Ref. ⑪

LSN-DN2002077063
ALB. 20050323.4535
Oct. 1, 2004

OCRWM	DESIGN CALCULATION OR ANALYSIS COVER SHEET	1. QA: QA 2. Page 1

3. System
Waste Isolation System

4. Document Identifier
CAL-WIS-AC-000002 REV 00A

5. Title
Mechanical Assessment of the Drip Shield Subject to Vibratory Motion and Dynamic and Static Rock Loading

6. Group
Repository Integration Team

7. Document Status Designation
☒ Preliminary ☐ Final ☐ Cancelled

9. No.	10. Reason For Revision	11. Total # of Pgs.	12. Last Pg. #	13. Originator (Print/Sign/Date)	14. Checker (Print/Sign/Date)	15. QER (Print/Sign/Date)	16. Approved/Accepted (Print/Sign)	17. Date
00A	Initial issue	132	6-6	Branko Damjanac	Tim Schmitt Ming Lin	D. J. Tunney		

CONTENTS

FIGURES

FIGURES (Continued)

TABLES

TABLES (Continued)

ACRONYMS AND ABBREVIATIONS

DE	distinct element (software)
DS	drip shield
DSC	drip shield connector
EBS	engineered barrier system
FE	finite element (software)
MN	megaNewton
MT	metric ton (1 MT = 1,000 kg)
PGV	peak ground velocity
PSHA	Probabilistic Seismic Hazard Assessment
PWR	pressurized water reactor
RT	room temperature
Ti	Titanium
TSPA-LA	Total System Performance Assessment - License Application

1. PURPOSE

The purpose of the drip shield (DS) is to divert water that may seep into emplacement drifts from contacting the waste packages, and to protect the waste packages from impact or static loading from rockfall. The objective of this document is to summarize, into one location, the results of a series of supporting engineering calculations[1] that were developed to study the effect of static and dynamic loads on the mechanical performance of the DS. The potential DS loads are a result of:

- Potential earthquake vibratory ground motion, and resulting interaction of the DS, waste package and pallet, and drift invert
- Dynamic impacts of rockfall resulting from emplacement drift damage as a result of earthquake vibratory motion
- Static load of the caved rock rubble that may come to rest on the DS as a result of vibratory motion or from time-dependent yielding of the rock mass surrounding the emplacement drift.

The potential mechanical failure mechanisms that may result from these loads include:

- Overturning and/or separation of the interlocking DS segments
- Loss of structural integrity and stability of the DS, including excessive deformation or buckling
- Localized damage[2] to the top and side-wall plates of the DS.

The scope of this document is limited to summarizing results presented in the supporting calculations in the areas of analysis of the potential for DS collapse, and determination of the damaged surface area of the DS plates. New calculations are presented to determine whether or not separation of DSs occur under vibratory motion.

The results of the supporting calculations, in terms of damaged surface area of DS plates for a given value of peak ground velocity (PGV) are reported in *D&E /PA/C IED Interlocking Drip Shield and Emplacement Pallet* (BSC 2004 [DIRS 169220]). These data are used as input to the *Seismic Consequence Abstraction* (BSC 2004 [DIRS 169183]), which utilizes this information to address the potential for advective flux of seepage water through the DS. Additionally, the new calculations presented in this document provide the technical basis for exclusion of separation of DSs under vibratory ground motion from consideration in the Total System Performance

---

[1] Most of the results reported here were previously reported in the following calculations: *Structural Calculations of Drip Shield Exposed to Vibratory Ground Motion* (BSC 2003, [DIRS 163425]); *Drip Shield Structural Response to Rock Fall* (BSC 2004, [DIRS 168993]); and, *Structural Stability of a Drip Shield Under Quasi-Static Pressure* (BSC 2004, [DIRS 170791]). This calculation provides new information on analysis of the potential for DS separation.

[2] The "damaged area" is defined in this document as the area where the residual first (major) principal stress exceeds a certain limit. The stress limit used throughout this document is defined as 50 percent of yield strength of the DS plate material, Titanium Grade 7 (Ti-7) (SB-265 R52400), at temperature of 150°C (see Assumptions 3.12 and 3.18 and Section 5.2.3.1.4).

Assessment-License Application (TSPA-LA). The exclusion arguments for DS separation are summarized in *Features, Events, and Processes: Disruptive Events* (BSC 2004 [DIRS 170017], Sections 6.2.1.5 and 6.2.1.3) (FEP 1.2.03.02.0A – Seismic Ground Motion Damages EBS Components) and the *Seismic Consequence Abstraction* (BSC 2004 [DIRS 169183]). The *Seismic Consequence Abstraction* subsequently provides the abstraction for the seismic scenario class used in support of the Total System Performance Assessment–License Application (TSPA-LA).

This document is prepared in accordance with the applicable technical work plan: *Technical Work Plan For: Regulatory Integration Modeling of Drift Degradation, Waste Package and Drip Shield Vibratory Motion and Seismic Consequences* (BSC 2004 [DIRS 171520]), which directs the work identified in work package ARTM05. The technical work plan was prepared in accordance with AP-2.27Q, *Planning for Science Activities*. This calculation was performed under the Repository Integration Project, in cooperation with the Waste Package and Components group of Design and Engineering. This document was developed in conformance with procedure AP-3.12Q, *Design Calculations and Analyses*. The DS is classified as a Safety Category item (BSC 2004 [DIRS 168361], p. A-5). Therefore, this calculation is subject to the *Quality Assurance Requirements and Description* (DOE 2004 [DIRS 171539]).

The DS design considered in the calculations summarized in this document is not presented in detail. Design drawings and material specifications can be found in *D&E / PA/C IED Interlocking Drip Shield and Emplacement Pallet* (BSC 2004 [DIRS 169220]) as well as in the calculations that support this summary document (BSC 2003 [DIRS 163425]; BSC 2004 [DIRS 168993] and BSC 2004 [DIRS 170791]). The dimensions and materials for the design of the 21-PWR (pressurized water reactor) waste package and emplacement pallet (pallet, for brevity, throughout the document) used in this calculation are also provided in *Emplacement Pallet* (BSC 2003 [DIRS 161520]) and *D&E/PA/C IED Typical Waste Package Components Assembly* (BSC 2004 [DIRS 169472]). The 21-PWR waste package was used as a basis for the calculations summarized in this document since it is the most commonly-occurring of the various waste package designs. More than 38 percent of all waste packages are 21-PWR waste packages, and the second most frequent design, the 44-boiling water reactor waste package (approximately 26 percent), has similar dimensions and mass as the 21-PWR waste package (BSC 2004 [DIRS 169472], Table 11).

2. METHOD

The DS calculations presented in this summary are conducted using commercial finite element (FE) and distinct element (DE) software. The FE method is a numerical technique in common use for analysis of engineering problems in structural dynamics. The method requires discretization of the structure (the DS in this case) into a number of elements (the FE mesh) that are interconnected by nodal points. The governing equations of motion, subject to imposed boundary and initial conditions, are solved to provide the solution of the transient mechanical response of the DS. The boundary and initial conditions are a result of the constraints supplied by the emplacement drift, waste package and pallet and from the applied static and dynamic loading conditions. The FE analysis is used primarily to examine damage to the DS surface plates and structure in response to vibratory motion, rockfall and quasi-static pressure from rock rubble resulting from possible drift collapse. Results of the FE analysis are given in terms of the transient induced stresses, strains and displacements of the finite element mesh. Three-dimensional graphical representation of the motion of the structure as well as the stress and strain states are used to aid in interpretation of the analysis results. The stability of the structure and damage to the surface plates can be inferred from this information. The DE method is a numerical technique used for analysis of mechanical interaction of a large number of solid (deformable or rigid) bodies, which can undergo large displacements and interact with each other in arbitrary ways. If the bodies are deformable, they are discretized into elements, which are interconnected by nodal (grid) points. The equations of motion are solved for each grid point using an explicit numerical integration scheme, and are subject to the applied initial and boundary conditions. The DE method is used to examine the potential for DS separation when subjected to vibratory motion. The time history of relative vertical offset of the DSs as well as axial forces generated in interlocking portions of the DSs are used to determine whether DSs separate.

The DS FE mesh is created by using either the commercially available software ANSYS V5.6.2 (STN: 10364-5.6.2-01, [DIRS 159357]) or TrueGrid V2.1.5 and TrueGrid V2.2. The FE calculations were then performed by using the commercially available LS-DYNA V960.1106 (STN: 10300-960.1106-00, [DIRS 158898]) and LS-DYNA V970 D MPP-00 (STN: 10300-970.3858 D MPP-00, [DIRS 166918]) FE codes. The LS-DYNA explicit solver uses the central difference method (Belytschko et. al. 2000 [DIRS 153664], Section 6.2.1 and Hallquist 1998 [DIRS 155373], Section 21.2) for time integration of the governing equations. The DE calculations were performed using the commercially available software UDEC V3.1 (STN: 10173-3.1-00, [DIRS 160331]). This software has integral mesh development and post processing graphical display capability.

After the FE and DE calculations are completed, results of the analyses are presented in terms of separation of the DSs, collapse of the DS and damage to the surface plates and support beams and bulkheads. Separation of the DSs is determined by comparison of the time history of relative vertical separation of adjacent DSs and by comparison of axial forces generated in the interlocking mechanism of adjacent DSs to their estimated load limit. Damage results are provided in terms of the damaged area of the DS plates or maximum vertical deflection of the DS apex node at the vertical symmetry plane (for comparison with clearance of DS to waste package separation). The damaged area is estimated based on the residual first principal stress plot for the DS plates. It is important to acknowledge the conservatism of the criterion used to define the damaged area (conservatism independent of the choice of the residual stress threshold). Namely, the failure criterion (see Section 1 and Assumption 3.18) does not account for the possibility of crack arrest once the crack is nucleated (i.e., the area "fails" regardless of the residual stress distribution across the thickness of the DS plates). Damage to the structural bulkheads and supporting columns is defined in terms of the plastic yield of the structural element cross section which may lead to formation of a plastic hinge, and thus loss of load-bearing capacity.

3. ASSUMPTIONS

In the course of developing this document, the following assumptions are made regarding the structural calculation.

3.1 The density and Poisson's ratio are not available for Titanium Grade 7 (Ti-7 [SB-65 R52400]), Titanium Grade 24 (Ti-24 [SB-265 R56405]), and Alloy 22 (SB-575 N06022), except at room temperature (RT) (20 °C). (Note: In regard to Unified Numbering System designation for Ti-24, notice that Ti-24 has the same mechanical properties as Ti-5 since the compositions are almost identical; see ASME 2001 [DIRS 158115], Section II, Part B, SB-265, Table 2.) The RT density and RT Poisson's ratio are assumed for these materials. The impact of using RT density and RT Poisson's ratio is anticipated to be negligible. The rationale for this assumption is that the material properties in question do not have dominant impact on the calculation results. This assumption is used in Section 5.2.3 and corresponds to paragraph 5.2.8.6 of Mecham (2004 [DIRS 170673]).

3.2 The temperature-dependent material properties are not available for TSw2 (Topopah Spring Welded welded, lithophysal-poor) rock except at RT. The TSw2 is used to represent the essentially unyielding invert, drift walls and rock blocks impacting the DS (Section 5.2) and the material properties are necessary only for the contact definitions. The corresponding RT material properties are assumed for this material. The impact of using RT material properties is anticipated to be negligible. The rationale for this assumption is that the material properties of the rock do not have a significant impact on the calculation results. This assumption is used in Section 5.2.3 and corresponds to paragraph 5.2.16.1 of Mecham (2004 [DIRS 170673]).

3.3 The rate-dependent material properties are not available for Ti-7, Ti-24, Alloy 22, and TSw2 rock mass at any strain rate. The material properties obtained under the static loading conditions are assumed for these materials. The impact of using material properties obtained under static loading conditions is anticipated to be negligible. The rationale for this assumption is that the change of mechanical properties of subject materials (Nicholas 1980 [DIRS 154072], Figure 28) at the peak strain rates that typically occur during the earthquake simulation and rockfall does not have significant effect on the results presented in this calculation. The maximum plastic-strain rate in the DS plates observed in the calculation of vibratory ground motion is 185 s-1 (as indicated by maximum slopes of the effective-plastic-strain time histories presented in *Structural Calculations of Drip Shield Exposed to Vibratory Ground Motion*, BSC 2003 [DIRS 163425], Figure IV-9). It is important to recognize that this strain rate is the maximum among all 1×10^{-6} realizations among all DS-plate elements; the typical strain rate is significantly lower. The average strain rate is approximately 85 s-1 (BSC 2003 [DIRS 163425], Figure IV-10b). It should be noted that realization 9 is conspicuous among the 1×10^{-6} realizations for a large number of high-intensity waste package-pallet impacts (BSC 2004 [DIRS 167083], Table 6.1.3-3) resulting in exceptionally large damaged area of the DS (Table 5-18). More typically, the next two largest strain rates among 1×10^{-6} realizations appear to be the strain rates in realizations 6 and 11, and they do not exceed 15 s-1 (BSC 2003 [DIRS 163425], Figures IV-11 and IV-12). The maximum strain rate during rockfall is approximately 40 s-1 as indicated by maximum slope (0.2/0.005 s) in *Drip Shield Structural Response to Rock Fall* (BSC 2004 [DIRS 168993], Figure II-3). This assumption is used in Section 5.2.3 and corresponds to paragraph 5.2.5 in Mecham (2004 [DIRS 170673]).

3.4 The Poisson's ratio of Alloy 22 is not available in the literature. The Poisson's ratio of Alloy 625 (SB-443 N06625) is assumed for Alloy 22. The impact of this assumption is anticipated to be negligible. The rationale for this assumption is that the chemical compositions of Alloy 22 and Alloy 625 are similar (ASME 2001 [DIRS 158115], Section II, Part B, SB-575, Table 1 and ASM 1980 [DIRS 104317], p. 143, respectively). This assumption is used in Section 5.2.3 and corresponds to paragraph 5.2.8.2 of Mecham (2004 [DIRS 170673]).

3.5 The uniform strains (the strains corresponding to the uniaxial tensile strengths) of Ti-7 and Ti-24 are not available in literature. Therefore, it is assumed that the uniform strain is equal to the elongation. The rationale for this assumption is that a small change in tangent modulus does not significantly affect the results of this calculation. This assumption is used in Section 5.2.3.1.2 and corresponds to Section 5.2.6.5 of Mecham (2004 [DIRS 170673]).

3.6 The modulus of elasticity and Poisson's ratio of the TSw2 are characterized by significant scatter of data. For the purpose of the present calculation modulus of elasticity is assumed to be 33 GPa, and Poisson's ratio 0.21. The rationale for this assumption is that these values represent the mean values of the middle nonlithophysal zone (Tptpmn) the uppermost interval of the TSw2 unit (BSC 2004 [DIRS 170583]), Tables 6 and 5, respectively, DTN: MO402DQRIRPPR.003 [DIRS 168901]). This assumption is used in Section 5.2.3.3 and corresponds to paragraph 5.2.16.3 of Mecham (2004 [DIRS 170673]).

3.7 The density of the TSw2 is assumed to be 2,370 kg/m. The rationale for this assumption is that this value represents the mean saturated bulk density value for the TSw2 unit determined from mechanical property measurements on core samples (DTN: SNL 02030193001.027 [DIRS 108410], Table S98487 007, Data for Tptpmn, Rows 82-89 and 128-132). It should be noted that this assumption has no effect on the calculation results since density of the rock affects only masses of the essentially rigid invert and the rigid drift walls. This assumption is used in Section 5.2.3.3 and corresponds to paragraph 5.2.16.4 of Mecham (2004 [DIRS 170673]).

3.8 The friction coefficients for metal-to-metal contact and metal-to-rock contact are considered random parameters in the calculation of vibratory motion because these parameters have a profound effect on calculation results. The range of values for both of these friction coefficients is 0.2 to 0.8. The following is the rationale for this assumption.

Avallone and Baumeister (1987 [DIRS 103508], Table 3.2.1, p. 3-26), provide coefficients of static and sliding friction for various metals and other materials. However, coefficients of friction for the materials used in this calculation are not specifically mentioned in this or other handbooks. The potential for long-term corrosion to modify the sliding friction must also be considered in defining the friction coefficient. In this situation, the appropriate coefficients of friction for the repository components have high uncertainty. It is then appropriate to pick a distribution of values for the coefficients of friction that encompass a range of materials and a range of mechanical responses from little or no sliding between components to substantial sliding between components.

A distribution of values for the friction coefficient between 0.2 and 0.8 will achieve these goals (see Table 5-17 and DTN: MO0301SPASIP27.004 [DIRS 161869], Table I-4). First, this distribution is broad enough to encompass typical values of the dry sliding friction coefficients for a wide variety of metals and other materials (Avallone and Baumeister 1987 [DIRS 103508], Table 3.2.1, p. 3-26). Second, the appropriateness of this range is independently confirmed by seismic analyses for spent fuel storage racks (DeGrassi 1992 [DIRS 161539]). This distribution is also broad enough to represent a range of mechanical response for the DS. A friction coefficient near 0.2 maximizes sliding of the DS on the invert. Similarly, a friction coefficient near 0.8 minimizes that sliding. This assumption is used in Section 5.2.3.2.

3.9 The friction coefficient for contact between Alloy 22 (DS base plate material, which is excluded from FE representation, see Assumption 3.17) and stainless steel is not available in literature. It is, therefore, assumed (in calculations of impact by the rockfall) that the dynamic (sliding) friction coefficient for this contact is 0.5. The rationale for this conservative assumption is that this friction coefficient represents a mean value for most dry nickel-on-steel contacts (Avallone and Baumeister 1987 [DIRS 103508], Table 3.2.1, p. 3-26), nickel being the dominant component in Alloy 22 (ASME 2001 [DIRS 158115], Section II, Part B, SB-575, Table 1). The sensitivity analysis of the impact of friction coefficient on the calculation results is not necessary (in calculation of impact by the rockfall), because the calculation results due to impact are not expected to be significantly affected by the friction coefficient between the rock and drip shield. This assumption is used in Section 5.2.3.2.

3.10 The friction coefficient for contacts occurring between the rock and Ti-7 or invert and Alloy 22 is not available in literature. It is, therefore, assumed (in all calculations except vibratory ground motion) that the dynamic (sliding) friction coefficient for this contact is between 0.4 and 0.5. The rationale for this assumption is that this friction coefficient represents a reasonable estimate based on available information for metal-on-stone contacts which is between 0.3 and 0.7 (Beer and Johnston 1977 [DIRS 145138], Table 8.1, p. 306). This parameter does not have a significant effect on the results since the relative surface-to-surface movement of these components is not a significant determining factor in the amount of deformation during impact or static load of caved rock mass. The sensitivity analysis of the impact of friction coefficient on the calculation results is not necessary (for different loading cases than the vibratory ground motion), because the calculation results are not expected to be significantly affected by the friction coefficient. In the case of vibratory ground motion, the friction coefficient between the invert and the DS is the major factor in transfer of the load from the invert to the DS. In cases of vertical rockfall impact or static load by the caved rock, which are critical for estimate of damage, the friction coefficient between the DS and the invert, or between the rock and the DS during the impact has no effect on results. This assumption is used in Sections 5.2.2 and 5.2.3.2.

3.11 The variation of functional friction coefficient between the static and dynamic value as a function of relative velocity of the surfaces in contact is not available in literature for the materials used in the calculations (Section 5.2.3.2). Therefore, the effect of relative velocity of the surfaces in contact is neglected in these calculations by assuming that the functional friction coefficient and static friction coefficient are both equal to the dynamic friction coefficient. The impact of this assumption on results presented in this document is anticipated to be negligible. The rationale for this conservative assumption is that it maximizes the relative motion of unanchored repository components by minimizing the friction coefficient within the given FE analysis framework. This assumption is used in Sections 5.2.2 and 5.2.3.2 and corresponds to paragraph 5.2.14.2 of Mecham (2004 [DIRS 170673]).

3.12 The temperature of the DS is assumed to be 150°C for temperature-dependent material properties. The rationale for this assumption is that this temperature is conservative for most of the regulatory period for high-temperature operating modes and strictly conservative for low-temperature operating modes. The waste package temperature in an open drift remains below 150°C for approximately 97 percent of the regulatory time period of 10,000 years (BSC 2001 [DIRS 156276], Figure 6-3) and the DS temperature is less than the waste package temperature. The drip shield temperature of 150°C is also considered appropriate for the case of potential drift collapse that could accompany a low-probability seismic event or from time-dependent strength loss of the surrounding rock mass. In either case, the drip shield could be partially or completely surrounded by rock rubble. The Multiscale Thermohydrologic Model was used to conduct a parameter study of the impact of thermohydrologic parameters on the in-drift environment (BSC 2004 [DIRS 169565], Section 6.3.7 and Table 6.3-8). The results show that the peak waste package temperature in a collapsed drift for the base case thermal conductivity of the rubble is greater than 200°C for a very brief period of time – less than 100 years – and the waste package temperature drops below 150°C within approximately 350 years after collapse, even for the "hottest" waste package considered in the parameter study. These results are for the case of a collapse occurring coincident with the closure of the repository. It follows that 150°C is a reasonable and conservative value for evaluation of material properties in a collapsed drift over 96.5 percent of the regulatory period. This assumption is used in Sections 1 and 5.2.3.

3.13 The thickness of the Ti-7 and Ti-24 plates are reduced by 2 mm. For Ti-7, this thickness reduction results from using the 95th percentile general corrosion rate values used in TSPA-LA for both sides of the titanium plate (BSC 2004 [DIRS 169845], Section 6.5.5; DTN: MO0408MWDGLCDS.002 [DIRS 171486]). For the outside and inside plates, the 95th percentile general corrosion rate values (a reasonably conservative estimate) are 1.12E-4 mm/yr and 8.59E-5 mm/yr, respectively. Therefore in 10,000 years, about 1.12 mm is removed from the outer surface by general corrosion and about 0.86 mm are removed from the inner surface (i.e., a total loss of about 2 mm of thickness). Alternatively, the highest measured general corrosion rate from the 5-year exposed Ti samples used for validation of the TSPA-LA general corrosion distributions is 77 mm/yr (BSC 2004 [DIRS 169845], Table 23; DTN: MO0408MWDGLCDS.002 [DIRS 171486]). Using this value for both sides of the drip shield, a total loss of about 1.54 mm of thickness can be calculated over an exposure period of 10,000 years. Therefore, a thickness reduction of 2 mm is a reasonable estimate of the total thickness loss for Ti-7 due to general corrosion in 10,000 years. For Ti-24, the thickness reduction over a 10,000 year period was determined to be about 0.75 mm per exposed surface in the *Aqueous Corrosion Rates for Waste Package Materials* report (BSC 2004 [DIRS 169982], Section 6.5.2). Therefore, a thickness reduction of 2 mm is a reasonable estimate of the total thickness loss for Ti-24 due to general corrosion in 10,000 years.

3.14 The rock shape is assumed to be a rectangular prism. The rationale for this assumption is that the rock block data (BSC 2004 [DIRS 168550]) show that some of the rock blocks are essentially rectangular prism. An FE representation of the rock with an inclined rectangular prism provides a conservative approach from the perspective that the rock center of gravity and the point of impact are on the line parallel with direction of the impact, transferring the maximum linear momentum to the DS. Impact by the sharp edge of the prism also results in maximum strain on the DS plate. The vertex coordinates of the prism are obtained from DTN: MO0301MWD3DE27.003 (*Block Geometry Information.doc*) in order to calculate the enveloping dimensions (DTN: MO0301MWD3DE27.003 provides details). This assumption is used in Section 5.4.2.1 and corresponds to paragraph 5.2.16.6 of Mecham (2004 [DIRS 170673]).

3.15 A value of rock compressive strength of 290 MPa is assumed in the calculation. The mean value determined from uniaxial compression tests on small, 25.4 mm diameter cores of the Tptpmn is 207.2 MPa; however, the range of the data is 38.4 to 326 MPa with a standard deviation of 61.2 MPa (Cikanek; et. al 2004 [DIRS 169642], Table 5; DTN: MO0311RCKPRPCS.003 [DIRS 166073]). The compressive strength of rock blocks in nonlithophysal rock mass is a function of block size (BSC 2004 [DIRS 166107], Figure E-22). The asymptotic value of about 70 MPa for large block sizes is representative of the block sizes predicted in the rockfall analysis. However, since the damage induced by rock block impact to the drip shield will be a partial function of the strength of the rock block, a conservative value of 290 MPa for rock compressive strength, which is near the high end of the measured data, is assumed. The rationale for this assumption is that it leads to bounding set of results. This assumption is used in Section 5.2.3.3.

3.16 The DS side-walls are assumed to be unconstrained in the lateral direction during the 10,000 year regulatory period in the calculation of static and dynamic loading by the rockfall (with the exception of the lateral constraint provided by the pallet used in the calculation of the static load in lithophysal rock mass). The rationale for this assumption is that the gantry rail is made of steel sets (BSC 2004 [DIRS 169776]), which are not anticipated to remain intact (eventually corrode away) during the 10,000-year regulatory period. This assumption is used in Sections 5.2.1 and 5.2.2.

3.17 The Alloy 22 base is excluded from the FE representation in the rockfall calculation for simplicity. The rationale for this assumption is that the effect of a thin plate at the bottom of the long side wall on the calculation results is negligibly small during rockfall. This assumption is used in Section 5.2.2.

3.18 The residual stress threshold for the DS damaged area evaluation is assumed to be a constant value, equal to 50 percent of the yield strength of Ti-7. The rationale for this assumption is the data provided in DTN: MO0303SPARESST.000 [DIRS 162030] and Section 5.2.3.1.4. This assumption is used in Sections 1, 2, 5.3.3.2, and 5.2.3.1.4.

3.19 The lifting feature, and DS connector assembly are excluded from the FE representations for simplicity (The DS connector assembly and base were included in the analysis of vibratory ground motion.). The rationale for this assumption is that the effect of these DS components on the calculation results is negligibly small. This assumption is used in Section 5.2.2.

3.20 The kinematic calculation of DS separation is two-dimensional in the vertical plane that is oriented along the axis of the DS. Consequently, only the vertical component and one component of horizontal ground motion were considered. The kinematic calculation was used for assessment of the potential of DS separation. The main mechanism that causes DS separation is unlocking of the DSs by vertical shear displacements of the connection. The horizontal component of the ground motion perpendicular to the "chain" of the DSs (i.e., the out-of-plane component) is not expected to cause vertical shear deformation of the connections between the DSs. The other possible mechanism of DS separation is by excessive deformation of the structural components in the connection or by shearing off of the welds in the connection interlocking mechanism. The out-of-plane component of the ground motion will contribute to deformation and strain of the chain of the DS, and consequently to the loads taken by the structural components and welds in the connection. The axial loading on the welds is assumed to be uniformly distributed along the entire length of the weld which is represented as two contact locations between adjacent DSs – one upper and one lower contact. One half the weld strength is assumed to be lumped at each of the two contacts. The ground motions that can cause separation of the DSs (1×10^{-5}, 1×10^{-6} and 1×10^{-7} probability of annual occurrence) result in at least some level of rockfall and rubble accumulation on the invert between the DSs and the drift walls. Even the limited amount of rubble on the sides of the DS will constrain the motion of the DS relative to the emplacement drift in the plane of the drift cross-section (i.e., the DS will move together with the emplacement drift). The out-of-plane deformation of the chain of the DSs will thus be small and the resulting bending deformation that will cause straining of the DS connections can be neglected. This assumption is used in Sections 5.2.2, 5.2.3.2 and 5.3.1.1.

3.21 The DS is represented in the kinematic DE calculations as a rectangular, deformable solid body with mass and outline dimensions (i.e., the length and height) equal to those of the actual DS. The mass is assumed to be uniformly distributed over the area of the geometrical representation of the DS. The separation of the DSs (which is analyzed by the kinematic calculation) is mainly affected by the differential rigid-body motion of adjacent DSs. The parameters that govern the rigid-body motion of the bodies are their mass and dimensions. This assumption is used in Sections 5.2.2 and 5.3.1.1.1.

3.22 Density of the rubble created by rockfall in the emplacement drift is assumed to be 2,000 kg/m3. The density of the rubble is a function of the volume of the caved rock, which includes the porosity between rock particles. The bulking factor, B, defined as the percentage increase in volume of the rock in going from an in situ rock mass to a granular rubble, is used to determine the rubble density. If the density of the in situ rock mass is assumed to be 2,370 kg/m3 (Assumption 3.7), the density of the rubble of 2,000 kg/m^3 corresponds to bulking factor of 18.5 percent (using the relation $\rho_r = \rho/(1+B)$, where ρ_r is the rubble density, ρ is the in situ rock mass density, and B is the bulking factor), which is approximately equal to the lower bound of the bulking factor usually observed in the mining operations (BSC 2004 [DIRS 166107], Section 6.4.2.5.2). This assumption is used in Section 5.2.3.5.

3.23 The analyses summarized and conducted in this document assume that there is no ground support present in the emplacement drifts that would prevent rockfall or drift degradation from occurring. The rock support, consisting of stainless steel rock bolts and thin, perforated stainless steel sheeting, will continue to provide support for some indeterminate time after repository closure (BSC 2004 [DIRS 165425]). This assumption applies to most of the postclosure period and the calculations are run with and without rockfall effects. This assumption is used in Sections 5.2.3.5.

3.24 In the kinematic analyses of the vibratory motion of a chain of interlinked drip shields (Section 5.2.3.2.2.1), the drip shields are represented as deformable blocks that rest on a rigid invert. It is necessary to estimate the stiffness of the contact between the drip shield and invert for normal and shear loading. The normal and shear stiffnesses of the interface between the DS and the invert are considered to be 3 MPa/m as a base condition in the majority of the kinematic simulations for drip shield vibratory motion in an open drift. The tangent modulus (E) of the crushed rock at low confinement is on the order of 10,000 psi, or approximately 70 MPa, according to Marachi et al. (1972 [DIRS 157883])[3]. Considering the width of the DS base (BSC 2004 [DIRS 166897], $l = 2 \times 75\text{ mm} = 150\text{ mm}$) and the thickness of the crushed tuff in the invert (d = 86 cm; see Figure 5-6), the normal stiffness of the contact is calculated as

$$k_n = \frac{El}{1.0 \times d} = \frac{70 \times 0.15}{1.0 \times 0.86} = 12.2\ \text{MPa/m} \qquad \text{(Eq. 3-1)}$$

In the majority of the calculations, a lower stiffness of 3 MPa/m was used to account for the effect of localized pressure at the base of the DS and nonlinear deformation of the invert during strong impacts. The value of 3 MPa/m was selected because it results in relatively small overlap of the simplified kinematic blocks that represent the DS and the invert, considering the load due to the weight of the DS only. This assumption is used in Section 5.2.3.2.2.1.

---

[3] The data supporting the value of tangent modulus (E) of tuff rock rubble is derived from laboratory triaxial compression testing of large (36 inch diameter by 7.5 feet in height) samples of crushed basalt at the Rockfill Testing Facility at the University of California at Berkeley. This data is reported in the Journal of the Soil Mechanics and Foundation Division, Proceedings of the American Society of Civil Engineers, a peer-reviewed journal. The reliability of this data source is considered high. The size-gradation curves for the crushed basalt tested are similar to the small rock fragments expected from lithophysal rock rubble, and the strength of the constituent grains from tuff and basalt are of similar magnitude as both are high strength volcanic rocks. For these reasons, this data source, used as direct input, is considered to be suitable for its intended use, which is to provide an approximate value for the Young's modulus of rock rubble.

3.25 In the simplified kinematic model of DS synchronous motion, the DSs are represented as deformable blocks that interact with one another via shear and normal contacts at their ends. Two contacts are used between these DS blocks – one at the top and one at the bottom of the block. The maximum axial force that can be taken by the welded interlocking DS connection is assumed to be half of the maximum value given in Equation 5-9, or 7.05 megaNewtons (MN) (Assumption 3.20). This estimate of the maximum axial force in the contact between the DSs is approximate, since the complex processes of nonlinear and inelastic deformation of different components of the DS structural connection are ignored. To take these effects into account, engineering judgment is used to reduce the maximum axial force used in the calculations by 50 percent, to 3.5 MN.