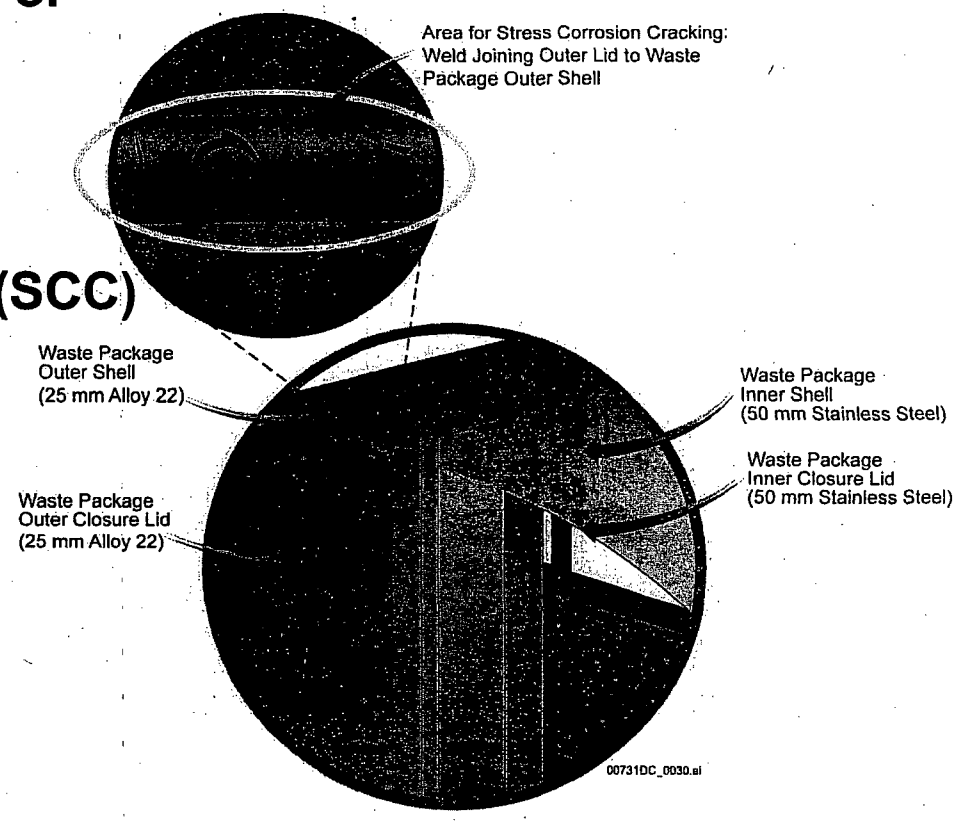


Model vs Data E_{corr}

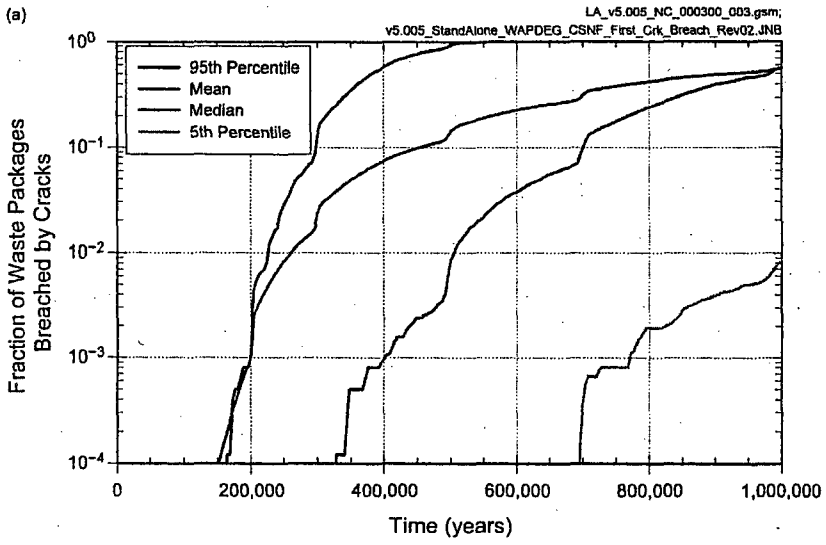
ANL-EBS-MD-000003 (fig 6-34,41)

Waste Package Stress Corrosion Cracking

- Only in closure weld regions (in absence of seismicity)
  - Weld region is plasticity burnished
  - Initiates at incipient defects or weld flaws
- Growth by Slip Dissolution Model
  - Stress Corrosion Cracking (SCC) Initiation Criterion of 90-105% of yield stress
  - Rate of crack growth a function of
    - Stress intensity factor
      - » Uncertainty
    - Repassivation rate
      - » Uncertainty

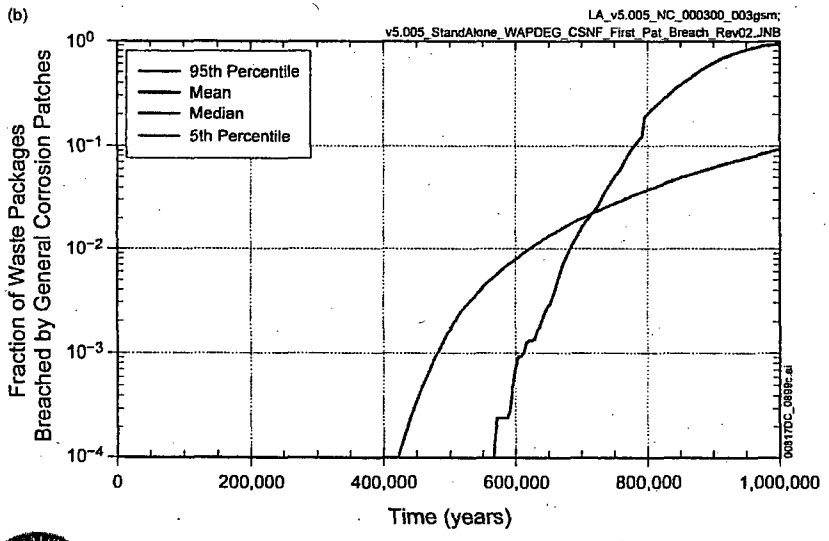


Nominal Scenario Waste Package Breaches



Crack Breaches (diffusive release)

Stress Corrosion Cracking



Patch Breaches (diffusive release if drip shield intact, advective release if drip shield failed)

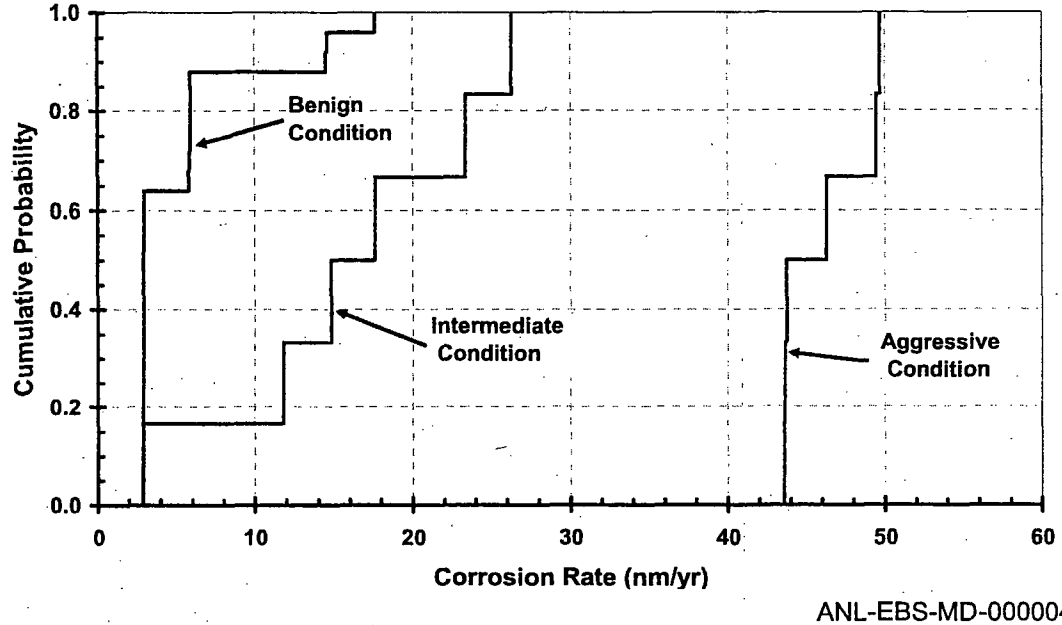
General Corrosion

Localized Corrosion

MDL-WIS-PA-000005 fig. 8.3-6[a]

Drip Shield General Corrosion

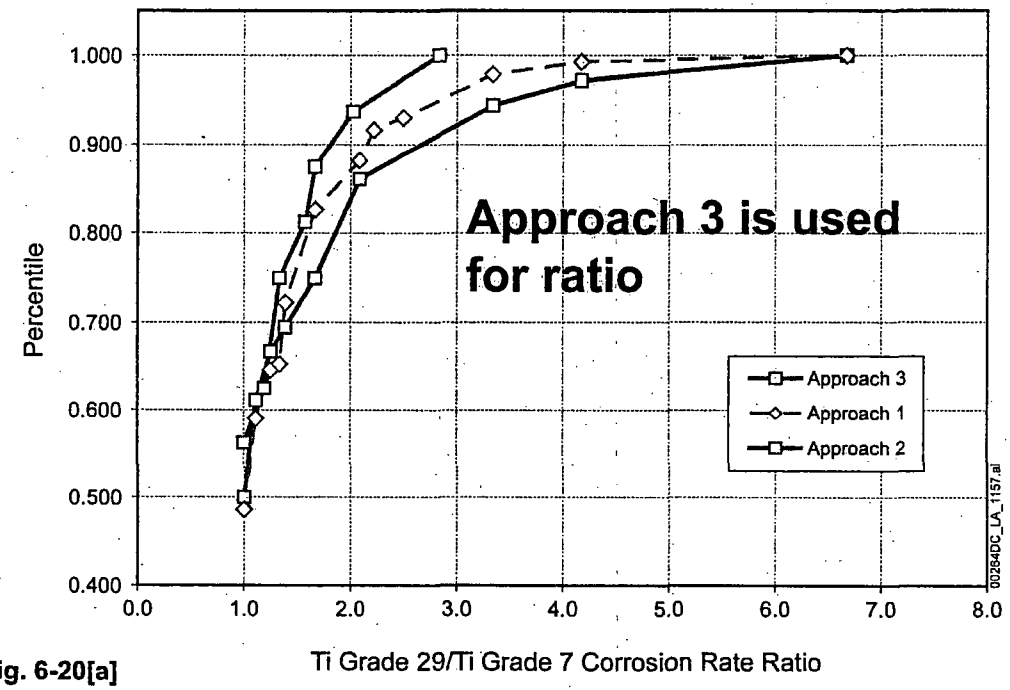
- Titanium grade 7 drip shield plates
  - Benign conditions on DS inner surface, aggressive conditions on outer surface
  - Uncertainty only
  - No temperature dependence



ANL-EBS-MD-000004 fig. 6-8[a]

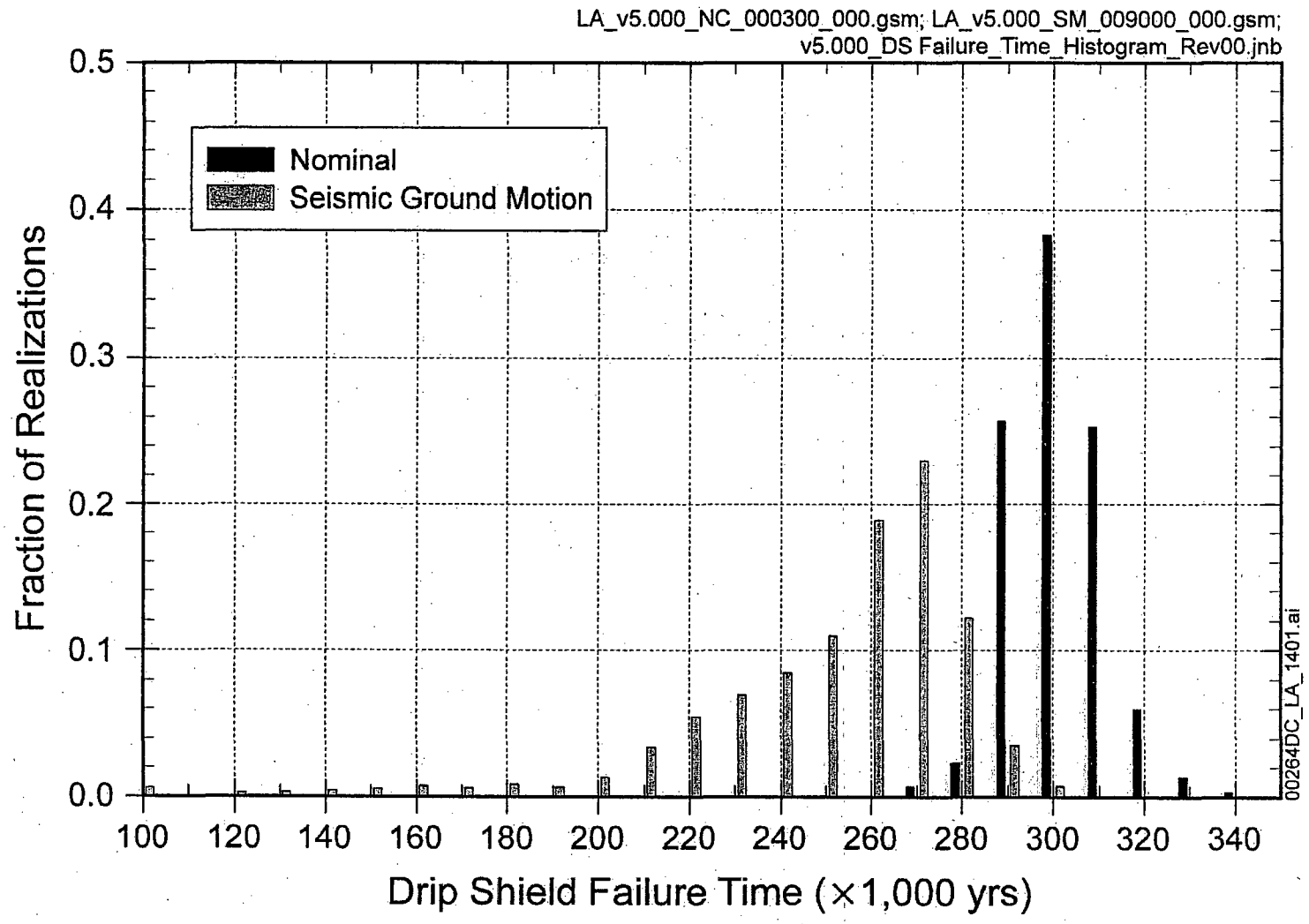
Drip Shield Structural General Corrosion

- **Titanium Grade 29 Structural Material**
  - Grade 7 aggressive condition rate is used multiplied by Grade 29/Grade 7 ratio
  - Ratio based upon CDF of corrosion rate ratios for several different conditions



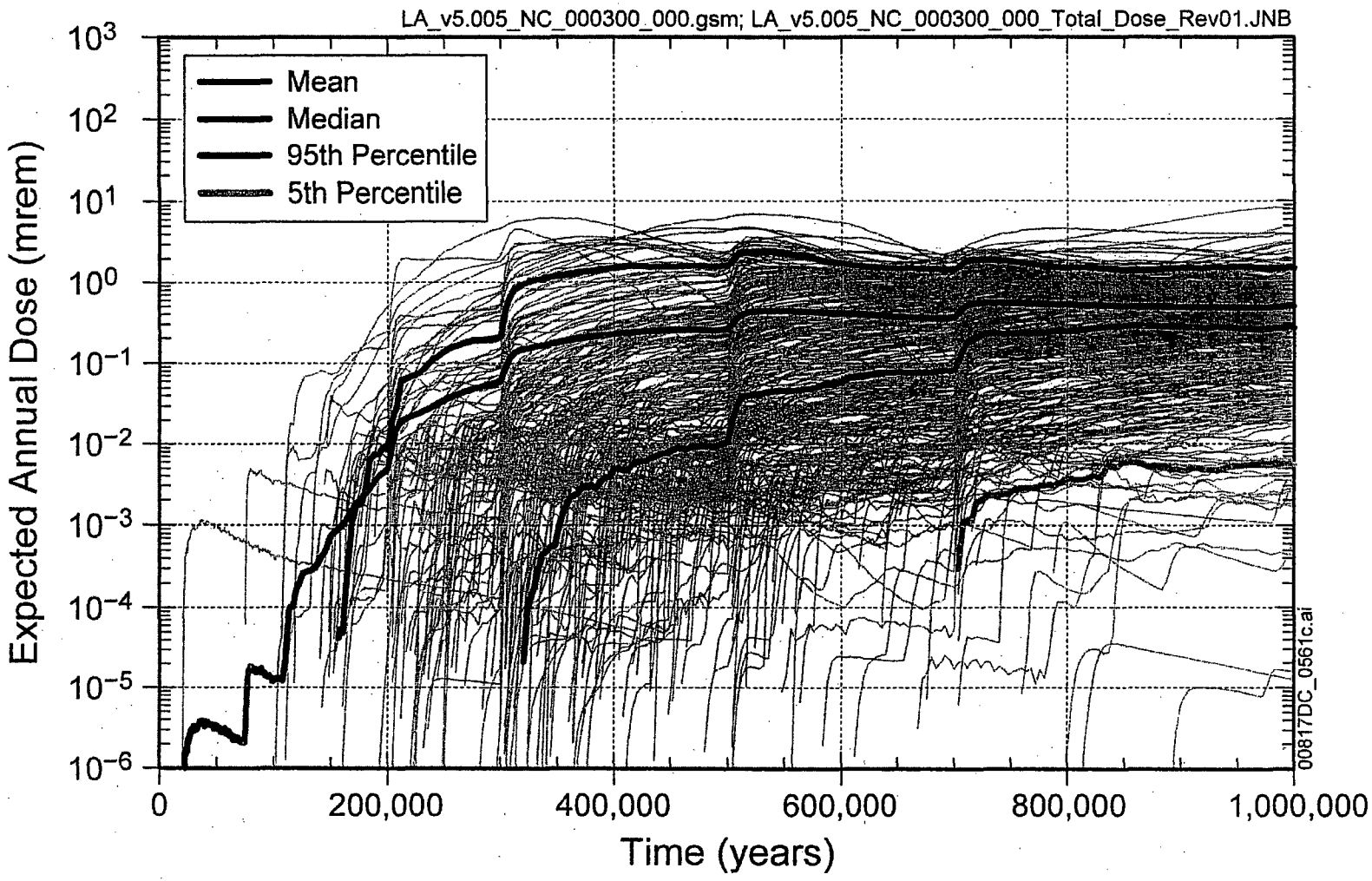
ANL-EBS-MD-000004 **fig. 6-20[a]**

Drip Shield Failures



MDL-WIS-PA-000005 fig 8.1-4 [a]

Dose Results Nominal Scenario



MDL-WIS-PA-000005 fig.8.2-1[a]

Summary

- Waste Package General Corrosion, Microbially Influenced Corrosion and Localized Corrosion:
  - Result in advective releases if drip shield has failed
  - Result in diffusive releases if drip shield is intact
- Waste Package Stress Corrosion Cracking:
  - Results in diffusive releases
- General corrosion results in waste package and drip shield thinning which feeds seismic consequence abstractions

Engineered Barrier System (EBS) Transport Model Abstractions

Presented to:
DOE/NRC Technical Exchange on Total System Performance Assessment (TSPA) for Yucca Mountain

Presented by:
Robert J. MacKinnon
Sandia National Laboratories

April 4, 2008
Las Vegas, Nevada

Presentation Outline

- EBS flow and transport model conceptualization
- Discretization for EBS flow and transport model
- Colloid facilitated transport (including sorption)
- Sorption model in the corrosion products domain
- EBS-unsaturated zone (UZ) interface – treatment of colloids
- EBS performance
- Summary

Objective of EBS Transport Abstraction

- Computes the advective and diffusive radionuclide mass flux through various components of the EBS once the waste package is breached and wasteform starts to degrade
- Provides time-dependent radionuclide mass flux from EBS to the fracture and matrix nodes of the UZ transport model

Inputs, Outputs, Basis for Model Confidence

EBS Thermal-Hydrologic Environment Submodel
- Liquid Saturation in Invert
- Temperature and Relative Humidity at Waste Package
- Imbibition Flux in Invert

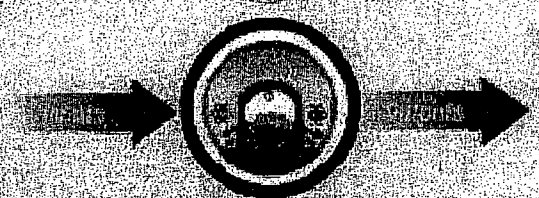
Waste Package and Drip Shield Degradation
- Time of Failure
- Number of Patch Breaches
- Number of SCC Breaches
- Number of Early Failed WPs
- Number of LC Failed WPs
- Number of GC and SCC Failed WPs

EBS Flow Submodel
- Flow Through the Waste Package and Invert

Waste Form Degradation and Mobilization
- Dissolved Concentration Limits
- Dissolution Rates
- Irreversibly Sorbed Radionuclide Mass on Colloid
- Reversibly Sorbed Radionuclide Mass on Colloid

Invert Material Properties
- Porosity and Diffusion Coefficients in Crushed Tuff

EBS Transport Submodel
- One-Dimensional Advective and Diffusive Transport Through the EBS
  - Retardation of Dissolved Species
  - Colloid Transport Included
  - Liquid Films Always Allow Diffusion Through WP Stress Corrosion Cracks



Unsaturated Zone Transport Submodel
- Radionuclide Mass Release Rate to the Unsaturated Zone

- Laboratory Data for Diffusivity of Unsaturated Crushed Tuff
- Process Level Modeling of EBS Response

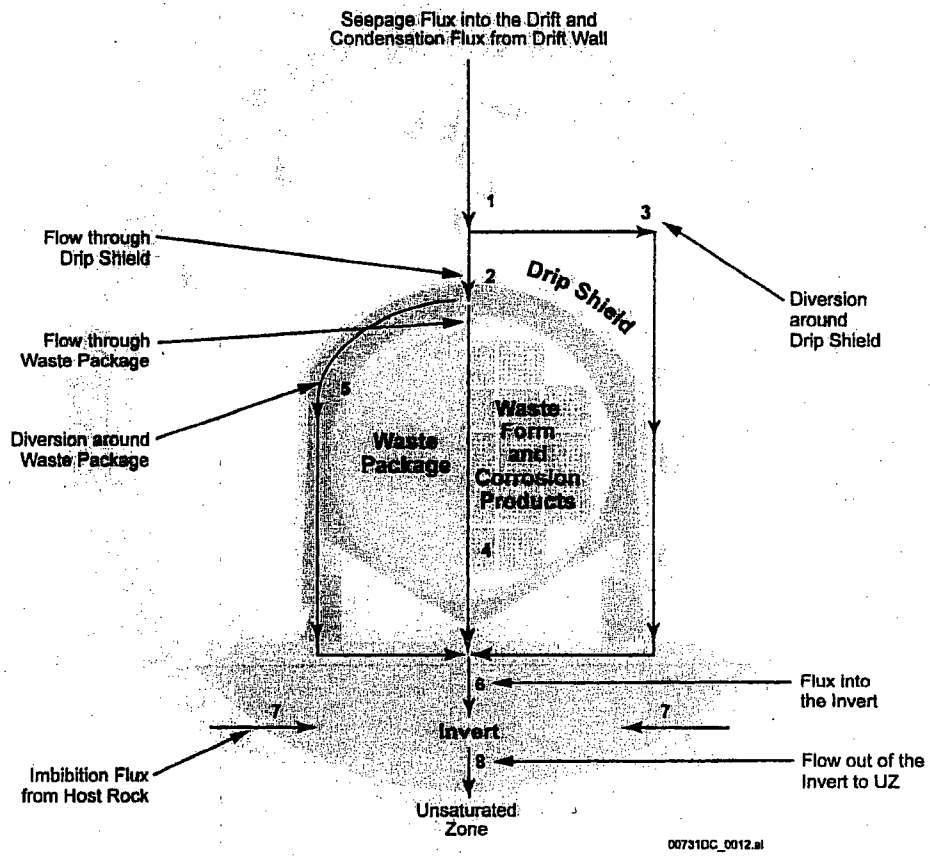
Model Confidence Foundation

Model Assumptions

- No diffusive or advective transport in the EBS when temperatures are above 100°C—source term can still degrade
- When T< 100°C but RH<95%, no diffusive transport in packages that have no seepage
  - Waste form degrades, but water is consumed in the chemical reactions (RH=95% corresponds to about 10 monolayers of adsorbed water)
- Presence of continuous thin films on the internals of the WP and waste form (when above two conditions are not applicable)
- WP is assumed to be in contact with the invert
  - Continuous thin water film assumed between WP and invert for diffusive transport
- All drift-seepage falls onto drip shield (DS), and all flux through the DS falls onto the WP

EBS Flow Conceptual Model

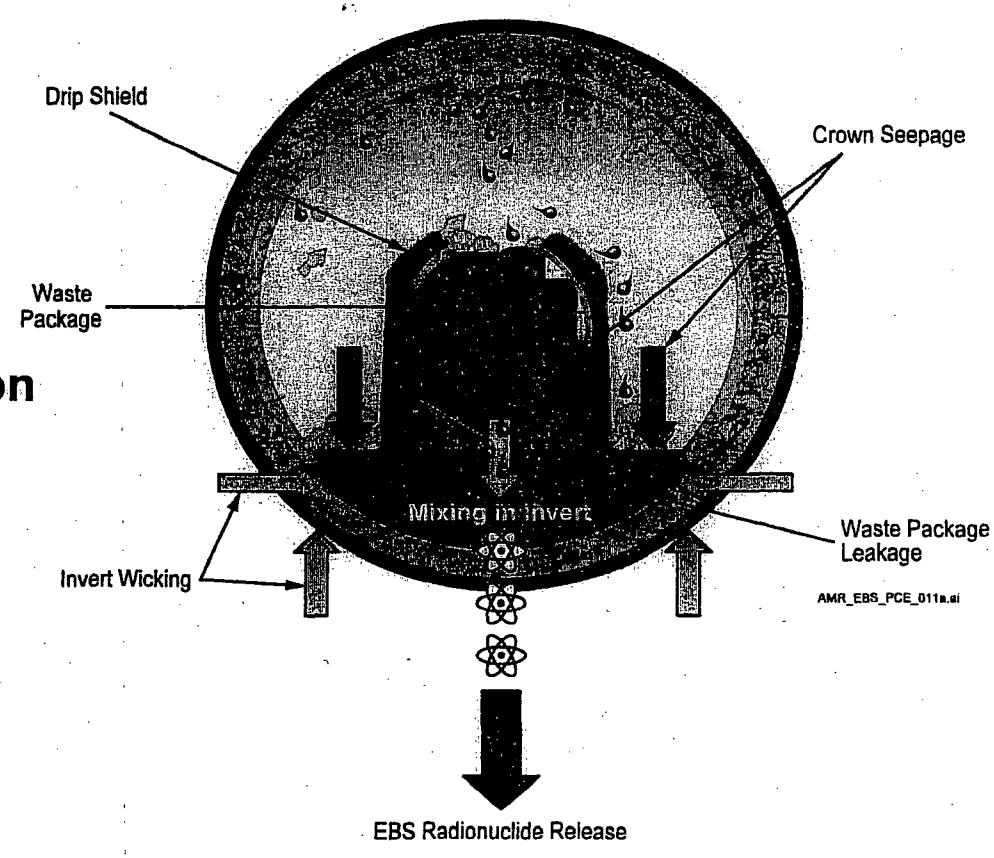
- EBS flow model describes the mass balance of water within various EBS components
- Continuity of flow assumed
- Evaporation is not modeled (conservative assumption)



Modified from ANL-WIS-PA-000001 REV 02

EBS Transport Conceptual Model

- After the waste form starts degrading, mass can be mobilized and released through the breached WP into the invert and to the UZ
- 1D and 2D advective and diffusive transport, including radioactive decay and (equilibrium and kinetic) sorption
- Species dependent free-water diffusion coefficient used
- Both dissolved and colloid-facilitated transport considered
- Effect of continued degradation of WP internals included (metal corrosion products)

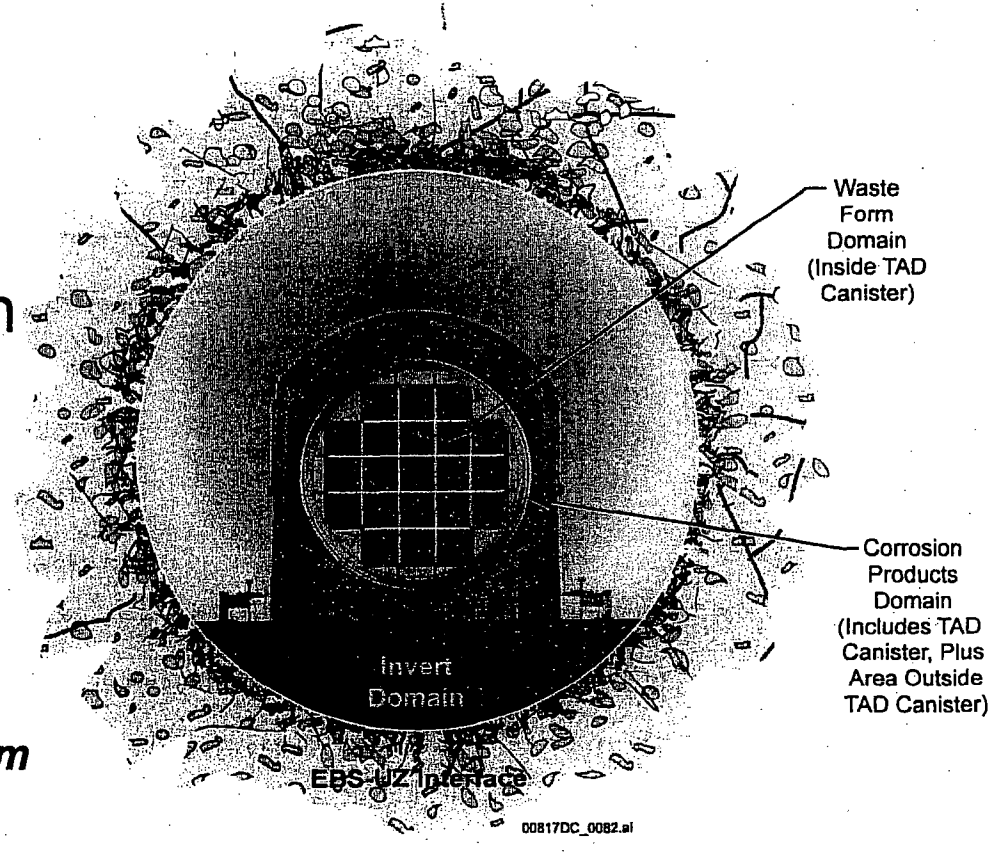


- Chemical conditions inside the WP and invert determined separately (for solubility and colloid stability calculations)

Spatial Discretization for EBS Transport

Four Transport Domains:

- Waste Form Domain
- Corrosion Products Domain
- Invert Domain
- EBS-UZ Interface Domain

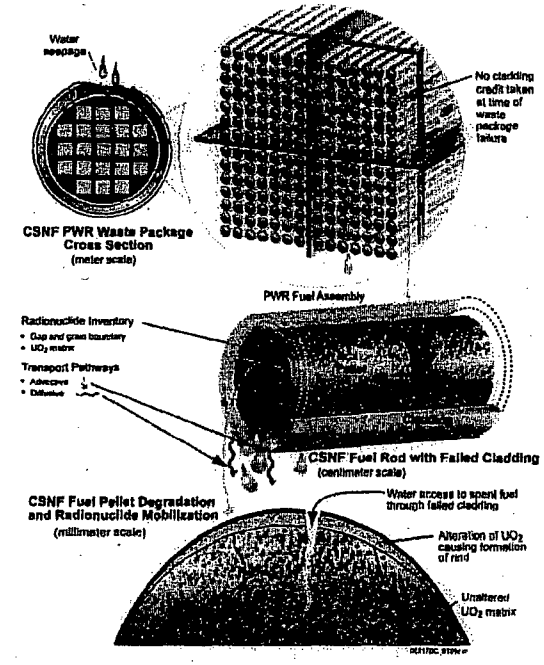


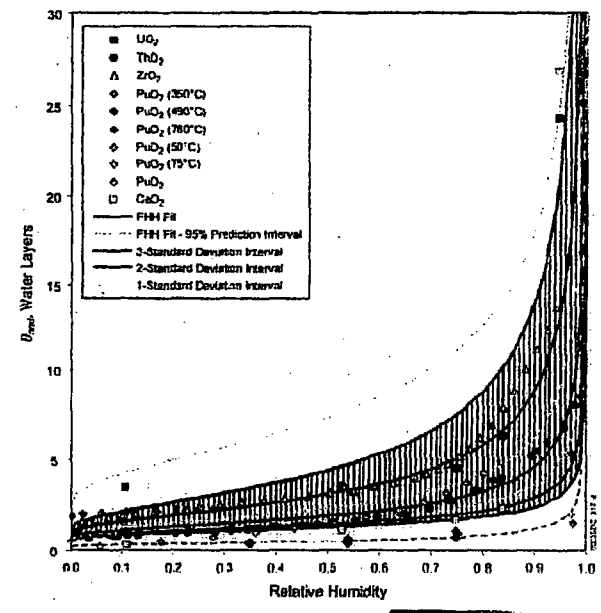
CSNF WP Configuration

Note: For Codisposal WP the Waste Form Domain is further divided into HLW and DSNF waste form subdomains

WF Domain—Implementation

- Commercial spent nuclear fuel (CSNF)—single waste form domain
  - represents fuel rods and steel inside the TAD canister
- Co-disposal—two WF subdomains
  - HLW (glass logs) and DSNF with canister steel and steel support tubes
- WF colloids are generated
- Pore volume is time-dependent and grows as both waste form and steel degrades (no cladding credit taken)
- Saturation is computed from water vapor adsorption isotherms when there is no advection after the breach; full saturation assumed in cases where there is advection



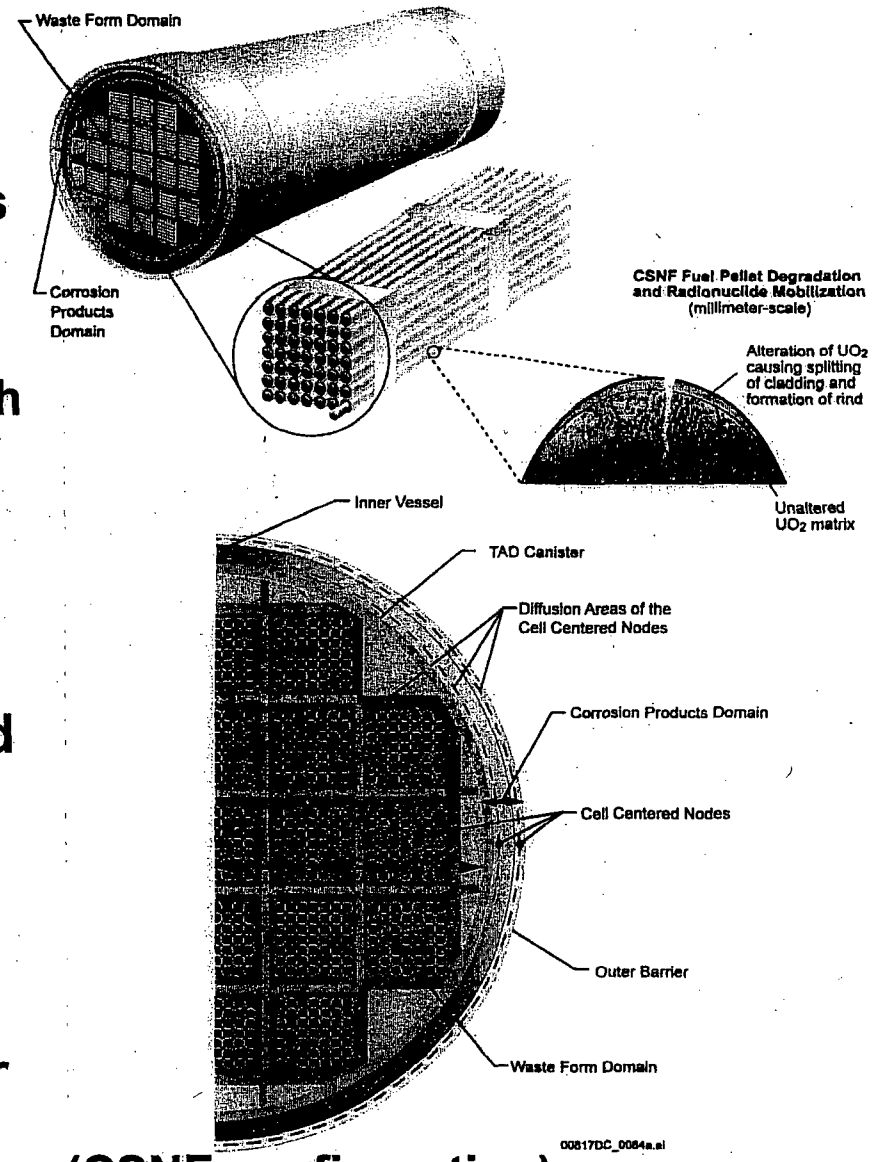


WF Domain—Implementation (continued)

- Waste form domain is conceptualized as a homogenous mixture of fuel and steel components
  - Volume expansion associated with fuel alteration and corrosion products formation is expected to fill up the inside of TADs canister for CSNF and the inner vessel for CDSP WPs
- Diffusive length and area is based on the geometry (as shown)
- Diffusion coefficient (assumes porous medium, Archie's law):

$$D_{WF} = \phi^{1.3} S_w^{\,2} D_0$$

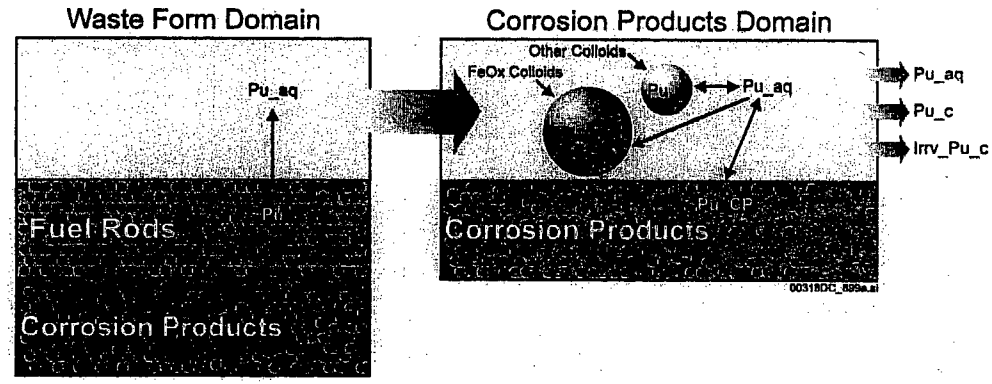
- Diffusion coefficient corrected for temperature

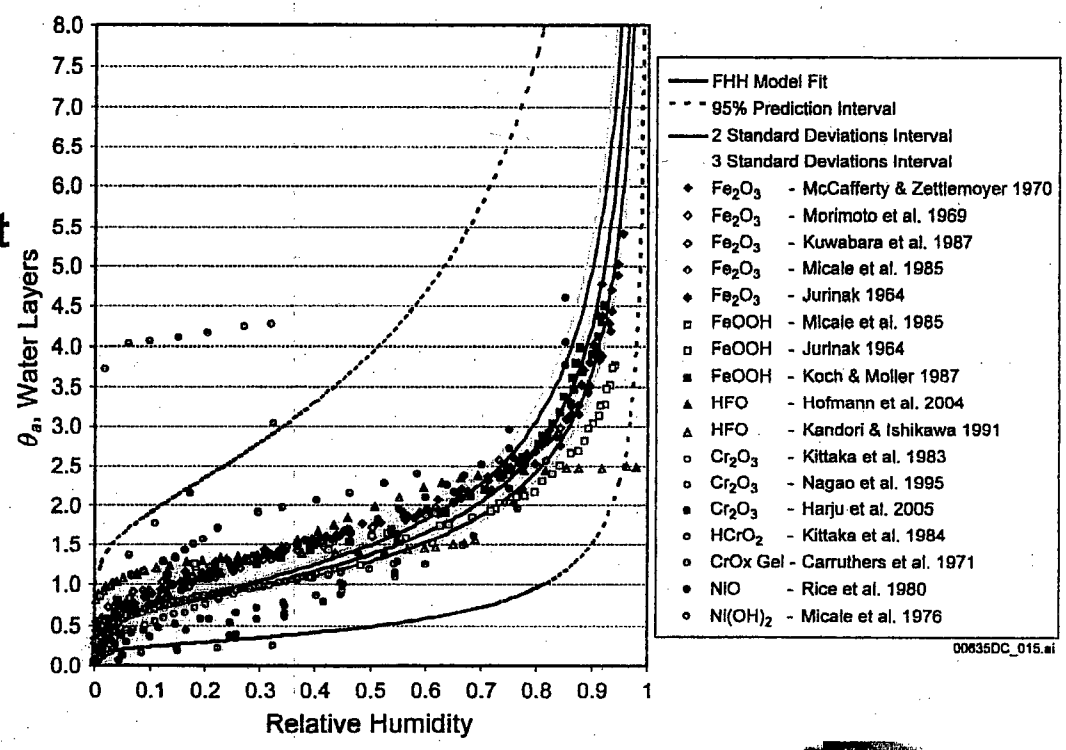


(CSNF configuration)

Corrosion Product Domain—Implementation

- Represents steel corrosion products (iron oxyhydroxides) from degradation of steel that is outside the fuel basket or fuel canisters
- Equilibrium and kinetic sorption modeled on the stationary corrosion products and on the iron oxyhydroxide colloids
- Pore volume is time-dependent and grows as steel degrades
- Saturation is computed from water vapor adsorption isotherms when there is no advection after the breach; full saturation assumed in cases where there is advection



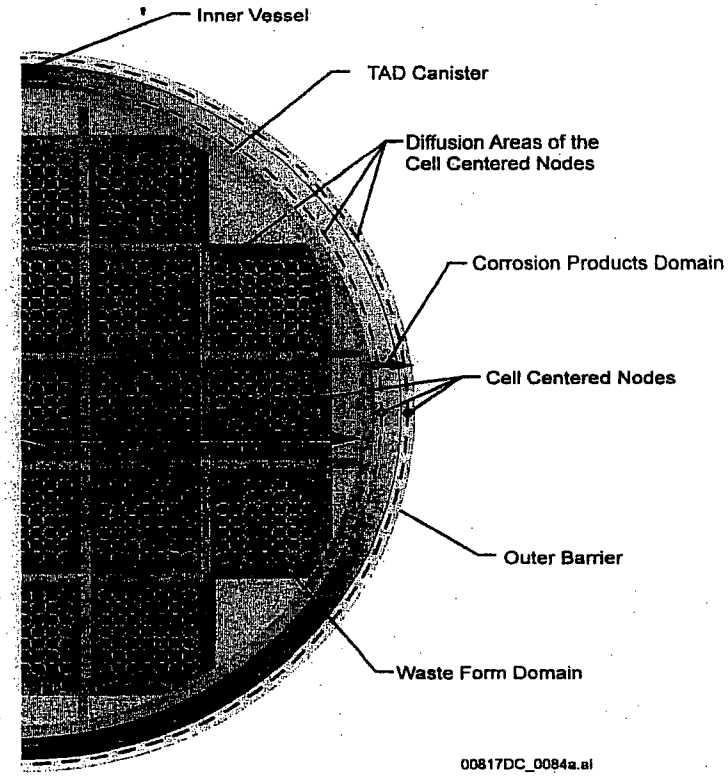


Corrosion Product Domain—Implementation
(continued)

- This domain is divided into two cells:
  - Corrosion Products cell
  - Outer Barrier cell
- Diffusive length and areas are based on the geometry, however, the diffusive area for the outer barrier cell is the breach area that varies by the scenario class being modeled
- Diffusion coefficient (assumes porous medium, Archie's law)

$$D_{CP} = \phi_{CP}^{1.3} S_w^{2} D_0$$

- Diffusion coefficient also corrected for temperature



(CSNF configuration)

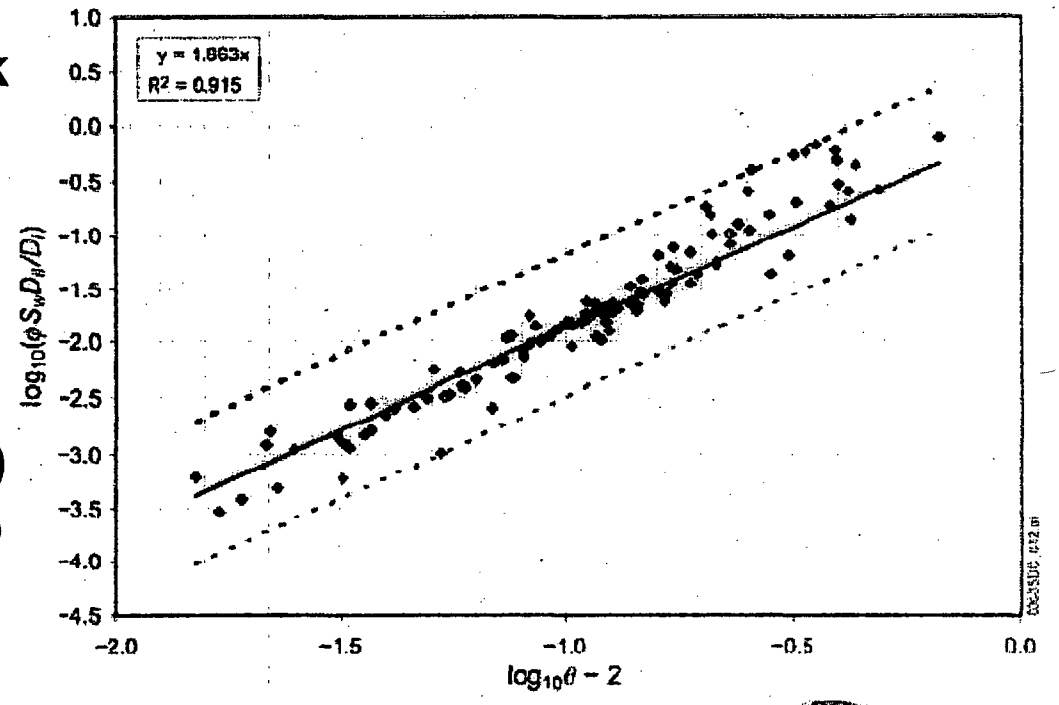
Invert Domain—Implementation

- Assumes rectangular geometry (fixed diffusive length and area)
- Reversible sorption on the crushed tuff modeled (same as that for devitrified rock unit in the UZ transport model)
- Stability checked for all colloids moving from WP to invert (groundwater colloids can occur in the invert if there is drift-seepage)
- Water volume of invert is based on computing the bulk water content from dual continuum representation of invert: intergranular and intragranular continuum
- Diffusion Coefficient:

  (based on experimental data)

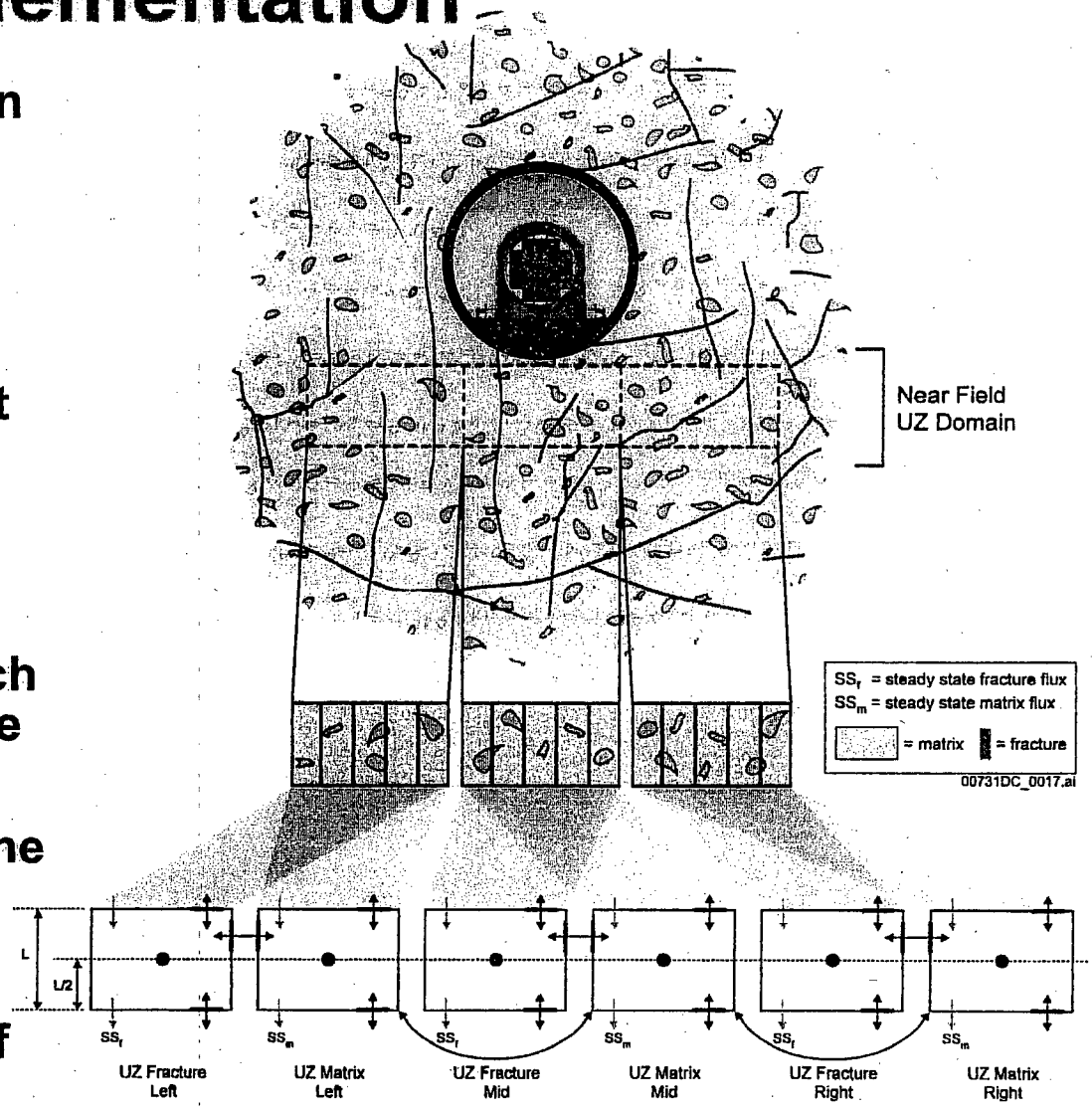
$$D = D_0 \phi^{1.863} S_w^{1.863} 10^{ND(\mu=0.033,\sigma=0.218)}$$

(*ND* = Normal Distribution)



EBS-UZ Interface Model Domain—Implementation

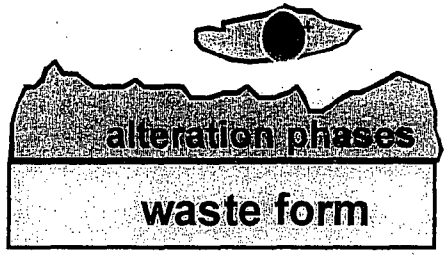
- 2-D dual continuum UZ domain (fracture and matrix continua)
- Reversible sorption in the UZ matrix continuum
- Hydrologic properties and percolation flux are consistent with the 3-D UZ model
- Mass flux (g/yr) going from invert to UZ domain is intercepted and passed to UZ transport model (FEHM) at each time step for each radionuclide
- Mass flux introduced into fracture and matrix nodes of the UZ transport model (FEHM) is <u>based on</u> the advective and diffusive mass flux going into the fracture and matrix cells of the EBS-UZ domain



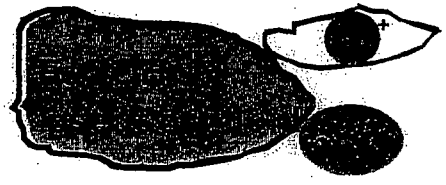
Colloid Facilitated Transport in EBS

Three classes of colloids modeled. Complex mineralogies are simplified for purposes of modeling:

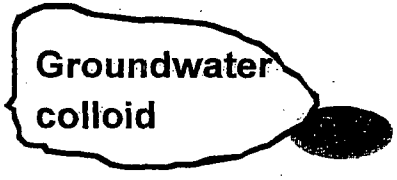
- **Waste form colloids**
  - Smectite mineralogy (HLW degradation)
  - Uranophane mineralogy (from CSNF and DSNF)
  - Pu-Zr oxide mineralogy (from CSNF degradation)



- **Iron oxyhydroxide (corrosion product) colloids**
  - Ferrihydrite and goethite mineralogy for sorption (Hematite mineralogy for stability calculation)



- **Groundwater (seepage water) colloids**
  - Smectite mineralogy



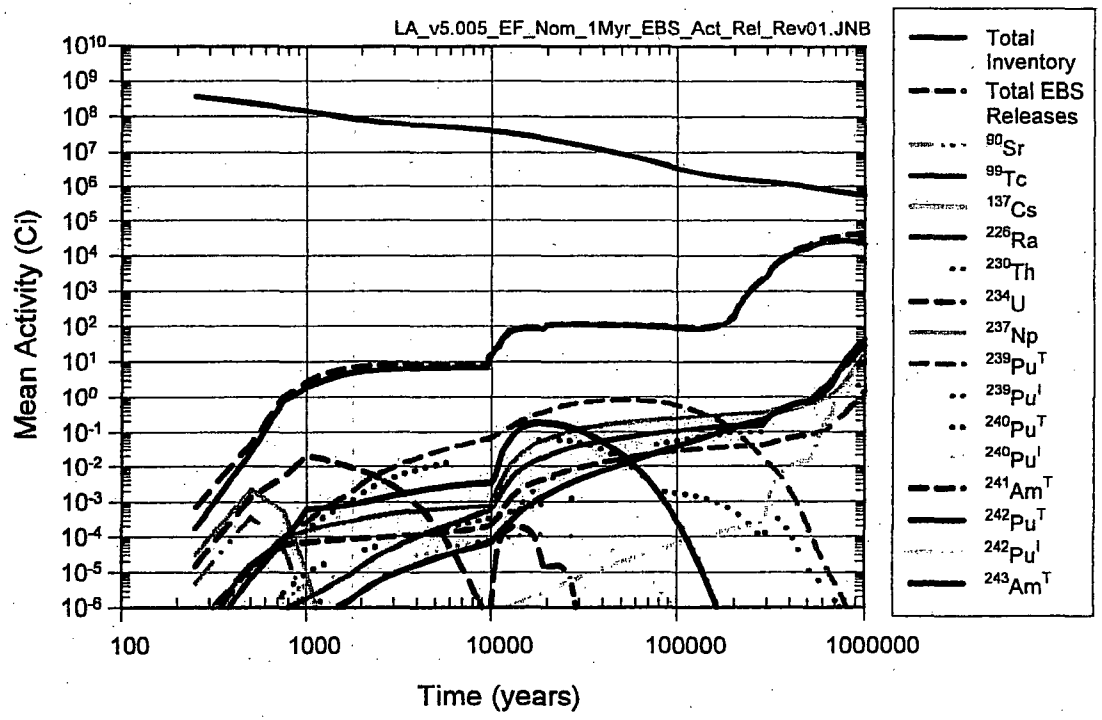
Sorption of Radionuclides on Colloids

- Type of Sorption on Colloids:
  - Waste form colloids
    - » HLW glass degradation colloids – reversible and irreversible
    - » SNF uranium mineral colloids – reversible
    - » CSNF degradation rind colloids – irreversible
  - Iron oxyhydroxide colloids – reversible and irreversible
  - Groundwater colloids – reversible
- Reversible sorption on waste form and groundwater colloids modeled for 9 elements: U, Np, Pu, Am, Cs, Pa, Th, Sn, and Ra (in all domains)
- Sorption on iron oxyhydroxide colloids is based on surface complexation based competitive sorption model for 5 elements: U, Np, Pu, Am, and Th (in corrosion products domain)
- Irreversible sorption modeled for only two elements: Pu and Am as a kinetic process (only in the waste form and corrosion products domain)
- Reversible sorption on waste form and groundwater colloids is based on sampled linear adsorption isotherm (K_d)
  - Initially sampled K_d may be further adjusted to limit sorption from exceeding the sorption capacity. Sorption sites are partitioned linearly amongst the radionuclides based on their sampled K_d and dissolved concentration in solution

Sorption Model in Corrosion Products Domain

- A surface complexation based competitive sorption model is developed for radionuclide sorption on stationary corrosion products and iron oxyhydroxide colloids
- The elements considered for competitive sorption are U, Np, Pu, Am, Th, and Ni along with carbonate ions
  - (Cr and Mo are much lower in concentration and thus not modeled; Ca^{2+}, Mg^{2+}, and SO_4^{2-} have small binding constants and thus have negligible effect; not modeled in final calcs.)
- Also used to compute the pH in the corrosion product domain
- Sorption only applied to steel degradation products in the corrosion products domain
  - Sorption on corrosion products in the Waste Form domain is ignored
- Sorption only modeled on iron oxides (ferrihydrite and goethite) from degradation of steel
  - Sorption on NiO and Cr_2O_3 is conservatively ignored

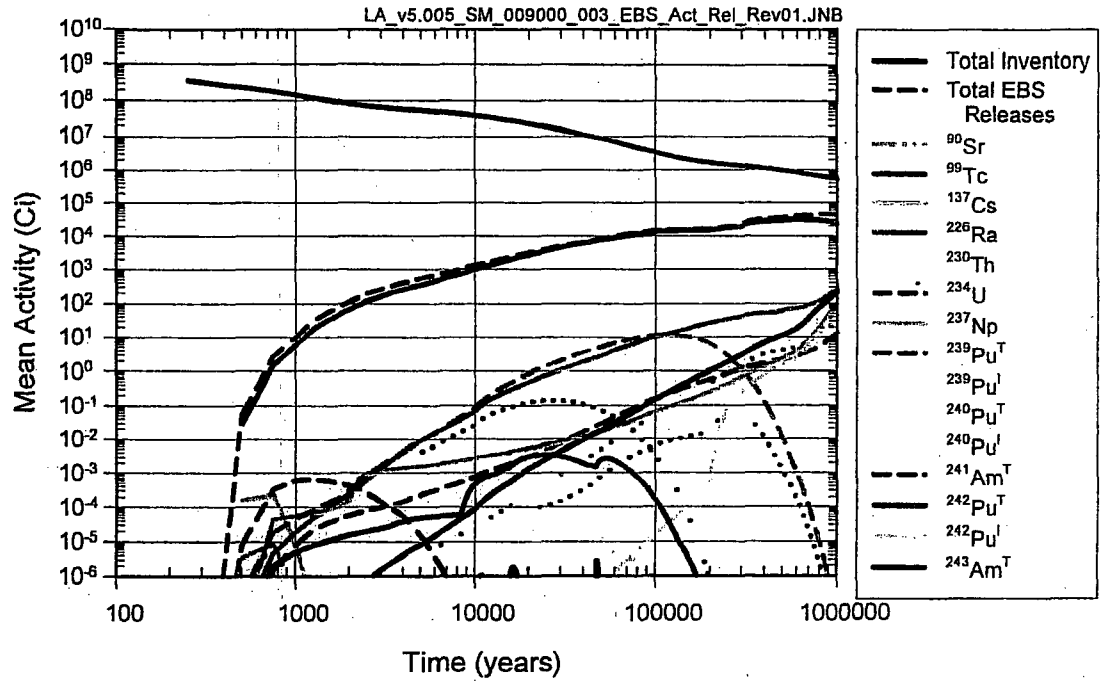
EBS Performance—Combined Nominal and Early Failure Modeling Cases



- Prior to 170,000 years releases are primarily from early WP failure and early DS failure. Afterwards, primarily from WP failure due to nominal processes
  - Expected number of EF WP = 1.09 (dominant contributor)
  - Expected number of EF DS = 0.018 (smaller contributor)
- DS failure times (from general corrosion) range between 270,000 and 340,000 years
- Increase in release around 10,000 years is due to contribution from early failure of CSNF WP. Prior to that the release is from early failure of CDSP WP
  - Note: No diffusive releases from WP while RH < 95% and T < 100°C (under no flow conditions inside WP).
- About 69% of the WPs are in the non-seeping environment (31% in seeping environment). This affects the mass fraction going to UZ fractures vs. UZ matrix

- Radionuclides that are modeled as non-sorbing with no solubility limit are released rapidly following waste-form degradation (e.g., ^{99}Tc, ^{129}I)
- Solubility limits the dissolved concentration of actinides in waste form domain
- U, Np, Pu, Am, and Th undergo reversible sorption on the stationary corrosion products (also separately on the crushed tuff in invert). Superscript "I" represents mass associated irreversibly with colloids. "T" denotes total mass.
- Nominal releases are mostly from diffusion due to larger number of WPs failing by SCC. Patches are unlikely prior to 600,000 years
  - Diffusion coefficient of colloids is significantly smaller than dissolved species

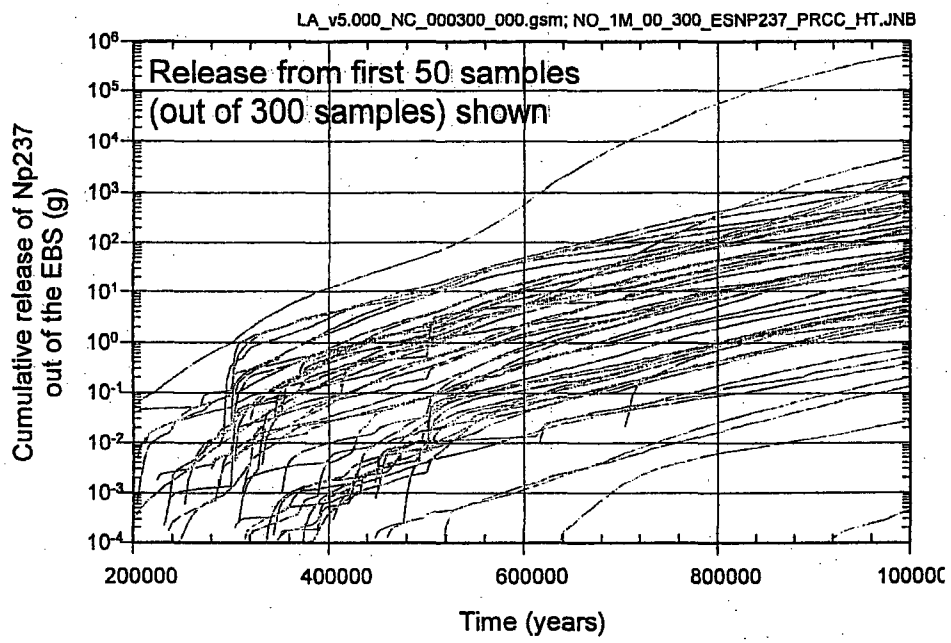
EBS Performance—
Seismic Ground Motion Modeling Case

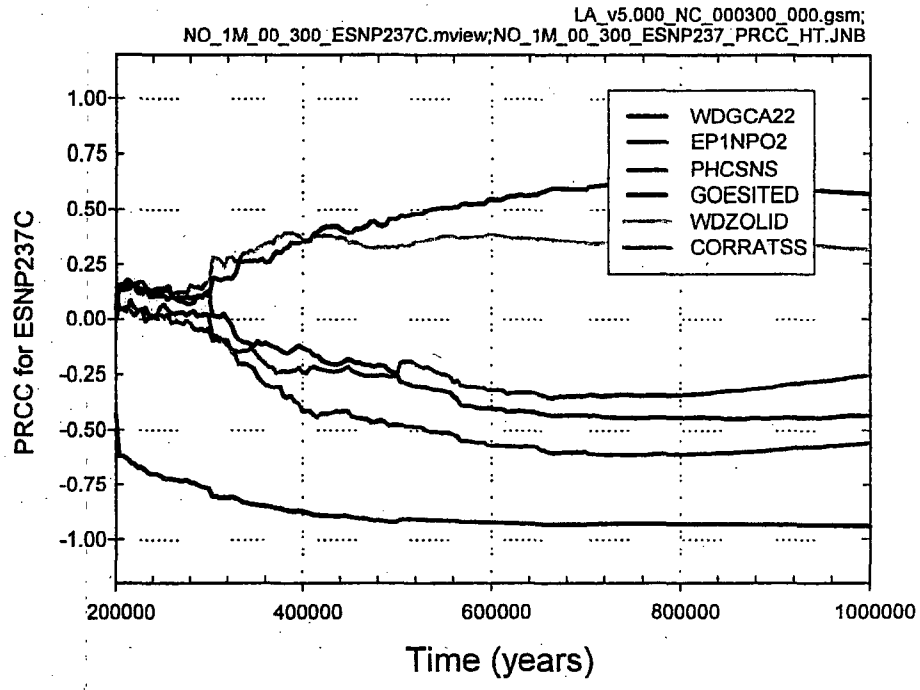


- Prior to 170,000 years releases are primarily from processes related to vibratory ground motion-induced WP failures.
- Between 170,000 and 600,000 years contribution to releases are from both nominal and vibratory ground motion-induced DS and WP failures
- Past 600,000 years releases are primarily from failure of WPs by nominal processes
- Seismically-induced SCC of the CSNF WPs is not likely prior to 61,000 years, whereas that for CDSP WPs may occur much earlier
  - In the first 10,000 years CDSP WPs are the predominant contributors to the release
- DS failure times (from combined seismically-induced ruptures and general corrosion) range from about 40,000 years and 300,000 years
- About 30% of the WPs are in the non-seeping environment (70% in seeping environment) for the post-10,000 year period due to ground motion-induced drift collapse. This affects the mass fraction going to UZ fractures vs. UZ matrix

- Radionuclides that are modeled as non-sorbing with no solubility limit are released rapidly following waste-form degradation (e.g., ^{99}Tc, ^{129}I)
- Solubility limits the dissolved concentration of actinides in waste form domain
- U, Np, Pu, Am, and Th undergo reversible sorption on the stationary corrosion products (also separately on the crushed tuff in invert). ^{226}Ra release is derived from decay of the parent radionuclides (^{230}Th and ^{234}U)
- Opening area resulting from SCC from ground-motion damage is greater than that from SCC from nominal processes leading to larger diffusive area
  - Patches are unlikely prior to 300,000 years

EBS Release of ^{237}Np— Nominal Modeling Case





Epistemically Uncertain Variables with Largest Partial Rank Correlation Coefficients (PRCC):

WDGCA22 : Temperature dependent slope term of Alloy 22 general corrosion rate (Kelvin)
EP1NPO2: Logarithm of the scale factor used to characterize uncertainty in NpO2 solubility at an ionic strength below 1 modal
PHCSNS: Pointer variable used to determine pH in CSNF Cell 1 under vapor influx conditions
GOESITED: Density of sorption sites on goethite (sites/nm^2)
WDZOLID: Deviation from median yield strength range for outer lid (dimensionless)
CORRATSS: Stainless steel corrosion rate (μm/yr)

Summary

- EBS transport model computes the advective and diffusive radionuclide mass flux through various components of the EBS once the waste package is breached and waste form starts to degrade
- Provides time-dependent radionuclide mass flux from EBS to the fracture and matrix nodes of the unsaturated zone (UZ) transport model
- Both dissolved and colloid-facilitated transport considered; three classes of colloids modeled
- A surface complexation based competitive sorption model is implemented for radionuclide sorption on stationary corrosion products and iron oxyhydroxide colloids
- Summarized key aspects of EBS performance that determine transport and release of radionuclides in the combined nominal/early failure demonstration modeling case and seismic ground motion modeling case

U.S. Department of Energy
Office of Civilian Radioactive Waste Management

www.ocrwm.doe.gov

Disruptive Scenario Classes: Seismic Consequence Abstraction

Presented to:
NRC/DOE Technical Exchange on Total System Performance Assessment for Yucca Mountain

Presented by:
S. David Sevougian
Sandia National Laboratories

April 04, 2008
Las Vegas, Nevada

Presentation Outline

- Definition of seismic scenario class
- Key characteristics and assumptions of seismic consequence models
- EBS State 1 abstractions: initial configuration
- EBS State 2 abstractions: after drip shield framework failure
- EBS State 3 abstractions: after drip shield plate rupture
- Seismic fault displacement abstraction
- Other processes
- Example results

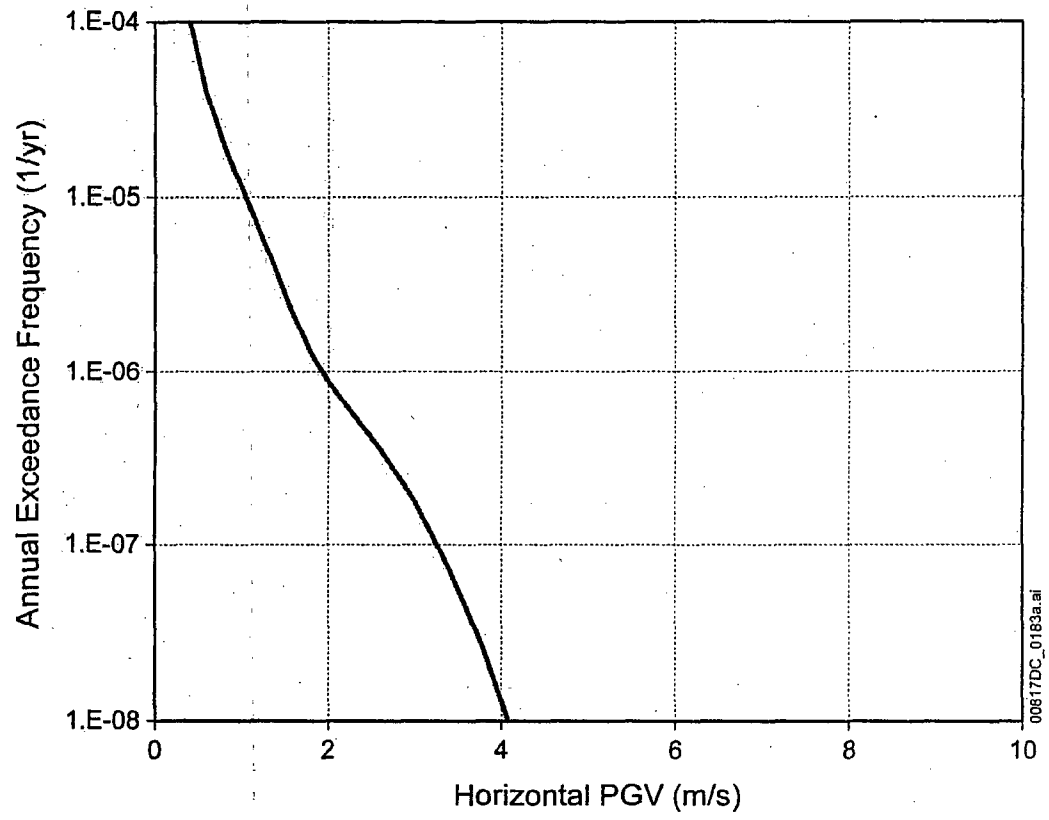
Definition of Seismic Scenario Class

- The seismic scenario class is defined as the set of possible repository futures that contain one or more seismic events
- The seismic scenario class includes all FEPs that are part of the nominal scenario class (all "expected" FEPs), plus FEPs associated with seismicity
- Two TSPA modeling cases:
  - Seismic ground motion modeling case
  - Seismic fault displacement modeling case

Definition of Seismic Scenario Class

(continued)

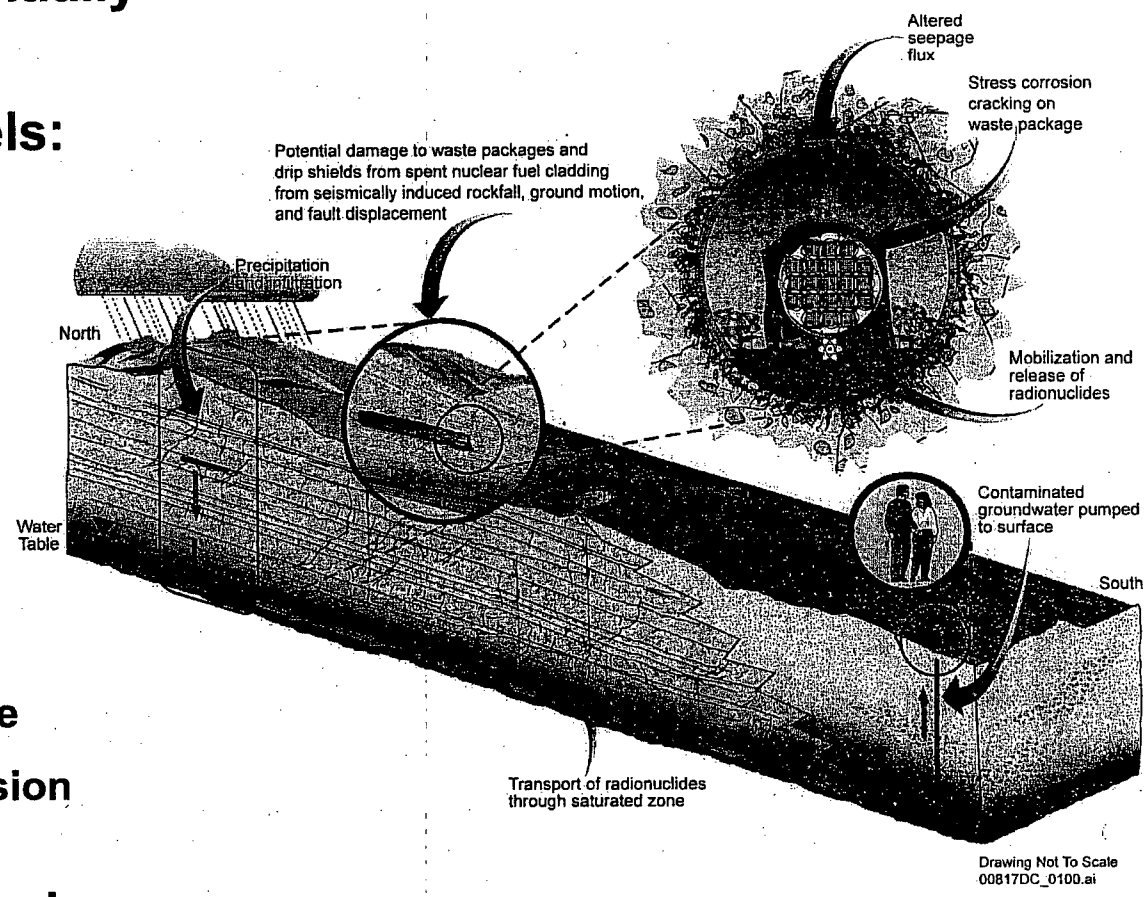
- The annual exceedance frequency (λ) of seismic events of varying magnitudes (PGV) is defined by the (mean) bounded seismic hazard curve
- Not all events can cause Engineered Barrier System (EBS) damage; small PGVs (i.e., more frequent, but small, events) are unlikely to have a consequence
- For most events of any magnitude, damage to the waste package (WP) is generally in the form of very small stress corrosion cracks (resulting from residual stresses caused by plastic deformation)



MDL-WIS-PA-000005, Figure 6.6-6

Conceptual Model—Overview

- Source term—Ground motion time history from a potentially damaging seismic event
- EBS consequence models:
  - Rubble accumulation and loading in drift
  - Drip shield (DS) fragility (static and dynamic loading)
  - WP damage when DS is intact: cracking or rupture
  - WP damage after DS has failed: cracking or puncture
  - Nominal WP and DS corrosion processes
- Changes to thermal hydrology, seepage, and transport



MDL-WIS-PA-000005, Figure 6.6-4

Characteristics of Seismic Consequence Models

- Most of the following presentation describes the seismic ground motion abstractions (rather than the fault displacement abstraction)
- Seismic scenario class includes both nominal and seismic degradation processes in the EBS
- Nominal and seismic WP degradation processes are strongly coupled through the thickness of the Alloy 22 outer barrier and the state (intact or degraded) of the WP internal structures
- General corrosion patch and stress corrosion cracking (SCC) failures in the WPs occur due to nominal corrosion processes
- Seismic DS damage in the form of framework buckling and plate rupture is based on
  - The thickness of the DS components, which is determined by the titanium general corrosion rate
  - The dynamic loading on the DS from rubble and vibratory ground motion (i.e., as a function of the PGV level of the seismic event)

Characteristics of Seismic Consequence Models

(continued)

- Seismic damage to WPs depends on the presence of the DS:
  - For intact DSs, SCC damage to the WP occurs through package-to-pallet impacts (most important) and package-to-package impacts (nearly negligible); there is a small chance of rupture damage
  - For failed DSs (by general corrosion, ground motion, rubble loading), crack damage to the WP occurs from stresses induced by the surrounding rubble during strong ground motions; there is a small probability of puncture of the WP by internal fragments
- Effect of fault displacement failures ($\lambda < 2.5\times10^{-7}$ per yr) is expected to be small
- Cladding credit not taken in TSPA Model
  - Cladding would be completely damaged in long timeframes based on simple fragility models

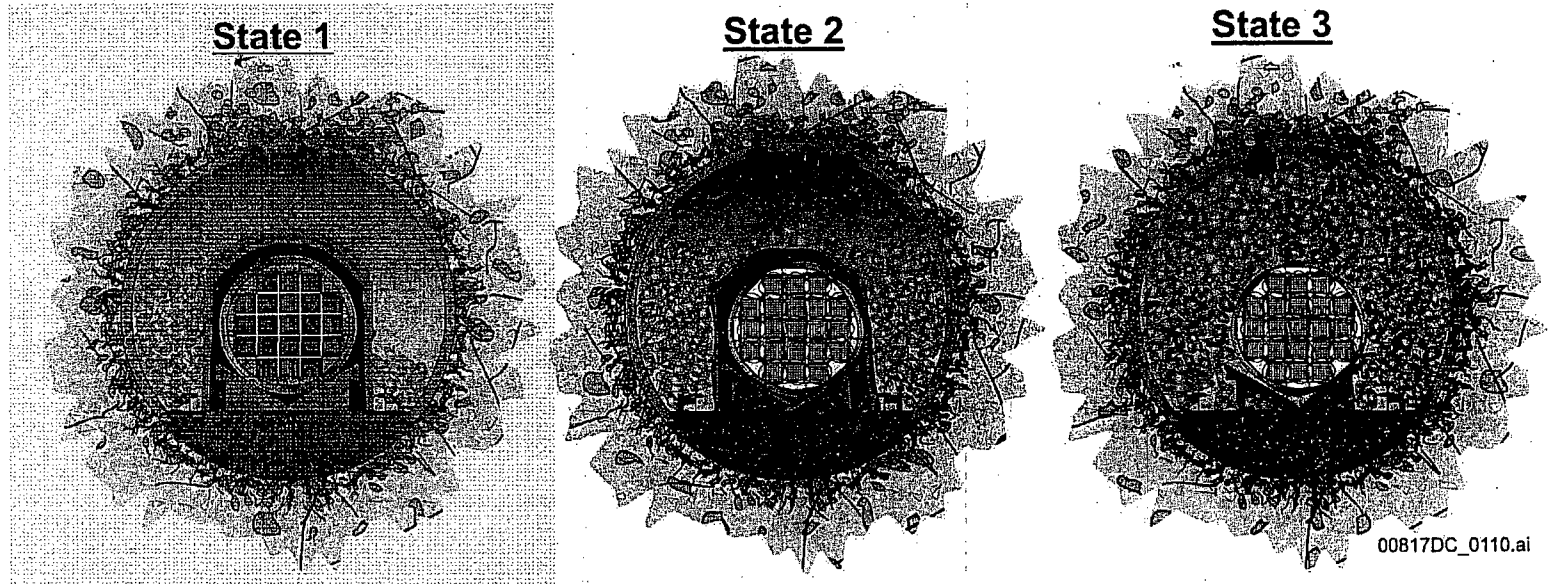
Model Assumptions

- The initial mechanical condition (or strength) of EBS components (WP or DS) for each event is a function only of spatially averaged thickness (due to general corrosion thinning), i.e., previous seismic damage does not affect the strength or configuration of the EBS components, with two exceptions :
  - State of waste package internals: intact or degraded
  - WP rupture model when the DS is intact: incipient or immediate ruptures
- Total WP and DS damaged areas from multiple events is the sum of the damaged areas from the individual events
- Total rubble accumulation from multiple events is the sum of the rubble from the individual events
- No explicit spatial variability in the TSPA model for damaged areas on WPs and DSs from vibratory ground motion, except for that due to coupling with nominal processes (however, drift-scale variability is incorporated in the underlying process-level damage abstractions)

Treatment of Uncertainty

- Aleatory uncertainty in the time of event, PGV of the event (seismic hazard curve), ground motion time history for a given event, occurrence and extent of WP damage, occurrence of DS failure, and rockfall volume
- Epistemic uncertainty in the friction coefficients, residual stress thresholds to initiate stress corrosion cracking in Alloy 22, general corrosion rates of Alloy 22 and Ti Grade 7 and Ti Grade 29

Conceptual Model for EBS Evolution



(a) Initial Configuration

(b) After Drip Shield Framework Failure

(c) After Drip Shield Plate Failure

Kinematic analyses and damage catalogs define damaged areas for a WP moving freely beneath the DS. WP SCC or rupture may occur, degrading internals

Fragility analysis for buckling of DS framework. Additional WP damage may occur

Fragility analysis for rupture of DS plates. WP damage defined by 2-D calcs for WP surrounded by rubble

DS Failure

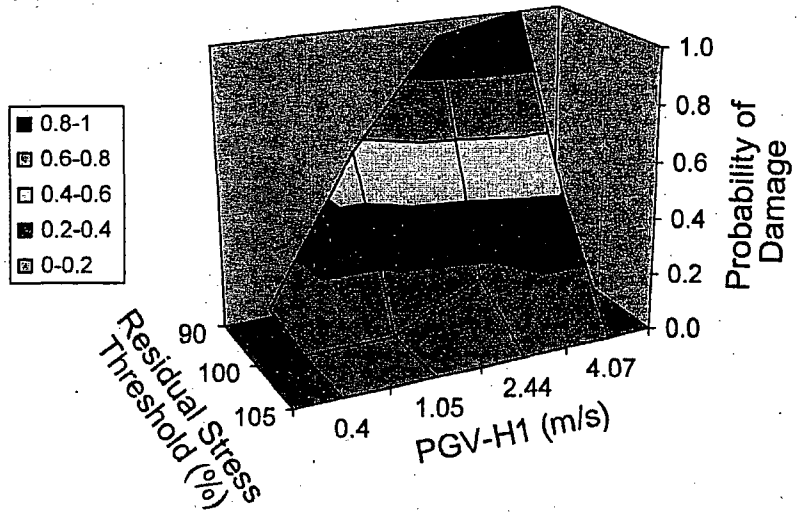
Time

MDL-WIS-PA-000005, Figure 6.6-5

EBS State 1 SCC Damage: (Intact DS, Intact Internals)

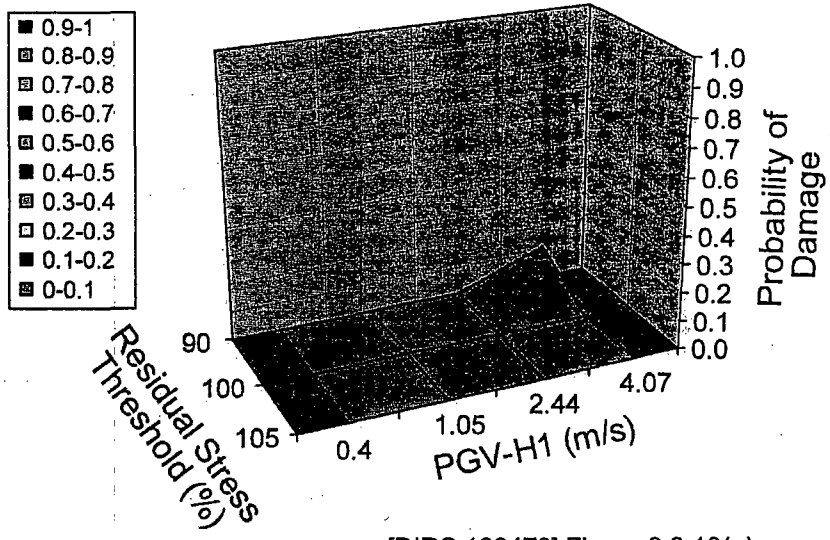
- **Codisposal WP probability of SCC damage for a 23-mm thick**

(a)



- **CSNF WP probability of SCC damage for a 23-mm thick**

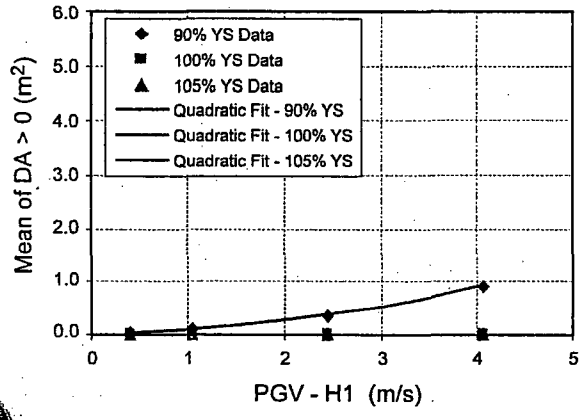
(a)



[DIRS 183478] Figure 6.6-10(a)

- **Codisposal WP mean damage area for a 23-mm thick**

(a)

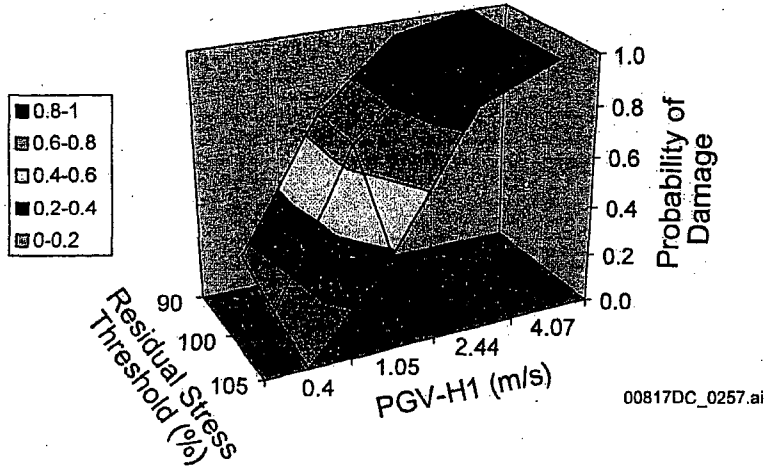


MDL-WIS-PA-000005, Figures 6.6-11 and 6.6-13

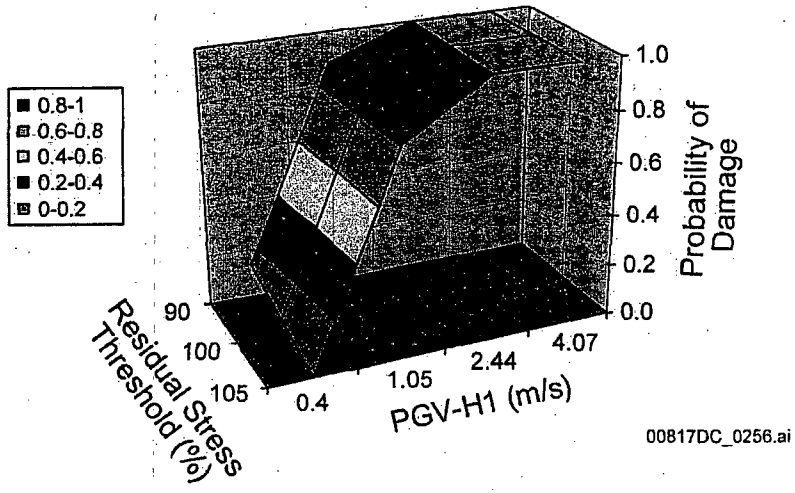
- **CSNF WP mean damage area for a 23-mm thick**
  - **0.00408 m^2 at PGV=4.07 m/s and RST=90% Y.S.**
  - **0.0 m^2 for all other data points**

EBS State 1 SCC Damage: (Intact DS, Degraded Internals)

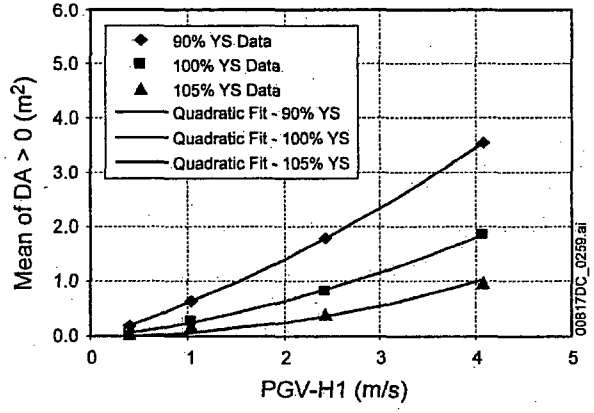
- **Codisposal WP probability of SCC damage for a 17-mm thick**



- **CSNF WP probability of SCC damage for a 17-mm thick**

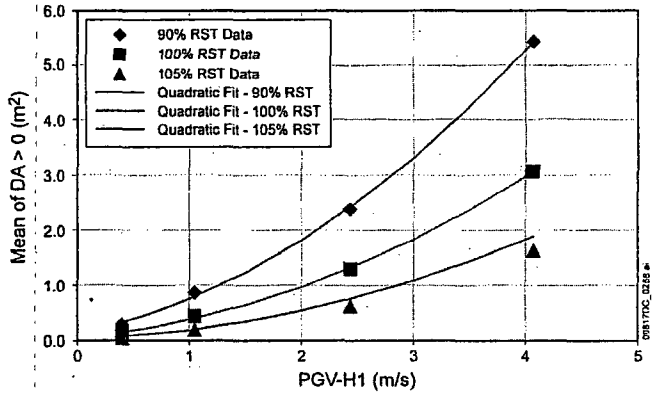


- **Codisposal WP mean damage area for a 17-mm thick**



MDL-WIS-PA-000005, Figures 6.6-11 and 6.6-13

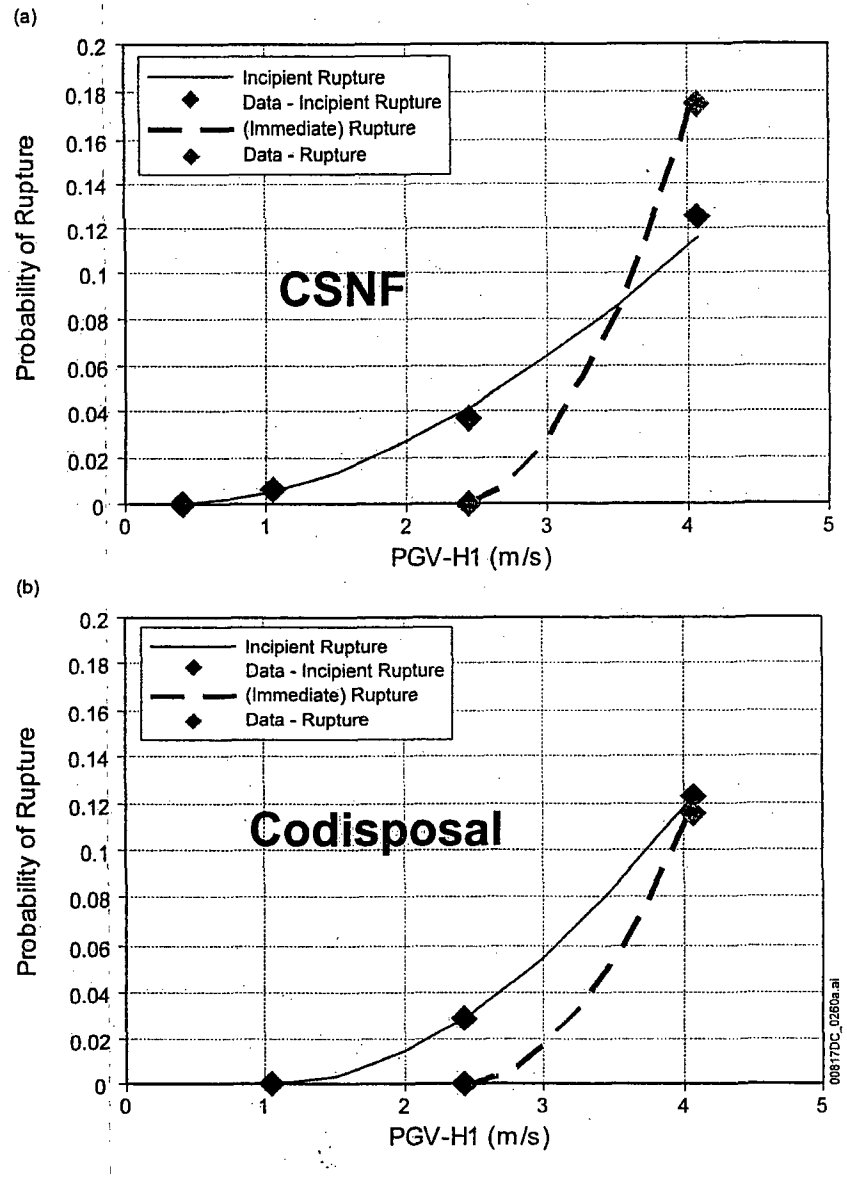
- **CSNF WP mean damage area for a 17-mm thick**



MDL-WIS-PA-000005, Figures 6.6-10 and 6.6-12

EBS State 1: WP Rupture
(Intact DS, Degraded Internals)

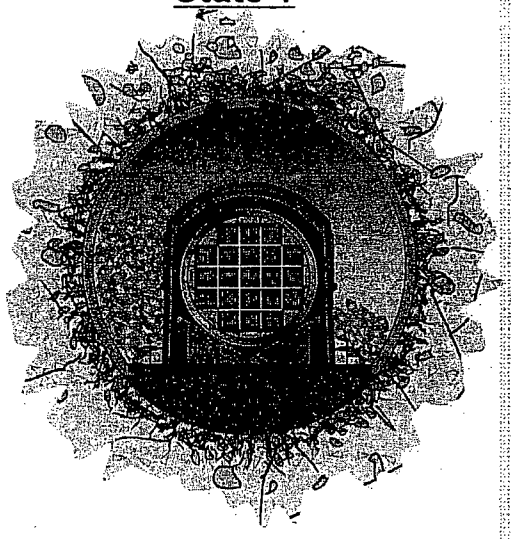
- **Probability of incipient and immediate rupture**
  - **incipient rupture requires a subsequent seismic event to cause damage**
  - **WP rupture allows advective releases**
- **Mean damage area is sampled uniformly**
  - **between 0 m^2 and the WP cross-sectional area 2.78 or 3.28 m^2**



MDL-WIS-PA-000005, Figure 6.6-14

Conceptual Model for EBS Evolution

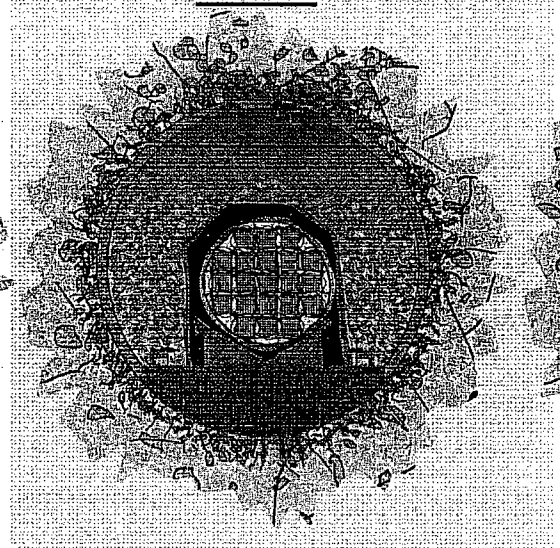
State 1



(a) Initial Configuration

Kinematic analyses and damage catalogs define damaged areas for a WP moving freely beneath the DS. WP SCC or rupture may occur, degrading internals

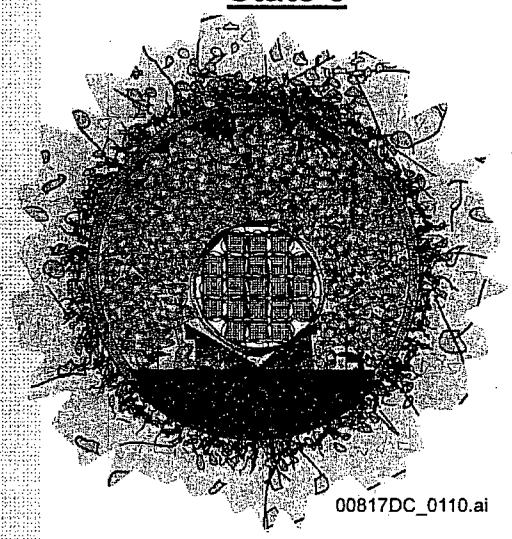
State 2



(b) After Drip Shield Framework Failure

Fragility analysis for buckling of DS framework. Additional WP damage may occur

State 3



(c) After Drip Shield Plate Failure

Fragility analysis for rupture of DS plates. WP damage defined by 2-D calcs for WP surrounded by rubble

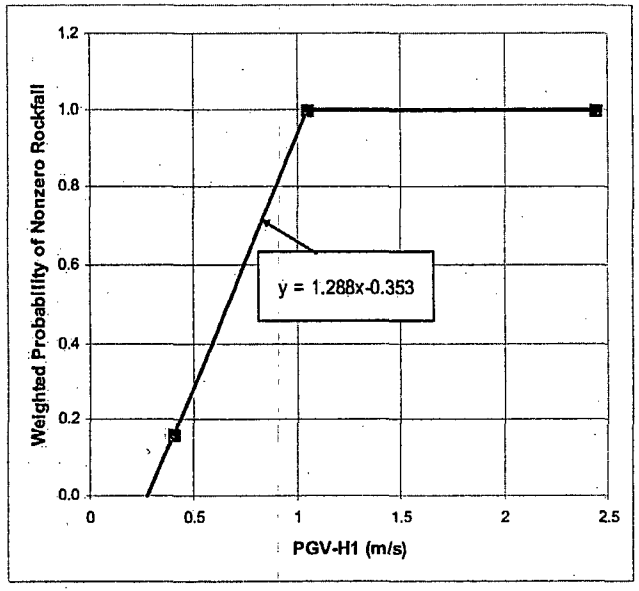
DS Failure

Time

MDL-WIS-PA-000005, Figure 6.6-5

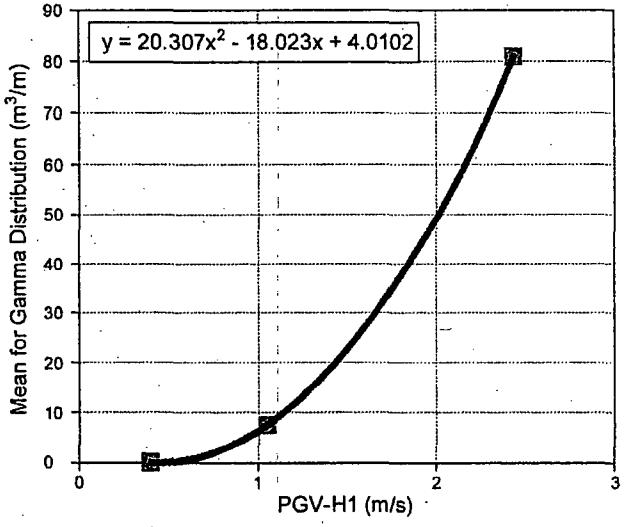
EBS Evolution State 2: Rubble Accumulation

- Rubble from multiple events is defined as the sum of the volumes from individual events until the drift is full
- Volume of rubble that fills the drift is an epistemic parameter [U(30,120) m^3/m]
- DS fragility abstractions are based on lithophysal rubble volume
- Abstractions for nonlithophysal rockfall are developed for use in the seepage abstraction



Weighted Probability of Lithophysal Rockfall

MDL-WIS-PA-000003, Figure 6-52



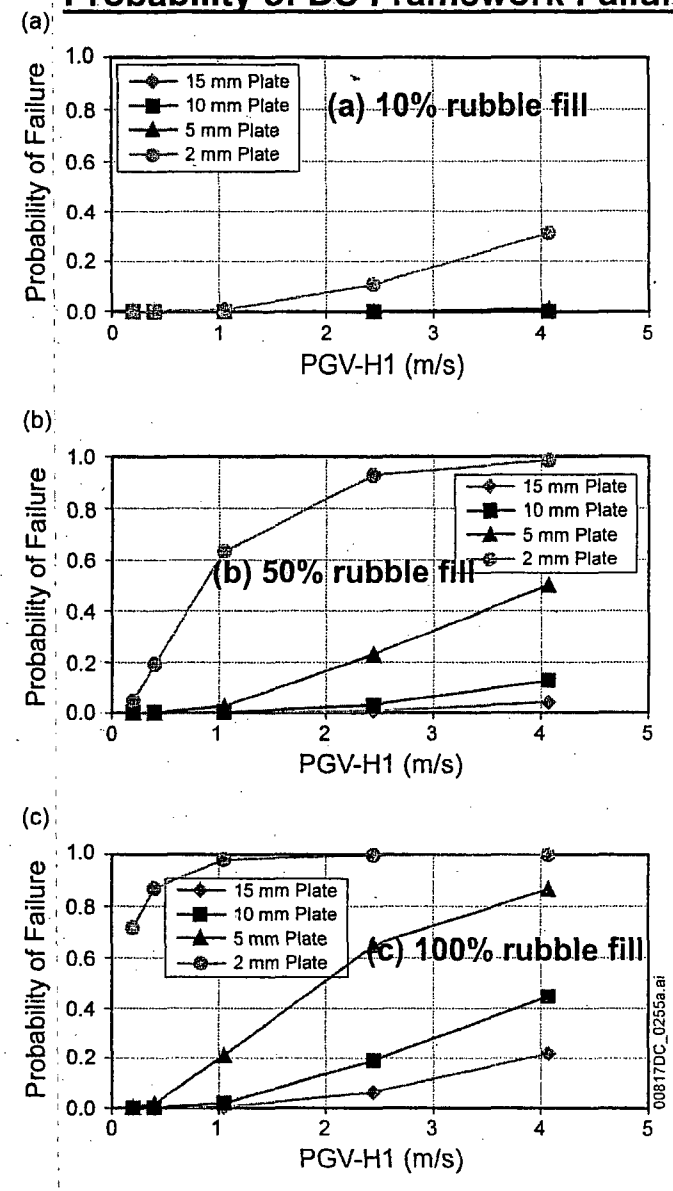
Mean Rubble Volume in the Lithophysal Zone

MDL-WIS-PA-000005, Figure 6.6-7(a)

EBS Evolution State 2:
Drip Shield Framework Collapse

- Failure of the DS framework prevents kinematic motion of the waste packages (always occurs before plate failure)
- Response surface for the probability of DS framework failure:
  - PGV levels of 0.2, 0.4, 1.05, 2.44, and 4.07 m/s
  - thickness reductions of 0, 5, 10, 13 mm for plates and structural elements of framework
  - Static rubble loads for drifts that are 10%, 50%, and 100% filled with lithophysal rubble
- DS is still a barrier to seepage

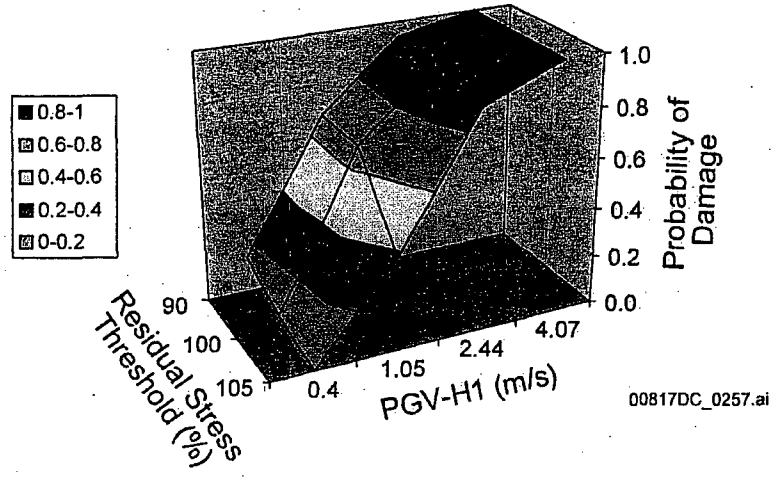
Probability of DS Framework Failure



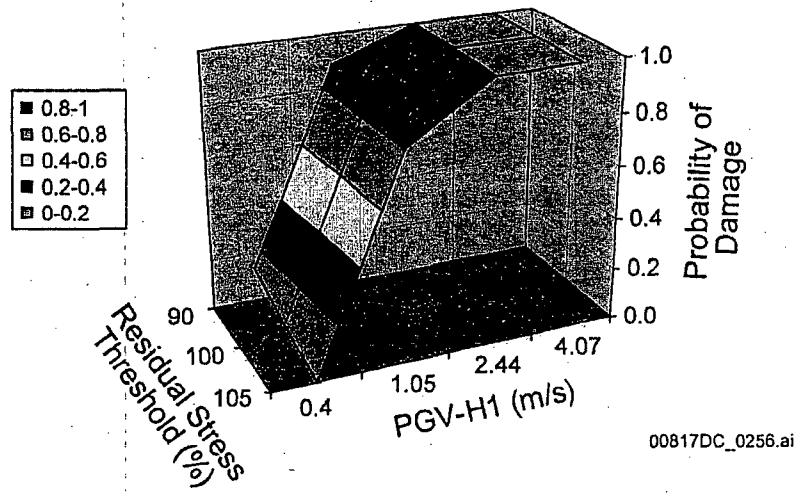
MDL-WIS-PA-000005, Figure 6.6-9

EBS State 2 SCC Damage: (Buckled DS, Degraded Internals)

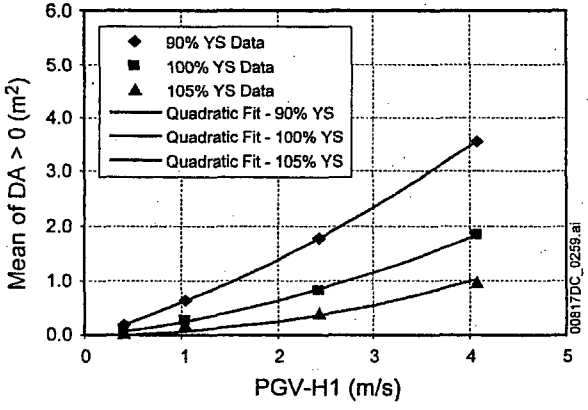
- **Codisposal WP probability of SCC damage for a 17-mm thick**



- **CSNF WP probability of SCC damage for a 17-mm thick**

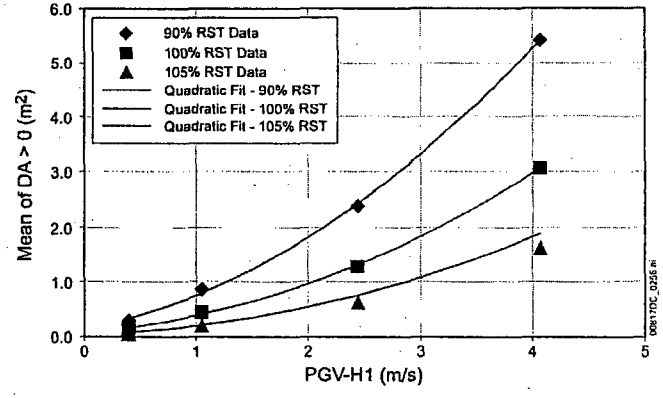


- **Codisposal WP mean damage area for a 17-mm thick**



MDL-WIS-PA-000005, Figures 6.6-11 and 6.6-13

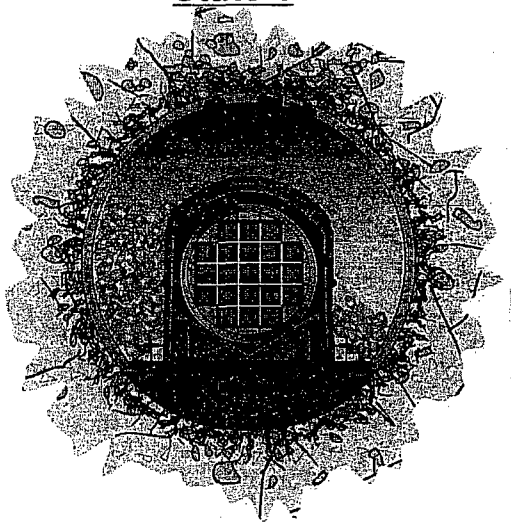
- **CSNF WP mean damage area for a 17-mm thick**



MDL-WIS-PA-000005, Figures 6.6-10 and 6.6-12

Conceptual Model for EBS Evolution

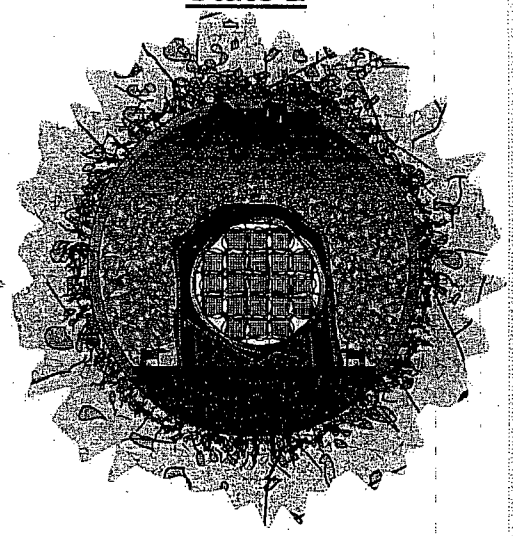
State 1



(a) Initial Configuration

Kinematic analyses and damage catalogs define damaged areas for a WP moving freely beneath the DS. WP SCC or rupture may occur, degrading internals

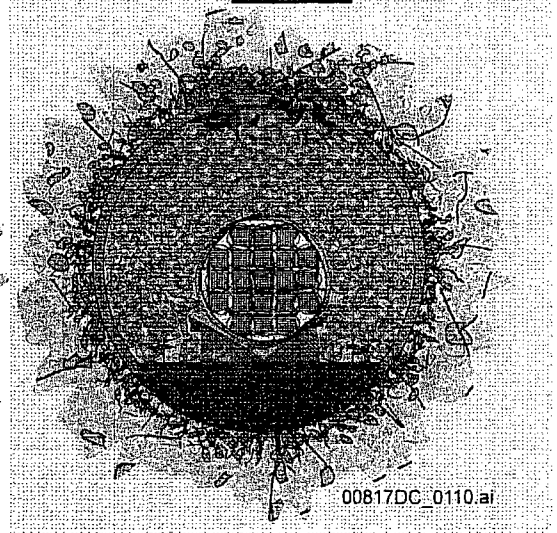
State 2



(b) After Drip Shield Framework Failure

Fragility analysis for buckling of DS framework. Additional WP damage may occur

State 3



(c) After Drip Shield Plate Failure

Fragility analysis for rupture of DS plates. WP damage defined by 2-D calcs for WP surrounded by rubble

DS Failure

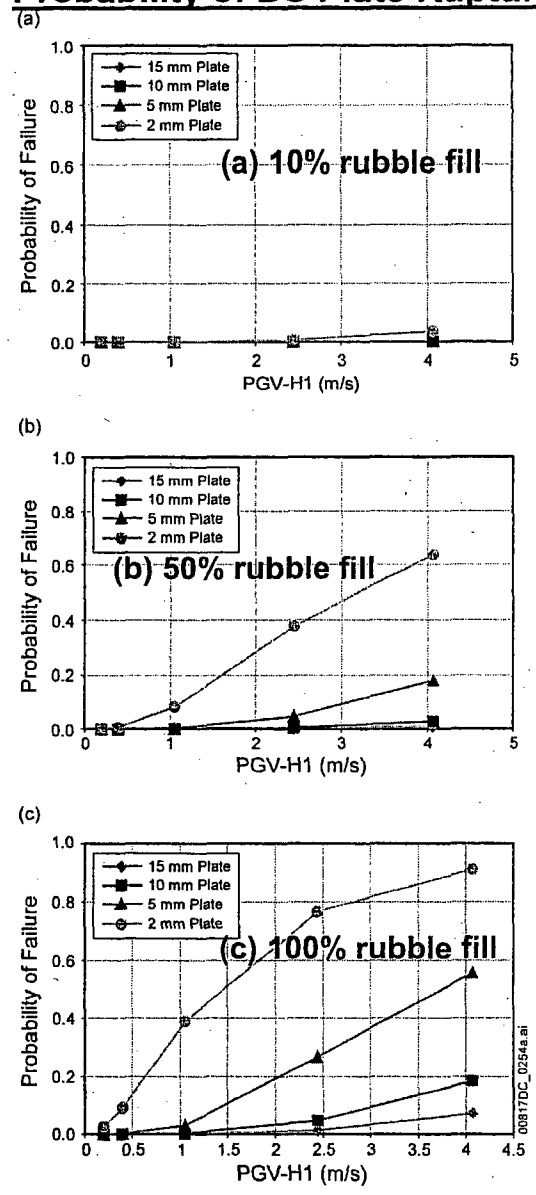
MDL-WIS-PA-000005, Figure 6.6-5

Time

EBS State 3:
Drip Shield Plate Rupture

- Failure of the DS plate results in complete failure as a barrier to flow
- Response surface for probability of DS plate failure:
  - PGV levels of 0.2, 0.4, 1.05, 2.44, and 4.07 m/s
  - plate thicknesses of 2 mm, 5mm 10 mm, and 15 mm
  - static rubble loads for drifts that area 10%, 50%, and 100% filled with lithophysal rubble

Probability of DS Plate Rupture

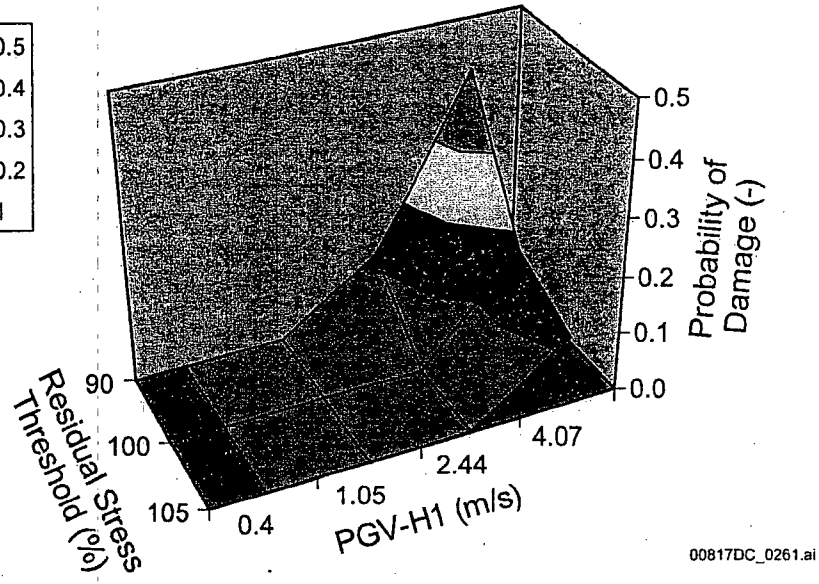


MDL-WIS-PA-000005, Figure 6.6-8

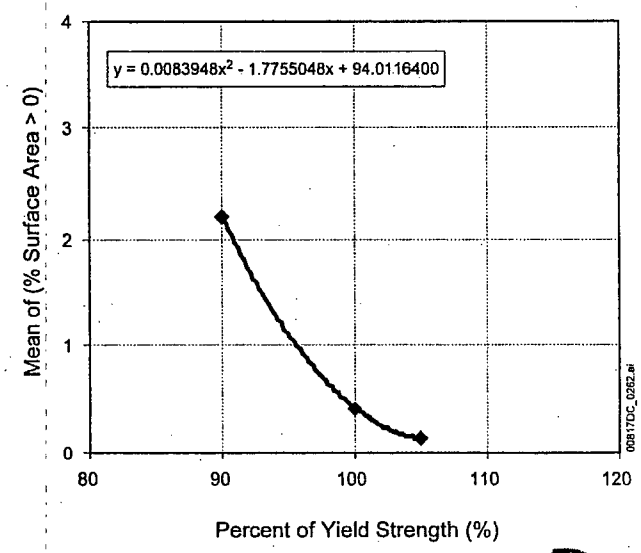
EBS State 3: WP Crack Damage

Failed DS, Degraded Internals

- Probability of SCC damage for a 17-mm thick CSNF WP <u>surrounded by rubble</u> (same abstraction is used for the CDSP WP)



- Mean damage area for a 17-mm thick CSNF (or CDSP) WP surrounded by rubble under a failed DS at 4.07 m/s

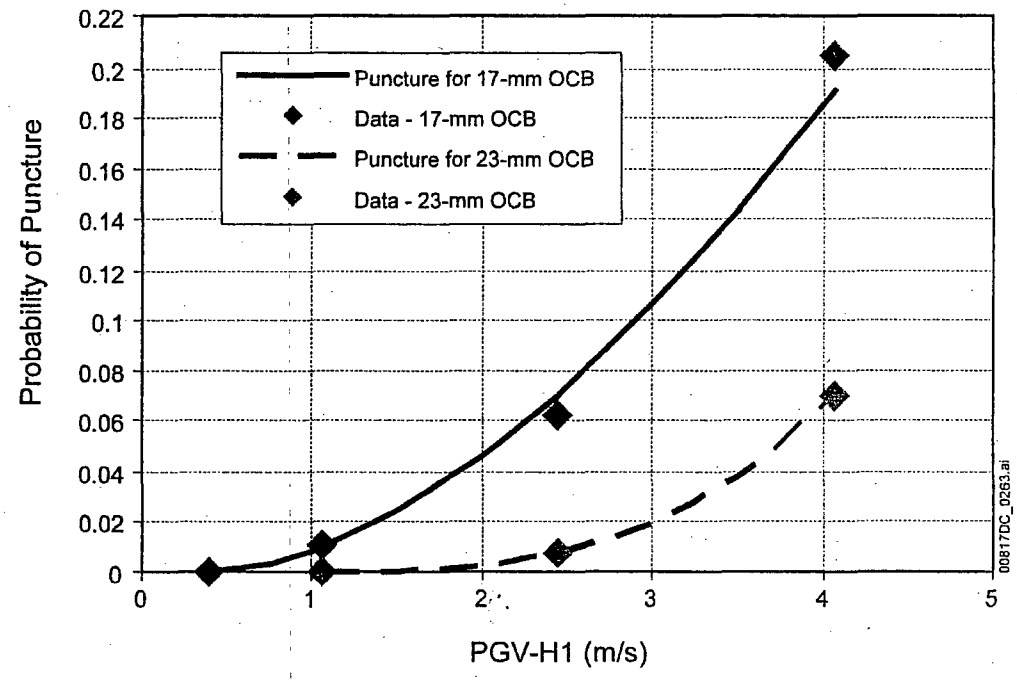


[Abstraction also used for CSNF (or CDSP) WP with intact internals under a buckled DS]

MDL-WIS-PA-000005, Figures 6.6-15(b) and 6.6-16(b)

EBS State 3: WP Puncture
(Failed DS, Degraded Internals)

- Probability of puncture for a CSNF WP surrounded by rubble under a failed DS
- Same abstraction used for a CDSP WP
- Damage area given by a uniform distribution U(0, 0.1 m^2)



MDL-WIS-PA 000005, Figure 6.6-17

Summary of WP Damage States

- There are eight possible WP damage states and associated abstractions:
  1. No damage
  2. SCC of WP under an intact DS with WP internals intact
  3. SCC of WP under an intact DS with WP internals degraded
  4. WP rupture under an intact DS with WP internals degraded
  5. SCC of WP under a buckled DS with internals intact
  6. SCC of WP under a buckled DS with internals degraded
  7. SCC of WP under a failed DS
  8. WP puncture under a failed DS
- Consequences are based on the magnitude of the event (PGV), the residual stress threshold (RST) for Alloy 22, and the Alloy 22 thickness for the eight modeled states of the system at the time of the event

Fault Displacement Abstraction

- The conceptual model was developed using displacement data from known and hypothetical (generic) faults
- The fault-displacement damage abstraction is based on a comparison of clearances between potentially displaced EBS components
  - Independent of component thicknesses (nominal corrosion processes not included)
- Expected number of WPs that could fail from fault displacement is small (the number of WPs lying on known, or generic, faults is about 214)
- Damaged area on the WP is determined by sampling a uniform distribution with a lower bound of 0 m^2 and an upper bound equal to the WP cross sectional area
  - The same damaged area applies to all failed WPs
  - The resulting damage allows advective flow and transport
  - The associated drip shield is taken to be 100% damaged

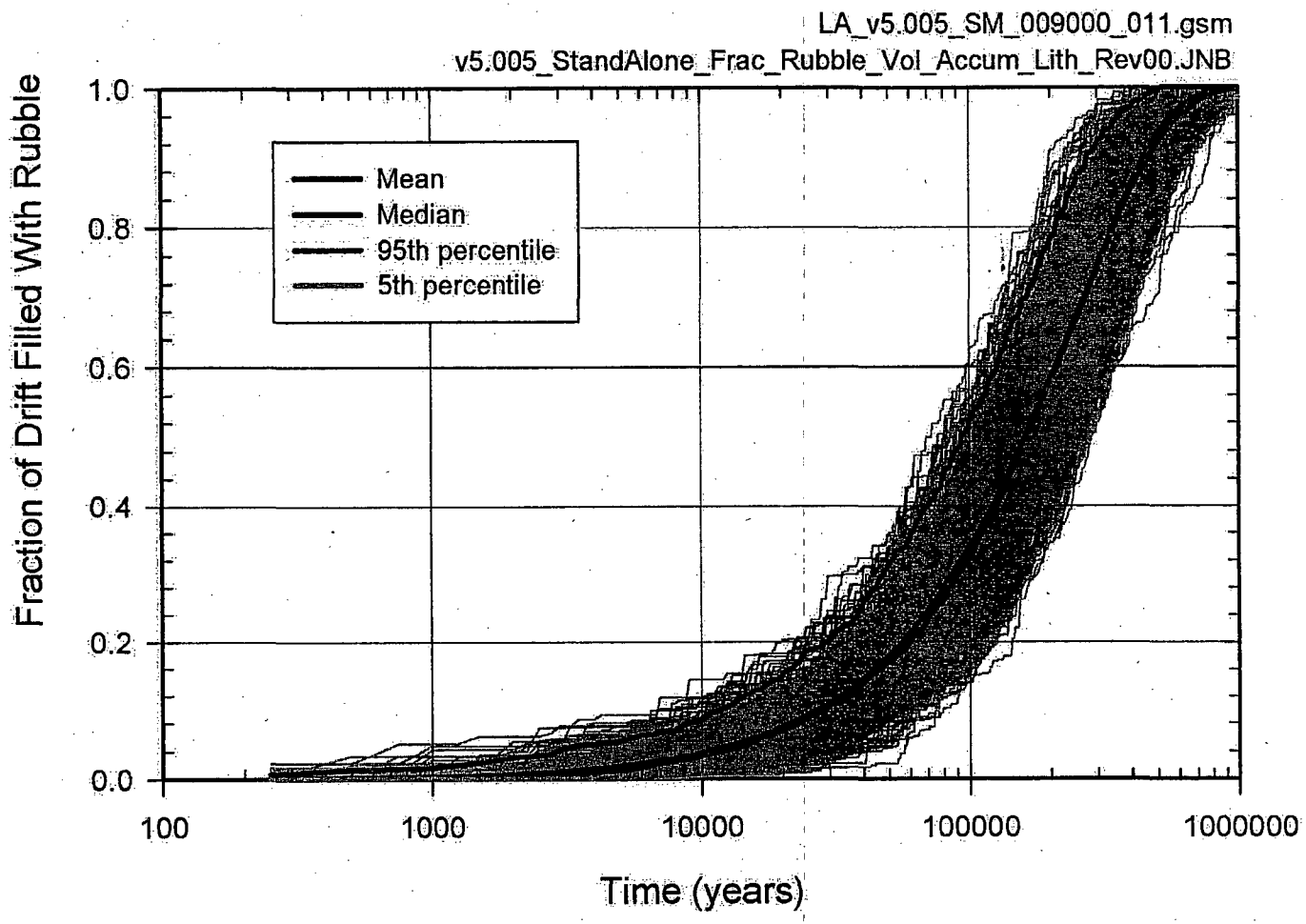
Other Processes

- **Seepage**
  - Seepage flux is interpolated between the intact-drift seepage flux and the fully collapsed seepage flux as a function of rubble accumulation in lithophysal zones
  - Collapsed-drift seepage fractions are used for the entire simulation but different seepage fractions are applicable for the first 10,000 years versus the post-10,000-year period
  - Separate calculations of rubble (rockfall) accumulation for lithophysal and nonlithophysal zones
- **EBS Environment**
  - WP temperature and WP relative humidity are changed after the drift fills with rubble (small effect because rubble accumulation is slow)
- **EBS Flow and Transport**
  - The WP damage area fraction (sum of seismic damage and corrosion damage) is an input to the diffusive transport and the water flux calculations of the EBS Transport submodel

Example Results

- Lithophysal Rubble Accumulation
- Drip Shield Plate Failure
- Waste Package Breach Fractions
  - Seismic and nominal processes
  - Seismic processes alone
- Waste Package Damage Area
  - Crack and patch damage by both seismic and nominal processes
  - Damage area on a per failed WP basis (failed by cracks or general corrosion patches or both)

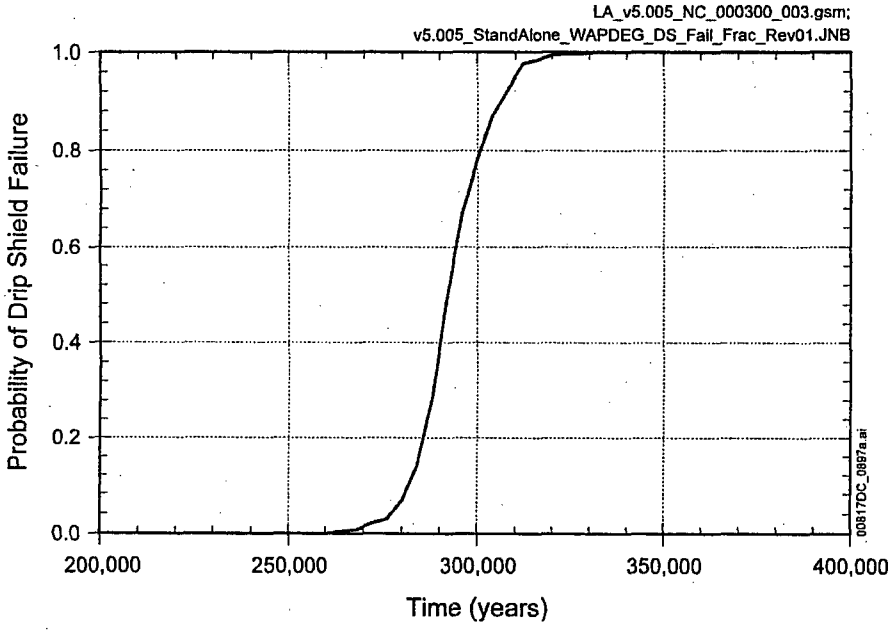
Lithophysal Rubble Accumulation



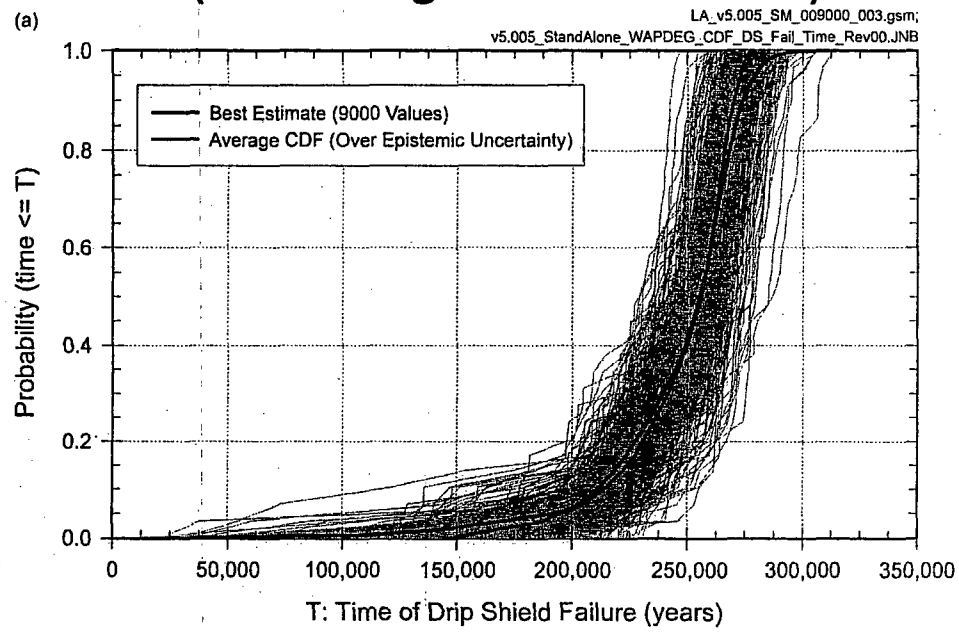
DTN: MO0803TSPAPSAR.000

Probability of Drip Shield Plate Failure

General Corrosion



Seismic Ground Motion (includes general corrosion)



Key Points:

- **DS failure under nominal conditions by general corrosion (GC) of Titanium Grade 7 plate**
- **Failure times from about 270,000 to 340,000 yrs**

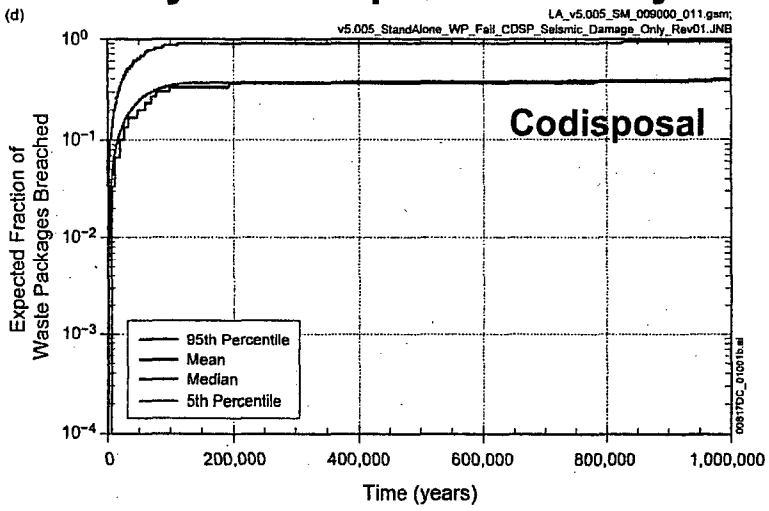
Key Points:

- **DS failure under seismic conditions by rubble accumulation and plate thinning by GC**
- **Probability of DS failure before 100,000 years is 0.0055**

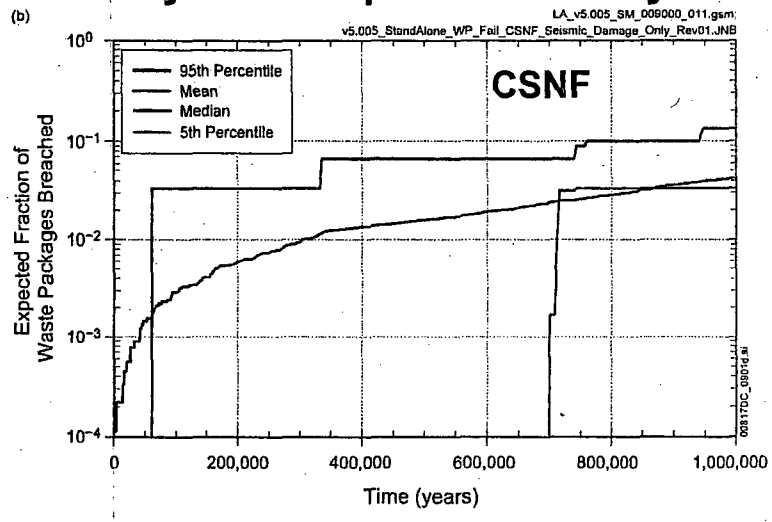
(Note: The TSPA model does not include spatial variability in drip shield failure)

Expected Fraction of Breached Waste Packages

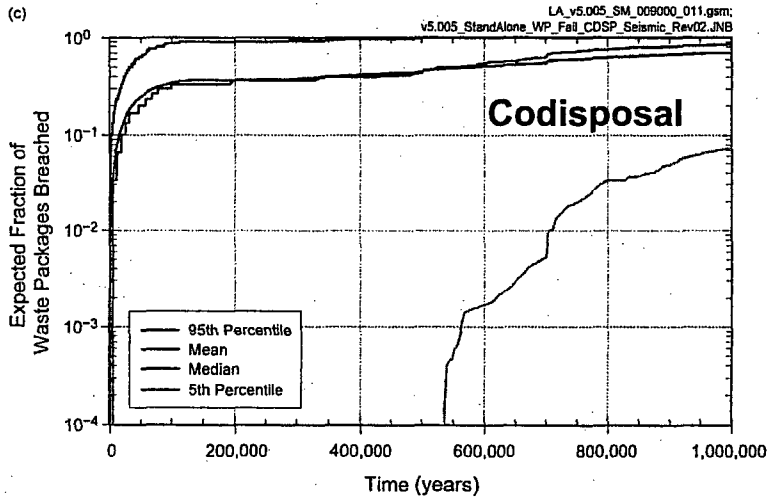
- By seismic processes only



- By seismic processes only

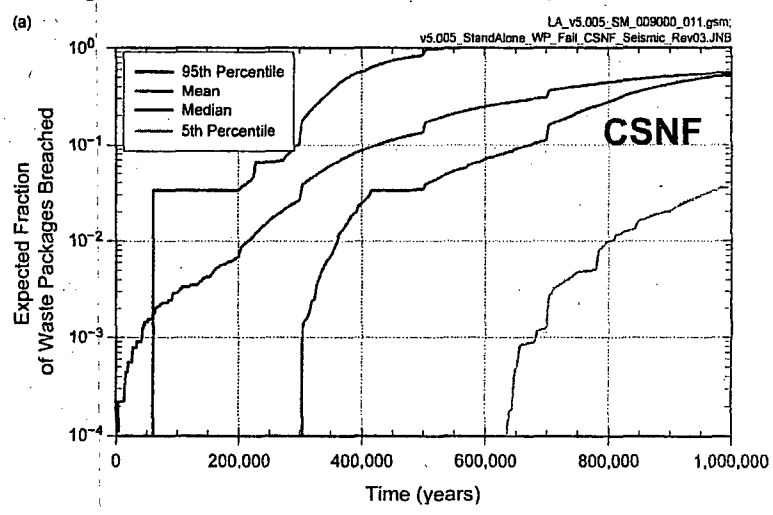


- By seismic and nominal processes



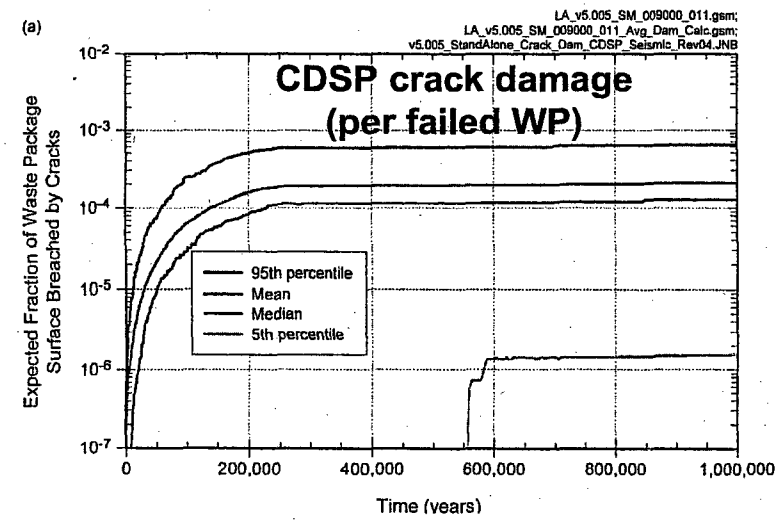
MDL-WIS-PA-000005, Figure 8.3-8(c and d)[a]

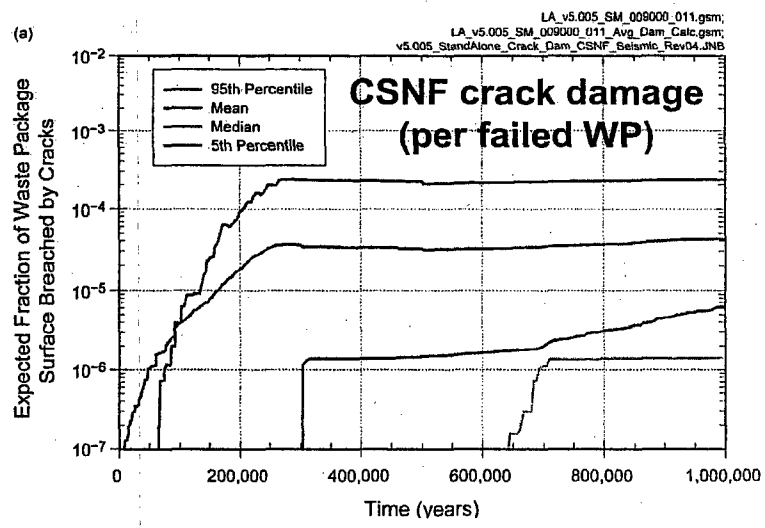
- By seismic and nominal processes

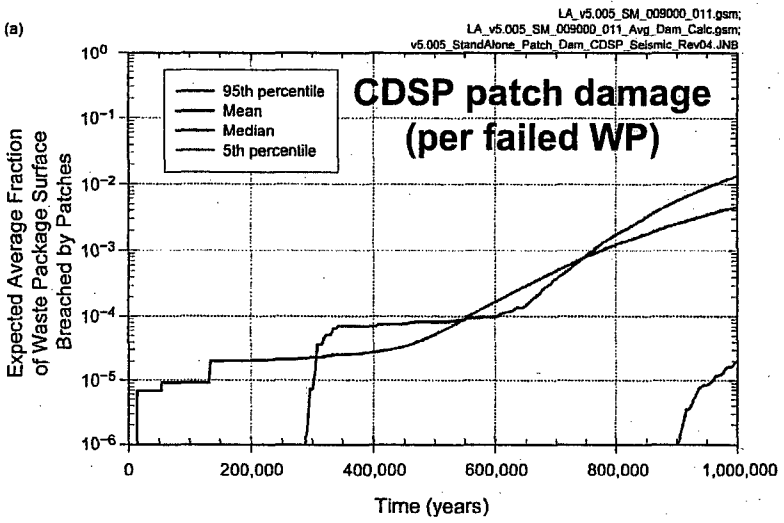


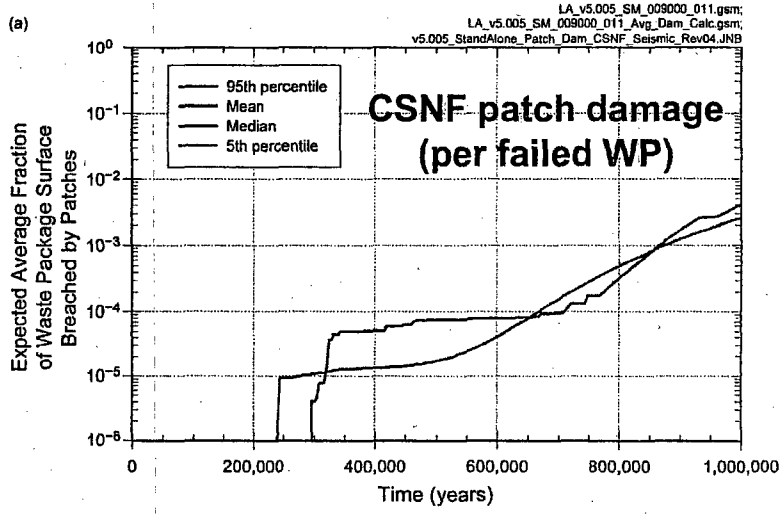
MDL-WIS-PA-000005, Figure 8.3-8(a and b)[a]

Breached WP Surface Area: (nominal and seismic processes)









MDL-WIS-PA-000005, Figures 8.3-9(a)[a], 8.3-10(a)[a] , 8.3-11(a)[a], 8.3-12(a)[a]

Summary

- Detailed damage analyses developed for degraded states of the EBS components
  - Intact DS analyses
  - Failed DS analyses
- Conservatism removed from the upper end of the seismic hazard curve
- Seismic consequence abstractions for CSNF/TAD package and codisposal package, including kinematic analyses, damage catalogs, and analyses for WP surrounded by rubble
- Multi-realization TSPA results reflect the varying probabilities and damage areas of the underlying abstractions

U.S. Department of Energy
Office of Civilian Radioactive Waste Management

www.ocrwm.doe.gov

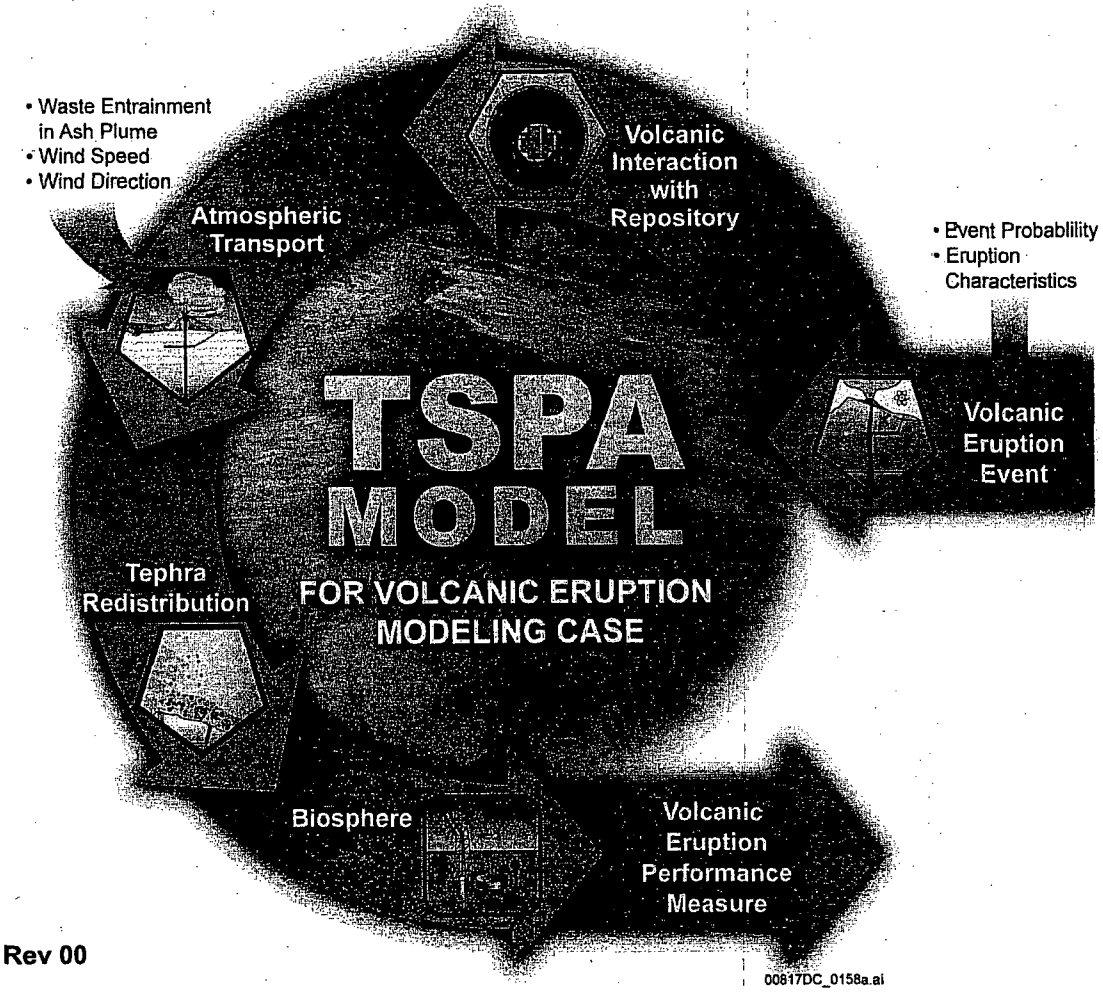
Disruptive Scenarios: Igneous Eruptive Model Abstraction

Presented to
NRC/DOE Technical Exchange on Total System Performance Assessment (TSPA) for Yucca Mountain

Presented by
Peter Swift and William Statham
Sandia National Laboratories/AREVA NP, Inc

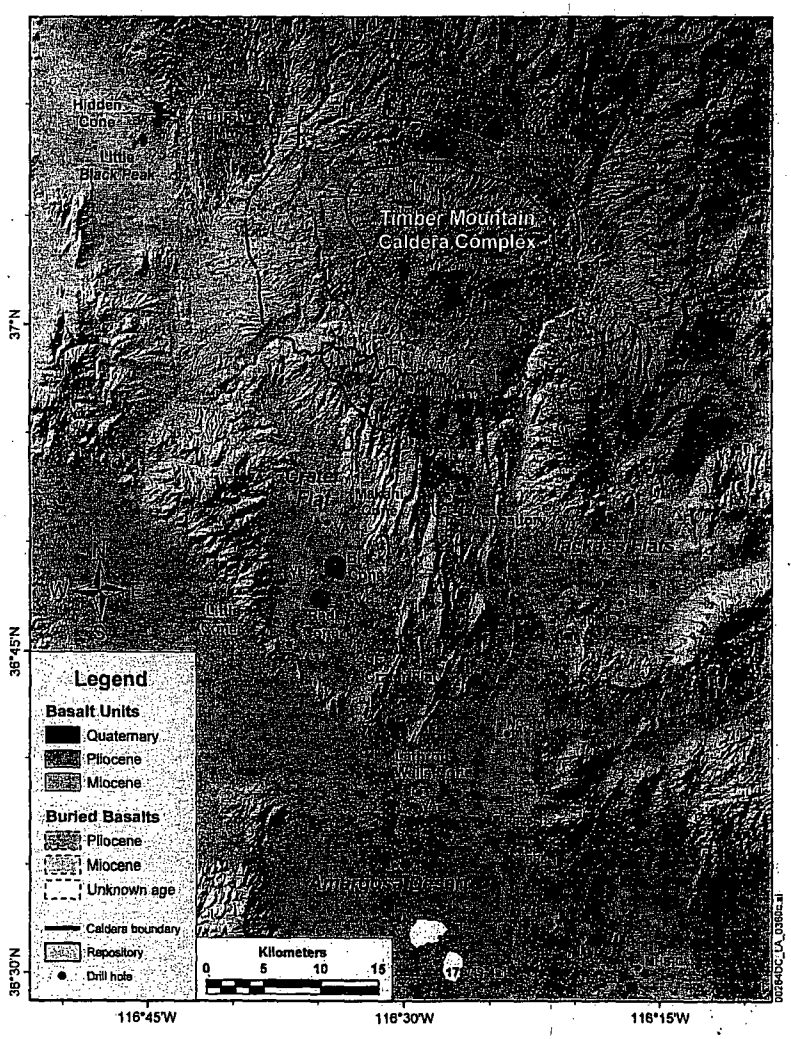
April 4, 2008
Las Vegas, Nevada

TSPA-LA Model Components for the Volcanic Eruption Modeling Case



MDL-WIS-PA-000005 Rev 00
Figure 6.5-7

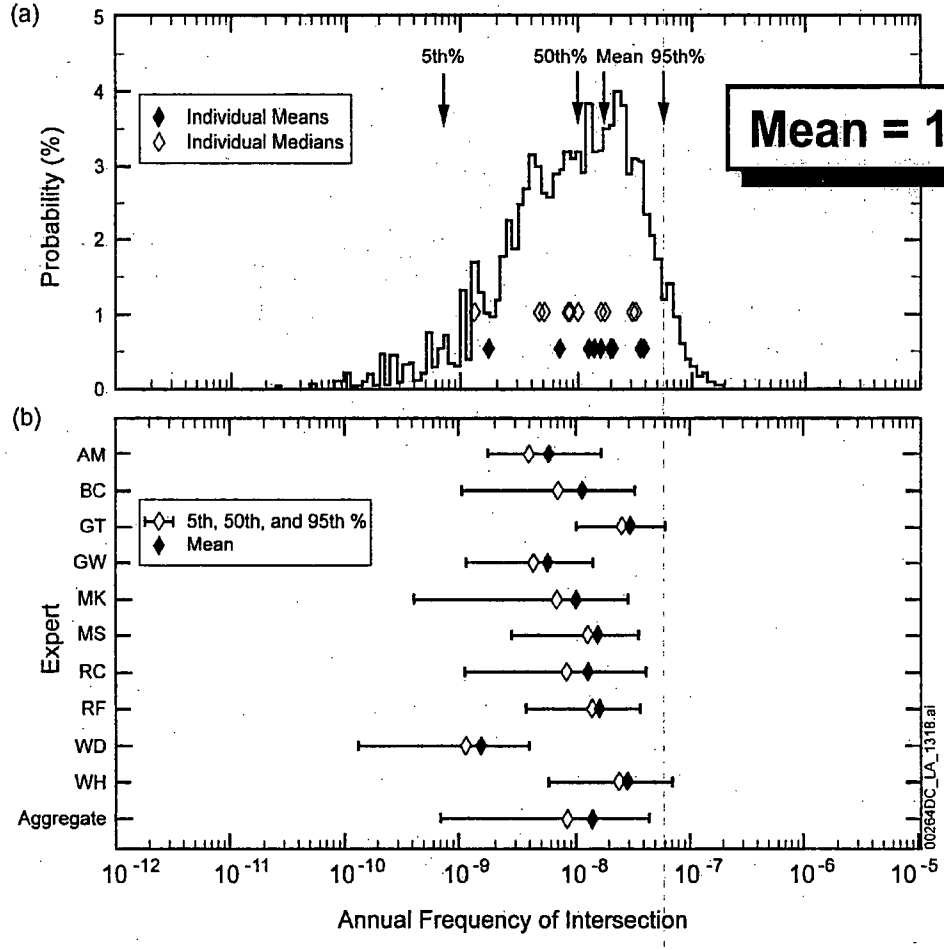
Distribution of Basaltic Rocks in the Yucca Mountain Region



MDL-WIS-PA-000005 Rev 00
Figure 6.5-1

Annual Frequency of Intersection by Dike

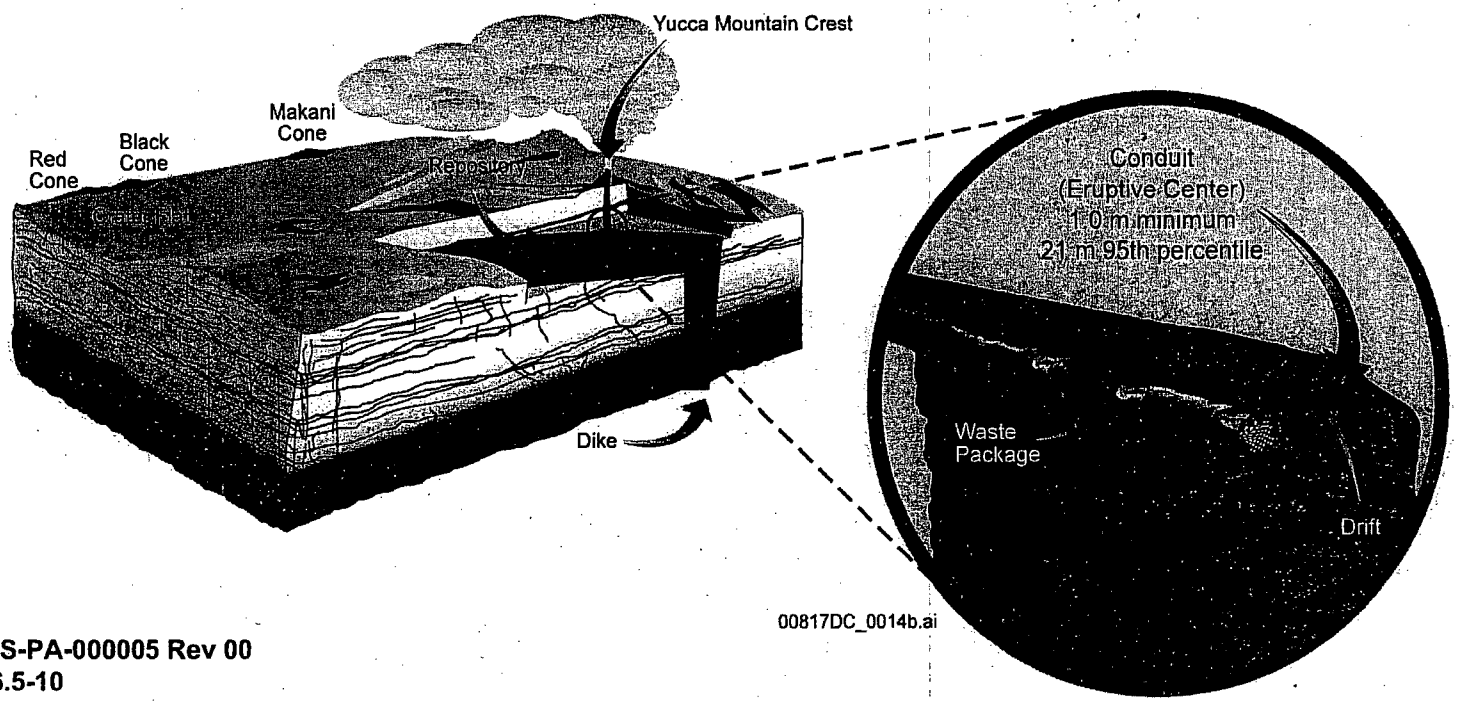
Probabilistic Volcanic Hazard Analysis Expert Interpretations (1996)



Mean = 1.7×10^{-8} per year

ANL-MGR-GS-000001 REV 03 ACN 01
Figure 6-18

Volcanic Interaction with Repository Submodel

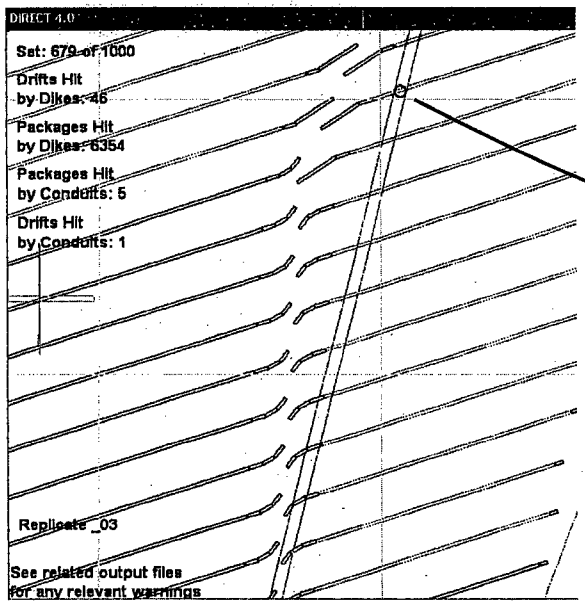


MDL-WIS-PA-000005 Rev 00
Figure 6.5-10

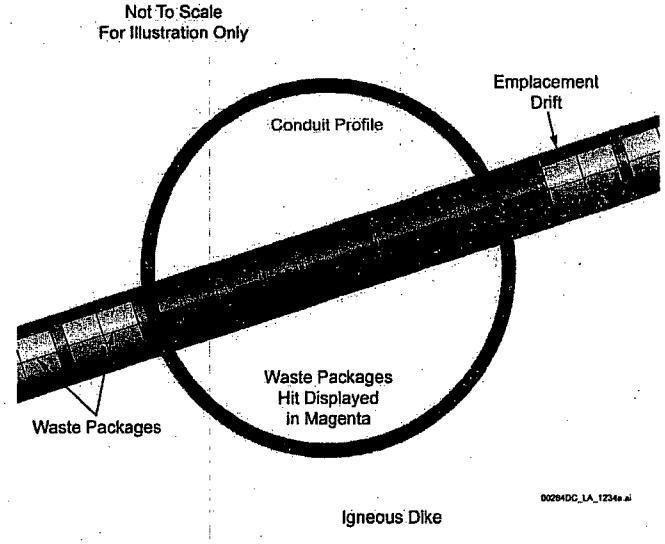
Probability of Conduit Intersecting Repository Footprint = 0.28
Probability of Intersecting Conduit Contacting Waste = 0.30

Mean Probability of Conduit Intersecting Waste = $(1.7 \times 10^{-8}) \times (0.28) \times (0.30)$
= 1.4×10^{-9} per year

Volcanic Interaction with Repository Submodel



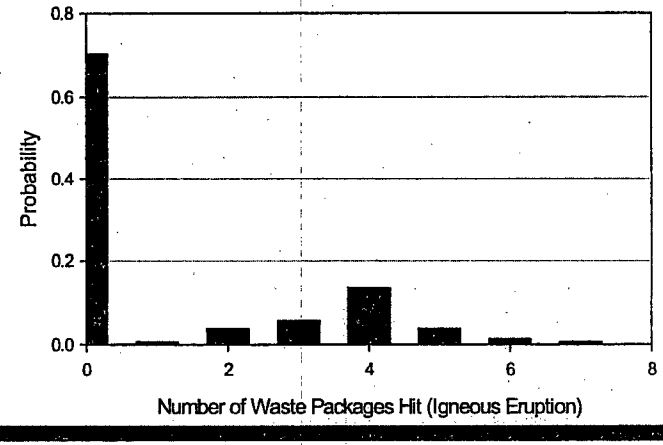
ANL-MGR-GS-000003 Rev 03 Figure 6-8



ANL-MGR-GS-000003 Rev 03 Figure 5-1

Number of dikes in a swarm: 1-5 (P of 1 = 0.40)
Dike width: normal, mean 8 m, 95th 12 m
Dike spacing: uniform, 0.5-1500 m
Number of conduits: 1-3 (P of 1 = 0.85)
Conduit diameter: normal, mean 15 m, 95th 21 m

ANL-MGR-GS-000003 Rev 03 Table 4-1



MDL-WIS-PA-000005
Rev 00 Figure 6.5-11

Atmospheric Transport of Contaminated Tephra Submodel (ASHPLUME)

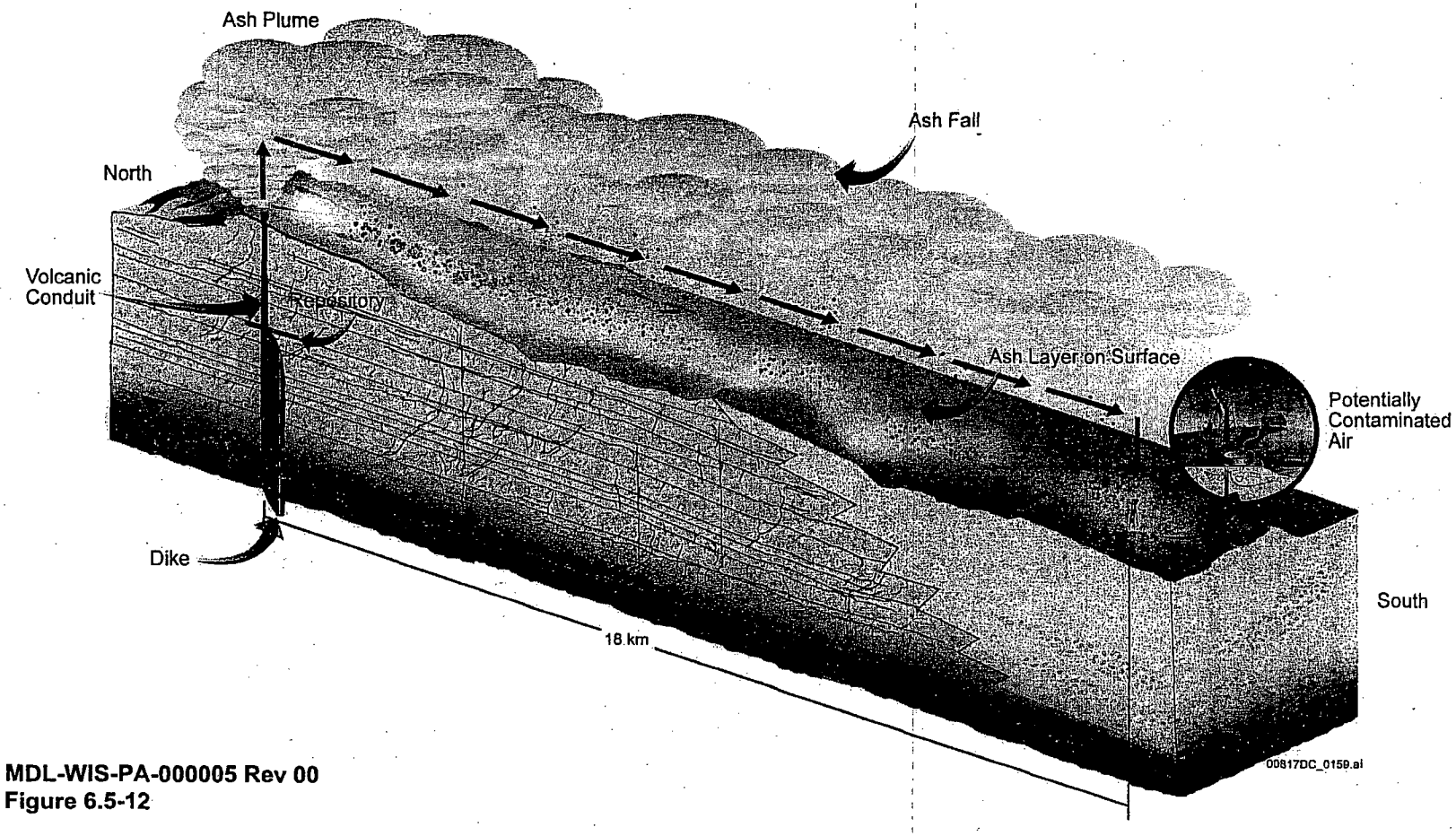


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Figure 6.5-12

Atmospheric Transport of Contaminated Tephra Submodel - Key Parameters

TSPA Parameter	Parameter Description	Uncertainty Type	Value(s)
C	Constant relating eddy diffusivity and particle fall time ($cm^2/s^{5/2}$)	Fixed value	400
Erupt Power	Eruptive power (W)	Aleatory	1.0×10^9 – 1.0×10^{12} (log uniform)
Erupt Velocity	Initial Rise Velocity (cm/s)	Aleatory	1.0 – 1.0×10^4 (uniform)
Beta Dist	Column diffusion constant	Epistemic	0.01 – 0.5 (uniform)
Dash Mean	Mean ash particle diameter (cm)	Epistemic	0.001 – 0.01 – 0.1 (log Tri.)
Dash sigma	Ash particle diameter standard deviation (log cm)	Epistemic	0.301 – 0.903 (uniform)
D_min	Minimum waste particle diameter (cm)	Fixed value	0.0001
D_mode	Mode of waste particle diameter (cm)	Fixed value	0.0013
D_max	Maximum waste particle diameter (cm)	Fixed value	0.2
Rhocut	Waste incorporation ratio	Fixed value	0.0
Erupt Time	Eruption duration (seconds)	Aleatory	DTN: LA0702PADE03GK.002
Wind Direction	Wind direction (degrees)	Aleatory	DTN: MO0408SPADRWSD.002
Wind Speed	Wind speed (cm/s)	Aleatory	DTN: MO0408SPADRWSD.002
Magma Partitioning	Fractional multiplier on waste mass to account for waste-containing magma erupted in scoria cone and lava flows	Aleatory	0.1 – 0.5 (uniform)

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Table 6.5-4

Tephra Redistribution Submodel
(FAR – Fortymile Wash Ash Redistribution)

Two Model Domains

1) **Drainage Basin**
   - Mobilization from hill slopes
   - Channel transport – mixing/dilution
2) **Alluvial Fan (RMEI location)**
   - Diffusion into soil column
   - Channel and Divides

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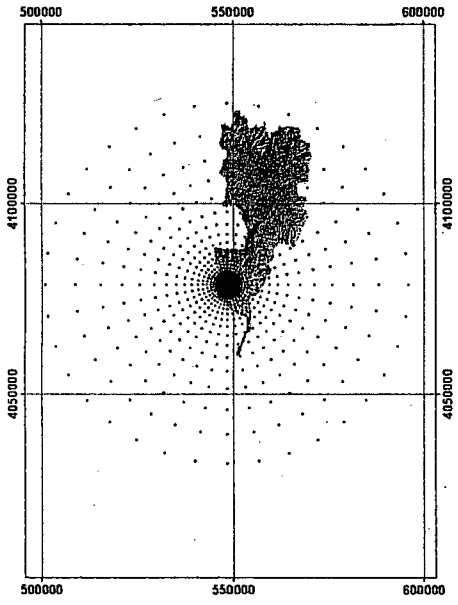
Figure 6.5-13

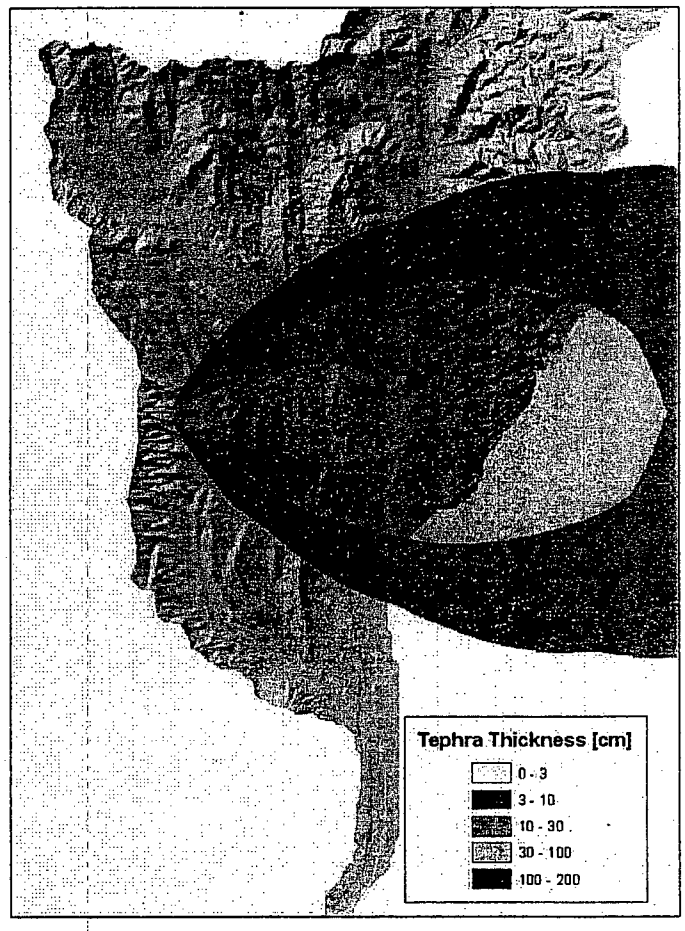
Tephra Redistribution Submodel (continued)

ASHPLUME results calculated for a hypothetical vent located at YM and superimposed on FAR domain

(Example shown with wind to east)



MDL-MGR-GS-000006 Rev 00 Figure 6.3.3-2



MDL-MGR-GS-000006 Rev 00 Figure 6.3.3-9

Tephra Redistribution Submodel
Vertical Transport of Radionuclides in Soil

Surface transport of contaminated tephra assumed to be instantaneous

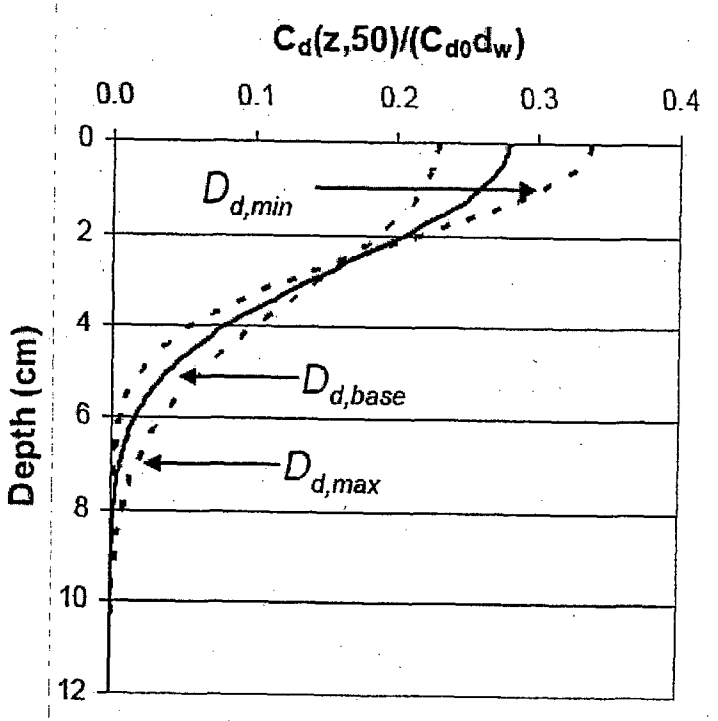
Subsequent vertical migration in soil estimated assuming bulk transport from all processes can be represented by diffusion (Fick's Law)

$$\frac{\partial C(z,t)}{\partial t} = D\frac{\partial^2 C(z,t)}{\partial z^2}; z \geq 0, \quad t \geq 0$$

Rate of transport depends on effective diffusivity and layer thickness

Effective diffusivity constants are uncertain parameters based on field measurements of ^{137}Cs

Validated by comparison to data from Chernobyl and Harwell



Example calculation: normalized concentration versus depth for a divide sample point 50 years after deposition MDL-MGR-GS-000006 Rev 00 Figure 7.1.3-3

Tephra Redistribution Submodel Key Parameters

TSPA Parameter Name	Parameter Description	Distribution type	Uncertainty Type	Value (s)
Critical_Slope_a	Critical gradient for tephra mobilization from hillslopes	Uniform	Epistemic	0.21 – 0.47
Drainage_Density_a	Average drainage density for the Fortymile Wash drainage basin	Uniform	Epistemic	20 – 33 km^{-1}
Scour_Depth_a	Scour depth in Fortymile Wash at the fan apex	Uniform	Epistemic	73 – 122 cm
RMEI_Area	Area of the Fortymile Wash fan	Constant	fixed value	33 km^2
Fraction_Channel_a	Fraction, *F*, of the Fortymile Wash fan subject to fluvial activity	Uniform	Epistemic	0.09 – 0.54
L_Channels_a	Depth of permeable soil on channels, L_c, of the Fortymile Wash fan (RMEI location)	Constant	fixed value	200 cm
L_Divides_a	Depth of permeable soil on divides, L_d, of the Fortymile Wash fan (RMEI location)	Uniform	Epistemic	102 – 140 cm
D_Channels_a	Diffusivity of waste in channels, D_c, of the Fortymile Wash fan (RMEI location)	Uniform	Epistemic	0.035 – 0.266 cm^2/yr
D_Divides_a	Diffusivity of waste in divides, D_d, of the Fortymile Wash fan (RMEI location)	Uniform	Epistemic	0.001 – 0.095 cm^2/yr
Ash_Density_a	Tephra settled density	Truncated normal	Epistemic	300 – 1,500 kg/m^3 mean = 1,000 kg/m^3 std. dev. = 100 kg/m^3
b_Tillage	Tillage depth	Uniform	Epistemic	0.05 – 0.30 m

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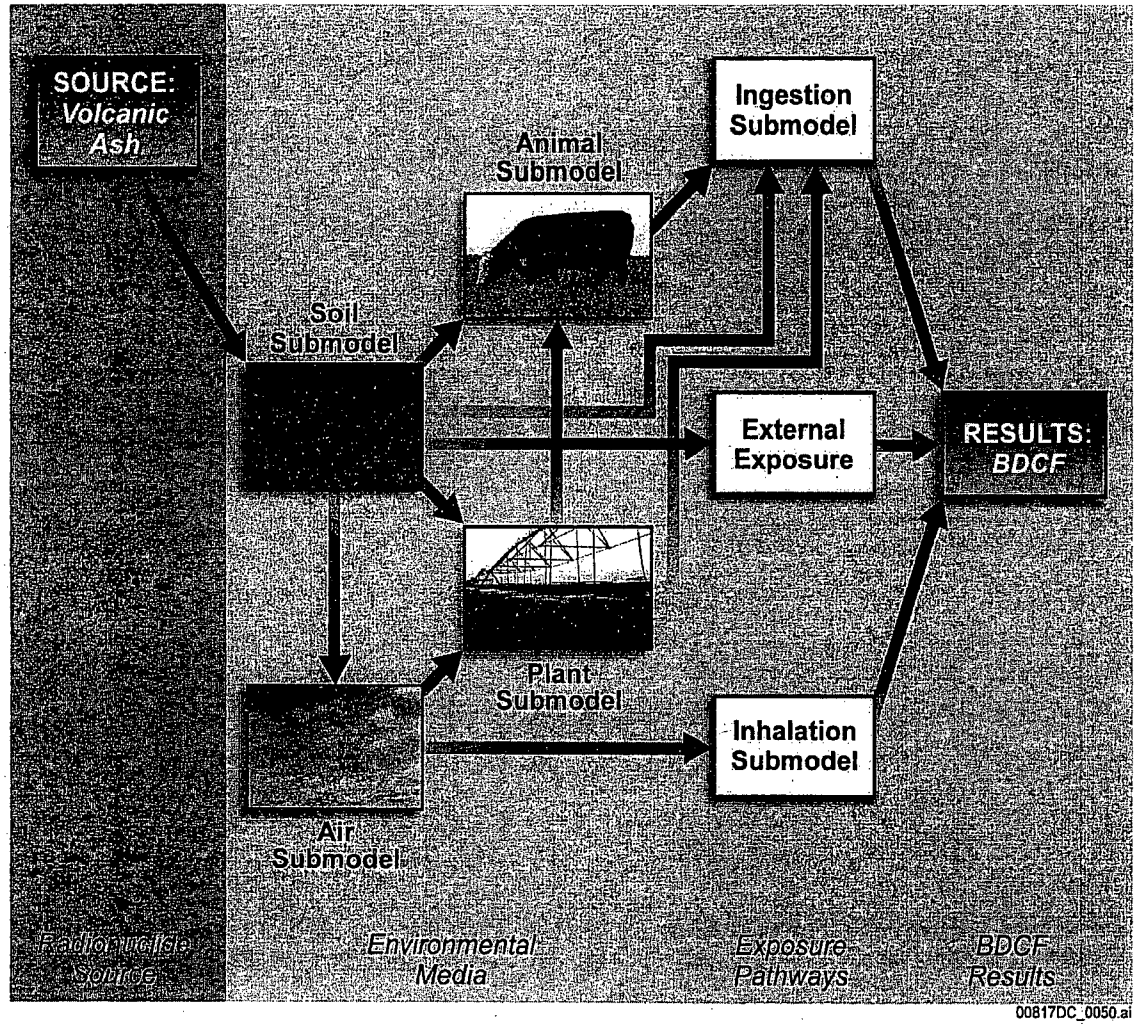
Table 6.5-5

Biosphere Submodel for the Volcanic Eruption Modeling Case



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Biosphere Dose Conversion Factors (BDCFs) for Volcanic Eruption Case

- **Ingestion pathway**
- **External exposure pathway**
- **Inhalation pathway**
  - Accounts for high air mass loading following eruption and longer-term soil stabilization

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Figure 6.3-11-6