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YUCCA MOUNTAIN - REQUEST FOR ADDITIONAL INFORMATION - SAFETY EVALUATION REPORT, VOLUME 3 - SET 1 FOR EACH OF THE FOLLOWING POSTCLOSURE CHAPTERS 2.2.1.4.1, 2.2.1.4.2, AND 2.2.1.4.3.

Reference: Ltr, Sulima to Williams, dtd 6/29/2009, "Yucca Mountain – Request for Additional Information – Safety Evaluation Report, Volume 3 – Set 1 for Each of the Following Postclosure Chapters 2.2.1.4.1, 2.2.1.4.2, AND 2.2.1.4.3"

The purpose of this letter is to transmit the U.S. Department of Energy's (DOE) responses to the Requests for Additional Information (RAI) identified in the above-referenced letter. Each RAI response is provided as a separate enclosure.

Most of the DOE references cited in the RAI responses have previously been provided with the License Application (LA), and the LA update. The DOE reference cited in the RAI response, which has not been previously provided to the Nuclear Regulatory Commission, is included with this submittal.

There are no commitments in the enclosed RAI responses. If you have any questions regarding this letter, please contact me at (202) 586-9620, or by email to jeff.williams@rw.doe.gov.

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OTM: CJM-0921

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EIE Document Components:

Enclosure #	File Name	File Size, KB
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1	002_Encl_RAI_1_3.2.2.1.4.1.pdf	12,353
2 and 3	003_Encl_RAI_2_3_3.2.2.1.4.1.pdf	27,903
3 thru 6	004_Encl_RAI_1_thru_3_3.2.2.1.4.2.pdf	7,172
7	005_Encl_RAI_1_3.2.2.1.4.3.pdf	804
8 (part 1 of 4)	006_DOC.20030619.0001TDREBSMD000025R01to37.pdf	20,944
8 (part 2 of 4)	007_DOC.20030619.0001TDREBSMD000025R038to60.pdf	21,016
8 (part 3 of 4)	008_DOC.20030619.0001TDREBSMD000025R061to128.pdf	14,826
8 (part 4 of 4)	009_DOC.20030619.0001TDREBSMD000025R0129to195.pdf	15,589

RAI Volume 3, Chapter 2.2.1.4.1, First Set, Number 1:

> For the combined seismic and nominal model case provide the fraction of waste packages breached, and the area damaged by (i) stress corrosion cracking, (ii) puncture and rupture, and (iii) general corrosion. Provide all these waste package fractions and damaged areas as functions of time for both commercial spent nuclear fuel and co-disposal packages. This information is needed to determine compliance with 10 CFR 63.114.
>
> Basis: The SAR includes statistics on the total fraction of waste packages breached in the combined seismic and nominal processes model case, without distinguishing crack or patch failure (e.g., SAR Figure 2.1-12). More detailed information is needed on the expected fraction of waste packages exhibiting crack failure, punctures and ruptures, and general corrosion to provide a comparison of the magnitude of the various waste package breach modes.

1. RESPONSE

In the 1,000,000-year seismic ground motion modeling case, which combines seismic ground motion and nominal corrosion processes, waste package damage mechanisms include: stress corrosion cracking in closure welds, general corrosion, seismic ground motion-induced stress corrosion cracking, and seismic ground motion-induced ruptures or punctures. Localized corrosion is also included as a waste package damage mechanism in the total system performance assessment (TSPA) model, but does not impact the waste package in the 1,000,000-year seismic ground motion modeling case because drip shield plate failure and subsequent wetting of the waste package during the period when localized corrosion can occur is unlikely and the contribution to mean dose from such waste package failures is insignificant (SAR Section 2.1.2.2.6; SNL 2008, Section 7.3.2.6.1.3.2). Stress corrosion cracking results in cracks on the waste package surface. General corrosion and seismic ground motion-induced ruptures and punctures result in larger openings, referred to as patches. SAR Figure 2.1-12 shows summary statistics for the expected fraction of the waste packages that are breached in the 1,000,000-year seismic ground motion modeling case by seismic and/or nominal corrosion processes without distinguishing the damage mechanism. SAR Figures 2.1-13 and 2.1-15 show summary statistics for the expected fraction of waste package surface area damaged by stress corrosion cracks per damaged waste package by seismic and/or nominal corrosion processes without distinguishing the stress corrosion crack damage mechanism. SAR Figures 2.1-16 and 2.1-17 show summary statistics for the expected fraction of waste package surface area damaged by patches per damaged waste package from seismic and/or nominal corrosion processes without distinguishing the patch damage mechanism. The damage fraction histories in these figures represent fractions of surface area damaged by the specified damage mechanism on all failed waste packages, including those damaged by other mechanisms.

This RAI response presents additional time history results for waste package damage in the 1,000,000-year seismic ground motion modeling case. Specifically, time history results that distinguish between damage mechanisms (i.e., stress corrosion cracking in closure welds, general corrosion, seismic ground motion-induced stress corrosion cracking, and seismic ground motion-induced ruptures or punctures) are presented separately for commercial spent nuclear fuel (SNF) and codisposal waste packages. In addition, time histories for the average fraction of surface area damaged for each of these mechanisms are reported by waste package type. Unlike the surface area damage fraction histories previously reported, the surface area damage fractions reported in these histories are conditional on the waste packages having damage by a particular mechanism, and the damage area included in the fraction is limited to damage caused by that mechanism.

1.1 WASTE PACKAGE CRACK DAMAGE

Two types of stress corrosion crack damage are considered in the 1,000,000-year seismic ground motion modeling case:

- Stress corrosion cracking in closure welds;
- Seismic ground motion-induced stress corrosion cracking.

In the TSPA model, damage from either type of stress corrosion cracking is additive and allows diffusive releases from the waste package. Whereas stress corrosion cracking in the closure welds may only impact a subset of waste packages within a percolation subregion, seismic ground motion-induced stress corrosion cracking, when it occurs, damages all waste packages of the same type and same percolation subregion equally.

1.1.1 Stress Corrosion Cracking in Closure Welds

Stress corrosion cracking in the closure welds is a nominal corrosion process. Stress corrosion cracks initiate in a material under stress in the presence of a corrosive environment, eventually resulting in through-wall propagation of incipient cracks and weld flaws that occur on the waste package outer corrosion barrier closure weld regions (SAR Sections 2.1.2.2 and 2.3.6.2.2). In the 1,000,000-year seismic ground motion modeling case, stress corrosion cracking in the closure welds is indirectly affected by seismic activity through the general corrosion depth, which is taken into account when determining the depth of the crack tip (SAR Section 2.3.6.5.4.1). When any penetration of the waste package outer barrier wall occurs, the wall starts thinning from both the outside and the inside due to general corrosion. This acceleration in waste package outer barrier wall thinning influences crack propagation by reducing the length of the crack needed to fully penetrate the remaining thickness of the waste package outer barrier wall. Consequently, the results for stress corrosion cracking in closure welds in the 1,000,000-year seismic ground motion modeling case vary slightly from the results for the nominal modeling case reported in SAR Figure 2.1-10a.

Figure 1 shows the expected fraction of commercial SNF waste packages that fail with at least one stress corrosion crack in the closure welds. Waste packages with stress corrosion cracks in the closure weld may also have damage from general corrosion, seismic ground motion-induced stress corrosion cracks, and seismic ground motion-induced ruptures or punctures that is not included in the results shown in Figure 1. The 300 histories shown in Figure 1 characterize the uncertainty in the expected fraction of waste packages that have stress corrosion cracks in the closure welds. The expected failure fraction for each epistemic realization is the average result of 30 aleatory realizations that apply random sequences of seismic events. The same sampled parameter values representing epistemic uncertainty are used for all 30 aleatory realizations, but the sequence of seismic events, which may influence crack propagation, varies between aleatory realizations. Figure 2 shows the analogous result for codisposal waste packages.

Figure 3 shows the average fraction of the waste package surface area that is damaged by stress corrosion cracks in the closure welds for commercial SNF waste packages that have at least one stress corrosion crack in the closure welds. This average surface area damage fraction excludes the surface area damaged by other mechanisms and the surface area of undamaged waste packages. Therefore, these time histories represent the average damage area fraction conditional on having damage by stress corrosion cracks in the closure welds. Figure 4 shows the analogous result for codisposal waste packages. The median and average histories shown in Figures 3 and 4 are based only on the waste packages with stress corrosion cracking damage in the closure welds and do not consider realizations without any waste package damage. Figures 3 and 4 do not provide 5th- and 95th-percentile histories because the number of realizations considered (i.e., with non-zero damage) changes through time. In contrast, most figures presented throughout SAR Section 2.1 show 5th- and 95th-percentiles based on the full set of 300 histories, and thus these percentiles indicate a fixed number (15) of realizations below and above the indicated percentile values. To avoid confusion between the SAR figures and the figures presented in this response, 5th- and 95th-percentiles are not shown on figures which display damage area fractions. Although the median quantity is susceptible to the same limitations, the median quantity provides a quantitative reference for an equal number of lines below and above a certain value.

In Figures 3 and 4, the average fraction of the surface area that is damaged by stress corrosion cracks in the closure welds increases and then decreases sharply for some of the histories plotted. This occurs because of changes in the number of waste packages with damage, not because the damage area is reduced. The plotted quantity shows the average surface area damage fraction for those waste packages with stress corrosion cracks in the closure welds. Initially, this could be represented by a few waste packages with a number of cracks. Damage to additional waste packages may not be as extensive as in the initial waste packages, and therefore the average surface area damage fraction decreases. This behavior is readily observed at 300,000, 500,000, and 700,000 years (corresponding to time steps in the waste package degradation calculation (SAR Section 2.4.2.2.3.1)) when a number of new waste package failures occur (see Figures 1 and 2).

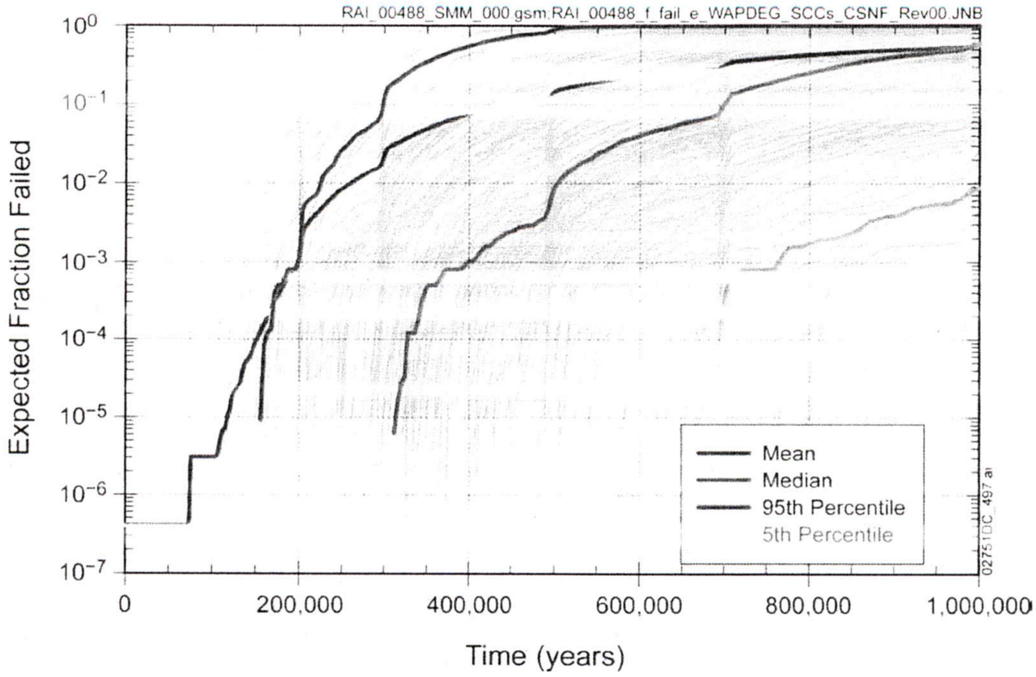


Figure 1. Expected Fraction of Commercial SNF Waste Packages Failed by Stress Corrosion Cracks in the Closure Welds: 1,000,000-Year Seismic Ground Motion Modeling Case

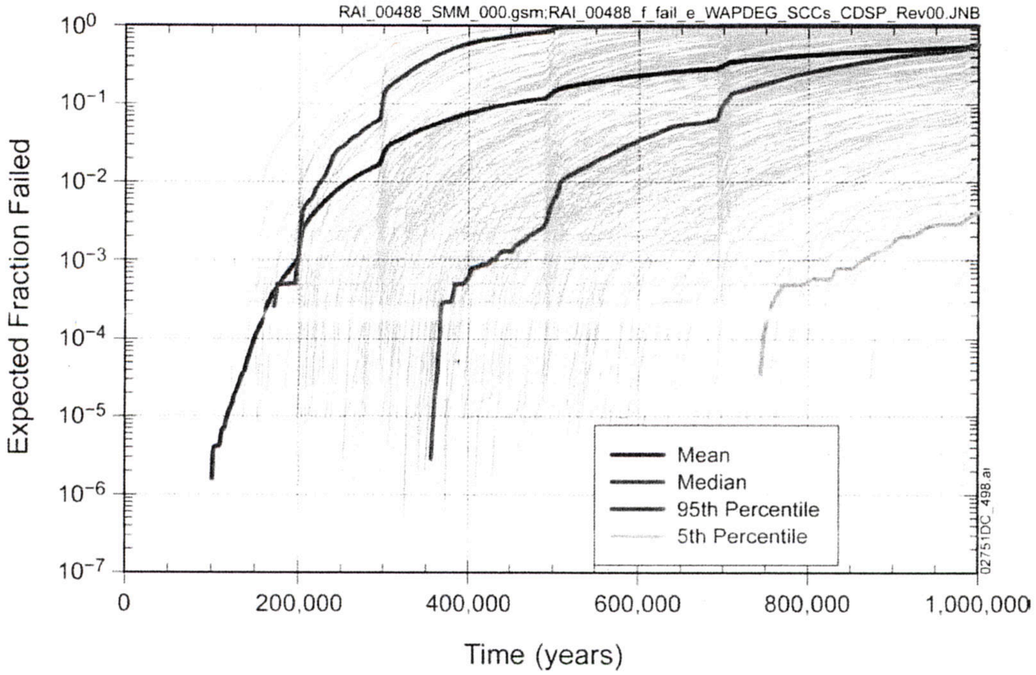


Figure 2. Expected Fraction of Codisposal Waste Packages Failed by Stress Corrosion Cracks in the Closure Welds: 1,000,000-Year Seismic Ground Motion Modeling Case

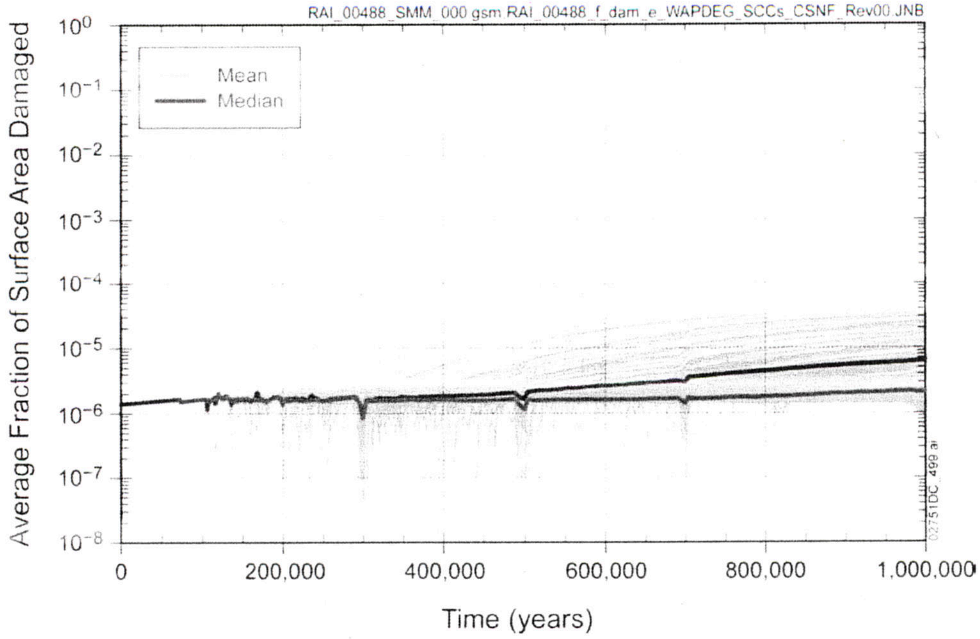


Figure 3. Average Fraction of Surface Area Damaged on Commercial SNF Waste Packages by Stress Corrosion Cracks in the Closure Welds: 1,000,000-Year Seismic Ground Motion Modeling Case

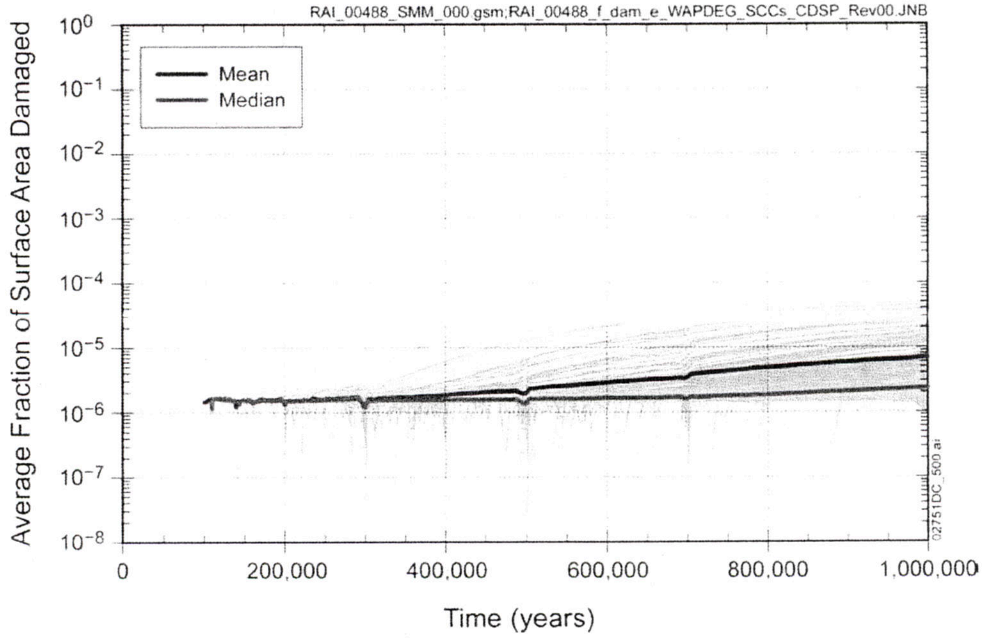


Figure 4. Average Fraction of Surface Area Damaged on Codisposal Waste Packages by Stress Corrosion Cracks in the Closure Welds: 1,000,000-Year Seismic Ground Motion Modeling Case

1.1.2 Seismic Ground Motion-Induced Stress Corrosion Cracking

Seismic ground motion-induced stress corrosion cracking is determined using the seismic consequence abstractions. The probability of the damage to the waste package by any event and the resulting damage area are a function of the waste package type, the peak ground velocity of the seismic event, whether or not the drip shield is intact, the thickness of the waste package, the uncertain residual stress threshold, and whether or not damage to the waste package has occurred previously. Seismic damage to the waste packages is modeled separately for each waste package type and percolation subregion, but the same sampled values for epistemically uncertain parameters are used for the different percolation subregions. Waste packages in different percolation subregions have different thermal hydrologic histories used to evaluate general corrosion of the waste package, and the thickness of the waste packages used in the damage abstractions may be different. Because the probability of damage caused by a seismic event is a function of the average waste package thickness, the abstractions for waste package damage may produce damage in some percolation subregions but not in others.

Figure 5 shows the expected fraction of commercial SNF waste packages that fail by stress corrosion cracks due to seismic ground motion activity. Waste packages with seismic ground motion-induced stress corrosion cracks may also have damage by stress corrosion cracks in the closure welds, general corrosion, and seismic ground motion-induced ruptures or punctures that are not included in the results shown in Figure 5. The 300 histories shown in Figure 5 characterize the uncertainty in the expected fraction of waste packages that have seismic ground motion-induced stress corrosion cracks. Considering a single seismic event, if the event causes damage to previously undamaged waste packages within a percolation subregion, all waste packages within that percolation subregion fail and the failure fraction increases from 0 to 1. The expected failure fraction for each epistemic realization is the average result of 30 aleatory realizations that apply random sequences of seismic events. Because seismic events are randomly generated for each aleatory realization, there is no expectation that all 30 aleatory realizations used to generate the expected failure fraction for each epistemic realization cause all of the waste packages to fail simultaneously. In addition, there is no expectation that all of the waste packages in the five percolation subregions are damaged by the same events. For these two reasons, the expected failure fraction histories for a given waste package type are not step function increases from 0 to 1. Figure 6 shows the analogous result for codisposal waste packages.

The expected fraction of waste packages with seismic ground motion-induced stress corrosion cracking damage is zero at all times for more than 5% of the epistemic realizations; therefore, the 5th-percentile time history does not appear in Figures 5 and 6, which use a logarithmic scale for the failure fraction. One of the most important parameters that contributes to the uncertainty in the expected dose for the 1,000,000-year seismic ground motion modeling case is the residual stress threshold (SAR Section 2.4.2.3.3.6), because the probability of damage depends strongly on the residual stress threshold (SAR, Tables 2.3.4-29, 2.3.4-30, 2.3.4-33, and 2.3.4-49). There are 48 realizations that have no seismic ground motion-induced stress corrosion cracking on any codisposal waste package in any of the 30 random sequences of seismic events modeled for each epistemic realization. The average sampled value for the residual stress threshold of Alloy 22 in these 48 realizations is 102.6 (in units of percent of the yield strength). For the remaining 252 realizations, the average value for this parameter is 96.53. Low values of residual stress threshold, which is sampled uniformly between 90 and 105, indicate greater susceptibility to seismic damage. Compared to the codisposal waste packages, the commercial SNF waste packages are not as susceptible to seismic ground motion-induced damage, and approximately 38% of the realizations have no seismic ground motion-induced seismic stress corrosion cracking damage.

Figures 5 and 6 also show the relative extent of damage caused by seismic events for the two waste package types. For codisposal waste packages, the mean fraction of waste packages that have seismic ground motion-induced stress corrosion cracks increases rapidly and plateaus within 150,000 years. For commercial SNF waste packages, the mean fraction of waste packages that have seismic ground motion-induced stress corrosion cracks increases much more gradually and plateaus at 250,000 years. Comparing Figures 2 and 6 shows that codisposal waste package failure by seismic ground motion-induced stress corrosion cracking tends to occur prior to stress corrosion cracking in the closure welds. Therefore, the codisposal waste packages tend to be damaged by seismic events whether previous damage to the waste packages has occurred or not. In contrast, for commercial SNF waste packages, seismic damage typically occurs only to waste packages that were previously failed by some other mechanism, such as stress corrosion cracking in the closure welds.

Figure 7 shows the average fraction of the commercial SNF waste package surface area that is damaged by seismic ground motion-induced stress corrosion cracks. This average surface area damage fraction is limited to commercial SNF waste packages that have seismic ground motion-induced stress corrosion cracks and excludes the damage area caused by other mechanisms and undamaged waste packages. Therefore, this time history does not represent an expected damage area fraction, but rather the damage area fraction conditional on having damage by seismic ground motion-induced stress corrosion cracks. Figure 8 shows the analogous result for codisposal waste packages. As discussed in Section 1.1.1, 5th- and 95th-percentile curves are omitted from the conditional damage fraction plots.

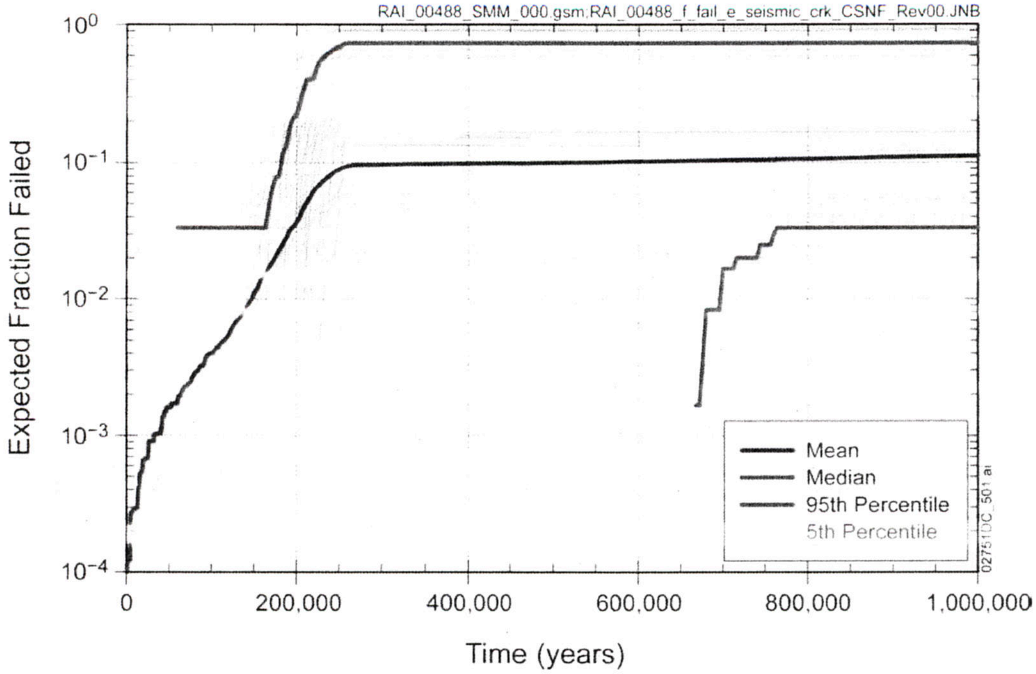


Figure 5. Expected Fraction of Commercial SNF Waste Packages Failed by Seismic-Induced Stress Corrosion Cracks: 1,000,000-Year Seismic Ground Motion Modeling Case

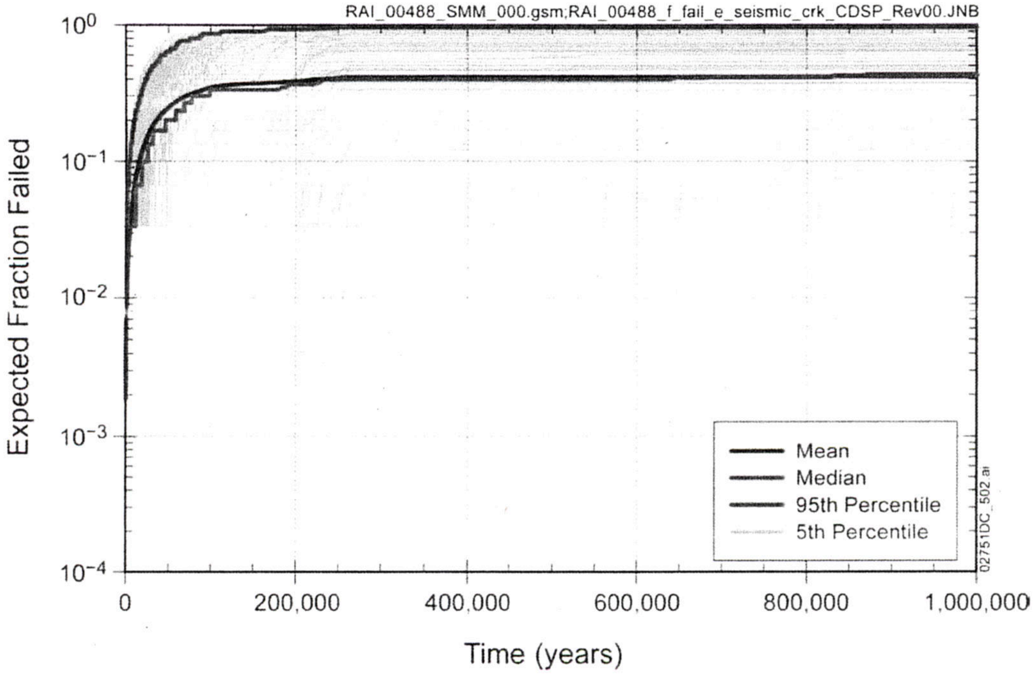


Figure 6. Expected Fraction of Codisposal Waste Packages Failed by Seismic-Induced Stress Corrosion Cracks: 1,000,000-Year Seismic Ground Motion Modeling Case

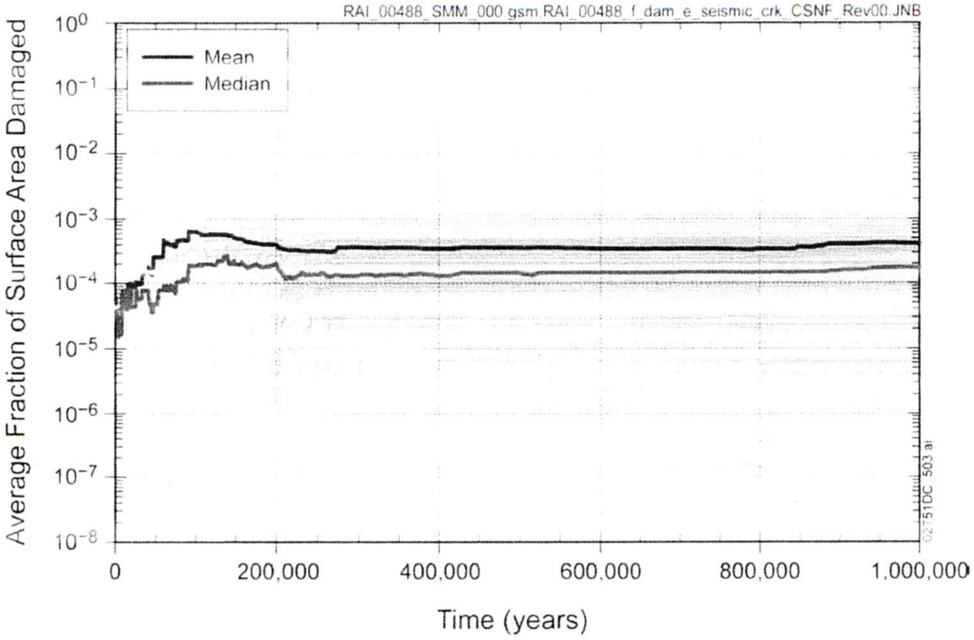


Figure 7. Average Fraction of Surface Area Damaged on Commercial SNF Waste Packages by Seismic-Induced Stress Corrosion Cracks: 1,000,000-Year Seismic Ground Motion Modeling Case

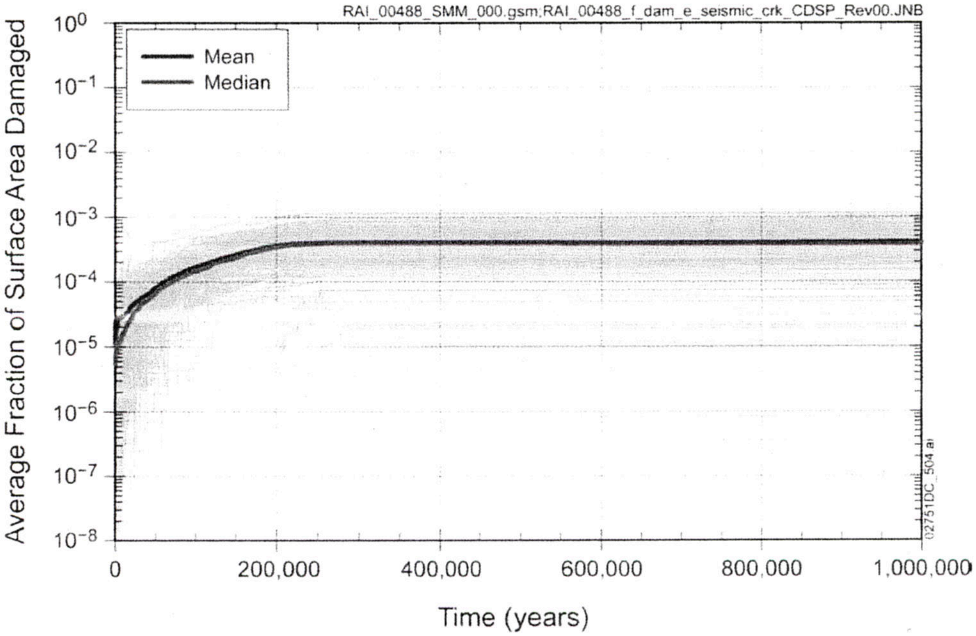


Figure 8. Average Fraction of Surface Area Damaged on Codisposal Waste Packages by Seismic-Induced Stress Corrosion Cracks: 1,000,000-Year Seismic Ground Motion Modeling Case

1.2 WASTE PACKAGE PATCH DAMAGE

Two types of patch damage are considered in the 1,000,000-year seismic ground motion modeling case:

- General corrosion damage;
- Seismic ground motion-induced ruptures and punctures.

In the TSPA model, damage from both patch mechanisms allows diffusive releases from the waste package. In addition, if water can contact the waste package (i.e., the drip shields above waste packages in the seeping environment are failed), waste package releases may also occur by advection. Whereas general corrosion may only impact a subset of waste packages within a percolation subregion, seismic ground motion-induced ruptures or punctures, when they occur, damage all waste packages of the same type and same percolation subregion equally.

1.2.1 General Corrosion

General corrosion is a nominal corrosion process. Spatial variability within the repository and on each waste package is accounted for by modeling a different general corrosion rate for each patch on each waste package (SAR Section 2.3.6.3.4.1). In the 1,000,000-year seismic ground motion modeling case, general corrosion is affected by seismic activity through the general corrosion rate. The rate of waste package outer barrier wall thinning increases due to inside-out corrosion when any through penetration of the waste package outer barrier wall occurs, which may lead to an increased number of general corrosion patch openings. Consequently, the results for general corrosion patch openings in the 1,000,000-year seismic ground motion modeling case vary slightly from the results for the nominal modeling case reported in SAR Figure 2.1-10b.

Figure 9 shows the expected fraction of commercial SNF waste packages that fail with at least one general corrosion patch opening. Waste packages with general corrosion patch openings may also have damage by stress corrosion cracks in the closure welds, seismic ground motion-induced stress corrosion cracks, and seismic ground motion-induced ruptures or punctures that is not included in the results shown in Figure 9. The 300 histories shown in Figure 9 characterize the uncertainty in the expected fraction of waste packages that have general corrosion patch openings. The expected failure fraction for each epistemic realization is the average result of 30 aleatory realizations that apply random sequences of seismic events. Epistemic uncertainty is consistent for all 30 aleatory realizations, but the sequence of seismic events, which may influence the general corrosion rate, varies between aleatory realizations. Figure 10 shows the analogous result for codisposal waste packages. The expected fraction of waste packages with general corrosion damage is zero at all times for more than 50% of the epistemic realizations; therefore, the 5th-percentile and median value time histories do not appear in Figures 9 and 10, which use a logarithmic scale for the failure fraction. The absence of a median and 5th-percentile value histories in Figures 9 and 10 reveals that fewer than one half of the 300 epistemic realizations result in general corrosion patch damage to any waste packages.

Figure 11 shows the average fraction of the commercial SNF waste package surface area that is damaged by general corrosion patch openings. This average surface area damage fraction is limited to commercial SNF waste packages that have at least one general corrosion patch opening and excludes the surface area damaged by other mechanisms and the surface area on undamaged waste packages. Therefore, this time history represents the damage area fraction conditional on having damage by general corrosion. Figures 12 and 10 show the analogous results for codisposal waste packages. As discussed in Section 1.1.1, 5th- and 95th-percentile curves are omitted from the conditional damage fraction plots (e.g., Figures 11 and 12). With approximately 1,400 patches per waste package (SAR Section 2.4.2.3.2.1.5), a surface area damage fraction of 7.1×10^{-4} is roughly equal to one patch. For general corrosion patches, the median surface area damage fraction reveals that, except for a few realizations, on a waste package with general corrosion damage, the damage comprises only a few patches.

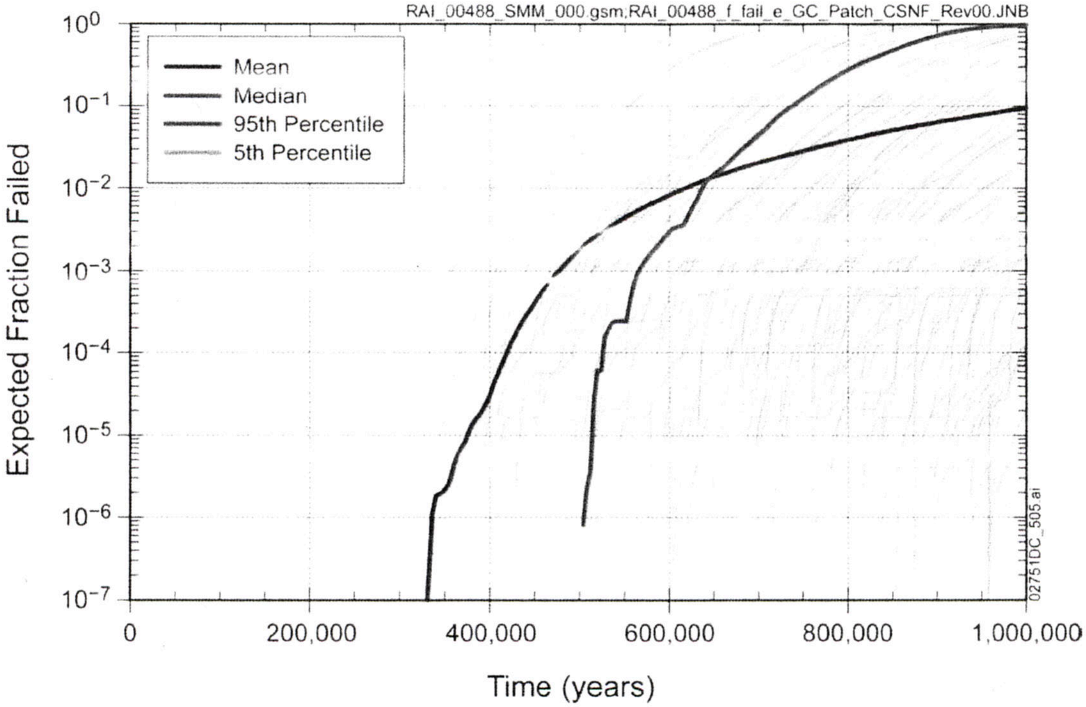


Figure 9. Expected Fraction of Commercial SNF Waste Packages Failed by General Corrosion: 1,000,000-Year Seismic Ground Motion Modeling Case

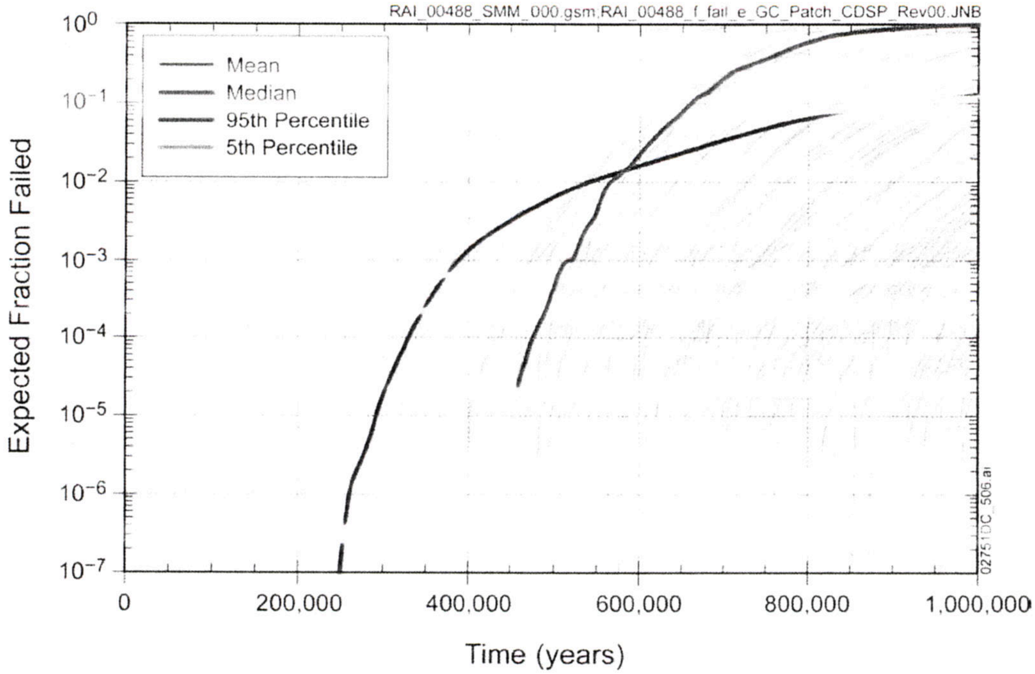


Figure 10. Expected Fraction of Codisposal Waste Packages Failed by General Corrosion: 1,000,000-Year Seismic Ground Motion Modeling Case

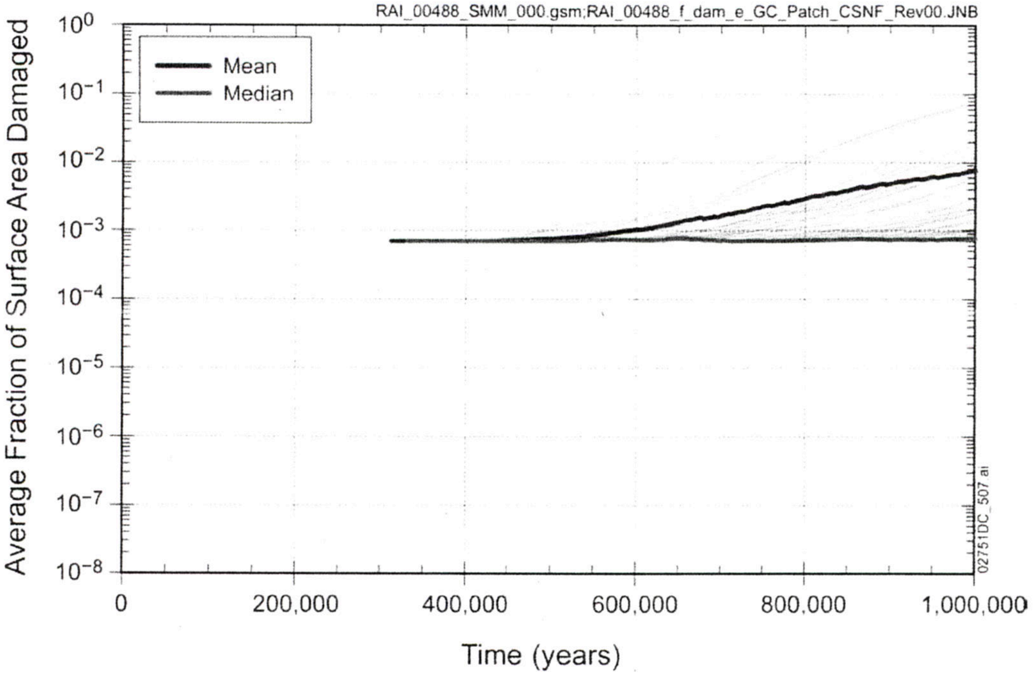


Figure 11. Average Fraction of Surface Area Damaged on Commercial SNF Waste Packages by General Corrosion: 1,000,000-Year Seismic Ground Motion Modeling Case

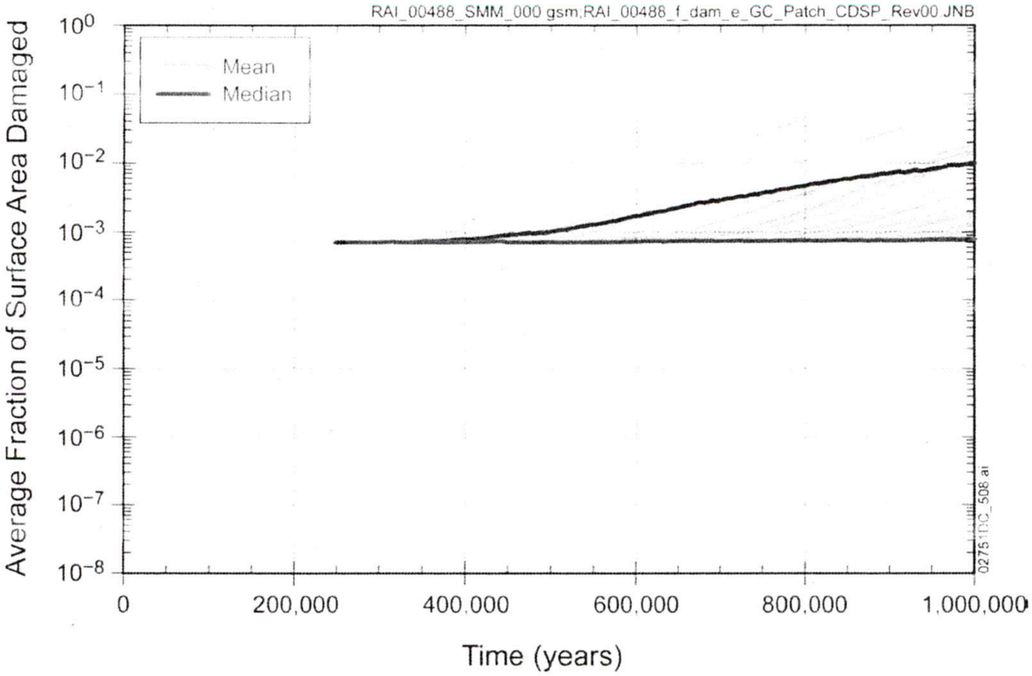


Figure 12. Average Fraction of Surface Area Damaged on Codisposal Waste Packages by General Corrosion: 1,000,000-Year Seismic Ground Motion Modeling Case

1.2.2 Seismic-Induced Ruptures and Punctures

Seismic ground motion-induced ruptures and punctures are determined using the seismic consequence abstractions. During a seismic event, dynamic loads on waste packages free to move beneath an intact drip shield have the potential to result in a rupture (tear) of a waste package if the local strain exceeds the ultimate tensile strain. The extreme deformation from a major seismic event could produce tensile strains in the Alloy 22 and weaken the outer corrosion barrier, potentially resulting in a ruptured outer corrosion barrier from a subsequent extreme seismic event. When the drip shield plates are failed and the waste package is surrounded by lithophysal rubble, extreme deformation of the cylindrical outer corrosion barrier can eliminate the free volume within the outer corrosion barrier, allowing the sharp corners or sharp edges from degraded internal elements to puncture the outer corrosion barrier (SNL 2007, Section 6.1.2). The probability of rupture is zero unless the waste packages are free to move beneath intact drip shield plates, the waste packages are previously damaged and the waste package internals offer no structural integrity, and the mean waste package thickness is below 23 mm (SAR Section 2.3.4.5.2.1.4 and SNL 2007 Sections 6.5 and 6.6). Otherwise, the probability is determined by the peak ground velocity of the seismic event. For a ruptured waste package, the damaged area is sampled from a uniform distribution between 0 m^2 and the cross sectional area of the waste package (~3 m^2) (SNL 2007, Section 6.12.2, pp. 6-233 and 6-240).

The probability of puncture is zero unless the drip shields plates are failed and the waste package is surrounded by rubble; if so, the probability is determined based on the thickness of the waste package and the peak ground velocity of the seismic event (SAR Section 2.3.4.6.1). For a punctured waste package, the damage area is sampled from a uniform distribution between 0 m^2 and 0.1 m^2 (SNL 2007, Section 6.12.2, p. 6-245).

Seismic damage to the waste packages is modeled separately for each waste package type and percolation subregion, but the same sampled values for epistemically uncertain parameters are used for the different subregions. Waste packages in different subregions have different thermal-hydrologic histories used to evaluate general corrosion of the waste package, and therefore the thickness of the waste packages in each percolation subregion may be different. Because the probability of seismic ground motion-induced punctures is a function of the average waste package thickness, the abstractions for waste package damage may produce damage in some percolation subregions but not in others.

Figure 13 shows the expected fraction of commercial SNF waste packages that fail by seismic ground motion-induced ruptures or punctures. Waste packages with seismic ground motion-induced ruptures or punctures may also have damage by stress corrosion cracks in the closure welds, general corrosion, and seismic ground motion-induced stress corrosion cracks that is not included in the results shown in Figure 13. The 300 histories shown in Figure 13 characterize the uncertainty in the expected fraction of waste packages that have seismic ground motion-induced rupture or puncture patch openings. The expected failure fraction for each epistemic realization is the average result of 30 aleatory realizations that apply random sequences of seismic events. The same sampled parameter values representing epistemic uncertainty are used for all 30 aleatory realizations, but the sequence of seismic events, which influences the ruptures and punctures, varies between aleatory realizations. Figure 14 shows the analogous result for codisposal waste packages. The expected fraction of commercial SNF waste packages with seismic ground motion-induced rupture or puncture damage is zero at all times for more than 50% of the epistemic realizations; therefore, the 5th-percentile and median value time histories do not appear in Figure 13, which uses a logarithmic scale for the failure fraction. For codisposal waste packages, the late time occurrence of the median value history in Figure 14 reveals that ruptures and punctures of codisposal waste packages occur in about one-half of the realizations. The expected fraction of codisposal waste packages with seismic ground motion-induced rupture or puncture damage is zero at all times for more than 5% of the epistemic realizations; therefore, the 5th-percentile does not appear in Figure 14, which uses a logarithmic scale for the failure fraction. Increases in the expected fraction of waste packages failed for a given epistemic realization (i.e., a single history in Figures 13 and 14) occur when one or more additional percolation subregions in the same or different aleatory realizations experience a rupture or puncture event.

Figure 15 shows the average fraction of the commercial SNF waste package surface area that is damaged by seismic ground motion-induced ruptures or punctures. This average surface area damage fraction is limited to commercial SNF waste packages that have seismic ground motion-induced ruptures or punctures and excludes the surface area damaged by other mechanisms and the surface area on undamaged waste packages. Therefore, this time history represents the average damage area fraction conditional on having damage by seismic ground motion-induced ruptures or punctures. The fraction of the commercial SNF waste packages that is represented by these histories is presented in Figure 13. Figures 16 and 14 show the analogous results for codisposal waste packages. With a maximum puncture area of 0.1 m^2, the maximum fraction of the surface damaged by punctures is approximately 3×10^{-3}. Therefore, damage fractions that exceed this quantity are due to ruptures. In addition, ruptures only occur while the drip shield plates are intact (drip shields typically fail between 200,000 and 300,000 years) (SAR Figure 2.1-11), whereas punctures only occur after the drip plates have failed and the waste package is surrounded by rubble. Therefore, the mean value for the damage fraction at early times is generally driven by rupture events and decreases later in time as puncture events contribute to the overall average damage area. Figures 15 and 16 show that rupture events are much less frequent than puncture events because the average surface area damage fraction is less than 3×10^{-3} for most realizations. Increases or decreases in the average fraction of surface area damaged for a given epistemic realization (i.e., a single history in Figures 15 and 16) occur when one or more aleatory realizations experience a rupture or puncture event.

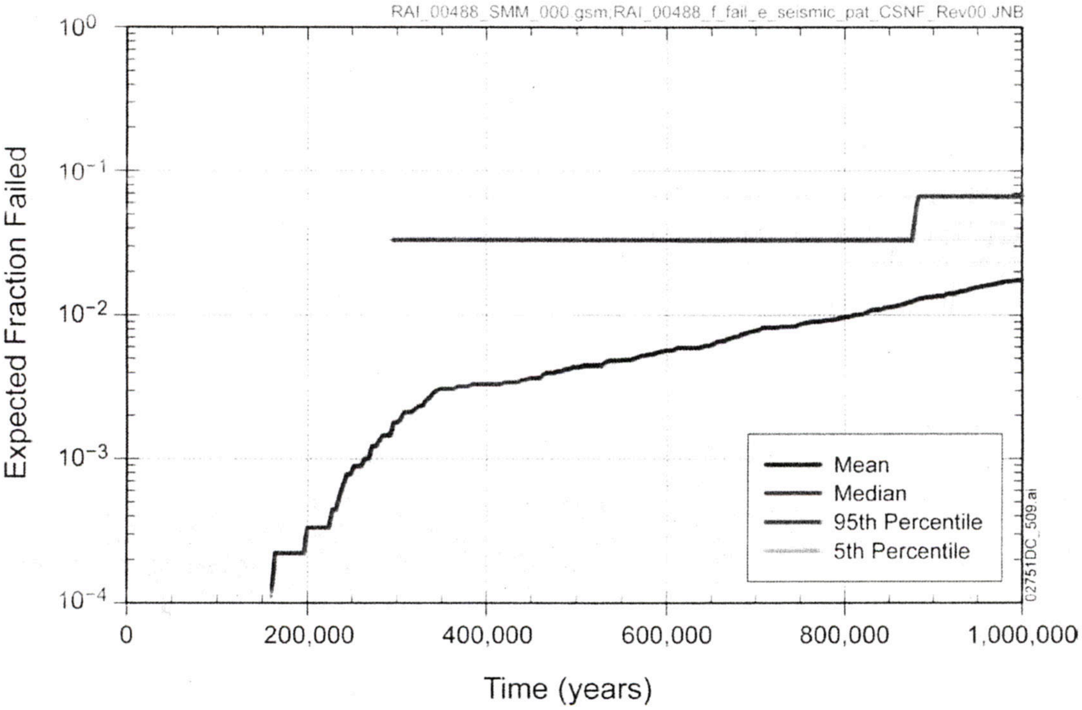


Figure 13. Expected Fraction of Commercial SNF Waste Packages Failed by Seismic-Induced Ruptures or Punctures: 1,000,000-Year Seismic Ground Motion Modeling Case

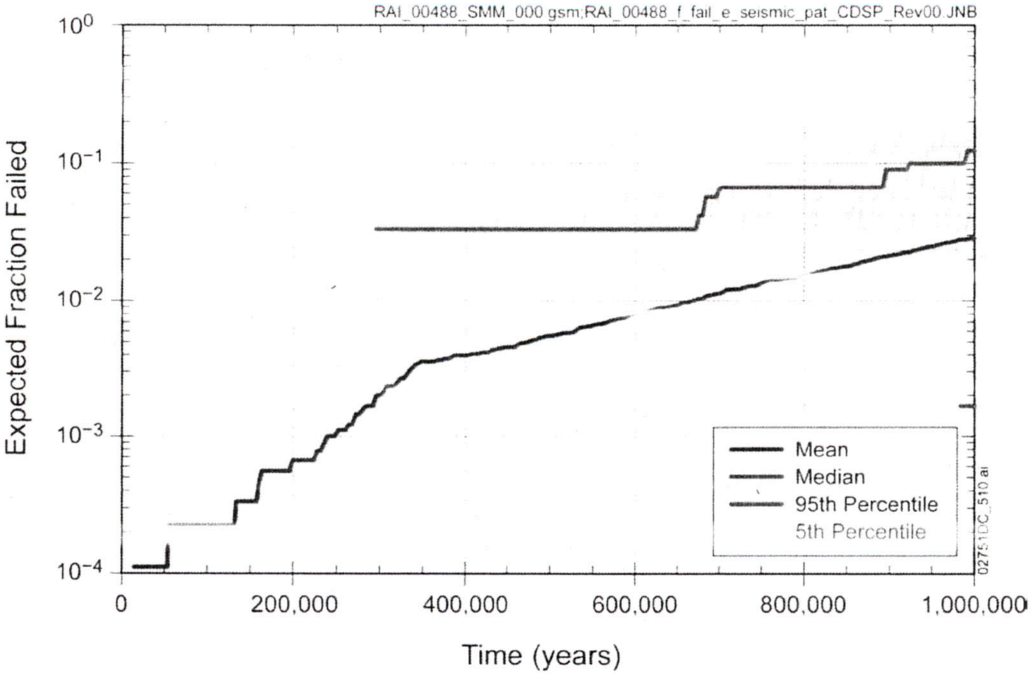


Figure 14. Expected Fraction of Codisposal Waste Packages Failed by Seismic-Induced Ruptures or Punctures: 1,000,000-Year Seismic Ground Motion Modeling Case

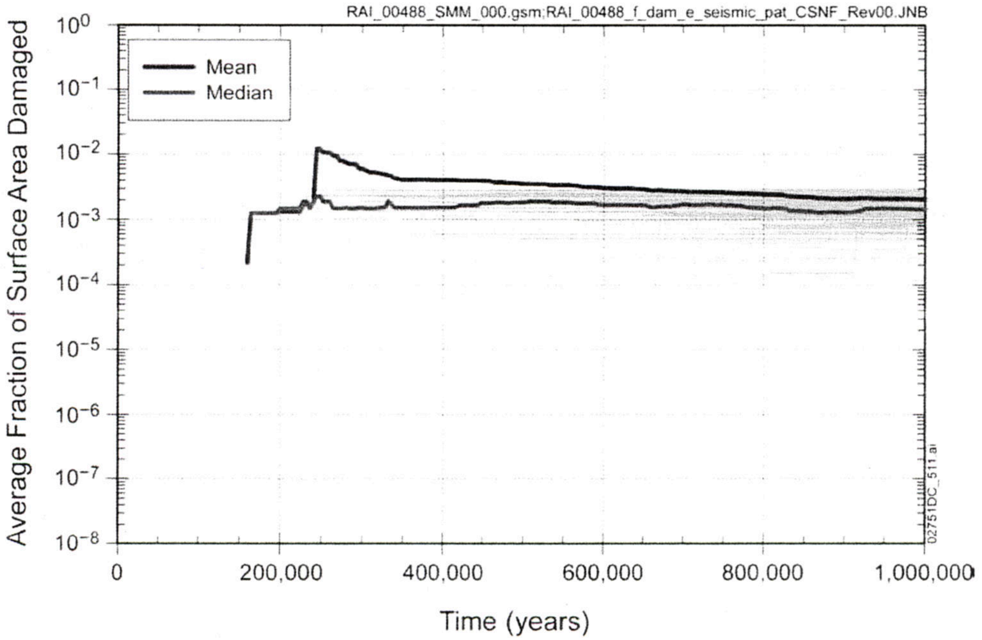


Figure 15. Average Fraction of Surface Area Damaged on Commercial SNF Waste Packages by Seismic-Induced Ruptures or Punctures: 1,000,000-Year Seismic Ground Motion Modeling Case

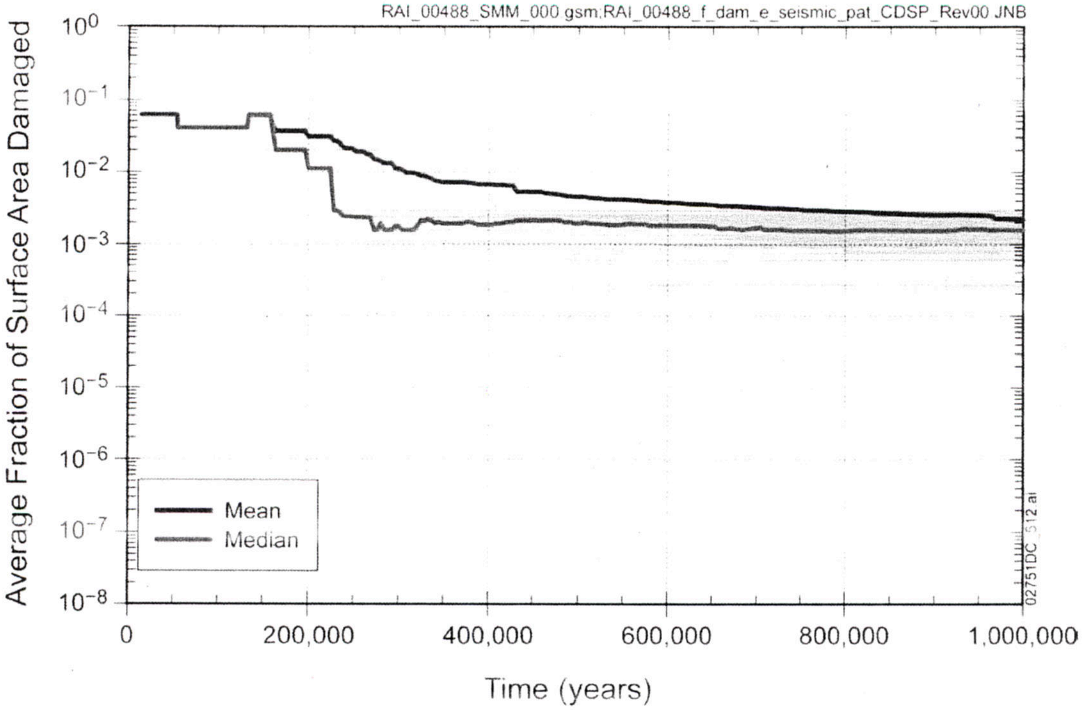


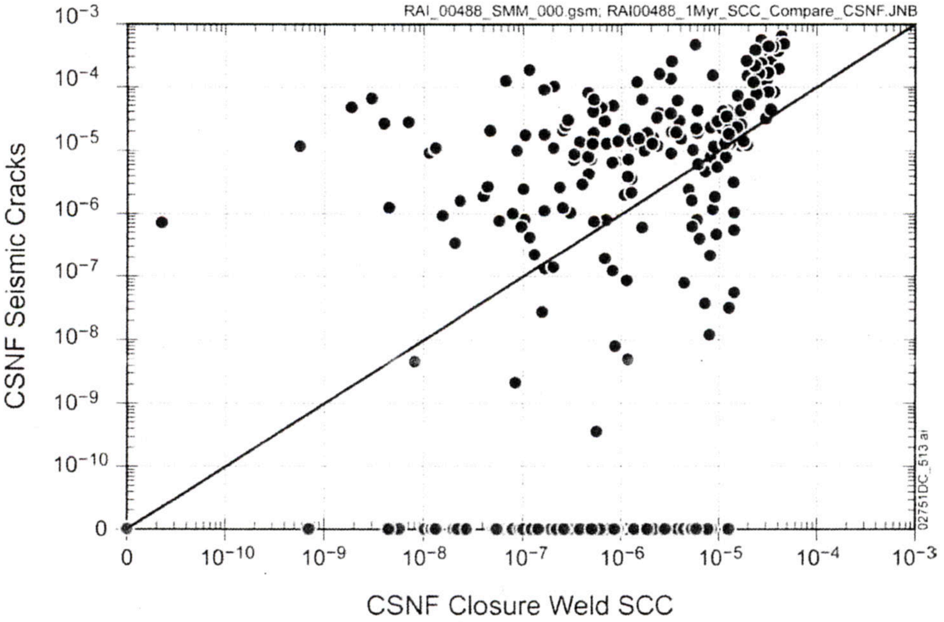
Figure 16. Average Fraction of Surface Area Damaged on Codisposal Waste Packages by Seismic-Induced Ruptures or Punctures: 1,000,000 Year Seismic Ground Motion Modeling Case

1.3 RESULTS COMPARISON

In the 1,000,000-year seismic ground motion modeling case, four separate, but not completely decoupled, waste package damage mechanisms are modeled. These damage mechanisms are stress corrosion cracking in closure welds, general corrosion, seismic ground motion-induced stress corrosion cracking, and seismic ground motion-induced ruptures or punctures. Figures 1 and 2 present the expected failure fraction for commercial SNF and codisposal waste packages that are damaged by stress corrosion cracks in the closure welds. Figures 3 and 4 show the average fraction of surface area damaged by stress corrosion cracks in the closure welds for the waste packages that are damaged by stress corrosion cracks in the closure welds. Figures 5 and 6 present the expected failure fraction for commercial SNF and codisposal waste packages that are damaged by seismic ground motion induced stress corrosion cracks, and Figures 7 and 8 show the average fraction of surface area damaged by seismic ground motion-induced stress corrosion cracks for the waste packages that are damaged by seismic ground motion-induced stress corrosion cracks.

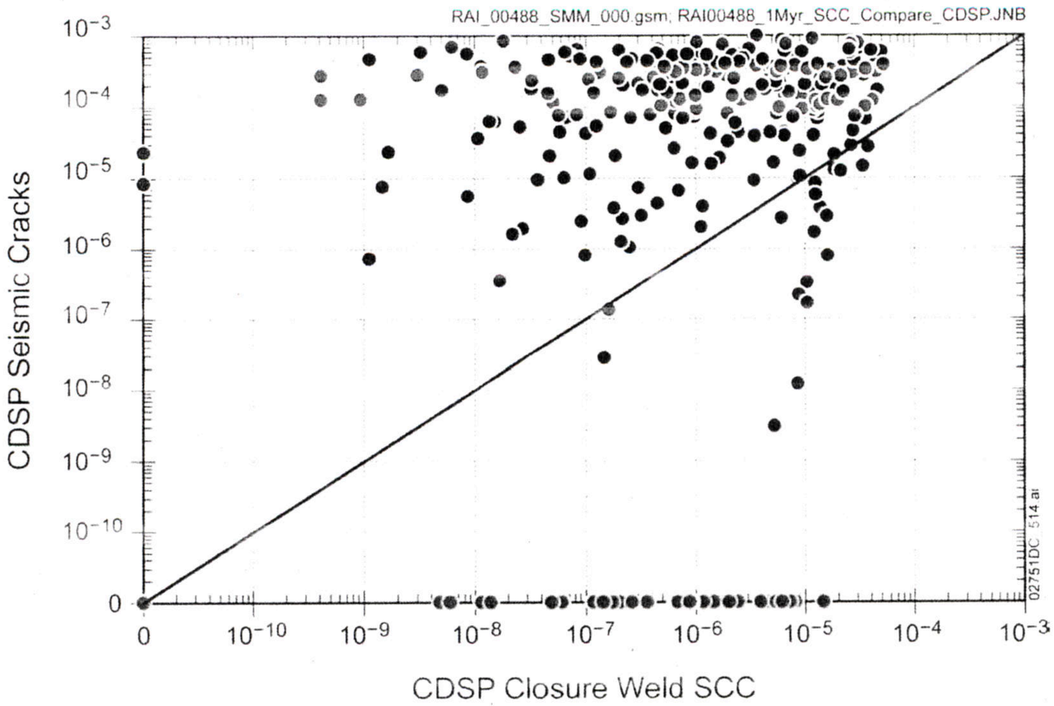
Comparing the eight figures shows that, at early times, the mean fraction of waste packages damaged by seismic ground motion-induced stress corrosion cracking (Figures 5 and 6) is larger than the mean fraction of waste packages damaged by stress corrosion cracking in the closure welds (Figures 1 and 2). However, at later times, the mean fraction of waste packages damaged by stress corrosion cracking in the closure welds exceeds the mean fraction of waste packages damaged by seismic ground motion-induced stress corrosion cracking. Seismic ground motion-induced stress corrosion cracking damage (Figures 7 and 8) is greater than the damage caused by stress corrosion cracking in the closure welds (Figures 3 and 4).

To compare the overall effect of the two damage mechanisms, Figures 17 and 18 provide the expected fractions of total repository-wide waste package surface area damaged by stress corrosion cracking, computed as the product of the expected failure fraction and the average surface area damage fraction at 1,000,000 years. For each waste package type, the plotted quantity is a surrogate for the total repository-wide waste package surface area damaged by nominal processes and seismic activity. Repository-wide nominal corrosion damage increases from left to right on the *x*-axis, and repository-wide seismic damage increases from bottom to top on the *y*-axis. Values plotted in color are realizations that have no damage from one or both of the two damage mechanisms. Values plotted along a diagonal stretching between the lower left corner to the upper right corner indicate equal damage between damage mechanisms. For commercial SNF waste packages, the large number of values plotted directly on the *x*-axis indicate that stress corrosion cracking of the closure welds happens more frequently than seismic ground motion-induced stress corrosion cracking. However, the expected fractions of repository-wide waste package surface area damaged by seismic ground motion-induced stress corrosion cracking tend to be greater than those for the damage caused by stress corrosion cracking in the closure welds. Similar conclusions hold for codisposal waste packages.



NOTE: Red data indicate stress corrosion cracking in the closure welds, but no seismic ground motion-induced stress corrosion cracking damage; green data indicate no stress corrosion cracking damage.

Figure 17. Comparison of Expected Fraction of Repository-Wide Waste Package Surface Area Damaged at 1,000,000 Years on Commercial SNF Waste Packages by Stress Corrosion Cracking in the Closure Welds and by Seismic Ground Motion-Induced Stress Corrosion Cracking Damage: 1,000,000-Year Seismic Ground Motion Modeling Case



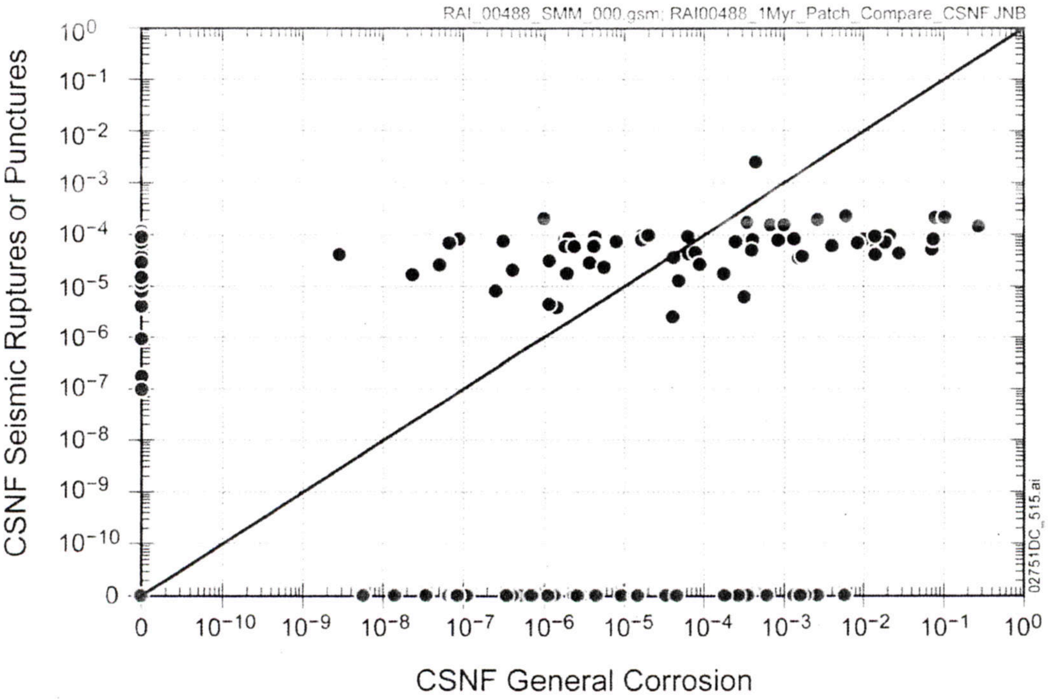
NOTE: Red data indicate stress corrosion cracking in the closure welds, but no seismic ground motion-induced stress corrosion cracking damage; blue data indicate seismic ground motion-induced stress corrosion cracking damage, but no stress corrosion cracking in the closure welds; green data indicate no stress corrosion cracking damage.

Figure 18. Comparison of Expected Fraction of Repository-Wide Waste Package Surface Area Damaged at 1,000,000 Years on Codisposed Waste Packages by Stress Corrosion Cracking in the Closure Welds and by Seismic Ground Motion-Induced Stress Corrosion Cracking Damage: 1,000,000-Year Seismic Ground Motion Modeling Case

In addition to showing damage by stress corrosion cracks, patch damage has also been investigated. Figures 9 and 10 present the expected failure fraction for commercial SNF and codisposal waste packages that are damaged by general corrosion. Figures 11 and 12 show the average fraction of surface area damaged by general corrosion for the waste packages that are damaged by general corrosion. Figures 13 and 14 present the expected failure fraction for commercial SNF and codisposal waste packages that are damaged by seismic ground motion-induced ruptures or punctures, and Figures 15 and 16 show the average fraction of surface area damaged by seismic ground motion-induced ruptures and punctures for waste packages that are damaged by seismic ground motion-induced ruptures and punctures.

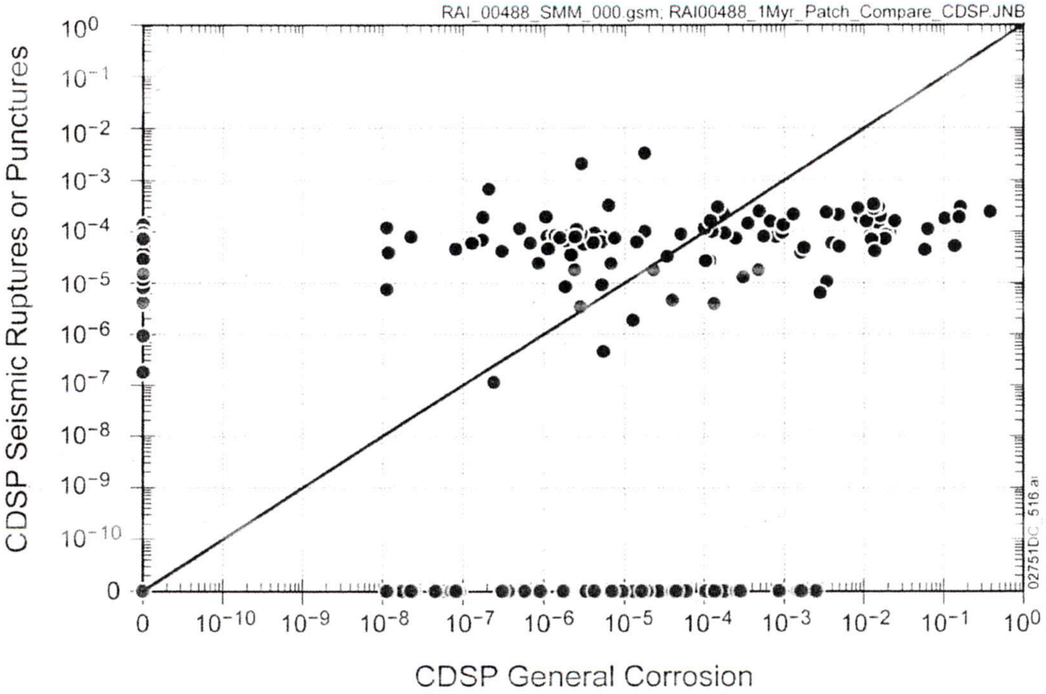
Comparing the eight figures shows that, at early times, the mean fraction of waste packages damaged by seismic ground motion-induced ruptures or punctures (Figures 13 and 14) is larger than the mean fraction of waste packages damaged by general corrosion (Figures 9 and 10). However, at later times, the mean fraction of waste packages damaged by general corrosion exceeds the mean fraction of waste packages damaged by seismic ground motion-induced ruptures or punctures. The average surface area damaged by seismic ground motion-induced rupture or puncture damage (Figures 15 and 16) is less than the average surface area damaged by general corrosion (Figures 11 and 12).

To compare the overall effect of the two damage mechanisms, Figures 19 and 20 provide the expected fractions of total repository-wide waste package surface area damaged by patches, computed as the product of the expected failure fraction and the average surface area damage fraction at 1,000,000 years. For commercial SNF waste packages, the range of damage caused by general corrosion exceeds the range of damage caused by seismic ground motion-induced ruptures and punctures. Damage by seismic ground motion-induced ruptures and punctures is limited to a single rupture or puncture event, and therefore the ruptured or punctured area on a waste package does not accumulate over multiple events. However, general corrosion processes continue for the entire simulation and general corrosion damage accumulates through time, potentially yielding a much larger range of values at 1,000,000 years. The results for the codisposal waste package are similar to the results for the commercial SNF waste packages.



NOTE: Red data indicate realizations with general corrosion damage, but no seismic ground motion-induced rupture or puncture damage; blue data indicate realizations with seismic ground motion-induced rupture or puncture damage, but no general corrosion damage; green data indicate no damage by general corrosion or seismic ground motion-induced ruptures or punctures.

Figure 19. Comparison of Expected Fraction of Repository-Wide Waste Package Surface Area Damaged at 1,000,000 Years on Commercial SNF Waste Packages by General Corrosion and by Seismic Ground Motion-Induced Rupture and Puncture Damage: 1,000,000-Year Seismic Ground Motion Modeling Case



NOTE: Red data indicate realizations with general corrosion damage, but no seismic ground motion-induced rupture or puncture damage; blue data indicate realizations with seismic ground motion-induced rupture or puncture damage, but no general corrosion damage; green data indicate no damage by general corrosion or seismic ground motion-induced ruptures or punctures.

Figure 20. Comparison of Expected Fraction of Repository-Wide Waste Package Surface Area Damaged at 1,000,000 Years on Codisposal Waste Packages by General Corrosion and by Seismic Ground Motion-Induced Rupture and Puncture Damage: 1,000,000-Year Seismic Ground Motion Modeling Case

1.4 SUMMARY

In the 1,000,000-year seismic ground motion modeling case, four separate, but not completely decoupled, waste package damage mechanisms are modeled. These damage mechanisms are stress corrosion cracking in closure welds, general corrosion, seismic ground motion-induced stress corrosion cracking, and seismic ground motion-induced ruptures or punctures. Time histories of the expected failure fraction and average fraction of waste package surface area damaged by each of these four mechanisms have been presented in Figures 1 through 16.

In addition, comparisons between damage mechanisms have been discussed and presented in Figures 17 through 20. The results indicate that stress corrosion cracking in the closure welds occurs more frequently than seismic ground motion-induced stress corrosion cracking, but the overall damage to the waste packages tends to be greater from seismic ground motion-induced stress corrosion cracking when it occurs. In addition, the results indicate that that general corrosion occurs more frequently than seismic ground motion-induced ruptures and punctures and that the overall damage from general corrosion tends to be greater than seismic ground motion-induced rupture and puncture damage when it occurs.

2. COMMITMENTS TO NRC

None.

3. DESCRIPTION OF PROPOSED LA CHANGE

None.

4. REFERENCES

SNL (Sandia National Laboratories) 2007. *Seismic Consequence Abstraction.* MDL-WIS-PA-000003 REV 03. Las Vegas, Nevada: Sandia National Laboratories. ACC: DOC.20070928.0011.

SNL 2008. *Total System Performance Assessment Model /Analysis for the License Application.* MDL-WIS-PA-000005 REV 00 AD 01. Las Vegas, Nevada: Sandia National Laboratories. ACC: DOC.20080312.0001