RAI Volume 3, Chapter 2.2.1.3.2, Second Set, Number 5:

Explain how the potential for tensile tearing of the waste package under a collapsed drip shield is bounded by the strain analyses for intact or fully degraded drip shields, such that the potential for tensile tearing is not underestimated.

Basis: For intact waste package internals and a collapsed drip shield, DOE considers tensile strain calculations from dynamic rock rubble loads after drip shield plate failure as bounding. For degraded internals and a collapsed drip shield, DOE considers the kinematic analyses for TAD-bearing waste packages as bounding. Thus, DOE did not present the results of models for tensile strain of the waste package after collapse of the drip shield (SAR section 2.3.4.5.4.4.1). However, DOE has not discussed how free interactions between the waste package and drip shield, or dynamic interactions with rock rubble, appropriately bound localized tensile strains that could occur between a collapsed drip shield and the waste package.

1. RESPONSE

This response documents the effective plastic strains for a waste package under a collapsed drip shield and compares these plastic strains to the tensile strains for two other waste package configurations: (1) the kinematic analysis for transportation, aging, and disposal (TAD)-bearing waste packages with degraded internals; and (2) the dynamic analyses for a waste package surrounded by rubble. Free interactions between the waste package and drip shield or dynamic interactions with rock rubble appropriately bound localized tensile strains that could occur between a collapsed drip shield and the waste package.

1.1 STRUCTURAL RESPONSE OF A WASTE PACKAGE UNDER A COLLAPSED DRIP SHIELD

The geometry for the DOE analysis of a waste package loaded by a collapsed drip shield is illustrated in Figure 1 (SNL 2007a, Figure 6-90). The model representation encompasses a quarter symmetry of the total waste package. Thus, it includes half of the two end bulkhead flanges and a quarter of the middle bulkhead flange of the drip shield. Figure 1 shows the waste package with fully degraded internals; a quarter-symmetry representation is also used for the waste package with intact internals (SNL 2007a, Figure 6-89).

In the structural analysis for this configuration, the drip shield bulkhead flanges are pushed uniformly downward against the outer corrosion barrier (OCB). This downward motion occurs slowly enough that the OCB is always near equilibrium, and is referred to as a quasi-static loading or quasi-static (as opposed to dynamic) analysis. The total load on the OCB increases as the bulkhead flanges are pushed downward, resulting in increasing the damaged area on the OCB, as shown in SAR Figure 2.3.4-93.

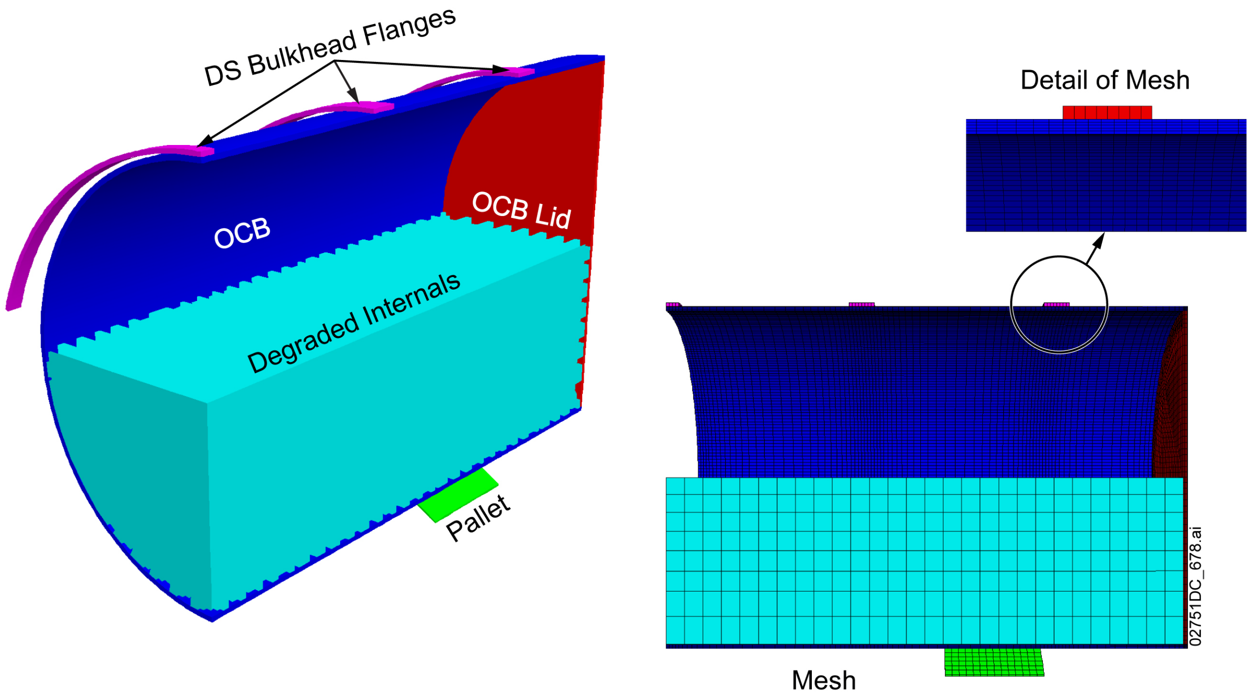


Figure 1. Geometrical Representation of the Waste Package Loaded by the Collapsed Drip Shield for the Case of Degraded Internals

1.2 MAXIMUM EFFECTIVE PLASTIC STRAIN FOR A WASTE PACKAGE UNDER A COLLAPSED DRIP SHIELD

Quasi-static loading also results in plastic yielding of the OCB. Figure 2 presents the maximum tensile strain in the OCB as a function of vertical load for a waste package under a collapsed drip shield. Effective plastic strain is an appropriate parameter for judging the potential for tensile rupture in a structural component (SNL 2007a, Appendix A2). The effective plastic strain is a positive quantity that always increases with plastic deformation. For these calculations, FLAC3D automatically calculates and stores the plastic shear strain, which is defined as the time integral of the square root of the second invariant of the deviatoric strain rate. The effective plastic strain is calculated by multiplying the maximum plastic shear strain by $\sqrt{4/3}$ (SNL 2007a, Section 6.4.3.1.3) and is compared with the ultimate plastic strain for Alloy 22 to assess the potential for rupture.

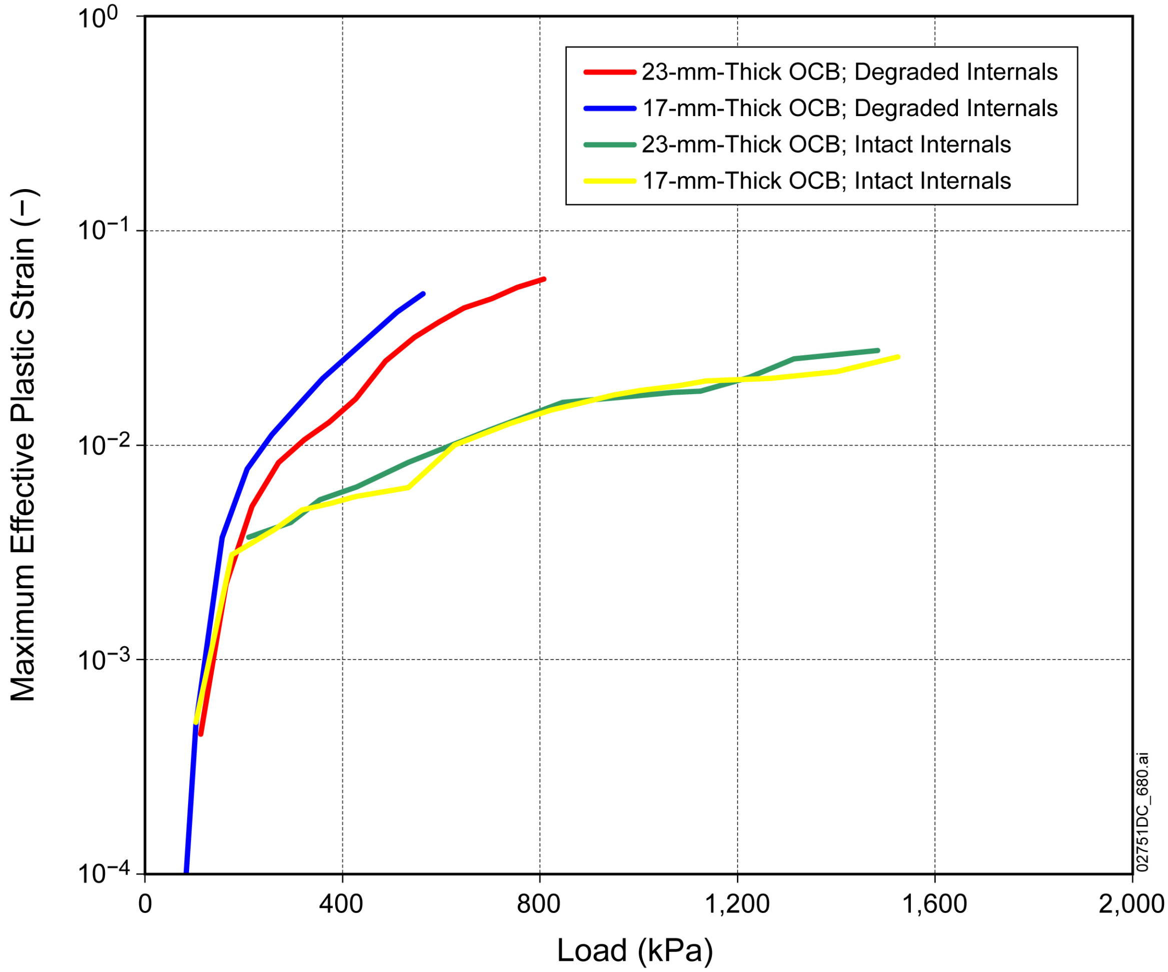


Figure 2. Maximum Tensile Strain in the OCB as a Function of Vertical Load for a Waste Package Loaded by the Collapsed Drip Shield

Figure 2 shows the effective plastic strain as a function of OCB thickness and state of the waste package internals, either intact or degraded. Figure 2 is similar to SAR Figure 2.3.4-93, but defines the maximum effective plastic strain in the OCB for a given load, rather than the percent damaged area on the OCB. Tables 1 and 2 present the numerical values for maximum effective plastic strain as a function of vertical load for intact and degraded internals, respectively.

Table 1. Maximum Effective Plastic Strain in OCB – Intact Internals under a Collapsed Drip Shield

Intact Internals, 23-mm-Thick OCB		Intact Internals, 17-mm-thick OCB	
Load (Pa)	**Maximum Effective Plastic Strain in OCB (−)**	**Load (Pa)**	**Maximum Effective Plastic Strain in OCB (−)**
0	0	0	0
2.10×10^{5}	3.72×10^{-3}	5.18×10^{4}	0
2.95×10^{5}	4.37×10^{-3}	1.03×10^{5}	5.11×10^{-4}
3.54×10^{5}	5.56×10^{-3}	1.76×10^{5}	3.08×10^{-3}
4.29×10^{5}	6.39×10^{-3}	2.62×10^{5}	4.03×10^{-3}
5.34×10^{5}	8.33×10^{-3}	3.18×10^{5}	4.98×10^{-3}
6.98×10^{5}	1.18×10^{-2}	3.77×10^{5}	5.36×10^{-3}
8.46×10^{5}	1.58×10^{-2}	4.27×10^{5}	5.75×10^{-3}
9.87×10^{5}	1.69×10^{-2}	5.33×10^{5}	6.35×10^{-3}
1.07×10^{6}	1.76×10^{-2}	6.27×10^{5}	1.00×10^{-2}
1.12×10^{6}	1.79×10^{-2}	7.38×10^{5}	1.26×10^{-2}
1.22×10^{6}	2.07×10^{-2}	8.22×10^{5}	1.46×10^{-2}
1.31×10^{6}	2.52×10^{-2}	8.80×10^{5}	1.57×10^{-2}
1.48×10^{6}	2.76×10^{-2}	9.49×10^{5}	1.71×10^{-2}
		1.00×10^{6}	1.80×10^{-2}
		1.08×10^{6}	1.89×10^{-2}
		1.14×10^{6}	1.99×10^{-2}
		1.27×10^{6}	2.05×10^{-2}
		1.40×10^{6}	2.20×10^{-2}
		1.52×10^{6}	2.58×10^{-2}

Table 2. Maximum Effective Plastic Strain in OCB – Degraded Internals under Collapsed Drip Shield

Degraded Internals, 23-mm-Thick OCB		Degraded Internals, 17-mm-thick OCB	
Load (Pa)	**Maximum Effective Plastic Strain in OCB (−)**	**Load (Pa)**	**Maximum Effective Plastic Strain in OCB (−)**
0	0	0	0
5.04×10^{4}	0	5.09×10^{4}	6.87×10^{-6}
1.13×10^{5}	4.50×10^{-4}	1.03×10^{5}	4.98×10^{-4}
1.64×10^{5}	2.25×10^{-3}	1.56×10^{5}	3.71×10^{-3}
2.17×10^{5}	5.17×10^{-3}	2.07×10^{5}	7.73×10^{-3}
2.70×10^{5}	8.28×10^{-3}	2.57×10^{5}	1.12×10^{-2}
3.22×10^{5}	1.06×10^{-2}	3.08×10^{5}	1.51×10^{-2}
3.73×10^{5}	1.28×10^{-2}	3.59×10^{5}	2.04×10^{-2}
4.27×10^{5}	1.64×10^{-2}	5.11×10^{5}	4.17×10^{-2}
4.87×10^{5}	2.47×10^{-2}	5.63×10^{5}	5.07×10^{-2}

Table 2. Maximum Effective Plastic Strain in OCB – Degraded Internals under Collapsed Drip Shield (continued)

Degraded Internals, 23-mm-Thick OCB		Degraded Internals, 17-mm-thick OCB	
Load (Pa)	Maximum Effective Plastic Strain in OCB (−)	Load (Pa)	Maximum Effective Plastic Strain in OCB (−)
5.45×10^{5}	3.18×10^{-2}		
5.95×10^{5}	3.76×10^{-2}		
6.46×10^{5}	4.37×10^{-2}		
7.02×10^{5}	4.83×10^{-2}		
7.54×10^{5}	5.44×10^{-2}		
8.08×10^{5}	5.94×10^{-2}		

1.3 ASSESSMENT OF THE POTENTIAL FOR TENSILE RUPTURE OR PUNCTURE

The relationship between the maximum effective plastic strain and the vertical load (Figure 2) can be converted to a relationship between the maximum effective plastic strain and the first horizontal component of peak ground velocity, denoted as PGV-H1. The vertical pressure on the drip shield, p_a, is expressed in terms of the mean static lithophysal rubble load, $p = 126.6\,\text{kPa}$ (SAR, Table 2.3.4-35) and the vertical seismic acceleration, PGA-V, as:

$$p_a = (1 + \text{PGA})\,p$$

Using a regression fit (SNL (2007b, Figure 6-64 and Equation 6.8-13) based on the relation between PGA-V and PGV-H1, the vertical load is expressed in terms of PGV-H1. The resulting relationship between the maximum effective plastic strains (for two OCB thicknesses and intact and degraded internals) and PGV-H1 is shown in Figure 3. The figure shows the equivalent values of PGV-H1 can be as large as 6 m/s for the calculations with intact internals. In other words, the FLAC3D calculations for intact internals span the full range of response for the seismic scenario, which has a maximum PGV–H1 value of 4.07 m/s on the bounded hazard curve (SNL 2007b, Section 6.4.3).

For degraded internals, the plots of the maximum effective plastic strain as functions of PGV-H1 show that the maximum equivalent values of PGV-H1 are 2.2 or 3.3 m/s for the FLAC3D calculations. Given that the calculations do not span the full range of PGV, the last two points are extrapolated with linear and log-linear methods. The extrapolations for the 23-mm-thick OCB with degraded internals shows peak strain of less than 0.08. The extrapolations for the 17-mm-thick OCB show peak strains of 0.12 and 0.22 for the linear and log-linear extrapolations, respectively. All of these values are less than the minimum tensile strain for failure of Alloy 22, which is 0.285 (SAR Section 2.3.4.5.1.4.2). Thus, no tensile failure occurs for the waste package loaded by a collapsed drip shield over the full PGV range of interest for the seismic scenario.

It follows that tensile rupture of the OCB is not predicted to occur when the drip shield collapses down onto a waste package with intact or degraded internals. Stated differently, the probability of rupture of the OCB is zero when the drip shield collapses down onto a waste package.

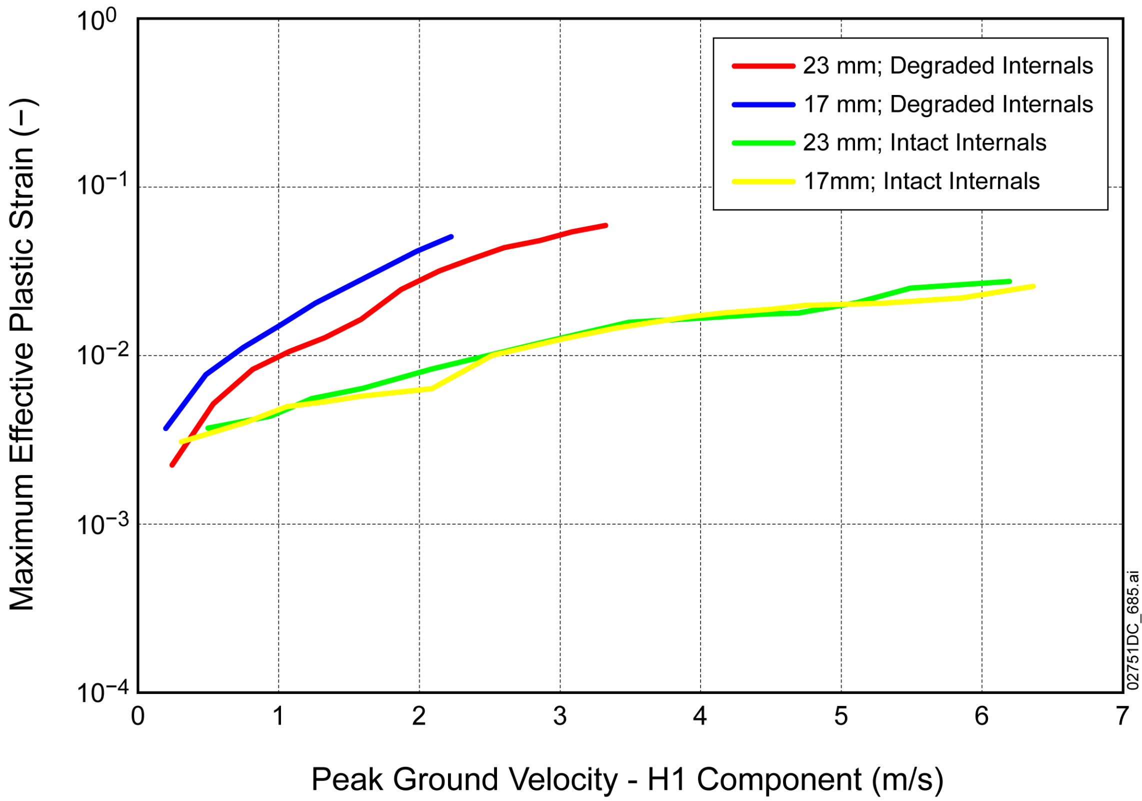


Figure 3 Maximum Tensile Strain in the OCB as a Function of PGV-H1

The kinematic analyses for waste package-to-pallet impacts bound the localized tensile strains for the TAD-bearing waste package with degraded internals under a collapsed drip shield. The rationale for this approach is explained in Section 1.4. The dynamic analyses for a waste package surrounded by rubble are used to bound the localized tensile strains for the TAD-bearing waste package with intact internals under a collapsed drip shield. The rationale for this approach is explained in Section 1.5 and was expanded to consider the potential for puncture of the OCB in Section 1.6.

1.4 KINEMATIC RESPONSE OF THE TAD-BEARING WASTE PACKAGE WITH DEGRADED INTERNALS

The seismic damage abstractions for the kinematic response of the TAD-bearing waste package with degraded internals incorporate a qualitative analysis of the potential for tensile rupture of the OCB from multiple waste package-to-pallet impacts. The rationale for this qualitative analysis is discussed in detail in the response to RAI 3.2.2.1.3.2-2-002. That qualitative analysis results in a nonzero probability for tensile rupture of the OCB, which bounds the zero probability for tensile rupture of the OCB when the drip shield collapses down onto a waste package with degraded internals.

It is instructive to confirm this result by comparing the amplitudes of the effective plastic strains from the waste package loaded by the collapsed drip shield to those for the kinematic calculations for waste package-to-pallet impacts. The maximum effective plastic strains from the kinematic calculations for the TAD-bearing waste package with degraded internals are documented for the 23-mm-thick OCB with degraded internals (SNL 2007a, Tables 6-58 through 6-60) and for the 17-mm-thick OCB with degraded internals (SNL 2007a, Tables 6-61 through 6-63). The maximum effective plastic strains from the kinematic calculations are usually larger than the greatest value of the maximum effective plastic strains for the waste package with degraded internals loaded by a collapsed drip shield. For example, for a 23-mm-thick OCB at an impact angle of -0.25 degrees, the effective plastic strain is 0.344 to 0.459 at an impact velocity of 10 m/s (SNL 2007a, Table 6-59). For the 17-mm-thick OCB at an impact angle of −0.25 degrees, the effective plastic strain is 0.201 to 0.344 at an impact velocity of 10 m/s (SNL 2007a, Table 6-62). The maximum effective plastic strains from the kinematic calculations are greater than the values of 0.12 (or 0.22) and 0.08 for the waste package with OCB thickness of 17 and 23 mm, respectively, under a collapsed drip shield (see Section 1.3). The effective plastic strains from waste package-to-pallet impacts therefore bound the localized tensile strains that could occur between a collapsed drip shield and the waste package with degraded internals at the maximum PGV level of 4.07 m/s for the seismic scenario.

1.5 RESPONSE OF THE TAD-BEARING WASTE PACKAGE SURROUNDED BY RUBBLE

The maximum effective plastic strain for the TAD-bearing waste package surrounded by rubble is documented for the 23-mm-thick OCB (SNL 2007a, Figures 6-79 to 6-82) and for the 17-mm-thick OCB (SNL 2007a, Figures 6-83 to 6-86) at four peak ground velocity (PGV) levels of 0.4, 1.05, 2.44, and 4.07 m/s. Averages for the 17 realizations at each of the four PGV levels (SNL 2007a, Figure 6-87 and Table 6-160) show that the average effective plastic strain is greater for the 17- than for the 23-mm OCB thickness for all velocities, and that the average plastic strain increases monotonically with velocity. Case 11 (SNL 2007a, Figures 6-82 and 6-86) produced the highest plastic strains of all cases analyzed. These strains occurred at the 4.07 m/s PGV level and were 0.193 for the 23-mm and 0.182 for the 17-mm OCB thicknesses.

The maximum effective plastic strain values of 0.193 and 0.182 are about two-thirds of the minimum tensile strain for failure (rupture) of Alloy 22, which is 0.285 with the “knockdown” factor of 2 for a triaxial stress state (SNL 2007a, Appendix A2). Therefore, none of the simulations for the waste package surrounded by rubble predict tensile rupture of the OCB. However, the average effective plastic strains at the 2.44 and 4.07 m/s PGV levels vary between 0.0225 and 0.0807 (SNL 2007a, Table 6-160). These values are greater than the values of maximum effective plastic strains for a waste package with intact internals under a collapsed drip shield, between 0.01 and 0.018 at the 2.44 and 4.07 m/s PGV levels (Figure 3), respectively. It follows that the effective plastic strains from the calculations for the waste package surrounded by rubble can be significantly greater than the greatest values for the waste package with intact internals under a collapsed drip shield. Therefore, the effective plastic strains for the waste package surrounded by rubble bound the localized tensile strains that could occur between a collapsed drip shield and the waste package with intact internals.

The seismic damage abstractions for the response of the TAD-bearing waste package surrounded by rubble incorporate a qualitative analysis of the potential for puncture of the OCB from partly degraded internals within the OCB. The potential for puncture of the OCB under a collapsed drip shield is discussed in the next section.

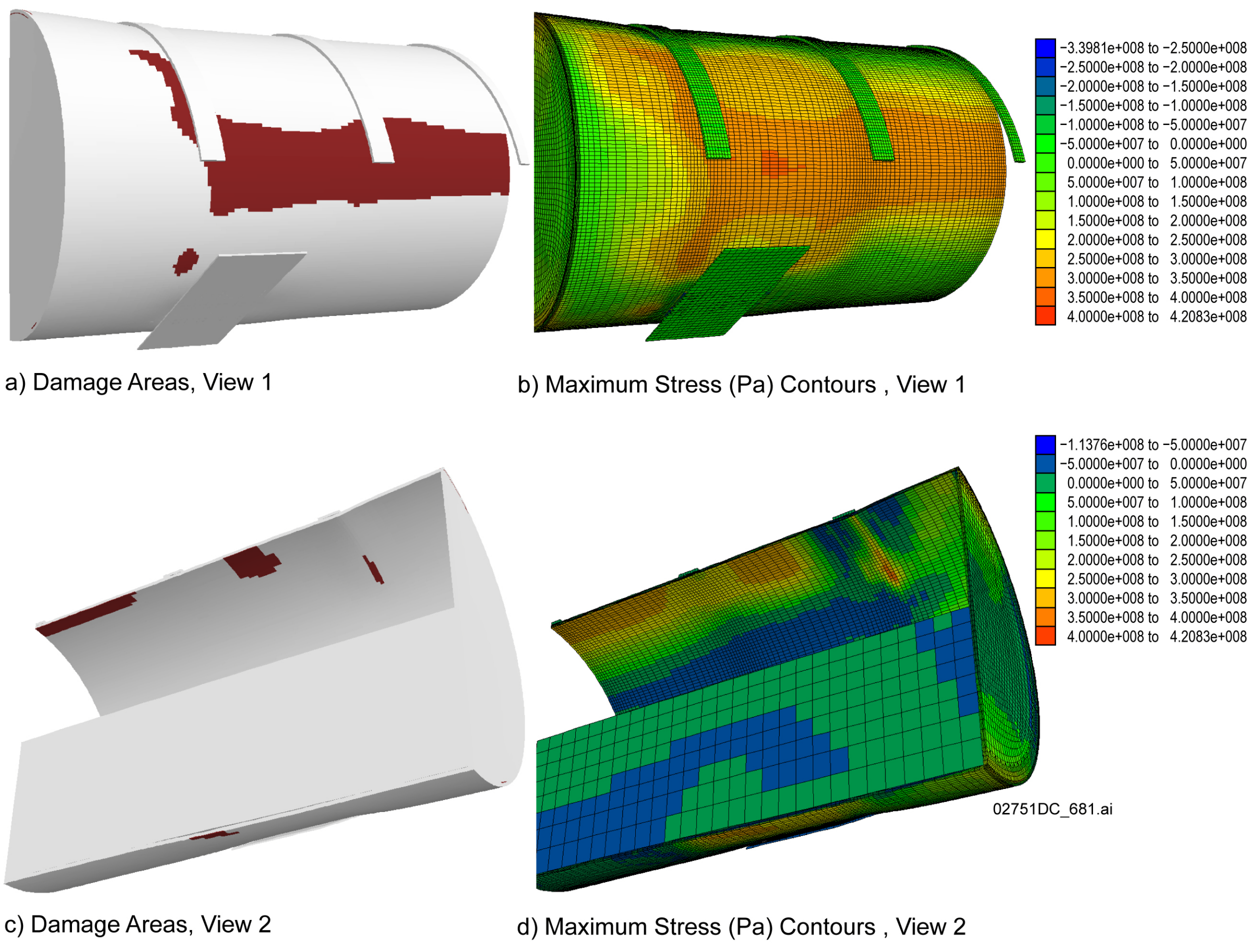
1.6 POTENTIAL FOR PUNCTURE OF THE OCB UNDER A COLLAPSED DRIP SHIELD

Deformation of the OCB does not result in strains sufficiently large to cause tensile failure in the OCB under a collapsed drip shield, as discussed in Section 1.3. Although the waste package internals are assumed to degrade as structural elements after the OCB is first breached, fragments of the stainless steel inner vessel and parts of the Zircaloy cladding could persist for some period of time (SNL 2007a, Section 1.2). The sharp edges or corners on these fragments might puncture a deformed OCB when it is loaded down by the drip shield.

The probability of puncture is based on the area within a deformed OCB (SNL 2007a, Section 6.5.1.4.1). The probability of puncturing the OCB by the waste package internals is judged to be 0.0 until OCB deformation is great enough to reduce the diametral distance across the OCB by 4 inches and is judged to be 1.0 when the OCB completely collapses onto the internals within the waste package (i.e., when the internal area within the OCB reduces to 50% of its original value). Further details of the approach to determining the probability of puncture are provided in *Mechanical Assessment of Degraded Waste Packages and Drip Shields Subject to Vibratory Ground Motion* (SNL 2007a, Section 6.5.1.4.1).

The probability of puncturing the OCB for a waste package surrounded by rubble is calculated from the cross-sectional areas of the final deformed configurations of the OCBs (SNL 2007a, Figures 6-79 through 6-86). The puncture probability at 0.4 m/s PGV is zero irrespective of the OCB thickness. That result is consistent with observations of the final shape of the OCB cross sections (SNL 2007a, Figures 6-79 and 6-83), which do not indicate significant permanent deformation or distortion. For the 23-mm-thick OCB, the puncture probability is also zero at the 1.05 m/s PGV level. The greatest puncture probability (0.20 based on the average of 17 analyzed cases) is for the 4.07 m/s PGV level with 17-mm-thick OCB (SNL 2007a, Section 6.5.1.4.1).

Figure 4 shows the response of the OCB loaded by a collapsed drip shield for the case of degraded internals and a 23-mm-thick OCB at the maximum vertical load of about 808 kPa as listed in Table 2. Figure 4 illustrates that no significant permanent deformation of the OCB occurs and that the OCB retains an almost circular cross section, even at the vertical load associated with the maximum tensile strain. A similar response (i.e., minimal deformation of the circular cross section of the OCB at maximum load) is observed for the 23-mm-thick OCB with intact internals (SNL 2007a, Figure 6-93). This observation is also expected to be valid for the 17-mm-thick OCB, based on the similarity of response for the 23-mm-thick and 17-mm-thick OCBs shown in Figure 1 and in SAR Figure 2.3.4-93 for the same condition of internals, intact or degraded. The probability of puncture of the OCB is therefore judged to be zero when the waste package is loaded by a collapsed drip shield because of minimal deformation of the circular cross section of the OCB. It follows that the probability of puncture for the waste package surrounded by rubble bounds the probability of puncture for a waste package with intact internals under a collapsed drip shield.



Source: SNL 2007a, Figure 6-92 and SAR Figure 2.3.4-91

NOTE: The damage area is the inner or outer surface of the OCB with maximum stress greater than 90% of the yield strength of Alloy 22 (i.e., 316 MPa). The damage area is shown in brown.

Figure 4. Damage Areas and Maximum Stress Contours Shown in Two Views for a 23-mm-Thick OCB of the Waste Package with Degraded Internals Loaded by the Collapsed Drip Shield With About 807 kPa Average Vertical Load

1.7 CONCLUSIONS

The key observations from this analysis are as follows:

- The greatest value of the maximum effective plastic strain for the waste package with intact internals, 0.018, at the 4.07 m/s PGV level is more than a factor of 10 below the minimum strain for tensile failure of Alloy 22, 0.285. The maximum effective plastic strain for the waste package with degraded internals, 0.22, at 4.07 m/s PGV level is also below the minimum strain for tensile failure of Alloy 22. It follows that tensile rupture of the OCB is not predicted to occur (i.e., has zero probability) when the drip shield collapses down onto a waste package with either intact or degraded internals.

- The seismic damage abstractions for the kinematic response of the TAD-bearing waste package with degraded internals have a nonzero probability for tensile rupture of the OCB. This positive probability bounds the zero probability for tensile rupture of the OCB when the drip shield collapses down onto a waste package with degraded internals.

  The maximum effective plastic strains from the kinematic calculations are greater than the maximum effective plastic strain of 0.22 for the waste package with degraded internals loaded by a collapsed drip shield. This result confirms that the effective plastic strains from waste package-to-pallet impacts with degraded internals bound the localized tensile strains that could occur between a collapsed drip shield and the waste package.

- The average effective plastic strains at the 2.44 and 4.07 m/s PGV levels for the waste package surrounded by rubble vary between 0.0225 and 0.0807. These values are greater than the values of maximum effective plastic strain for a waste package with intact internals under a collapsed drip shield, in the range between 0.01 and 0.018.

  The effective plastic strains from the calculations for the waste package surrounded by rubble are often significantly greater than the greatest value of the maximum effective plastic strain for the waste package under a collapsed drip shield. The effective plastic strains for the waste package surrounded by rubble bound the localized tensile strains that could occur between a collapsed drip shield and the waste package with intact internals.

- The probability of puncture of the OCB is judged to be zero when the waste package is loaded by a collapsed drip shield, so the nonzero probability of puncture for the waste package surrounded by rubble bounds the probability of puncture for a waste package with intact internals under a collapsed drip shield.

2. COMMITMENTS TO NRC

None.

3. DESCRIPTION OF PROPOSED LA CHANGE

None.

4. REFERENCES

SNL (Sandia National Laboratories) 2007a. *Mechanical Assessment of Degraded Waste Packages and Drip Shields Subject to Vibratory Ground Motion*. MDL-WIS-AC-000001 REV 00. Las Vegas, Nevada: Sandia National Laboratories. ACC: DOC.20070917.0006.

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