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

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# Disruptive Scenario Classes: Seismic Consequence Abstraction

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

**Presented by:**
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**Sandia National Laboratories**

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# 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

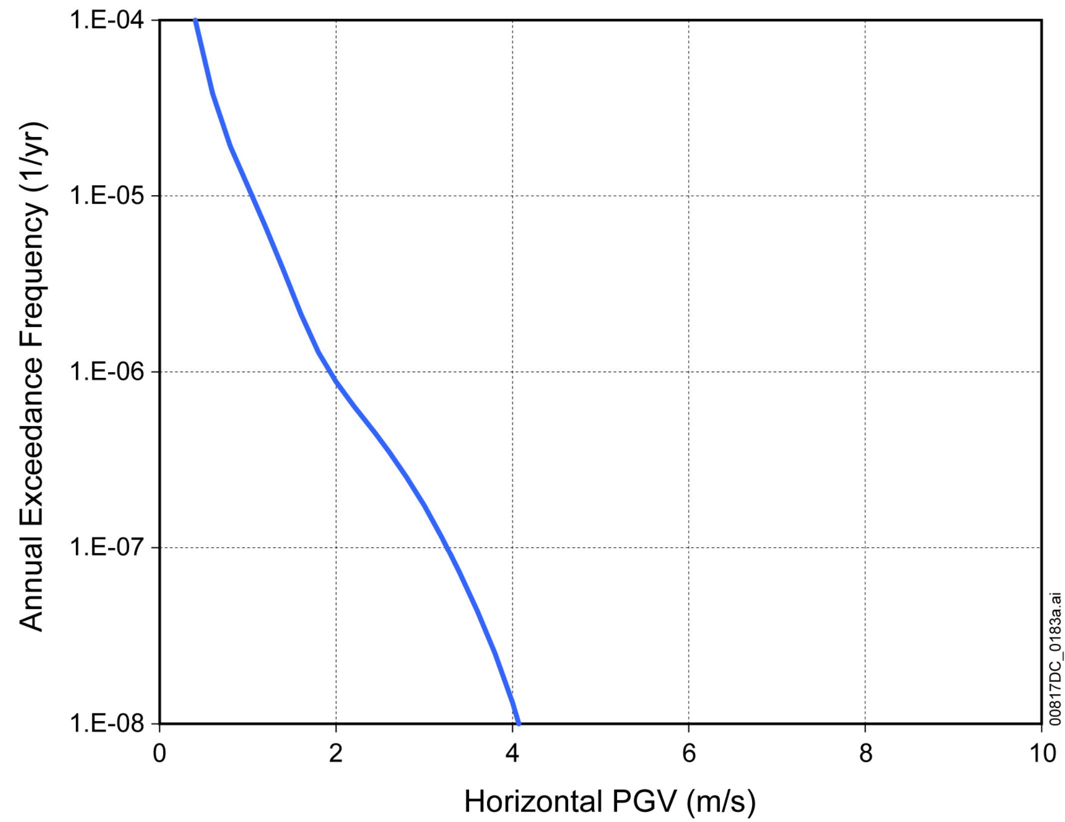
# Definition of Seismic Scenario Class

- **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)

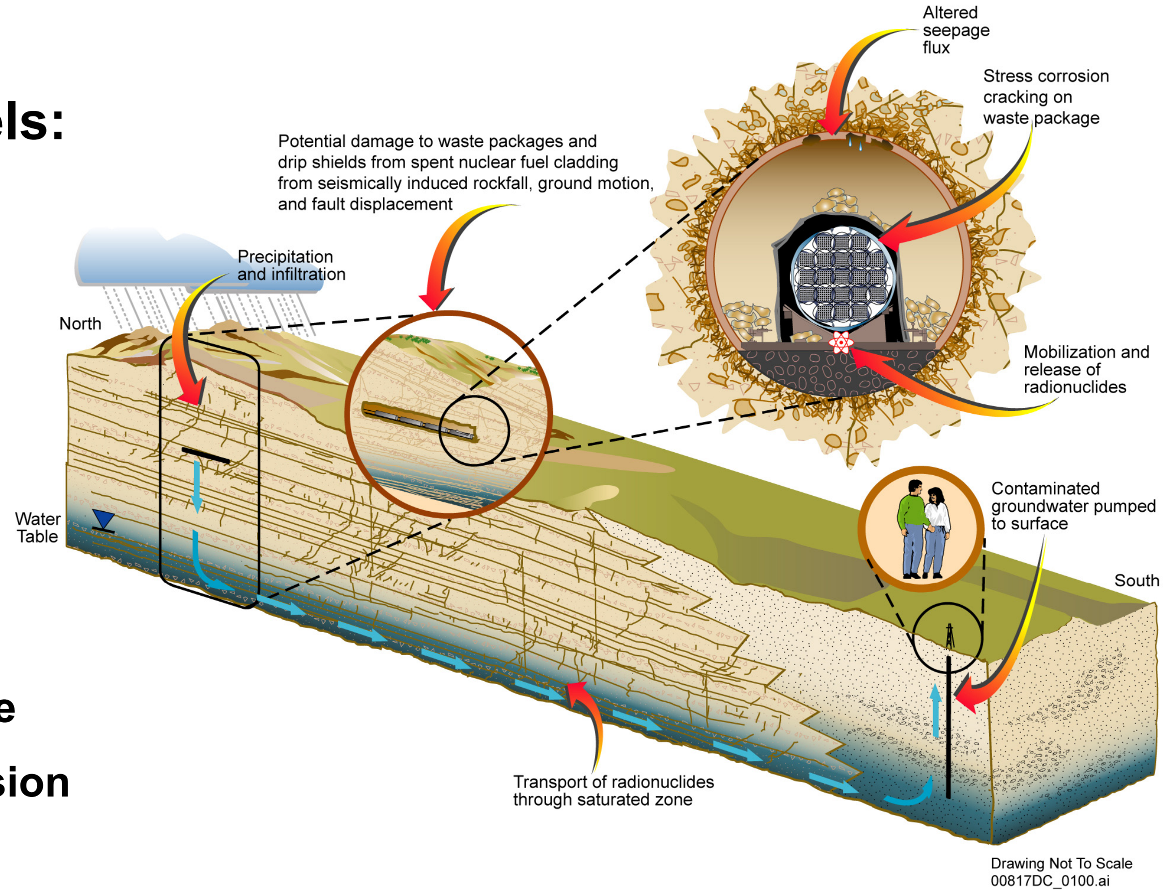
- **The annual exceedance frequency (λ) of seismic events of varying magnitudes (PGV) is defined by the (mean) bounded seismic hazard curve**
- **Not all events can cause Engineered Barrier System (EBS) damage; small PGVs (i.e., more frequent, but small, events) are unlikely to have a consequence**
- **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 <u>coupled</u> 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

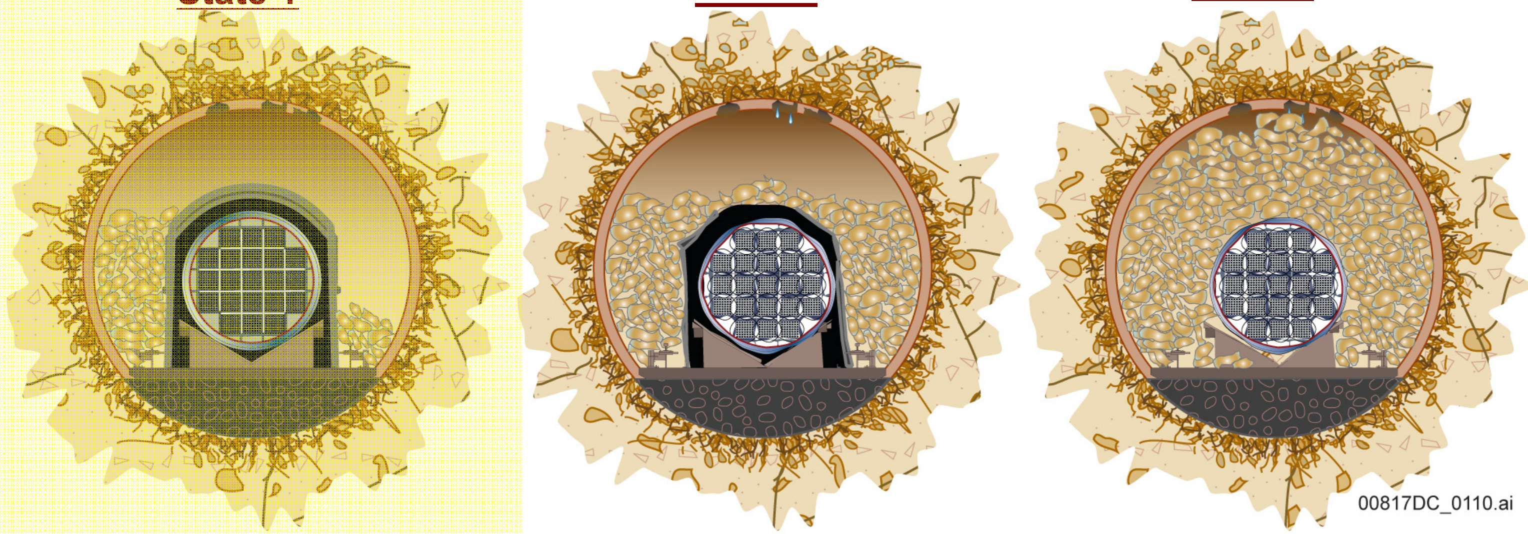
- The initial mechanical condition (or strength) of EBS components (WP or DS) for each event is a function only of spatially averaged thickness (due to general corrosion thinning), i.e., previous seismic damage does not affect the strength or configuration of the EBS components, with two exceptions :
  - 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

| State 1 | State 2 | State 3 |
|---|---|---|




| (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**

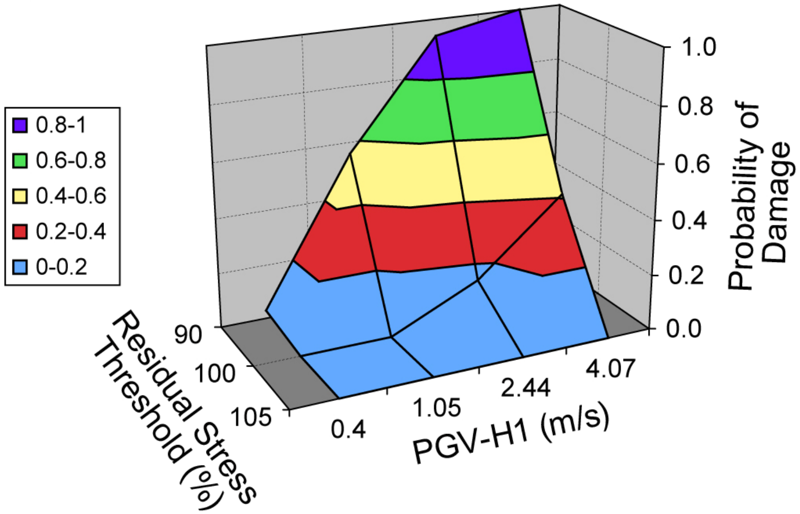
**Time**

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

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

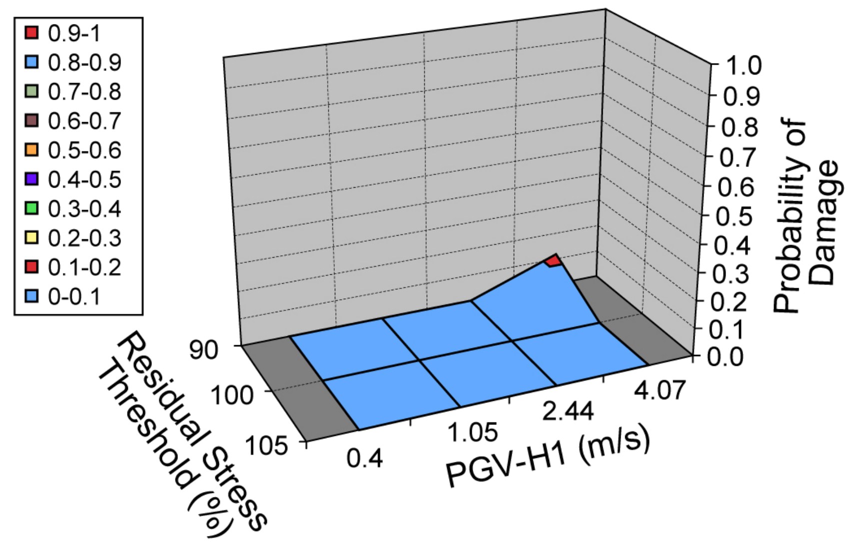
- **Codisposal WP probability of SCC damage for a 23-mm thick**

(a)




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

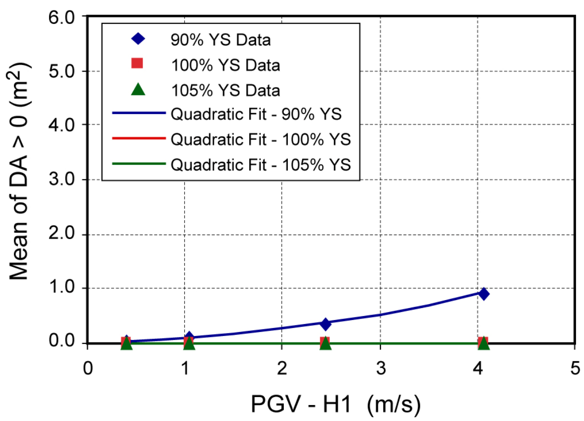
(a)




[DIRS 183478] Figure 6.6-10(a)

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

(a)

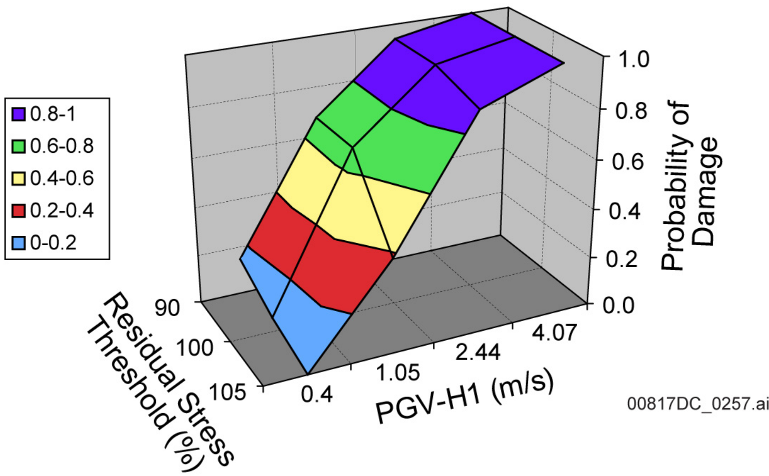



MDL-WIS-PA-000005, Figures 6.6-11 and 6.6-13

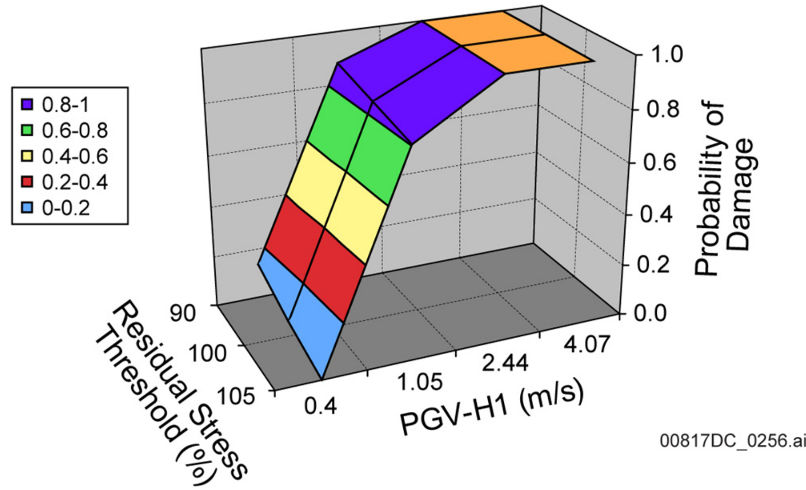
- **CSNF WP mean damage area for a 23-mm thick**
  - **0.00408 m$^2$ at PGV=4.07 m/s and RST=90% Y.S.**
  - **0.0 m$^2$ for all other data points**

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

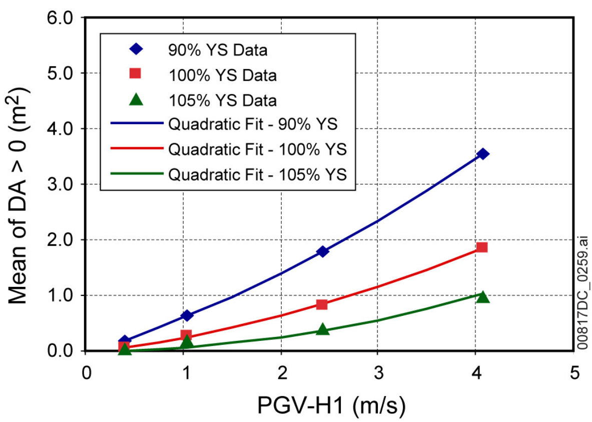
- **Codisposal WP probability of SCC damage for a 17-mm thick**




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

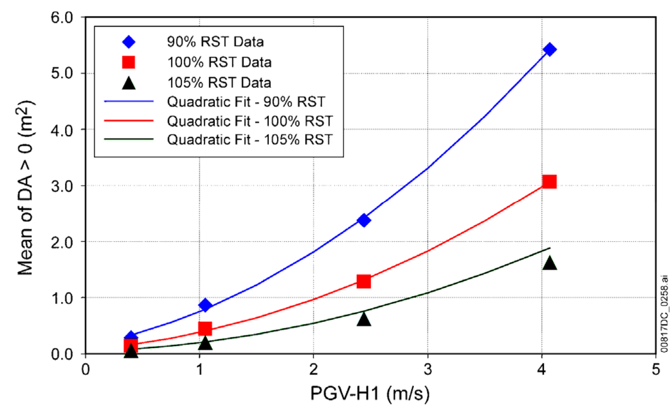



- **Codisposal WP mean damage area for a 17-mm thick**




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

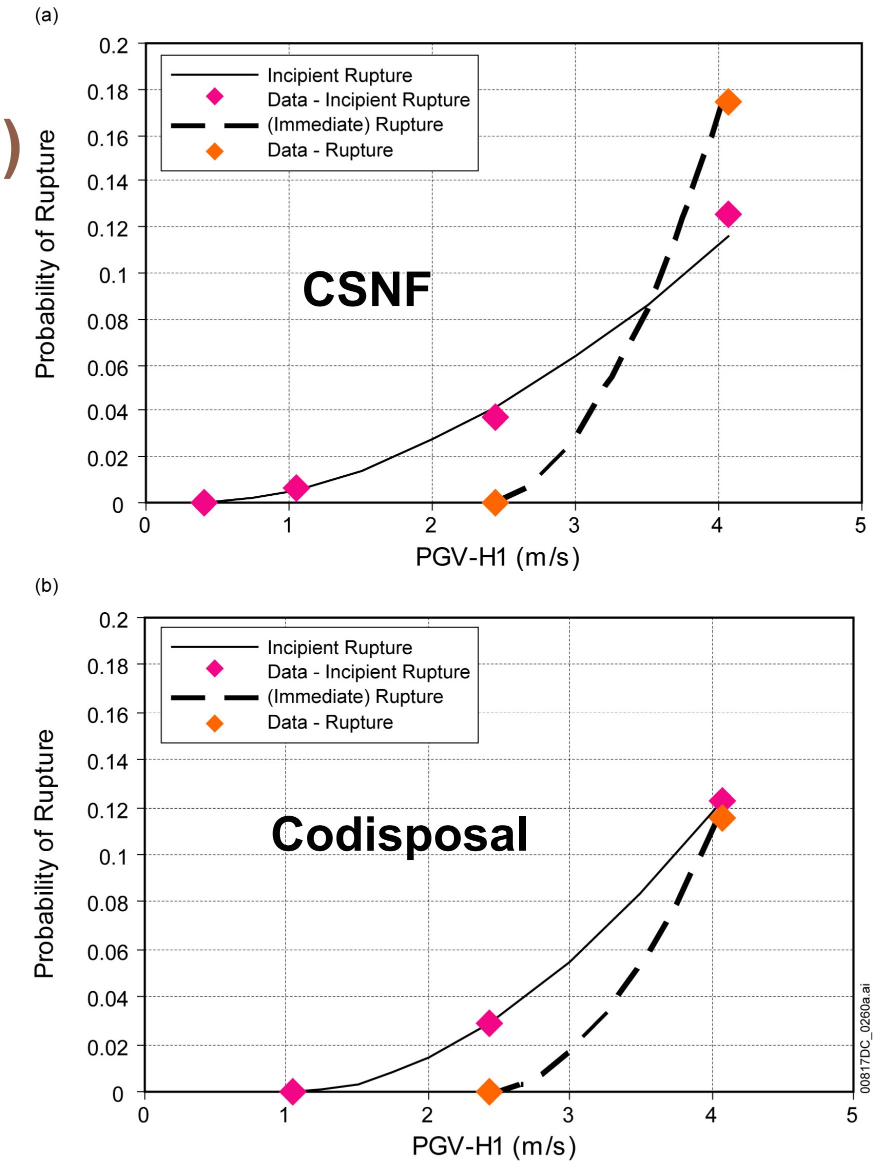
- **CSNF WP mean damage area for a 17-mm thick**




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

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

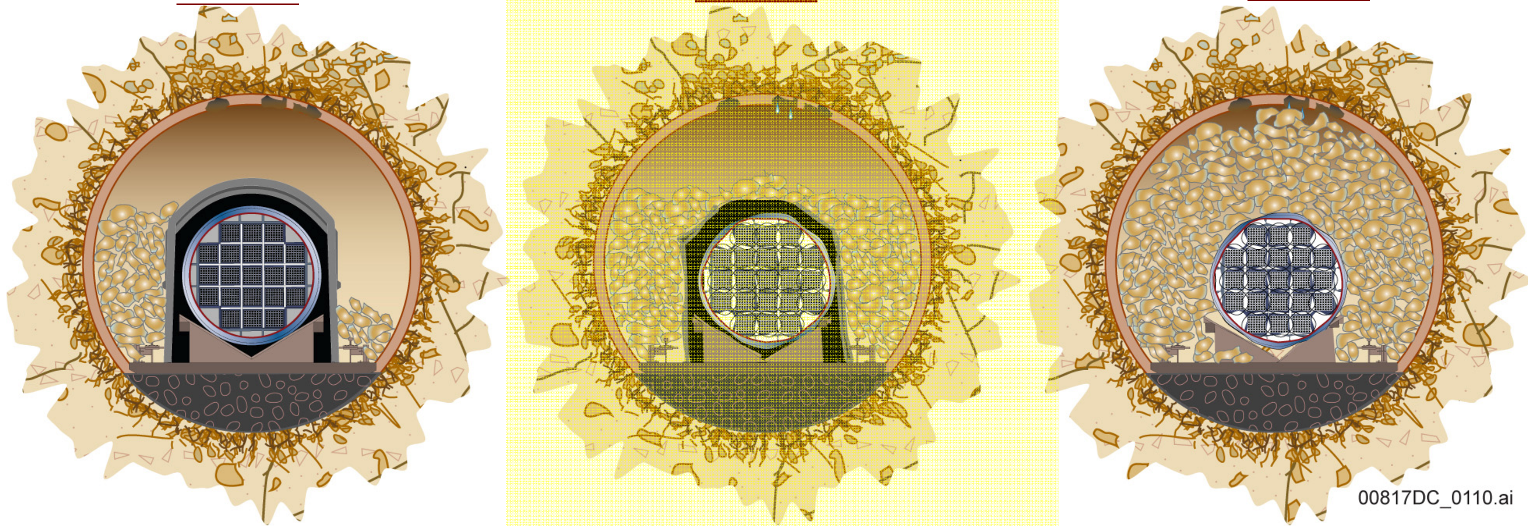
- **Probability of incipient and immediate rupture**
  - **incipient rupture requires a subsequent seismic event to cause damage**
  - **WP rupture allows advective releases**
- **Mean damage area is sampled uniformly**
  - **between 0 m$^2$ and the WP cross-sectional area 2.78 or 3.28 m$^2$**




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

# Conceptual Model for EBS Evolution

**State 1** | **State 2** | **State 3**




(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**

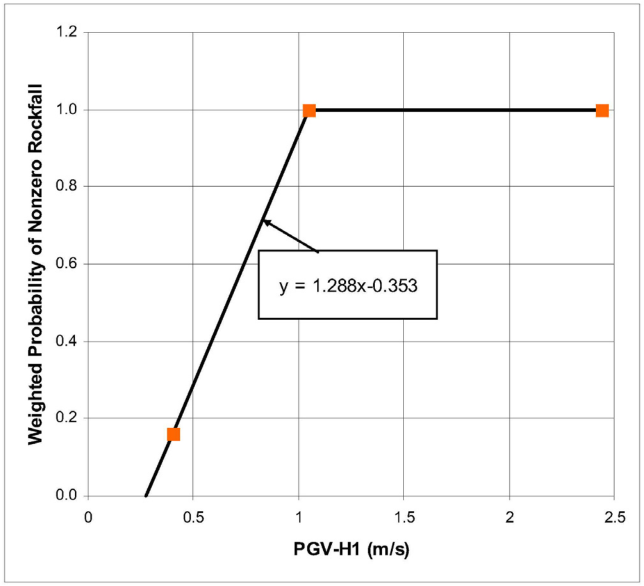
**DS Failure**

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

**Time**

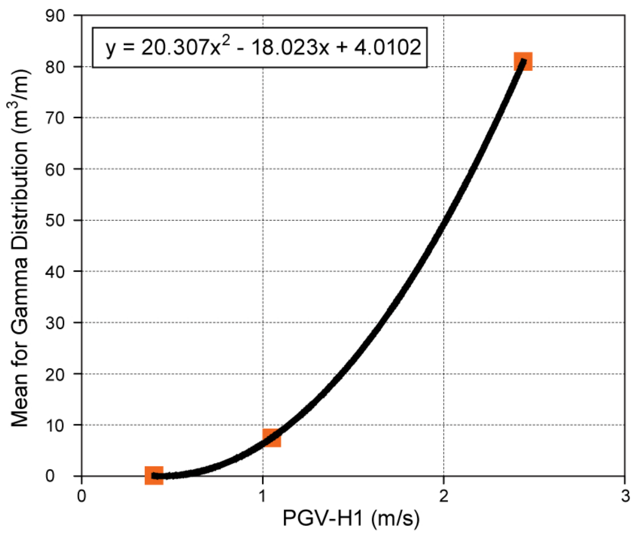
# EBS Evolution State 2: Rubble Accumulation

- 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**



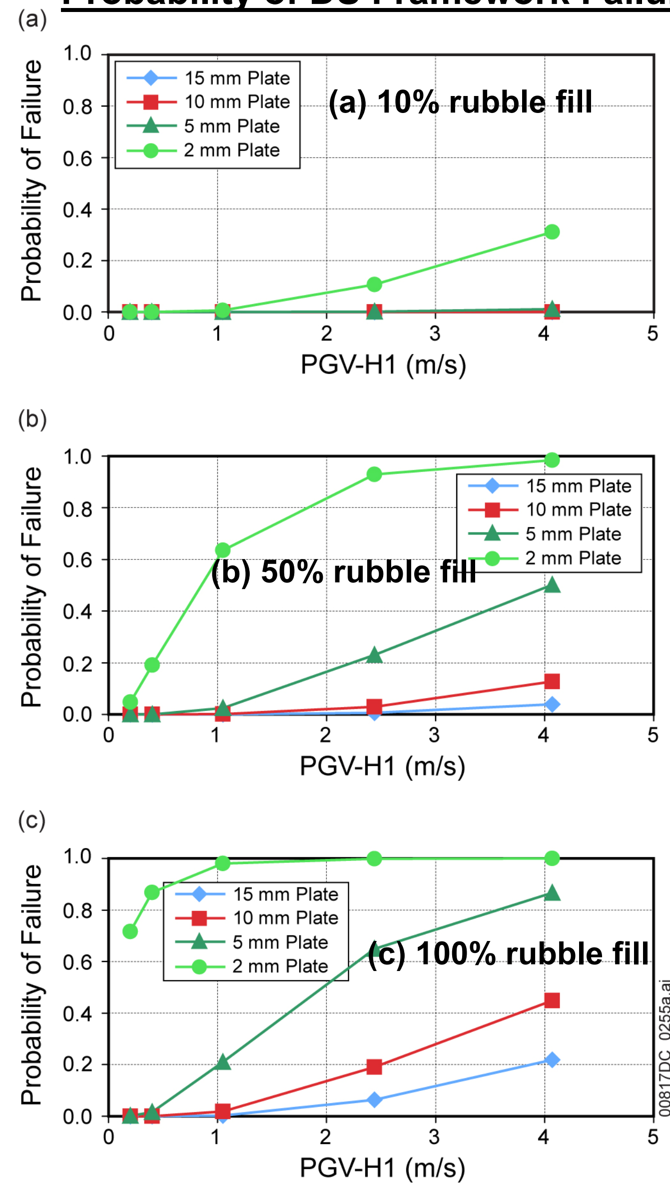

**Mean Rubble Volume in the Lithophysal Zone**

**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**

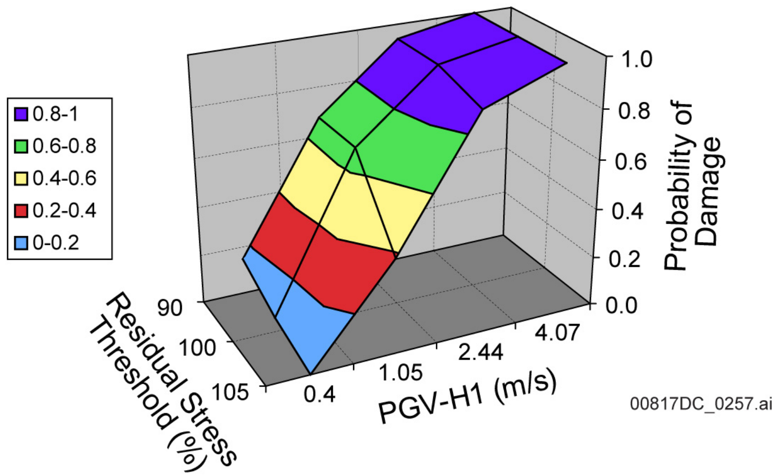
**Probability of DS Framework Failure**



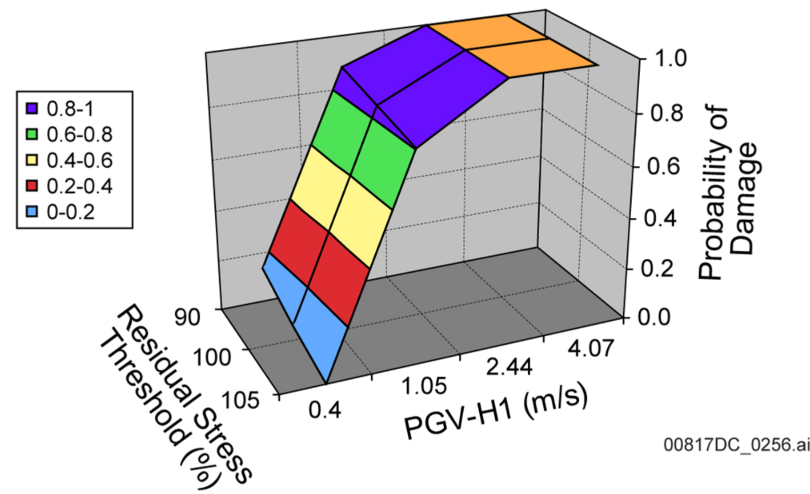

**MDL-WIS-PA-000005, Figure 6.6-9**

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

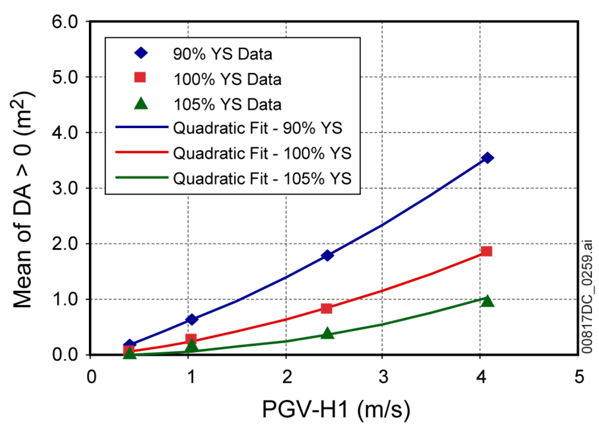
- **Codisposal WP probability of SCC damage for a 17-mm thick**




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

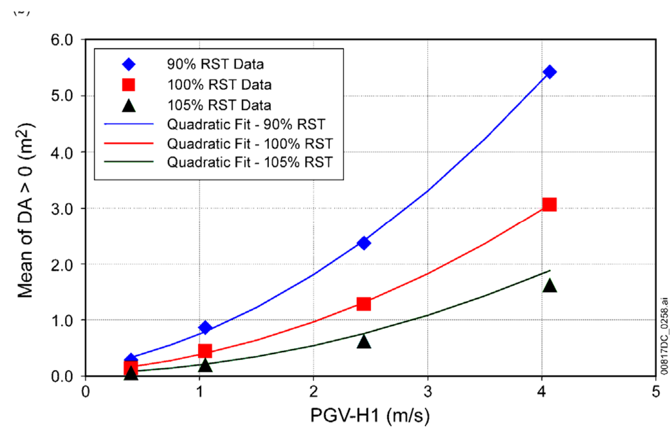



- **Codisposal WP mean damage area for a 17-mm thick**




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** | **State 2** | **State 3**


(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**

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

**DS Failure**

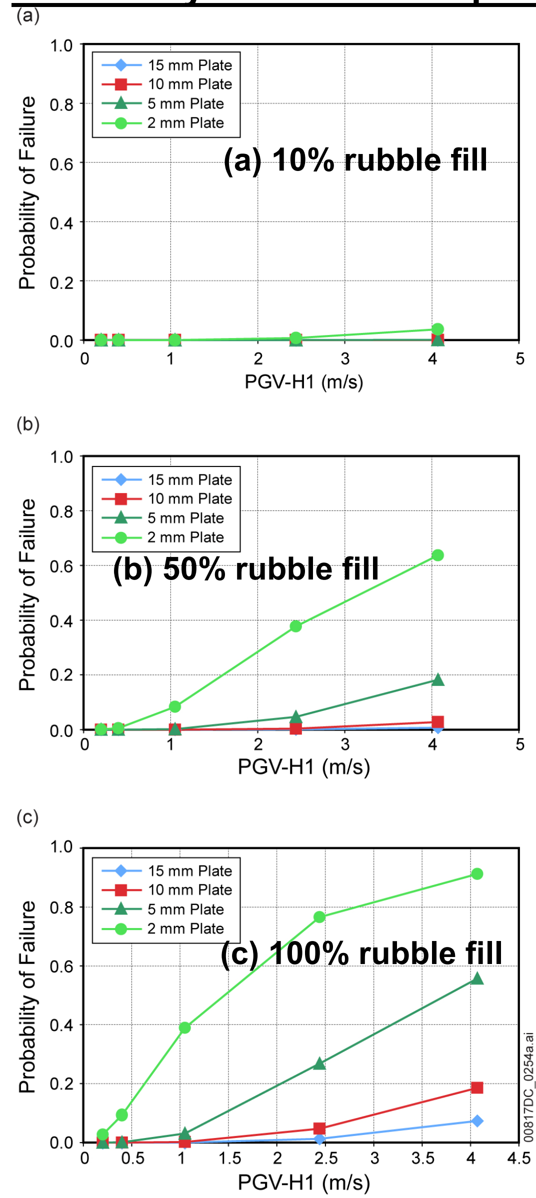
MDL-WIS-PA-000005, Figure 6.6-5

**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**

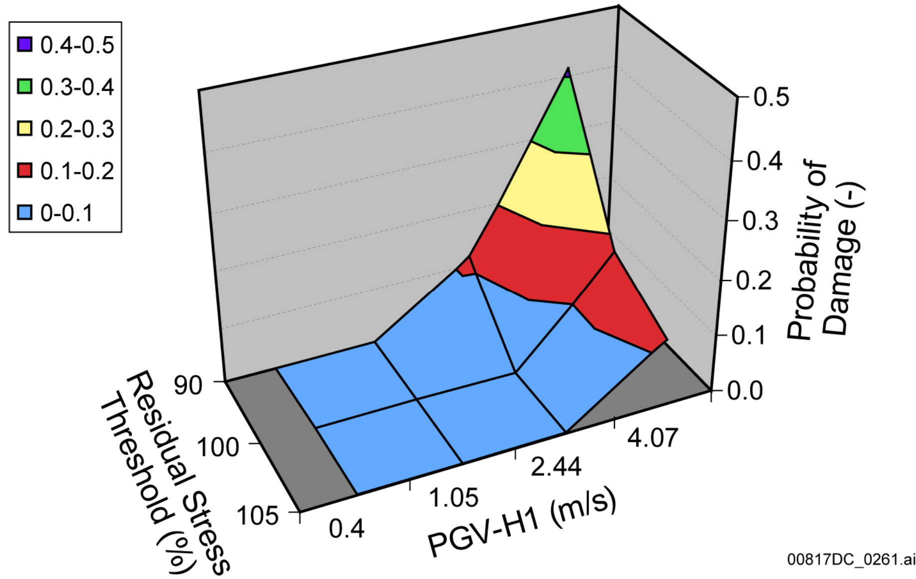



**MDL-WIS-PA-000005, Figure 6.6-8**

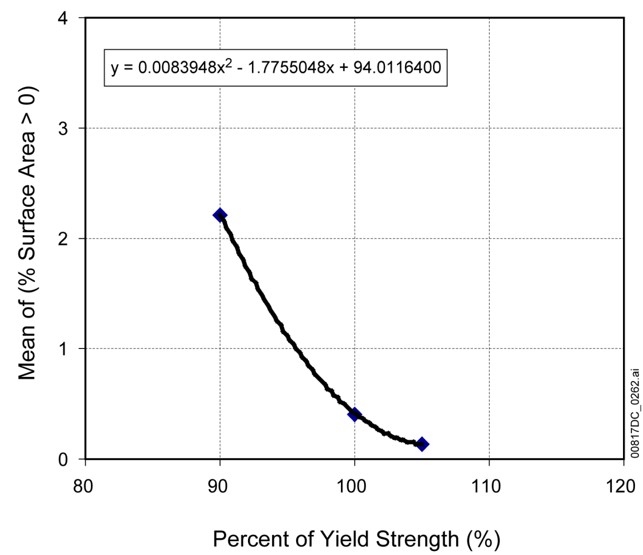
# EBS State 3: WP Crack Damage

## 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**

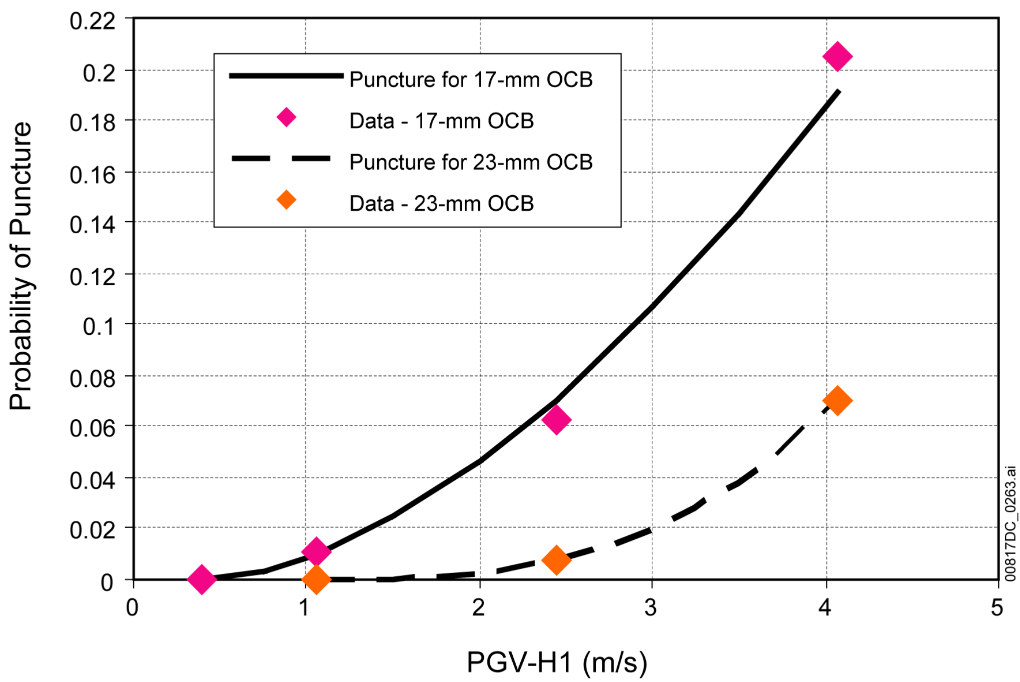



**[Abstraction also used for CSNF (or CDSP) WP with intact internals under a buckled DS]**

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

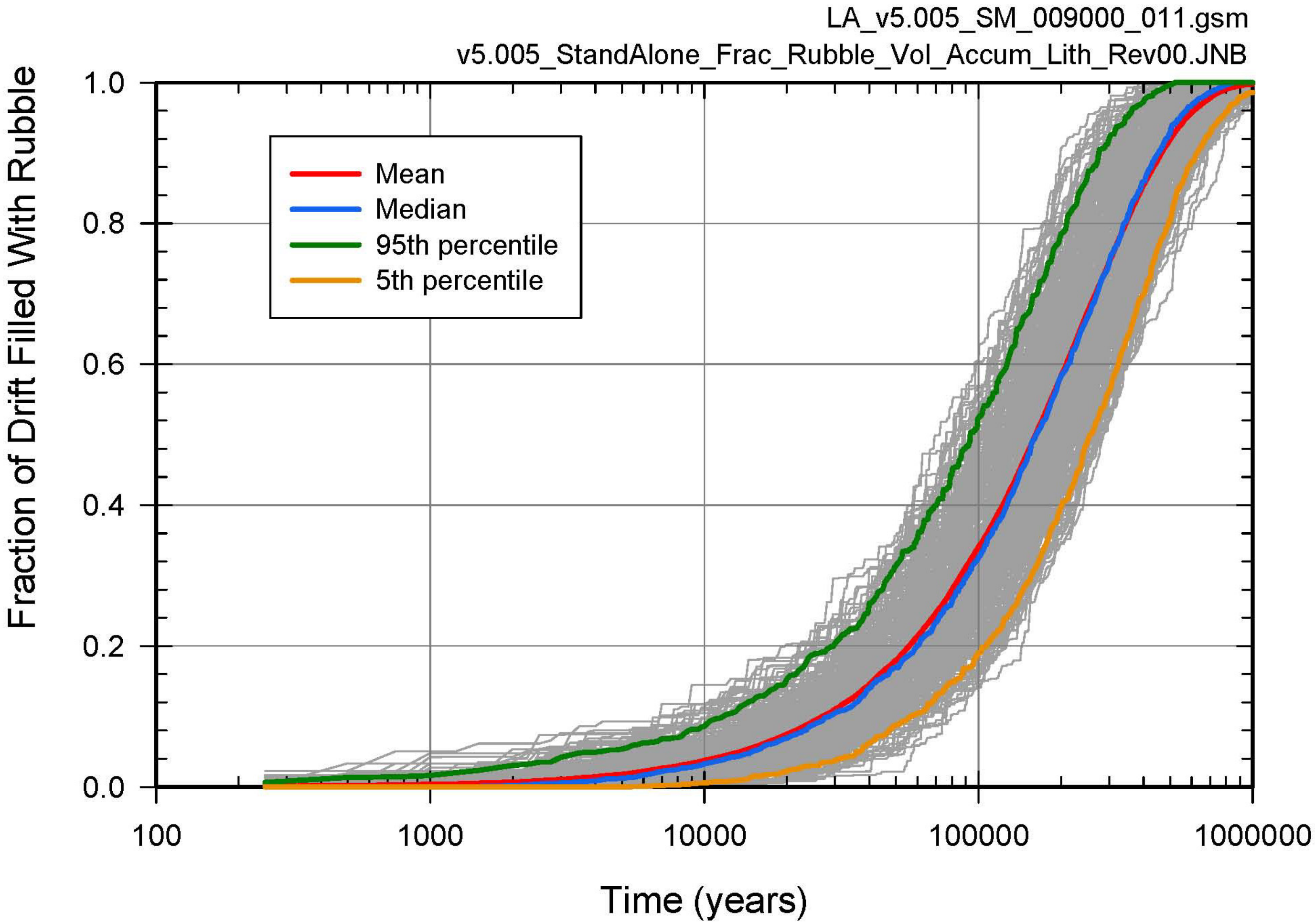
# Other Processes

- **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

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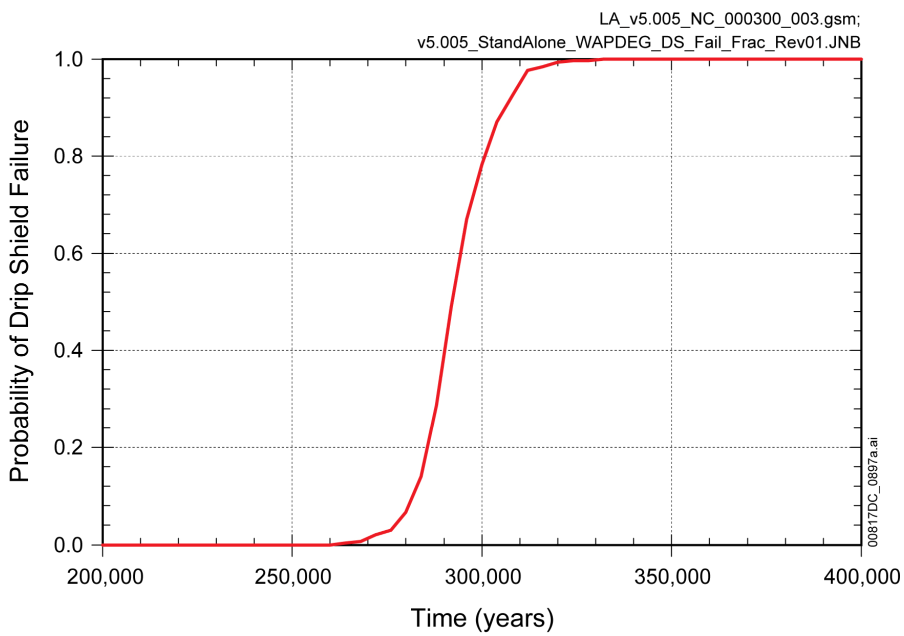
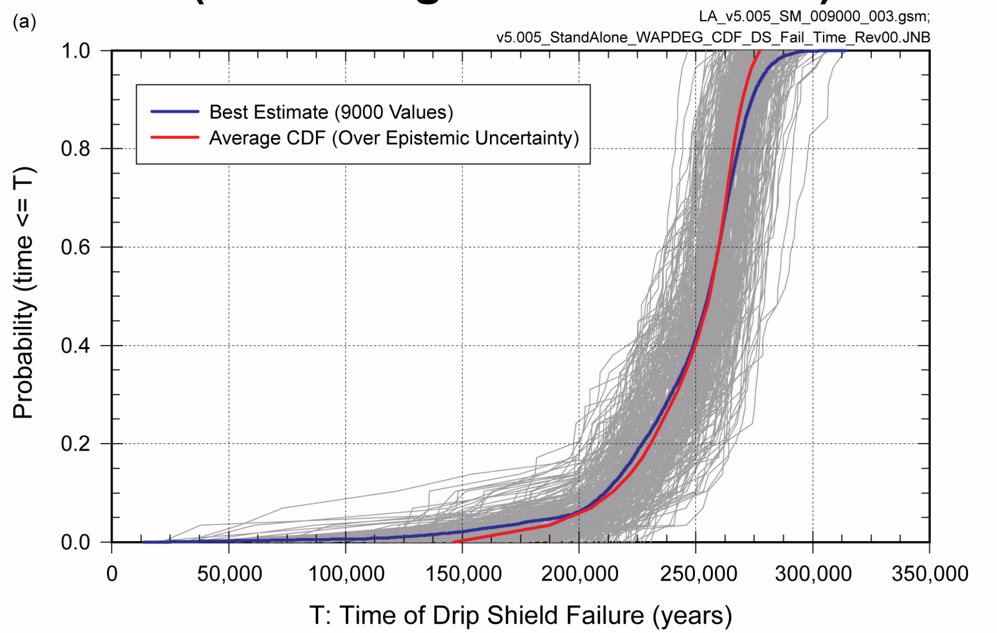
# Probability of Drip Shield Plate Failure

## 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**

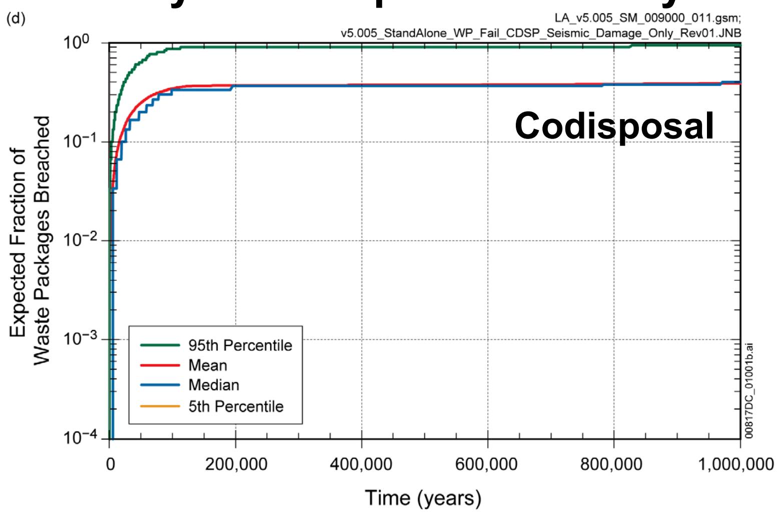
**Key Points**:

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

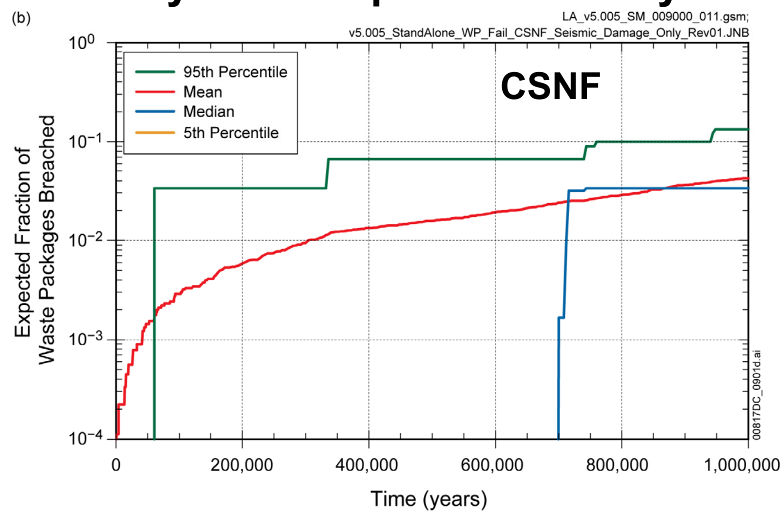
**(Note: The TSPA model does not include spatial variability in drip shield failure)**

# Expected Fraction of Breached Waste Packages

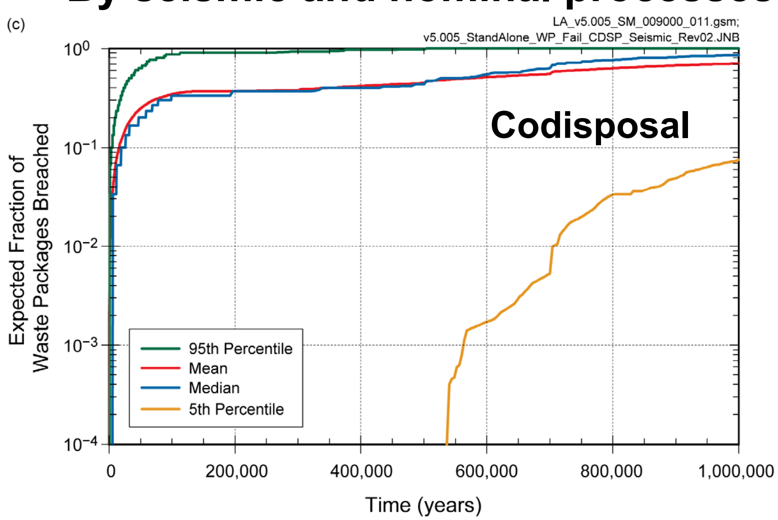
- **By seismic processes only**



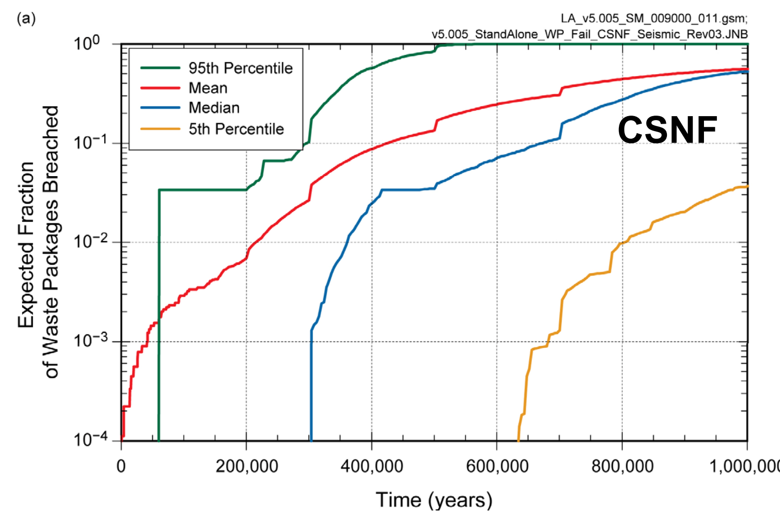

- **By seismic processes only**




- **By seismic and nominal processes**



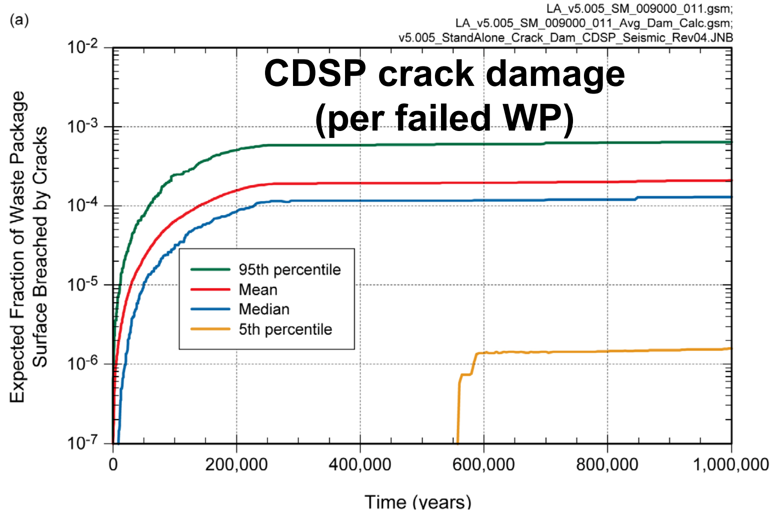

- **By seismic and nominal processes**

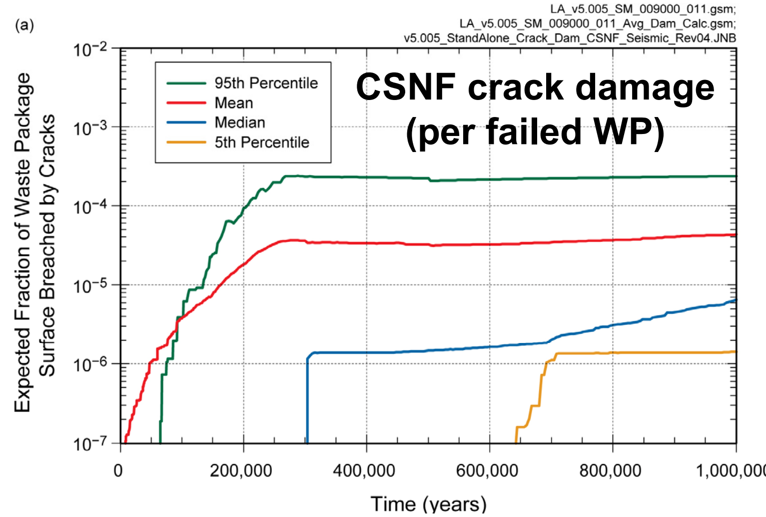


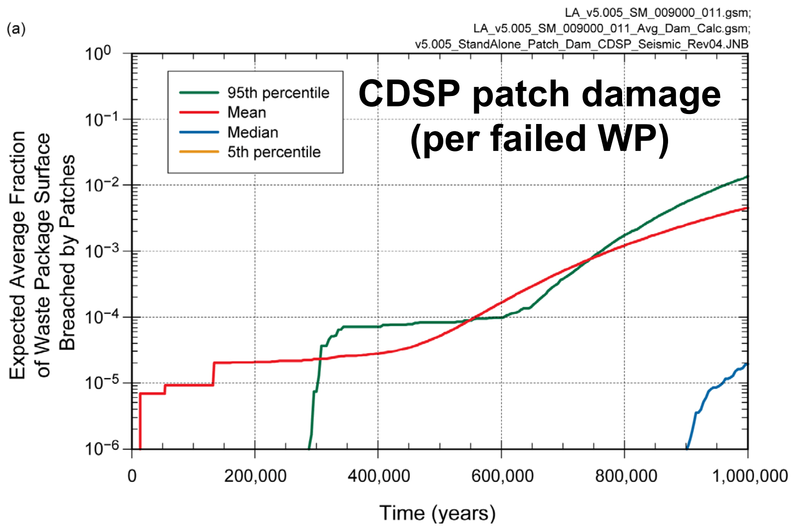

MDL-WIS-PA-000005, Figure 8.3-8(c and d)[a]

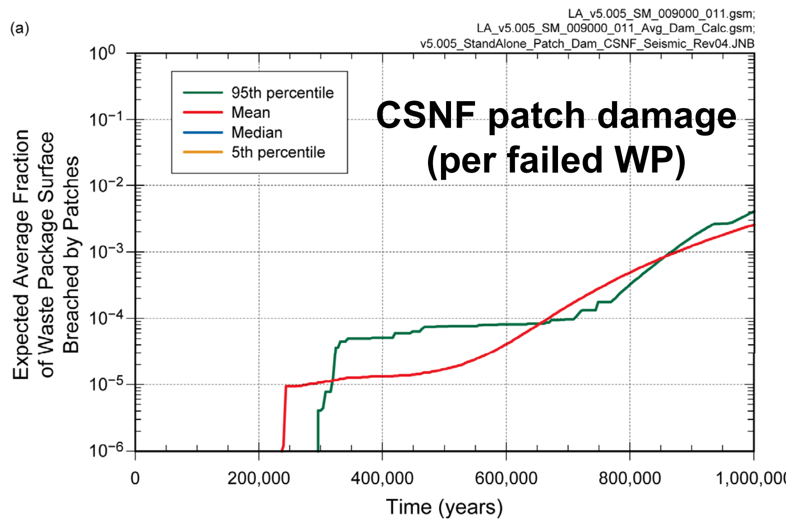
MDL-WIS-PA-000005, Figure 8.3-8(a and b)[a]

# 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**