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

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Total System Performance Assessment: Modeling Approach and Overview of Results

Presented to:
Nuclear Waste Technical Review Board

Presented by:
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May 29, 2008
Las Vegas, Nevada

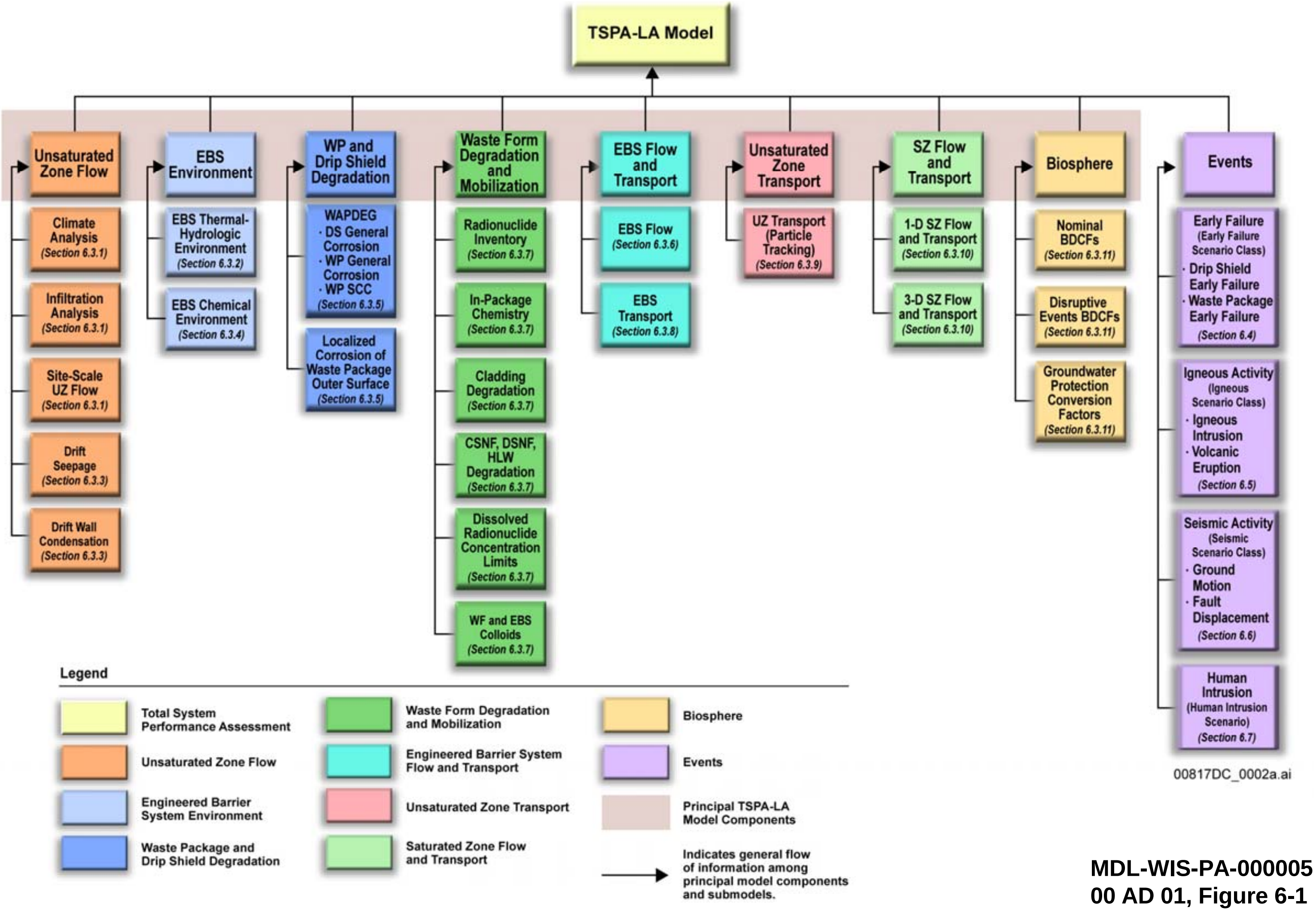
Outline

- Summary of the modeling approach for the Total System Performance Assessment for the License Application (TSPA-LA)
- Scenarios and modeling cases for the TSPA-LA
- Overview of TSPA-LA results
  - Total dose (summed over scenarios)
  - Important scenarios and radionuclides
    - Shape of expected dose history
    - Magnitude of expected dose
    - Uncertainty in expected dose
  - Stability of total dose results
- Water and radionuclide movement in the Engineered Barrier System (EBS): seismic ground motion damage
- Water and radionuclide movement in the EBS: igneous intrusion

Major Steps in Iterative Performance Assessment for Yucca Mountain

- ***Screen Features, Events, and Processes (FEPs)*** **and develop scenario classes**
- ***Develop models*** **and abstractions, along with their scientific basis, for logical groupings of FEPs within scenario classes**
- ***Evaluate uncertainty*** **in model inputs**
- ***Construct integrated TSPA model*** **using all retained FEPs and** ***perform calculations*** **for the scenario classes and "modeling cases" within scenario classes**
- ***Evaluate total system performance,*** **incorporating uncertainty through Monte Carlo simulation**

Postclosure Science Supporting the TSPA



TSPA-LA Model

Unsaturated Zone Flow
- Climate Analysis (*Section 6.3.1*)
- Infiltration Analysis (*Section 6.3.1*)
- Site-Scale UZ Flow (*Section 6.3.1*)
- Drift Seepage (*Section 6.3.3*)
- Drift Wall Condensation (*Section 6.3.3*)

EBS Environment
- EBS Thermal-Hydrologic Environment (*Section 6.3.2*)
- EBS Chemical Environment (*Section 6.3.4*)

WP and Drip Shield Degradation
- WAPDEG
  - DS General Corrosion
  - WP General Corrosion
  - WP SCC

  (*Section 6.3.5*)
- Localized Corrosion of Waste Package Outer Surface (*Section 6.3.5*)

Waste Form Degradation and Mobilization
- Radionuclide Inventory (*Section 6.3.7*)
- In-Package Chemistry (*Section 6.3.7*)
- Cladding Degradation (*Section 6.3.7*)
- CSNF, DSNF, HLW Degradation (*Section 6.3.7*)
- Dissolved Radionuclide Concentration Limits (*Section 6.3.7*)
- WF and EBS Colloids (*Section 6.3.7*)

EBS Flow and Transport
- EBS Flow (*Section 6.3.6*)
- EBS Transport (*Section 6.3.8*)

Unsaturated Zone Transport
- UZ Transport (Particle Tracking) (*Section 6.3.9*)

SZ Flow and Transport
- 1-D SZ Flow and Transport (*Section 6.3.10*)
- 3-D SZ Flow and Transport (*Section 6.3.10*)

Biosphere
- Nominal BDCFs (*Section 6.3.11*)
- Disruptive Events BDCFs (*Section 6.3.11*)
- Groundwater Protection Conversion Factors (*Section 6.3.11*)

Events
- Early Failure (Early Failure Scenario Class)
  - Drip Shield Early Failure
  - Waste Package Early Failure

  (*Section 6.4*)
- Igneous Activity (Igneous Scenario Class)
  - Igneous Intrusion
  - Volcanic Eruption

  (*Section 6.5*)
- Seismic Activity (Seismic Scenario Class)
  - Ground Motion
  - Fault Displacement

  (*Section 6.6*)
- Human Intrusion (Human Intrusion Scenario) (*Section 6.7*)

Legend

- 🟨 Total System Performance Assessment
- 🟧 Unsaturated Zone Flow
- 🟦 Engineered Barrier System Environment
- 🟦 Waste Package and Drip Shield Degradation
- 🟩 Waste Form Degradation and Mobilization
- 🟦 Engineered Barrier System Flow and Transport
- 🟥 Unsaturated Zone Transport
- 🟩 Saturated Zone Flow and Transport
- 🟨 Biosphere
- 🟪 Events
- 🟫 Principal TSPA-LA Model Components
- → Indicates general flow of information among principal model components and submodels.

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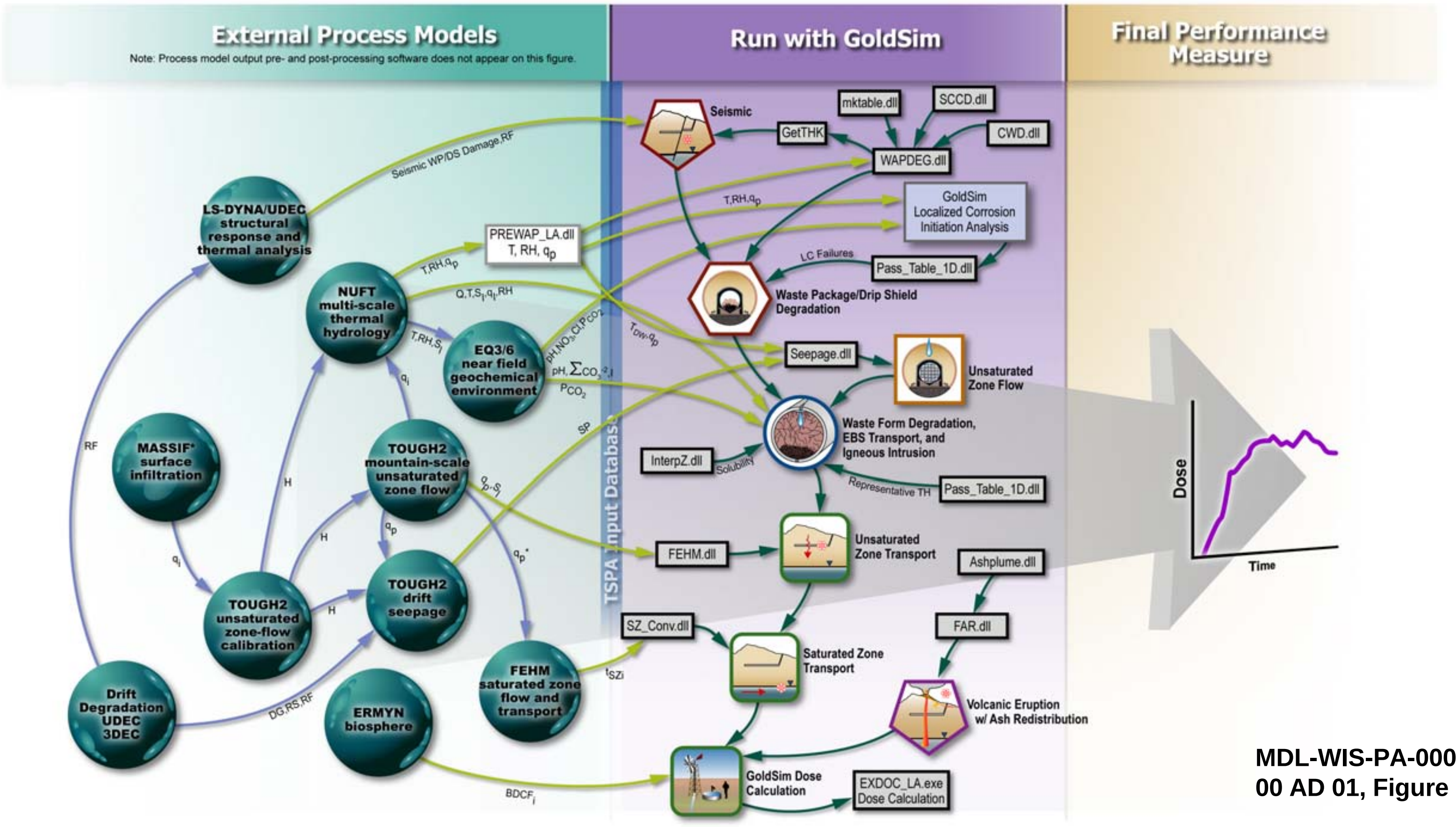
MDL-WIS-PA-000005 REV 00 AD 01, Figure 6-1

TSPA Architecture



MDL-WIS-PA-000005 REV 00 AD 01, Figure 3-2[a]

Output Parameters

f_S	Fraction of WPs with Seeps	q_p	Percolation Flux	q_i	Infiltration Flux	H	Hydrologic Properties
EBS	Engineered Barrier System	NO_3	Nitrate Concentration	DG	Drift Geometry	SP	Seepage Parameters
Q_S	Seep Flow Rate	T	Temperature	Cl	Chloride Concentration	RS	Rock Strength
Q	Evaporation Rate	RH	Relative Humidity	I	Ionic Strength	RF	Rockfall Size and Number
pH	pH	S_l	Liquid Saturation	t_{SZi}	Saturated Zone Transport Time		
ΣCO_3^{-2}	Carbonate Concentration	X_a	Air Mass Fraction	$BDCF_i$	Biosphere Dose Conversion Factor		
P_{CO_2}	Partial Pressure of CO_2	q_l	Liquid Flux	q_g	Gas Flux		

*Note: q_p derived from INFIL model

Legend

→ Response Surface between Process Models
→ Response Surface from Process Model to GoldSim
→ Connection in GoldSim
☐ Preprocessor
▨ TSPA Model DLL

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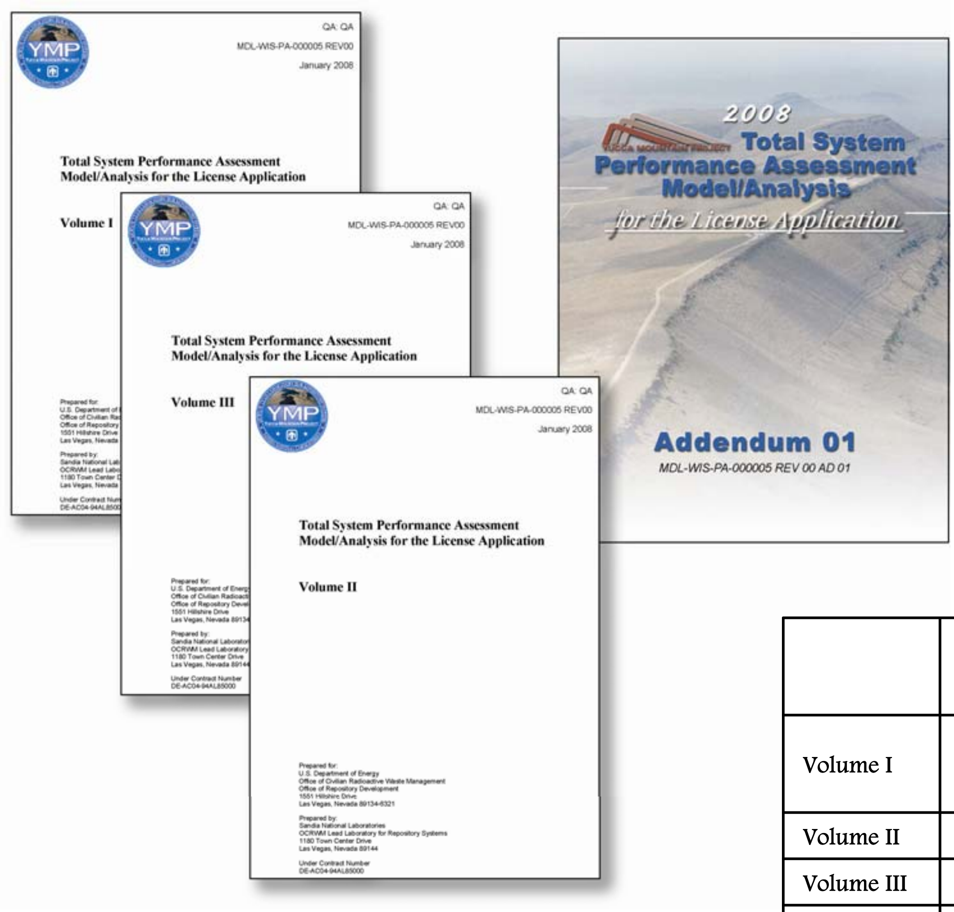
TSPA Documentation

MDL-WIS-PA-000005 REV 00 AD 01



QA: QA
MDL-WIS-PA-000005 REV00
January 2008

Total System Performance Assessment
Model/Analysis for the License Application

Volume I

QA: QA
MDL-WIS-PA-000005 REV00
January 2008

Total System Performance Assessment
Model/Analysis for the License Application

Volume III

QA: QA
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Volume II

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Total System
Performance Assessment
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for the License Application

Addendum 01
MDL-WIS-PA-000005 REV 00 AD 01

Four volumes
4272 pages

11,843 pages of supporting technical documents that provide direct input

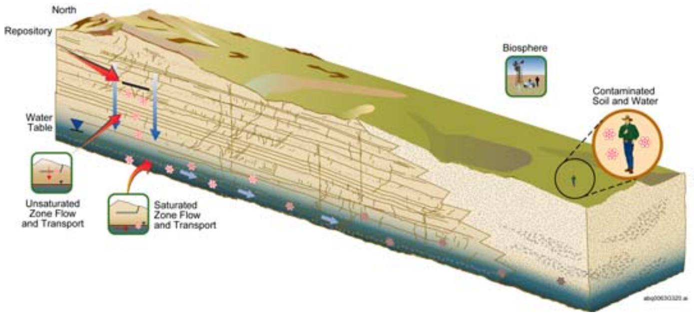
	Total Pages	Number of Tables	Number of Figures	Number of Actual Plots	Number of Word Files
Volume I	1111	183	255		83
Volume II	600	41	221	261	49
Volume III	1767	130	519	1498	54
Addendum	794	34	321	601	12
TOTALS	4272	388	1316	2360	198

Future Scenarios for Yucca Mountain

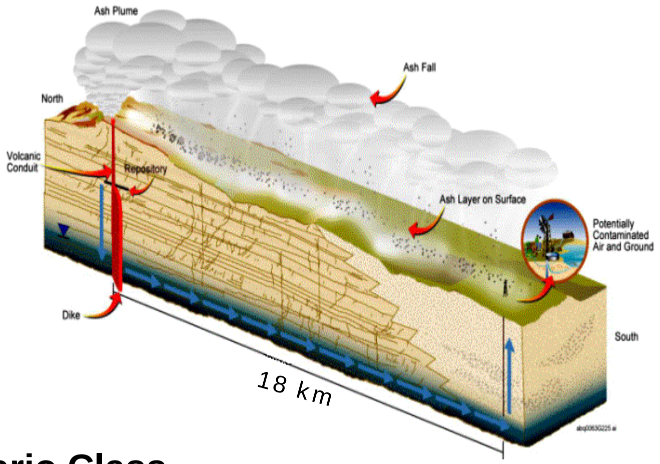
Four scenario classes divided into seven modeling cases

- **Nominal Scenario Class**
    - **Nominal Modeling Case**

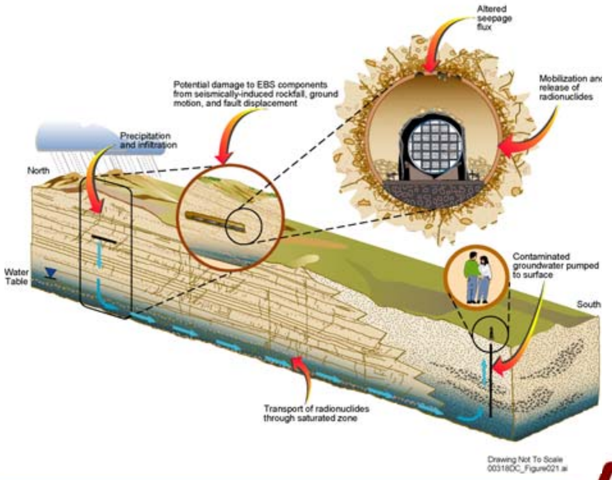
- **Early Failure Scenario Class**
    - **Waste Package Modeling Case**
    - **Drip Shield Modeling Case**



- **Igneous Scenario Class**
    - **Intrusion Modeling Case**
    - **Eruption Modeling Case**



- **Seismic Scenario Class**
    - **Ground Motion Modeling Case**
    - **Fault Displacement Modeling Case**



Scenarios and Modeling Cases

Nominal Scenario Class (1 modeling case)

- No releases until waste package (WP) corrosion creates pathway
- WP failures rare before 100,000 years
- WP failures due to stress corrosion cracking (SCC) of closure welds occur as general corrosion removes annealed layer
  - SCC common by 500,000 years
  - Releases through SCC occur by diffusion only
- Drip shield (DS) failures due to general corrosion occur between 270,000 and 340,000 years
- WP "patch" failures due to general corrosion rarely occur before 500,000 years
  - Mean of 9% of WPs show patch failures at 1 million years
  - Patch failures allow advective releases

Scenarios and Modeling Cases (Cont)

- Early Failure Scenario Class (2 modeling cases)
  - Early Failure WP Modeling Case
    - Failures occur at time of repository closure
    - Median probability of early failure = 4.4 x 10^{-5} per WP
    - Probability of 1 or more early failure waste packages = 0.44
    - Expected number of early failure waste packages (given early failures occur) = 2.5
    - Diffusion until DS failure by corrosion
  - Early Failure DS Modeling Case
    - Failures occur at time of repository closure
    - Median probability of early failure = 4.3 x 10^{-7} per DS
    - Probability of 1 or more early failure drip shields = 0.017
    - Expected number of early failure drip shields (given early failures occur) = 1.1
    - Simplifying assumption: WP under early failed DS is also failed in seeping conditions
    - Transport by both advection and diffusion

Scenarios and Modeling Cases (Cont)

- **Igneous Scenario Class (2 modeling cases)**
  - **Intrusion Modeling Case**
    - **Mean frequency 1.7 x 10^{-8}/yr (uncertain event frequency)**
    - **All waste packages and drip shields sufficiently damaged to provide no barrier to flow and transport**
    - **Seepage equal to percolation flux (no capillary barrier)**
  - **Eruption Modeling Case**
    - **Probability of waste intersection by eruption conditional on igneous event is 0.08**
    - **Mean number of waste packages intersected = 3.8**
    - **Mean fraction of waste package content ejected = 0.3**
    - **Ash redistribution by fluvial processes after deposition**

Scenarios and Modeling Cases (cont.)

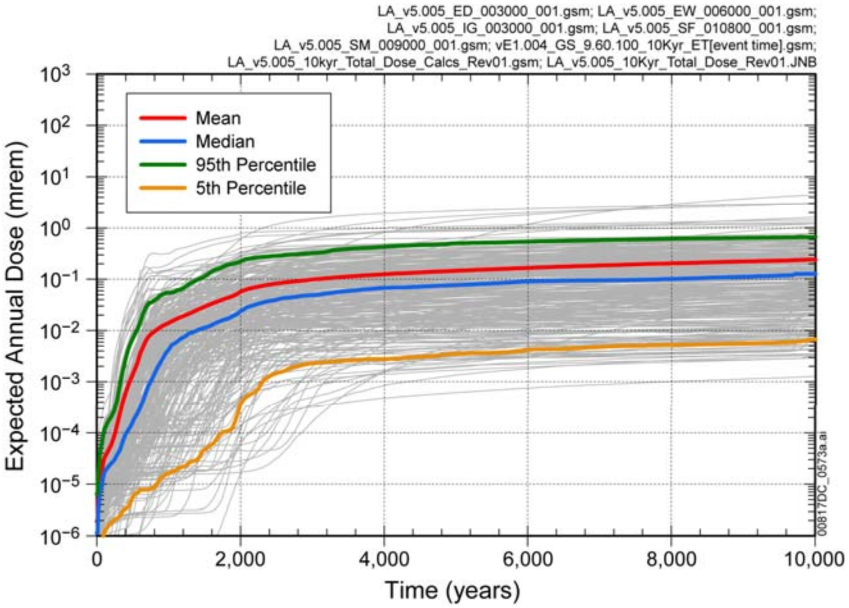
- **Seismic Scenario Class (2 Modeling Cases)**
  - **Seismic Ground Motion (GM) Damage Modeling Case**
    - **Ground motions result in SCC that allow diffusive releases**
      - **Frequency of events that damage codisposal (CDSP) packages: ~ 10^{-5} / yr**
      - **Frequency of events that damage transportation, aging, and disposal (TAD) packages for commercial spent nuclear fuel (CSNF): ~ 10^{-8} / yr**
    - **Cracked area accumulates with additional seismic events**
    - **Repeated damage may cause WP rupture ($<10^{-8}$ / yr)**
    - **Drip shield thins by general corrosion and fails due to dynamic loading of accumulated rockfall**
  - **Nominal corrosion processes included for million-year analyses**
    - **Corrosion affects EBS response to ground motion**
      - **Damage analyses consider thinning of Alloy 22 and titanium**
      - **SCC allows corrosion of internal steel components**

Scenarios and Modeling Cases (cont.)

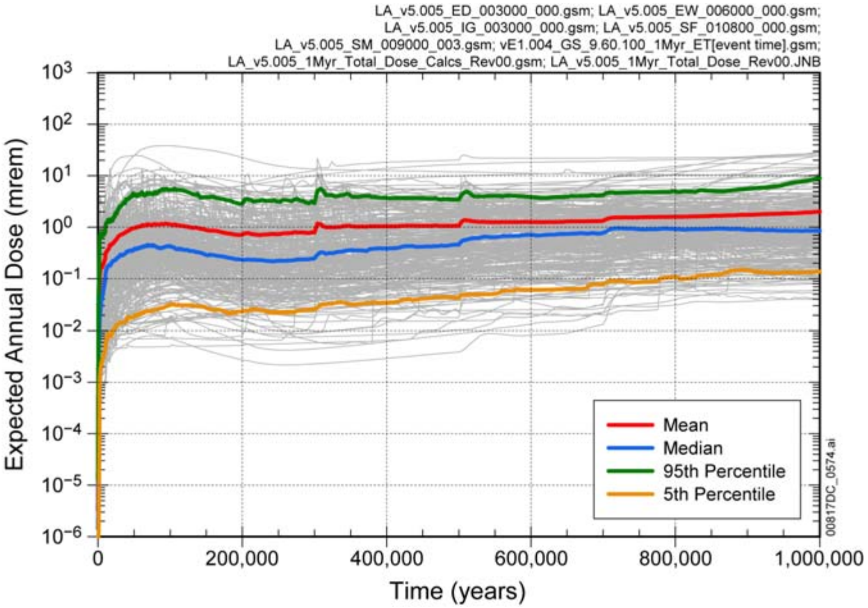
- **Seismic Scenario Class (2 Modeling Cases) (cont.)**
  - **Seismic Fault Displacement Modeling Case**
    - **Annual frequency approximately 2 x 10^{-7} / yr**
    - **Fault displacements rupture waste packages and drip shields, allowing advection and diffusion**
      - **Size of rupture uncertain, 0 to cross-sectional area of WP**
    - **mean of ~ 47 waste packages and drip shields damaged**

Total System Performance Assessment Results

Total Mean and Median Annual Dose



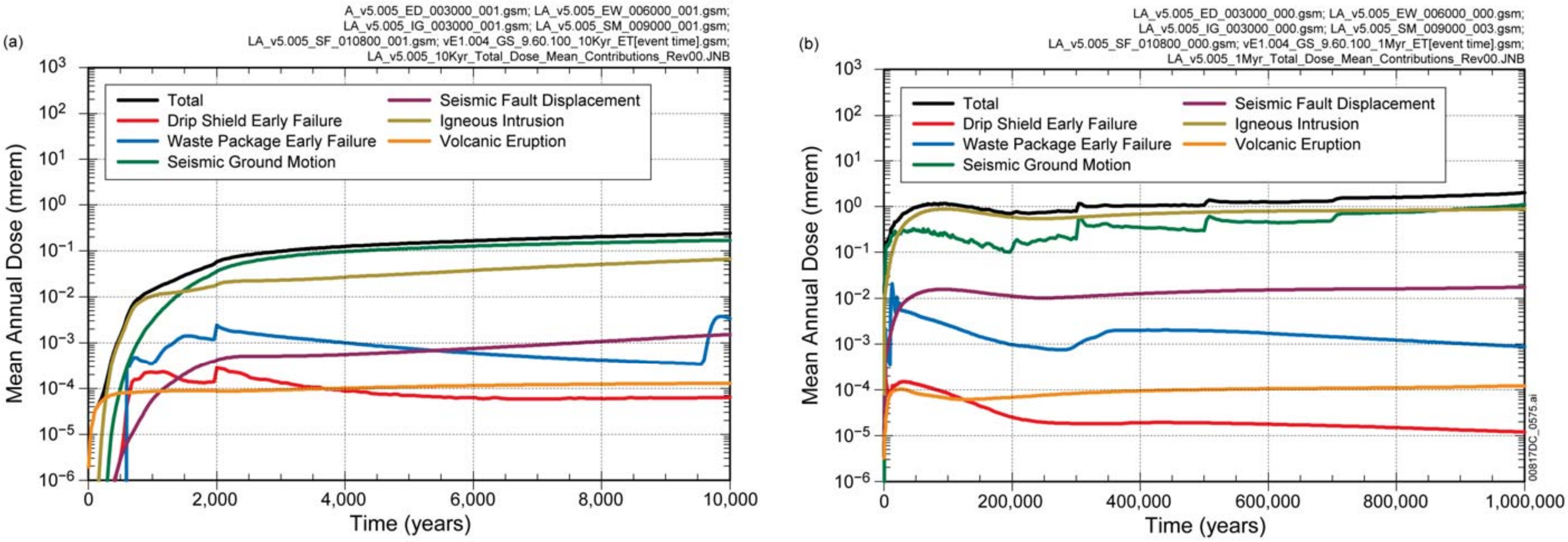
10,000 years



1,000,000 years

MDL-WIS-PA-000005 REV 00 AD 01, Figure 8.1-1[a] and Figure 8.1-2[a]

TSPA Results: Modeling Cases Contributing to Total Mean Annual Dose



10,000 years

1,000,000 years

MDL-WIS-PA-000005 REV 00 AD 01, Figure 8.1-3[a].

Terminology

- **"Dose" – annual dose to the Reasonably Maximally Exposed Individual (RMEI) as a function of time**

  $$D_{MC}\left(\tau \middle| \mathbf{a}, \mathbf{e}\right)$$

  - **Depends on both aleatory and epistemic uncertainty**
  - **Summed over all radionuclides**
- **"Expected Dose"**

  $$\bar{D}_{MC}\left(\tau \middle| \mathbf{e}\right)$$

  - **Expectation is taken over aleatory quantities**
  - **Conditional on epistemic uncertainty**
  - **Calculated for each modeling case**
- **"Mean Dose"**

  $$\bar{\bar{D}}_{MC}\left(\tau\right)$$

  - **Expectation is taken over both epistemic and aleatory**
  - **Calculated for each modeling case**
- **"Total Expected Dose"**

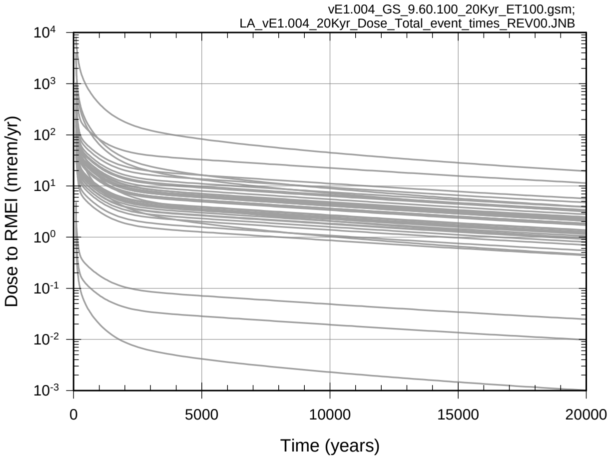
  $$\bar{D}\left(\tau \middle| \mathbf{e}\right) = \sum_{MC} \bar{D}_{MC}\left(\tau \middle| \mathbf{e}\right)$$

  - **Summed over modeling cases by epistemic vector**
- **"Total Mean Dose"**

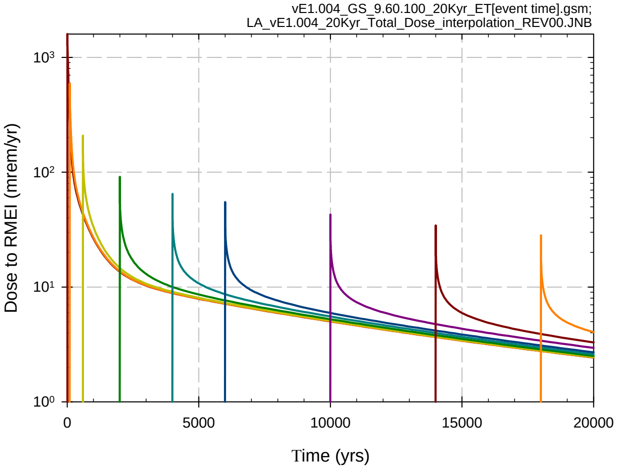
  $$\bar{\bar{D}}\left(\tau\right) = \frac{1}{N}\sum_{i=1}^{N} \bar{D}\left(\tau \middle| \mathbf{e}_i\right)$$

  - **Average of Total Expected Dose**

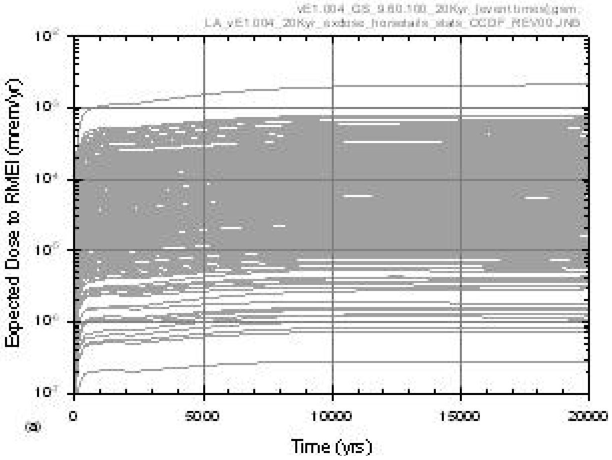
Example: Eruptive Dose



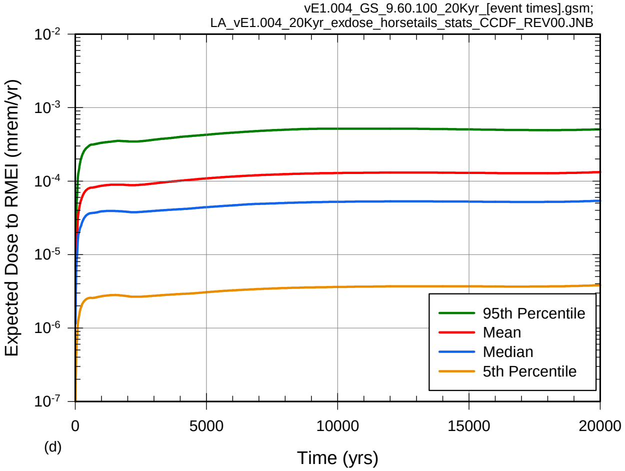
Eruptive dose: 40 realizations of aleatory uncertainty conditional on a single eruption of 1 WP at time zero



Eruptive dose averaged over aleatory uncertainty associated with a single eruption of 1 WP, eruptions at multiple times



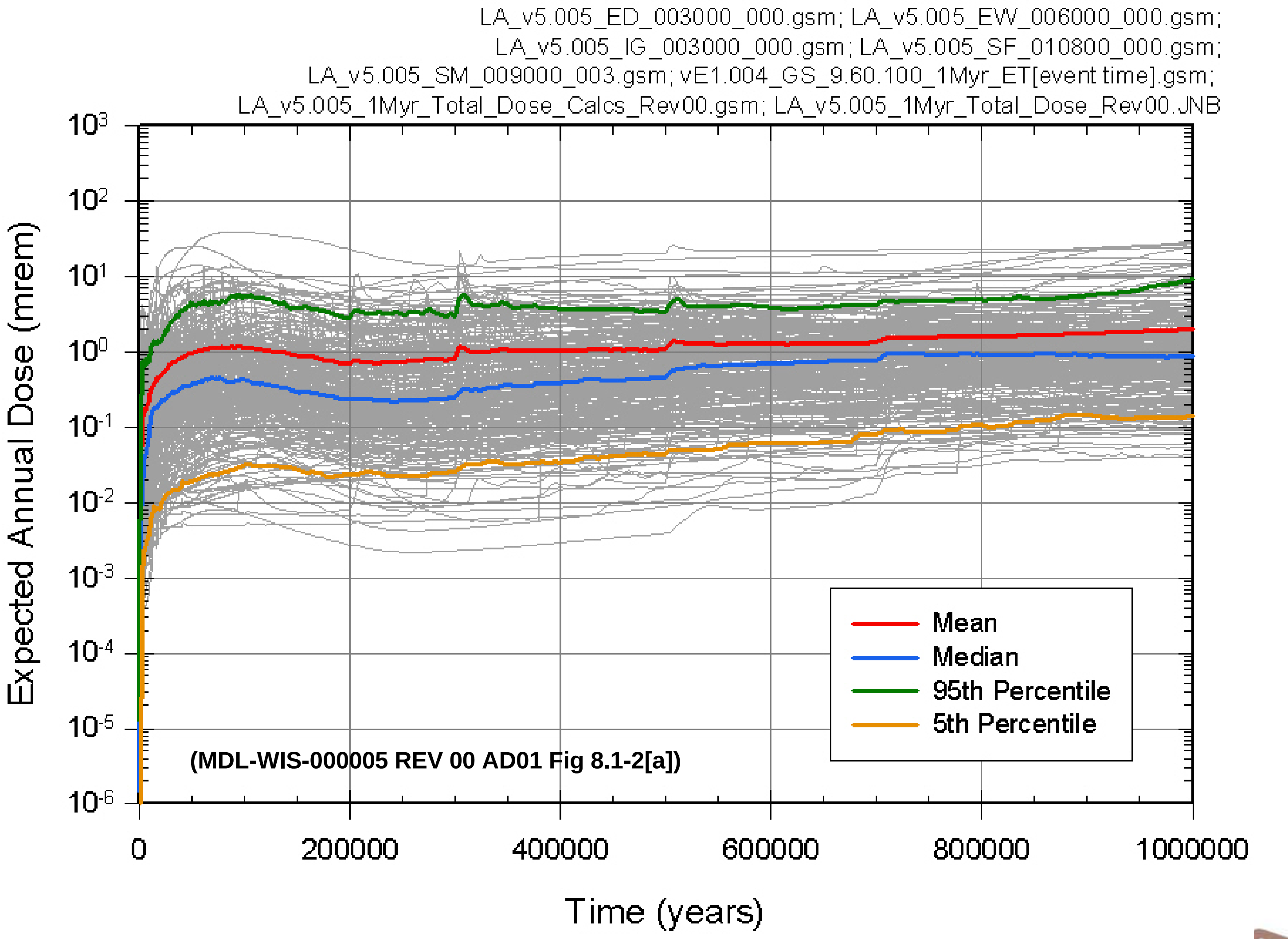
Expected eruptive dose; 300 realizations, each showing expected dose from a single sampling of epistemic uncertainty with events at all times



Summary curves showing overall mean dose from eruption

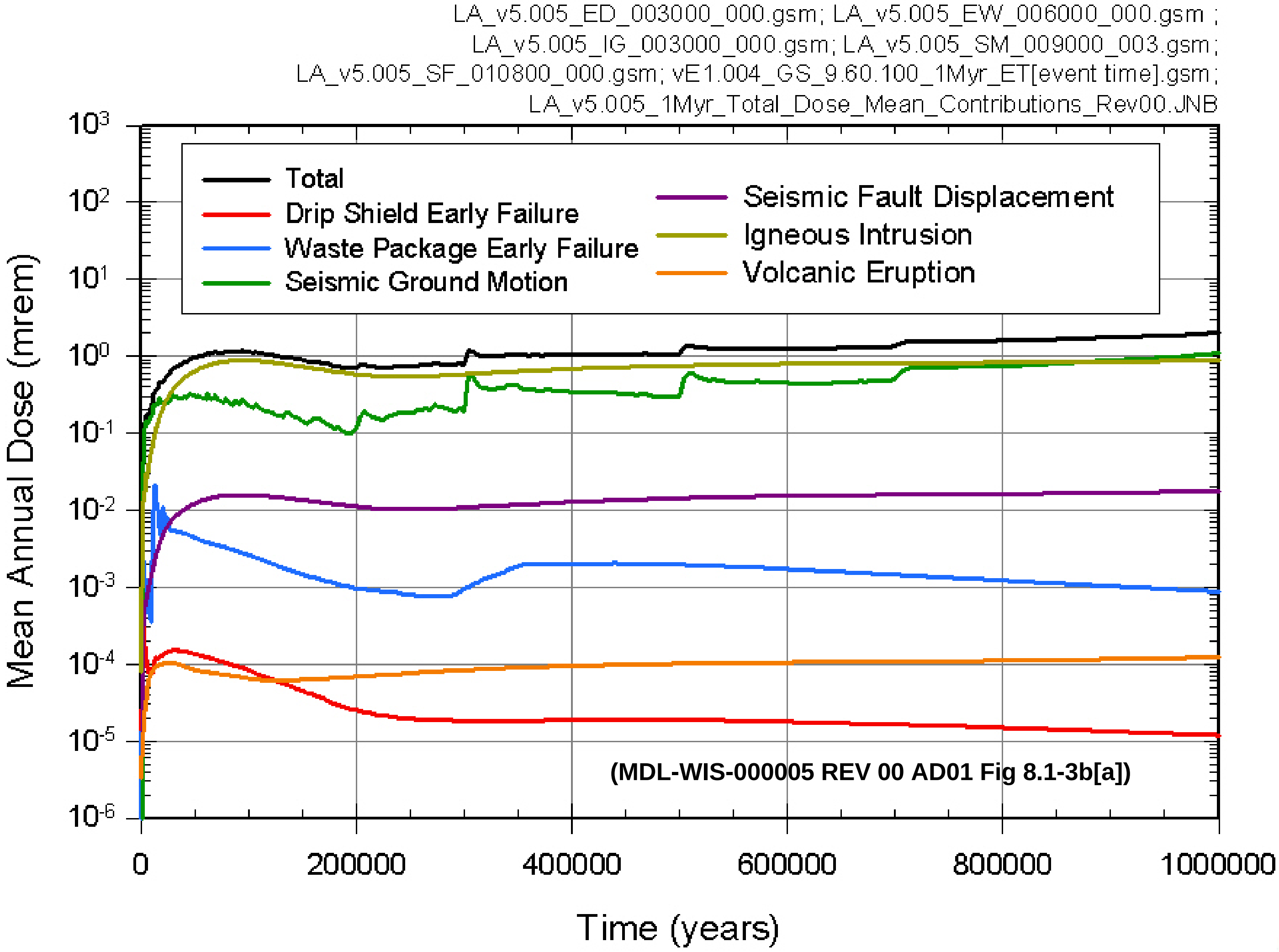
MDL-WIS-PA-000005 Rev 00, Figures J7.3-1, 2,&4

Uncertainty in Total Expected Dose
(1 million years)



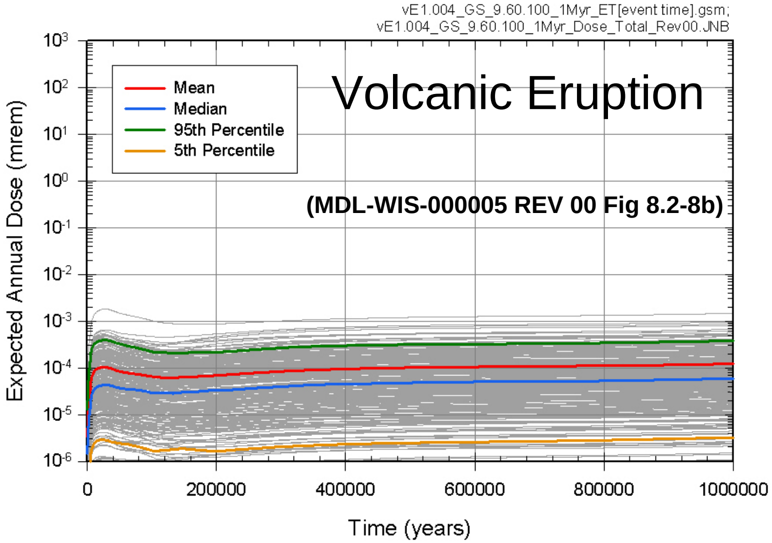
(MDL-WIS-000005 REV 00 AD01 Fig 8.1-2[a])

Total Mean Dose Contribution By Modeling Case



(MDL-WIS-000005 REV 00 AD01 Fig 8.1-3b[a])

Construction of Total Dose


vE1.004_GS_9.60.100_1Myr_ET[event time].gsm;
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Volcanic Eruption

(MDL-WIS-000005 REV 00 Fig 8.2-8b)

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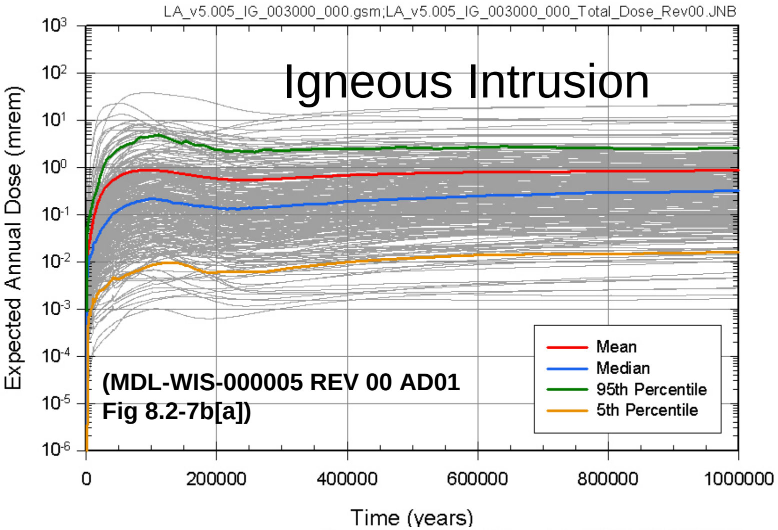
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Igneous Intrusion

(MDL-WIS-000005 REV 00 AD01
Fig 8.2-7b[a])

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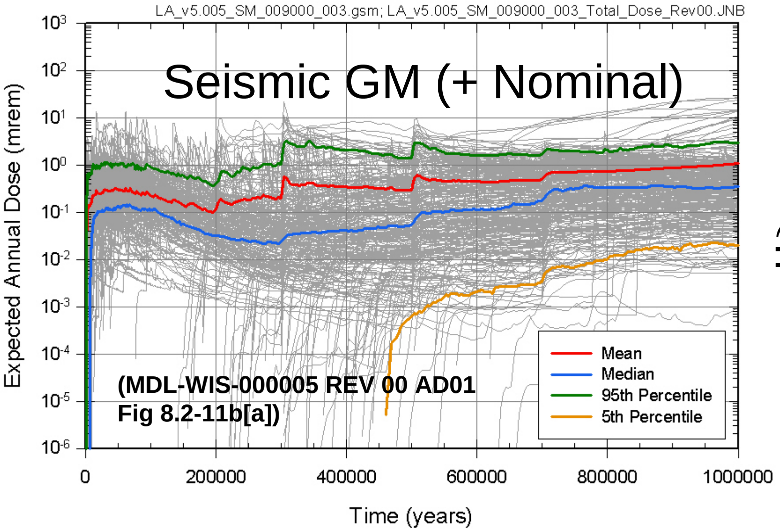
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Seismic GM (+ Nominal)

(MDL-WIS-000005 REV 00 AD01
Fig 8.2-11b[a])

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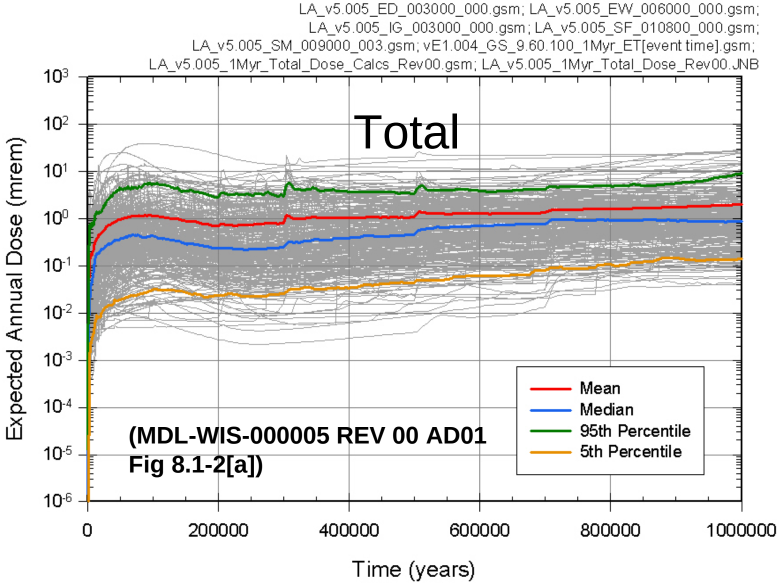
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LA_v5.005_SM_009000_003.gsm; vE1.004_GS_9.60.100_1Myr_ET[event time].gsm;
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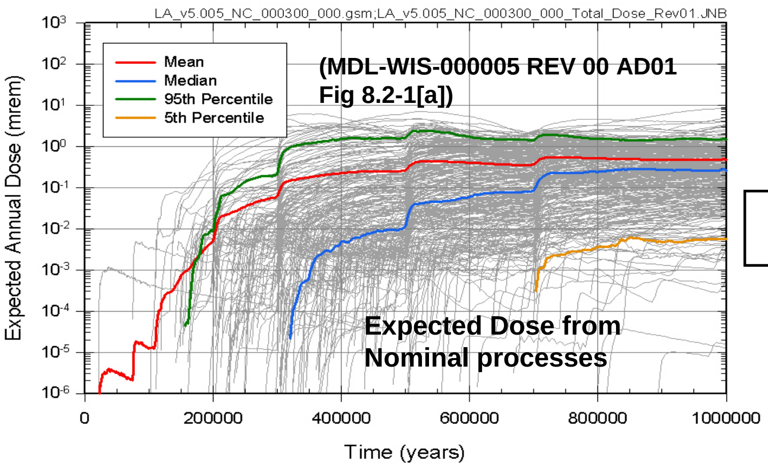
Total

(MDL-WIS-000005 REV 00 AD01
Fig 8.1-2[a])

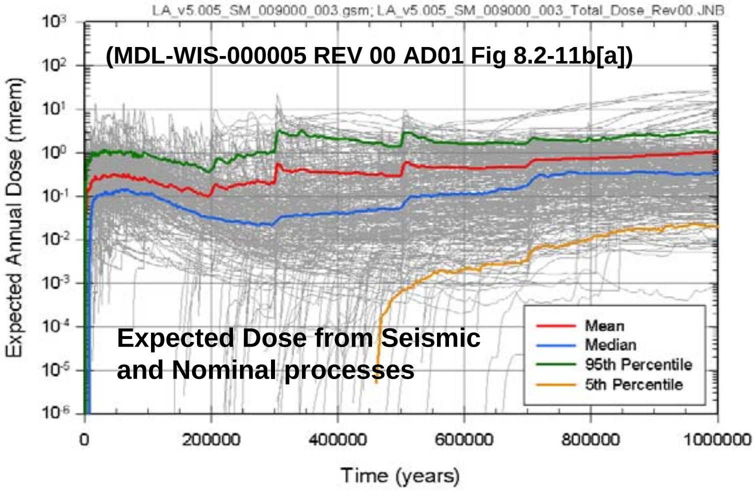
Composition of Dose from Seismic GM



(MDL-WIS-000005 REV 00 AD01 Fig 8.2-1[a])

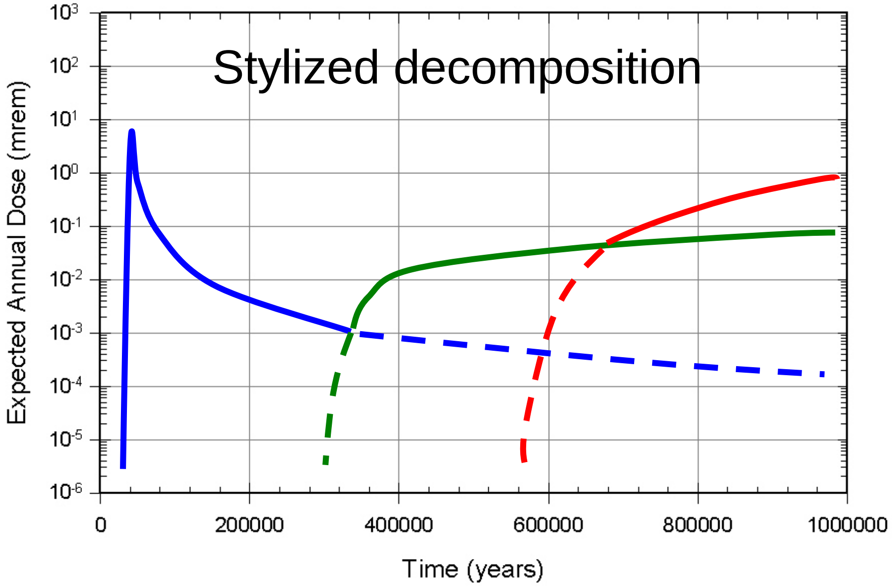
Expected Dose from Nominal processes

Included



(MDL-WIS-000005 REV 00 AD01 Fig 8.2-11b[a])

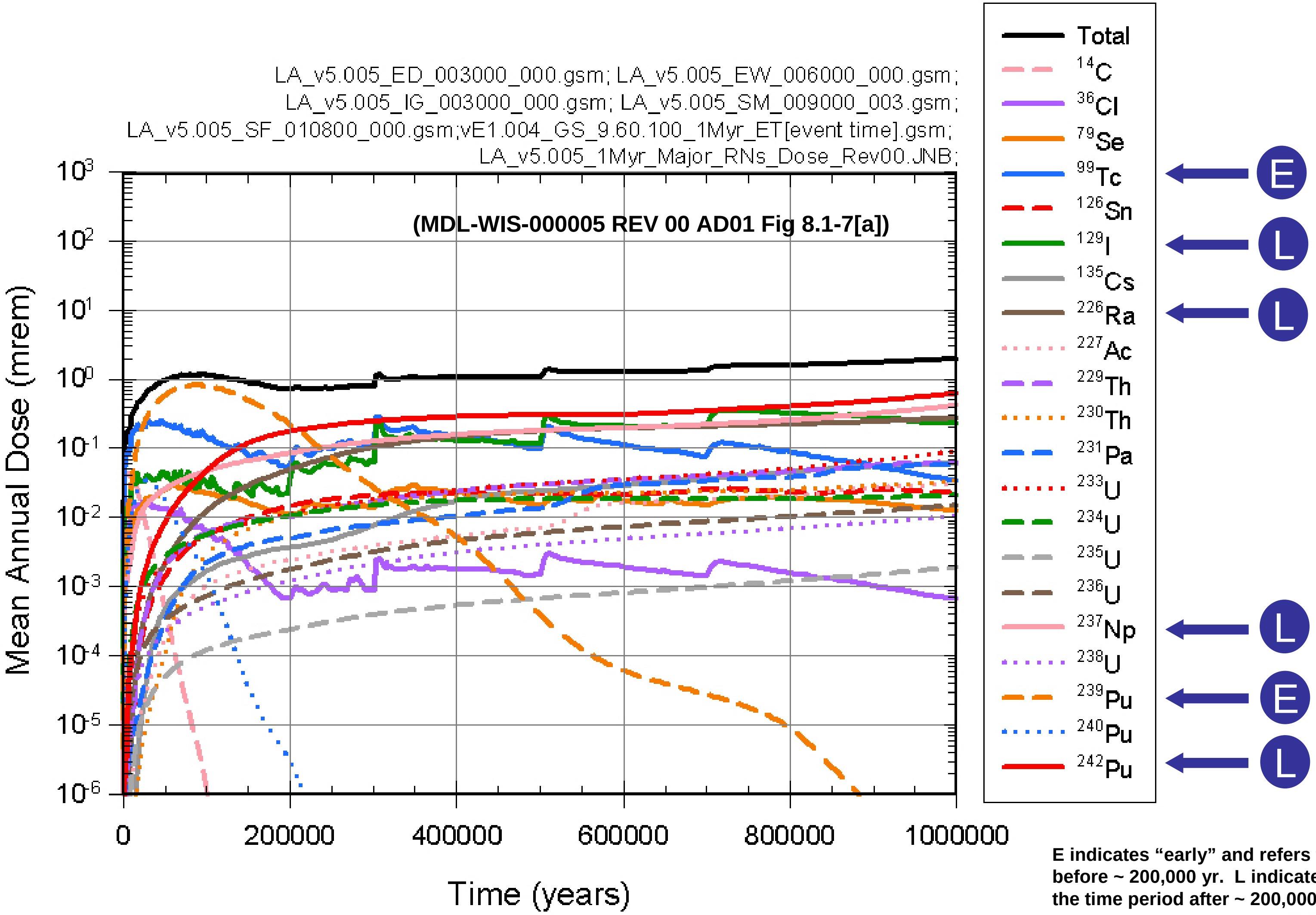
Expected Dose from Seismic and Nominal processes



Stylized decomposition

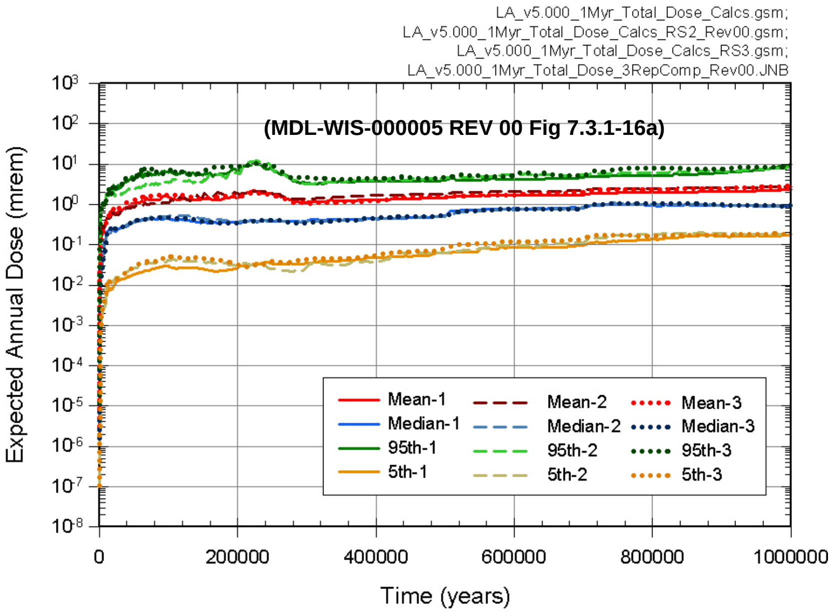
- From seismic damage to CDSP WP (diffusion)
- From SCC failure of CSNF WP (diffusion)
- From general corrosion failure of both WPs (advection)

Radionuclides Important to Mean Dose

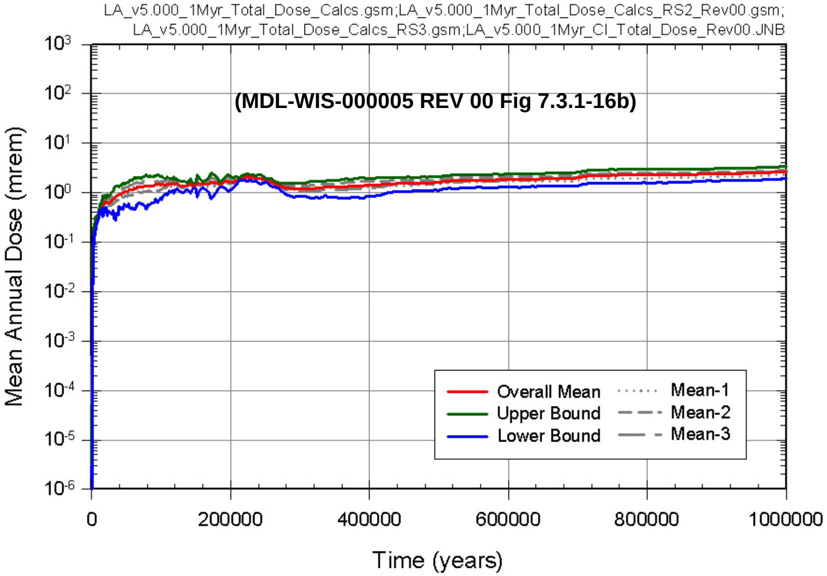


E indicates "early" and refers to the time period before ~ 200,000 yr. L indicates "late" and refers to the time period after ~ 200,000 yr

Stability of Total Dose



Replicated sampling demonstrates that sample size is sufficient

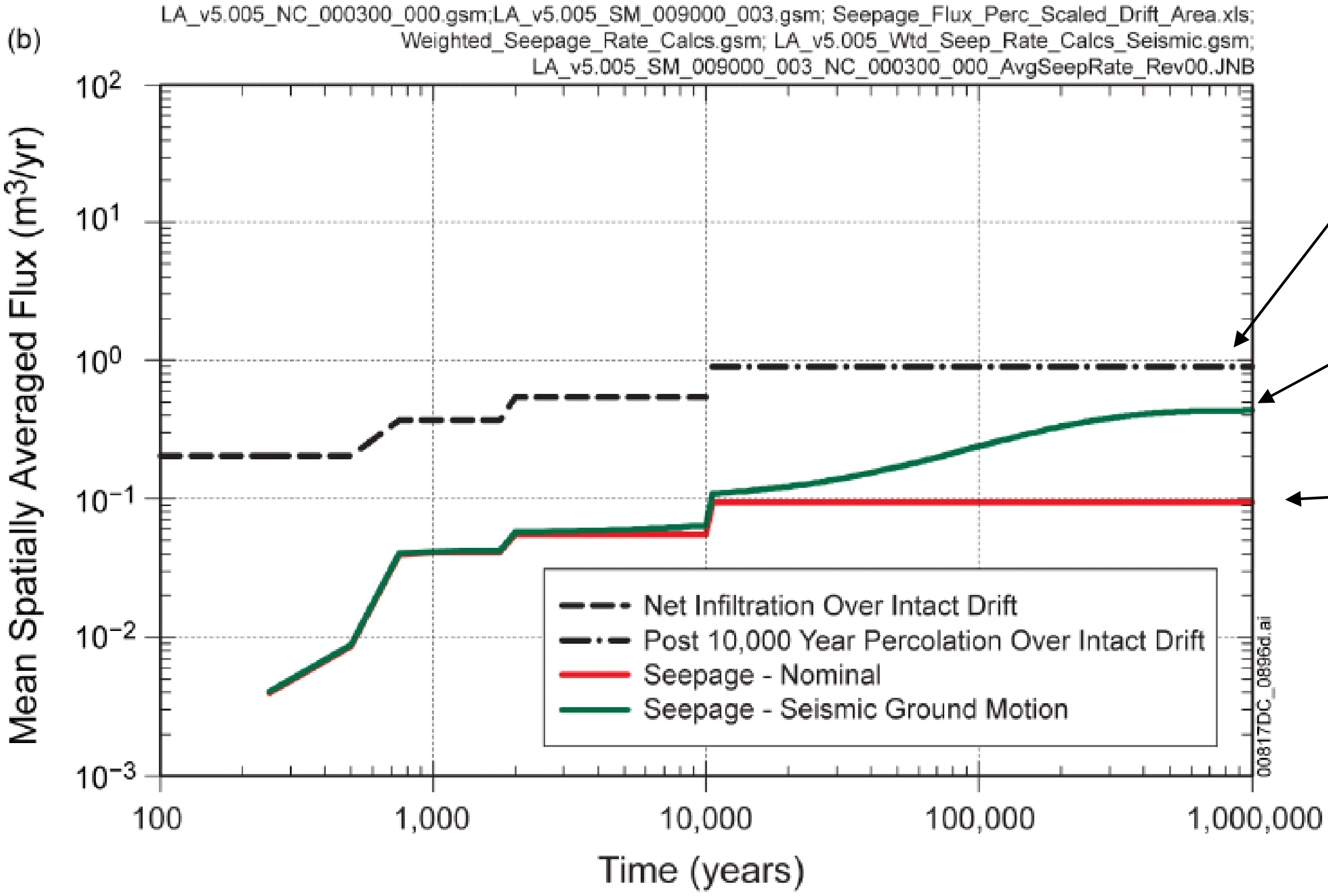


Confidence interval illustrates precision of estimate of total mean dose

Water and Radionuclide Movement in the EBS Seismic Ground Motion Modeling Case

- **Water movement following ground motion**
  - **Nominal seepage model accounts for capillary and thermal effects around drift**
    - **Nominal model shows seepage in a mean of 40% of WP locations, mean seepage rates are 2-11% of percolation flux**
  - **Seepage model adjusted for rockfall accumulation**
    - **Additional seepage model developed for rubble-filled drifts; seepage for seismic GM case in mean of 70% of WP locations, mean seepage rates are up to 48% of percolation flux**
    - **Lithophysal rock (~85% of emplacement area): nominal model used when rubble <5 m^3/m; rubble-filled model used when rubble > 60 m^3/m**
      - **Linear interpolation between nominal and rubble-filled seepage based on calculated amount of rubble**
    - **Non-lithophysal rock (~15 % of emplacement area): collapse events rare, percolation flux used when rubble > 0.5 m^3/m**

Mean TSPA Seepage Rates



890 kg/yr

434 kg/yr

95 kg/yr

Units are m^3/5.1m of drift, also shown as kg/yr per waste package; mean of all realizations

MDL-WIS-PA-000005 REV 00 AD 01 Figure 8.3-3b[a]

Water and Radionuclide Movement in the EBS Seismic Ground Motion Modeling Case (cont.)

- Water movement following ground motion (cont.)
  - Flow through EBS components
    - Drip Shields
      - Flow through SCC in drip shield is negligible, screened out from TSPA (see discussion in FEP 2.1.03.10.0B)
      - After general corrosion thinning and failure due to accumulated rockfall (approx. 300,000 yr), DS no longer provides flow barrier
    - Waste Packages
      - Diffusion of water through SCC in WPs assumed to be sufficient to degrade stainless steel internal components
      - Flow occurs through general corrosion WP patch failures and rare WP ruptures or punctures
      - Flow fraction entering WP is proportional to ratio of patch failure length to WP length: conceptually, GC failures along crown of WP allow all available flow to enter WP when a small fraction (mean of 4%) of patches have failed
      - Flow allowed to leave WP at same rate it enters
    - Flow in invert same as in nominal case

Water and Radionuclide Movement in the EBS Seismic Ground Motion Modeling Case (cont.)

- **Radionuclide transport following ground motion**
  - **Diffusion is the only release mechanism prior to patch failures by general corrosion or rupture/puncture**
    - **Diffusion of water into WPs allows waste form degradation**
    - **Diffusion of radionuclides occurs through continuous water films from waste form to invert when relative humidity > 95%**
      - **High solubility, non-sorbing nuclides dominate dose: ^{99}Tc and ^{129}I**
      - **Rate of diffusion controlled by cross-sectional area of cracks, path length, concentration gradient**
  - **After patch failures, advective releases dominate**
    - **Long-lived actinides dominate dose: ^{242}Pu, ^{237}Np, ^{239}Pu**
    - **Water flux, solubility limits, sorption processes in WP affect rate of release**

Water and Radionuclide Movement in the EBS Igneous Intrusion Modeling Case

- Water movement following igneous intrusion
  - Seepage model replaced with percolation flux to bound uncertainty associated with capillary properties of magma-filled drifts
    - Seepage equal to percolation flux occurs at all waste package locations
    - Water re-enters drifts when temperatures drop below boiling
      - Temperatures fall below boiling within a few years at post-thermal times, ambient temperatures are reached after ~ 100 yr
  - All water entering drifts reaches waste
    - Magmatic material filling drifts assumed to have properties equivalent to fractured tuff
    - Drip shield and waste packages provide no barrier to flow
  - Water flow in invert is unchanged from nominal case

Water and Radionuclide Movement in the EBS Igneous Intrusion Modeling Case (cont.)

- Radionuclide transport following intrusion
  - CSNF and HLW waste forms assumed to be fully degraded by high temperature of intrusion
  - Waste package geometry and materials assumed to be intact for purposes of water chemistry and radionuclide transport
    - In-package chemistry model used to determine solubility limits
    - Transport pathways are the same as for nominal case with patch failures
  - Contents of all waste packages are available for advective transport

Summary of TSPA Results

- Total mean dose determined by occurrence of igneous events, seismic damage and general corrosion
- Major contributors to dose are ^{99}Tc, ^{129}I, ^{239}Pu, ^{242}Pu, ^{226}Ra, and ^{237}Np
- 10,000-yr total estimated maximum mean annual dose: 0.24 mrem/yr
  - Largest contributor is ^{99}Tc from co-disposed waste, dominant pathway is diffusion through stress corrosion cracks following ground motion damage
- 1,000,000 total estimated maximum median annual dose: 0.96 mrem/yr (mean annual dose at 1,000,000 yr: 2.0 mrem/yr)
  - Largest contributors are ^{242}Pu, ^{237}Np, ^{226}Ra, ^{239}Pu, and ^{129}I
    - Actinide releases occur due to advective transport following igneous intrusion and general corrosion patch failure
    - Iodine releases are dominated by diffusive pathways through stress corrosion cracks
  - Nominal general corrosion processes dominate at 1 million years

Backup

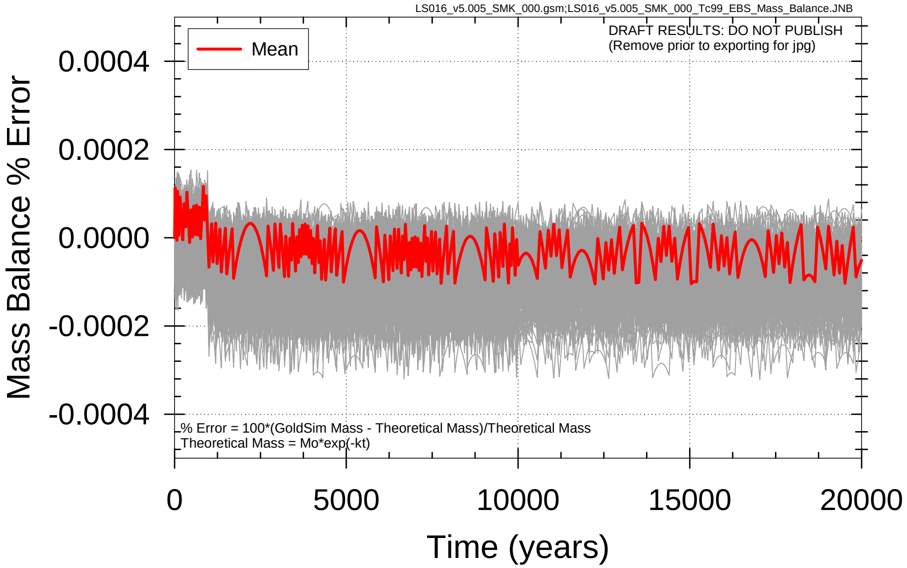
Water Mass Balance in the EBS

- Liquid water balance is maintained within the unsaturated zone flow, thermal hydrology, seepage and EBS flow models
  - Water entering drifts is equal to water leaving drifts
  - Exception:
    - Removal of vapor-phase water by evaporation is not included; addition of water from condensation is included during the first 2000 years (evaporation/condensation processes are not explicitly balanced)
- Consumption of water by chemical reactions (e.g., in degradation of engineered materials) is assumed to be insignificant
- Movement of water vapor through SCCs is assumed to be sufficient to sustain degradation reactions and maintain continuous water films that allow diffusive transport

Radionuclide Mass Balance in the EBS

- **Radionuclide mass balance maintained in EBS submodel in GoldSim**
  - **^{99}Tc example shown for ground motion case, single sampling of aleatory uncertainty (event at 1000 years) , 300 realizations of epistemic uncertainty**
  - **Mean mass balance discrepancy is approximately 0.001%**

LS016_v5.005_SMK_000: ^{99}Tc Mass Balance
300 Epistemic Realizations (150 plotted), Seismic-GM Modeling Case
Event Time = 1,000-yrs, Damage Fraction = 10^{-6}



% Error = 100*(GoldSim Mass - Theoretical Mass)/Theoretical Mass
Theoretical Mass = Mo*exp(-kt)

Localized Corrosion in the TSPA

- **Drip Shields**
  - **Localized corrosion is screened out**
    - **FEP 2.1.09.28.0B; Localized corrosion on drip shield surfaces due to deliquescence**
    - **FEP 2.1.03.03.0B; Localized corrosion of drip shields**
- **Waste Packages**
  - **Localized corrosion of Alloy-22 due to dust deliquescence is screened out**
    - **FEP 2.1.09.28.0A; Localized corrosion on waste package outer surface due to deliquescence**
  - **Localized corrosion in seepage water is included in TSPA**
    - **FEP 2.1.03.03.0A; Localized corrosion of waste packages**

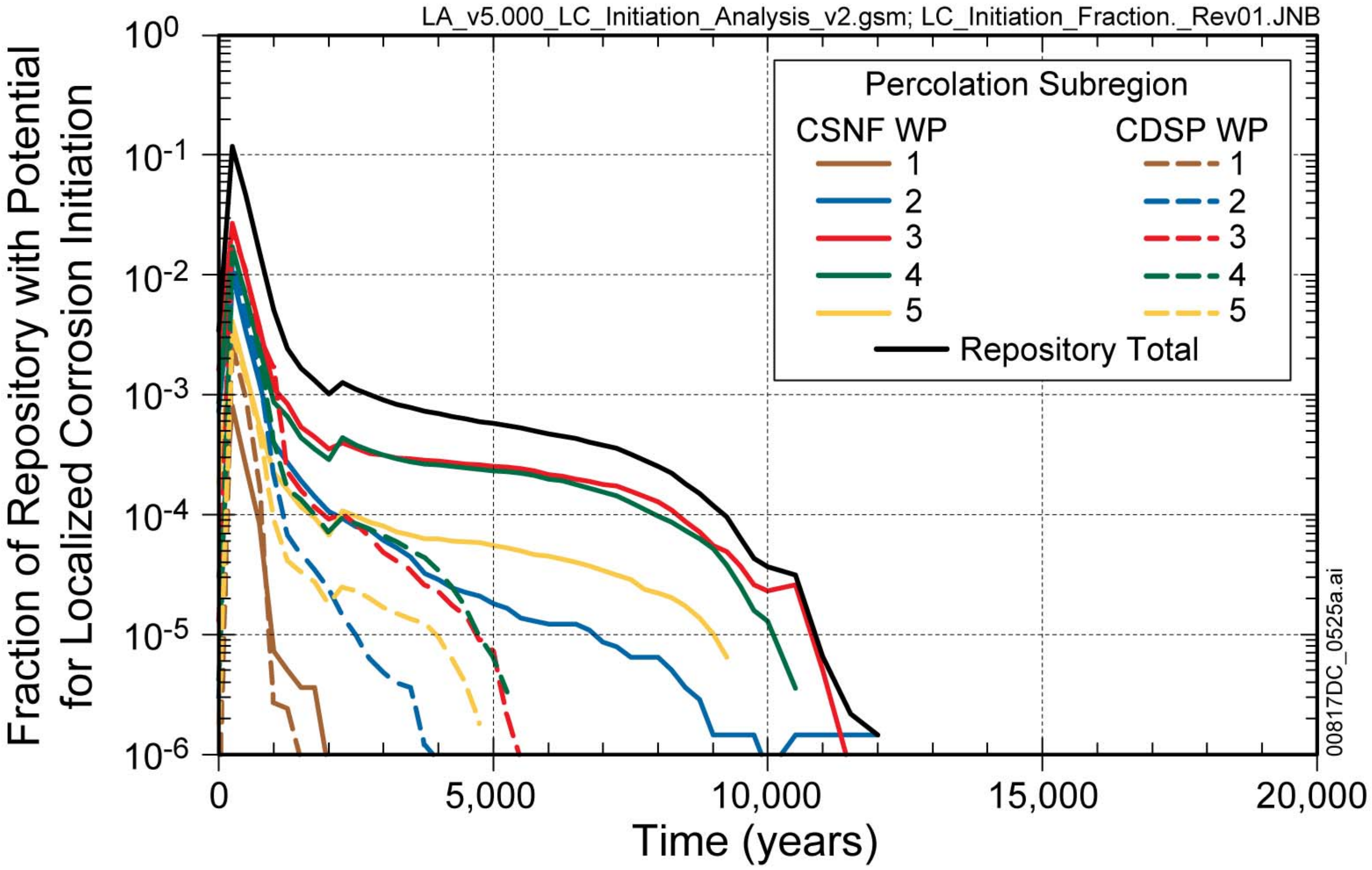
Localized Corrosion of Alloy-22

Note: This overhead contains an error. See correction letter of April 30, 2009, for the corrected version of this overhead. The letter may be reached via the "meetings" page.

- **Environmental conditions for LC initiation are analyzed using TSPA model independent of the drip shield (MDL-WIS-PA-000005 REV 003 AD 01, Appendix 0)**
  - **Temperature, pH, and nitrate/chloride ratios modeled as a function of time for 3,264 nodes in repository**
  - **The potential for LC peaks in the first few hundred years when temperatures are highest**
    - **LC conditions could exist at approximately 10 % of modeled WP locations at early time**
    - **By 5000 years, less than 0.1 % of WP locations have LC conditions**
    - **LC conditions do not occur at any locations after 12,000 years**
- **LC is included by bounding assumptions for modeling cases in which the DS is compromised before 12,000 years**
  - **For DS Early Failure case, failure of WP due to LC is assumed for all seeping locations, regardless of actual environment**
  - **For Seismic Fault Displacement, WP is assumed to be sheared by the fault displacement event**
  - **For Igneous modeling cases, WPs are assumed to be fully compromised by the event**

Localized Corrosion in TSPA (cont.)

Note: This overhead contains an error. See correction letter of April 30, 2009, for the corrected version of this overhead. The letter may be reached via the "meetings" page.



Fraction of locations in each percolation subregion with the potential for localized corrosion (MDL-WIS-000005 REV 00 AD01 Fig O-2)

Localized Corrosion in TSPA (cont.)

Localized corrosion has the potential to initiate when $E_{corr} \geq E_{crit}$, where E_{crit} is the crevice repassivation potential E_{rcrev}

$$E_{critical} = E_{rcrev} = a_o + a_1 T + a_2 \ln\left[Cl^-\right] + a_3 \frac{\left[NO_3^-\right]}{\left[Cl^-\right]} + a_4 T\left[Cl^-\right] + \varepsilon_{rcrev}$$

$$E_{corr} = c_o + c_1 T + c_2\, pH + c_3 \frac{\left[NO_3^-\right]}{\left[Cl^-\right]} + c_4 T \frac{\left[NO_3^-\right]}{\left[Cl^-\right]} + c_5\, pH \frac{\left[NO_3^-\right]}{\left[Cl^-\right]} + c_6\, pH \ln[Cl^-] + \varepsilon_{corr}$$

MDL-WIS-000005 REV 00 AD01 Appendix O, Equations O-1 and O-2