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Design Calculation or Analysis Cover Sheet

1. QA: QA

2. Page i

Complete only applicable items.

3. System Waste Isolation System		4. Document Identifier CAL-WIS-AC-000001 REV 0B																						
5. Title Mechanical Assessment of the Waste Package Subject to Vibratory Ground Motion																								
6. Group Post Closure Activities-Seismic Studies																								
7. Document Status Designation ☐ Preliminary ☒ Committed ☐ Final ☐ Cancelled																								
8. Notes/Comments The preparer and checker for each section in this report are identified as follows: <table border="1"> <thead> <tr> <th>Section</th> <th>Preparer</th> <th>Checker</th> </tr> </thead> <tbody> <tr> <td>I to 6, Attachments III, IV, and VII</td> <td>Ming Lin</td> <td>Dwayne Kicker</td> </tr> <tr> <td>Attachment I</td> <td>Michael Gerhard</td> <td>Tim Schmitt</td> </tr> <tr> <td>Attachments II, V, VIII, and IX</td> <td>Branko Damjanac</td> <td>Dwayne Kicker</td> </tr> <tr> <td>Attachments VI and XI</td> <td>Michael Mullin</td> <td>Tim Schmitt</td> </tr> <tr> <td>Attachment X</td> <td>Michael Gross</td> <td>Dwayne Kicker</td> </tr> <tr> <td>Output DTNs</td> <td>Ming Lin</td> <td>Tim Schmitt (files related to Attachments I, VI and XI) Dwayne Kicker (files for the rest of the sections and Attachments)</td> </tr> </tbody> </table>				Section	Preparer	Checker	I to 6, Attachments III, IV, and VII	Ming Lin	Dwayne Kicker	Attachment I	Michael Gerhard	Tim Schmitt	Attachments II, V, VIII, and IX	Branko Damjanac	Dwayne Kicker	Attachments VI and XI	Michael Mullin	Tim Schmitt	Attachment X	Michael Gross	Dwayne Kicker	Output DTNs	Ming Lin	Tim Schmitt (files related to Attachments I, VI and XI) Dwayne Kicker (files for the rest of the sections and Attachments)
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Attachments			Total Number of Pages																					
Attachment I			54																					
Attachment II			28																					
Attachment III			12																					
Attachment IV			28																					
Attachment V			20																					
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1. QA: QA

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3. System Waste Isolation System				4. Document Identifier CAL-WIS-AC-000001 REV 0B		
5. Title Mechanical Assessment of the Waste Package Subject to Vibratory Ground Motion						
RECORD OF REVISIONS						
9. No.	10. Reason For Revision	11. Total # of Pgs.	12. Last Pg. #	13. Originator (Print/Sign/Date)	14. Checker (Print/Sign/Date)	15. Approved/Accepted (Print/Sign/Date)
00A	Initial Issue	166	6-6	Michael Gross	Steten Mastilovic	Mark Board 10/14/2004
0B	Updated kinematic analysis results and waste package-drip shield interaction analysis results included. Condition Report 4180-002 is addressed in Assumption 3.2.23 and Attachment XI. Editorial changes are made to address Condition Report 4734. This is an extensive revision.	414	XI-10	Ming Lin 08/23/05 Branko Damjanac 08/23/05 Michael Gerhard R.C. Quitt for MG Michael Mullin 9/29/05 Michael Gross R.C. Quitt for MG	Dwayne Kicker 8/23/05 Tim Schmitt 8/23/05	Paul Dixon 8-23-05

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ACRONYMS

5-DHLW/DOE-Long	5-defense high-level waste/U.S. Department of Energy-Long
21-PWR	21-pressurized water reactor
44-BWR	44-boiling water reactor
COR	coefficient of restitution
CS	carbon steel
DE	distinct element
DC	damping constant
EBS	engineered barrier system
FE	finite-element
g	acceleration of gravity
IV	inner vessel
OCB	outer corrosion barrier
PC	personal computer
PGV	peak ground velocity
PSHA	probabilistic seismic hazard analysis
RT	room temperature
SDOF	single degree of freedom
SNF	spent nuclear fuel
SS	stainless steel
STN	software tracking number
TDMS	Technical Data Management System
Ti-7	Titanium Grade 7
Ti-24	Titanium Grade 24
TSPA-LA	total system performance assessment for the license application

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1. PURPOSE

The purpose of this document is to summarize the results on the topic of the mechanical assessment of the waste package subject to vibratory ground motion and provide information for the damage abstractions for the seismic scenario class developed and documented in *Seismic Consequence Abstraction* (BSC 2005 [DIRS 173247]). Revision 00A of this document (BSC 2004 [DIRS 170063]) provides an integrated overview of the previously completed calculation reports that define the response of the waste package and its internals to vibratory ground motion. Additional calculations have been performed with more elaborate and realistic representation of the engineered barrier system (EBS) components (i.e., waste package, drip shield, emplacement pallet, invert, and the surrounding rock mass) for the assessment. The new analyses provided in this revision include:

- kinematic analyses for the response of multiple waste packages to vibratory ground motions, and
- waste package and the drip shield interaction analyses.

The previously completed calculation reports for waste package response to vibratory ground motion that have been used in this study are identified in Table 1-1. These calculation reports describe the potential for mechanical damage to the waste package, fuel assemblies, and cladding from a seismic event. The summary from these calculation reports combined with the results from the analyses presented here form the basis for the information feeding to the seismic scenario class for total system performance assessment for the license application (TSPA-LA).

Table 1-1. Major References for Waste Package Damage Calculations

Damage Process	Calculation Report
Key Report for Kinematics and Structural Response of Waste Package	
Damage due to the waste package– emplacement pallet interaction from vibratory ground motion	<i>Structural Calculations of Waste Package Exposed to Vibratory Ground Motion</i> , 000-00C-WIS0-01400-000-00A (BSC 2004 [DIRS 167083]) <i>Additional Structural Calculations of Waste Package Exposed to Vibratory Ground Motion</i> , 000-00C-WIS0-01700-000-00B (BSC 2004 [DIRS 171717])
Key Report for Damage Caused by Side and End Impacts	
Calculation of damaged area caused by end-to-end impacts of adjacent waste packages for a predefined set of impact velocities and impact angles	<i>21-PWR Waste Package End Impacts–A Mesh Study</i> , 000-00C-WIS0-02100-000-00B (BSC 2005 [DIRS 173178])
Key Report for G-Loads on Fuel Assemblies Caused by End Impacts	
Acceleration of the fuel assemblies from end-to-end waste package impacts	<i>Maximum Accelerations on the Fuel Assemblies of a 21-PWR Waste Package During End Impacts</i> , 000-00C-DSU0- 01100-000-00A (BSC 2003 [DIRS 162602])

NOTE: 21-PWR = 21-pressurized water reactor spent nuclear fuel waste package.

The results from the structural response calculations also address portions of Integrated Subissue for the Mechanical Disruption of Engineered Barriers, including the acceptance criteria for this

subissue defined in Section 2.2.1.3.2.3 of *Yucca Mountain Review Plan, Final Report* (NRC 2003 [DIRS 163274]).

This document is prepared in accordance with *Technical Work Plan For: Analysis of Waste Package and Drip Shield Response to Vibratory Ground Motion and Revision of the Seismic Consequence Abstraction*, which directs the work identified in work package ADEM21¹. The technical work plan (BSC 2005 [DIRS 173171]) was prepared in accordance with LP-2.29Q-BSC, *Planning for Science Activities*. The spent nuclear fuel (SNF) waste packages are classified as a Safety Category item by *Q-List* (BSC 2005 [DIRS 174269], p. A-6 under Engineered Barrier System). Therefore, this calculation is subject to *Quality Assurance Requirements and Description* (DOE 2004 [DIRS 171539]) requirements. This document is prepared in accordance with LP-3.12Q-BSC, *Design Calculations and Analyses*.

1.1 SCOPE

The scope of this report is to summarize the mechanical response of the waste package and its internals to vibratory ground motion during the postclosure period. The scope includes two major tasks: (1) summarizes the previously completed calculations which are relevant to the seismic consequence abstraction, (2) documents the updated analyses undertaken to reduce uncertainty and overconservatism. The mechanical responses considered for waste packages subject to vibratory ground motion are:

- waste package to waste package interaction,
- waste package to emplacement pallet interaction, and
- waste package to drip shield interaction.

The list of the major reports used in this document is provided in Table 1-1. These reports are summarized in Sections 5.4.3, 5.5, 5.7 and Attachments III, IV, and VII. Section 5.1 provides an overview of the general organization of this document and outputs to *Seismic Consequence Abstraction* (BSC 2005 [DIRS 173247]).

The kinematic analyses are aimed at estimating the occurrence of end-to-end impact and the impact velocities between adjacent waste packages. The damage abstractions for the waste package and cladding are not documented in this report; rather, the results from these design calculations and analyses provide the input data that the abstractions are based on. The damage abstractions for the seismic scenario class are developed and documented in the *Seismic Consequence Abstraction* model report (BSC 2005 [DIRS 173247]).

The waste package to drip shield interactions and resulting potential stability assessment to the drip shield from impacts are examined. Whereas the present calculation examines the stability effects of waste package–drip shield interactions, a separate calculation, *Mechanical Assessment of the Drip Shield Subject to Vibratory Motion and Static and Dynamic Rock Loading*

¹ Subsequent to the approval of the technical work plan, a new work package, ADEM23, was defined for the new work described in this document. This change was made to facilitate tracking the new work separately from the pre-existing work contained in work package ADEM21.

(BSC 2004 [DIRS 169753]) examines mechanical effects of vibratory motion on the drip shield, specifically.

This report does not address the performance of naval SNF during seismic events. The Naval Nuclear Propulsion Program Technical Support Document for the License Application will provide the seismic analysis for naval SNF.

1.2 LIMITATIONS

The major limitations of these design calculations are as follows:

- The calculations include degradation of the waste package over a 20,000-year time frame, which includes the initial 10,000-year regulatory period. The 20,000-year duration for the seismic analyses is designed to demonstrate that repository performance remains robust well after the 10,000-year regulatory period has ended.
- Calculations are performed mainly for the 21-PWR waste package type. This type of waste package is the most common in the repository, constituting 38 percent of the anticipated inventory by waste package type (BSC 2005 [DIRS 173501], Table 13). In the LS-DYNA kinematic analyses described in Attachment I, two waste types are included to represent the range in waste package type: the 21-PWR/44-BWR and the 5-DHLW/DOE-Long. The rationale for using these waste package types is provided in Assumption 3.2.17.
- The ground motion time histories² for structural response calculations were created using different approaches for intercomponent variability and for spectral matching. The results from a limited sensitivity study (Attachment IV, Section IV-5) indicate that the original damage calculations using ground motion time histories for the 2.44 m/s peak ground velocity (PGV), level are conservative. Section 1.3.2 provides a discussion on the methodology for defining the suites of ground motions that are used in the structural response calculations.

1.3 BACKGROUND INFORMATION ON SEISMIC SCENARIO CLASS

This section summarizes information about the seismic scenario class that is relevant to the structural response of the waste package and cladding under vibratory ground motion. This information includes:

- A description of the components of the EBS
- The Probabilistic Seismic Hazard Analysis that provides a framework for definition of ground motions at Yucca Mountain

² A ground motion time history defines the three-dimensional motion of the earth during a seismic event. Each ground motion time history defines the displacement, velocity, and acceleration in three perpendicular axes as a function of time at a specific location in or near the repository. Peak ground velocity (PGV) is the peak value selected from the ground motion time history.

- The procedure for developing site-specific ground motions
- The hazard levels and terminology that are relevant to these calculations.

The focus of this background discussion is on the response of the waste package to vibratory ground motion; the response of the drip shield to ground motion or to rockfall induced by ground motion and the response of EBS components to fault displacement is only mentioned in passing. A complete discussion of the technical basis for the seismic scenario class in TSPA-LA can be found in the *Seismic Consequence Abstraction* model report (BSC 2005 [DIRS 173247]).

Figure 1-1 illustrates the major components of the EBS in a typical emplacement drift. The major EBS components are the waste package, the drip shield, the emplacement pallet, and the fuel rod cladding (the cladding is not shown in Figure 1-1). These are important components because failure of these components has the potential to directly release radionuclides or to form diffusive or advective transport pathways. The effectiveness of these barriers is potentially compromised by the direct effects from an earthquake, which include vibratory ground motion, fault displacement, and rockfall induced by ground motion. The effectiveness of these barriers is also potentially compromised by indirect effects after an earthquake, including changes in seepage, temperature, and relative humidity if an emplacement drift collapses completely during a very low probability earthquake.

The drift invert, the waste package internals, and the mass of the waste form are considered in structural response calculations or in rockfall analyses, but are not represented as separate damage abstractions in TSPA because they do not directly control the release radionuclides or the formation of advective flow pathways. Figure 1-1 also shows the steel sets that will be added as ground support in some drifts. Steel sets are not considered in postclosure seismic analysis because rapid corrosion of mild steel is anticipated to limit their effectiveness in the postclosure repository environment.

The major EBS components are free standing structures. The drip shield and the emplacement pallet rest on top of the invert, while the waste package rests on top of the emplacement pallet. The invert consists of a framework of mild steel structural components that is filled with ballast from run-of-the-mine tunneling operations. Because the EBS components are unconstrained, impacts can occur between waste packages, drip shields, emplacement pallets, the invert, and the drift walls in response to significant ground motions.

Figure 1-1. Schematic Diagram of the EBS Components in a Typical Emplacement Drift

Description of the failure mechanisms under seismic loads and residual stress damage threshold for the waste package is provided in Section 5.3.

1.3.1 Probabilistic Seismic Hazard Analysis

A probabilistic seismic hazard analysis (PSHA) was performed to assess the seismic hazards of vibratory ground motions and fault displacement at Yucca Mountain. The PSHA (CRWMS M&O 1998 [DIRS 103731]) provides quantitative hazard results to support an assessment of the repository's long-term performance and to form the basis for developing seismic design criteria for the License Application. Key attributes of the PSHA methodology for Yucca Mountain are: (1) utilization of an extensive geologic and seismologic database developed over a 20 year period in the Yucca Mountain region; (2) explicit consideration and quantification of uncertainties regarding alternative seismic-source, ground-motion, and fault-displacement models; and (3) use of a formal, structured expert elicitation process to capture the informed scientific community's views of key inputs to the PSHA.

The PSHA methodology for vibratory ground motions has become standard practice for deriving vibratory ground motion hazards for design purposes. Less commonly, probabilistic fault displacement analyses are conducted to provide quantitative assessments of the location and amount of differential ground displacement that might occur. Both analyses provide hazard curves, which express the probability of exceeding various amounts of ground motion (or fault displacement). The probability is usually expressed as a frequency of exceedance per year. The resulting seismic hazard curves represent the integration over all earthquake sources and magnitudes of the probability of future earthquake occurrence and, given an occurrence, its effect at a site of interest.

The basic elements of a PSHA for vibratory ground motions are:

- a) Identification of seismic sources that contribute to the vibratory ground motion hazard at Yucca Mountain and characterization of their geometry
- b) Characterization of seismic sources by the recurrence rate of earthquakes of various magnitudes and the maximum magnitude
- c) Attenuation relations that define a specified ground motion parameter (such as PGV) as a function of magnitude, source-to-site distance, local site conditions, and, in some cases, seismic source characteristics
- d) Integration of the seismic source characterization and ground motion attenuation evaluations, including associated uncertainties, into a seismic hazard curve and associated uncertainty distribution.

The PSHA incorporates both variability and uncertainty. Variability, also termed randomness or aleatory variability, is the natural randomness in a process. For discrete variables, the randomness is parameterized by the probability of each possible value. For continuous variables, the randomness is parameterized by the probability density function. An example of variability is the amplitude of ground motion that would occur at a particular location from repeated earthquakes having exactly the same magnitude at exactly the same distance (for example: magnitude 6 at 25-km distance). Variations in ground motion amplitude are expected due to unknowable complexities in earthquake-to-earthquake source properties and in the propagation path.

Uncertainty, also termed epistemic uncertainty, is the scientific uncertainty in the model of the process. It is due to limited data and knowledge. The uncertainty is characterized by alternative models. For discrete random variables, the epistemic uncertainty is modeled by alternative probability distributions. For continuous random variables, the uncertainty is modeled by alternative probability density functions. Examples of uncertainty are alternative ground motion attenuation relations that express the amplitude of ground motion at a particular site as a function of distance to the source and earthquake magnitude. Unlike variability, uncertainty is potentially reducible with additional knowledge and data.

Given the input evaluations, the hazard calculation method integrates over all values of the variables and estimates the annual probability of exceedance of any ground-shaking amplitude at the reference rock outcrop. The hazard curve quantifies the variability of the earthquake

occurrence and ground-shaking attenuation. In addition to the variability of the seismic hazard, there is uncertainty about the seismotectonic environment of a site. Significant advances in development of methodology to quantify uncertainty in seismic hazard have been made in the past 20 years (Budnitz et al. 1997 [DIRS 103635]). These advances involve the development of alternative interpretations of the seismotectonic environment of a site by multiple experts and the structured characterization of uncertainty. Evaluations by multiple experts are made within a structured expert elicitation process designed to minimize uncertainty due to uneven or incomplete knowledge and understanding (Budnitz et al. 1997 [DIRS 103635]). The weighted alternative interpretations are expressed by use of logic trees. Each pathway through the logic tree represents a weighted interpretation of the seismotectonic environment of the site for which a seismic hazard curve is computed. The result of computing the hazard for all pathways is a distribution of hazard curves representing the full variability and uncertainty in the hazard at a site.

1.3.2 Site-Specific Ground Motions

Site-specific ground motions are needed for the structural response calculations supporting postclosure performance assessment. Ground motion results from the PSHA are for a hypothetical reference rock outcrop and do not reflect site-specific soil and rock properties at the locations for which the ground motions are needed (e.g., the horizon where the emplacement drifts are located). The PSHA was conducted in this fashion because the site-specific rock and soil properties were not characterized at the time of the PSHA. Thus, further analyses are carried out to modify the PSHA results to reflect the appropriate site-specific conditions for the site of interest.

For analyses supporting postclosure performance assessment, site-specific ground motions are developed for the waste emplacement level. Selection of annual exceedance probabilities is motivated by the requirement to “consider only events that have at least one chance in 10,000 of occurring over 10,000 years” (10 CFR 63.114(d) [DIRS 173273]). To address this requirement, ground motions are developed for annual exceedance probabilities of 10^{-5} , 10^{-6} , and 10^{-7} per year (the hazard curve used to develop the ground motion is unbounded as explained in Section 1.3.3). These ground motions form the basis for evaluating repository performance for the full range of seismic events that must be considered in TSPA.

A detailed site response model provides the basis for development of seismic time histories at the emplacement drifts. Different approaches are used for developing time histories depending on how they will be used (e.g., in design or in evaluating postclosure repository performance). For Yucca Mountain, three approaches have been used to develop time histories: spectral matching, scaling to PGV, and scaling to PGV preceded by spectral conditioning. The spectral-matching approach is used primarily to develop time histories that will be used in design analyses and is not discussed further here.

The peak-ground-velocity scaling approaches are used to develop time histories for postclosure analyses, such as the calculations documented in this report. In addition to determining the consequences of these low-probability ground motions, another goal is to evaluate the variability in the consequences. Because much of the variability in consequences will be driven by random

variability in ground motion, the time histories for postclosure analyses are developed to capture and represent that random variability.

PGV is selected as the scaling parameter for the ground motions because damage to underground structures has been correlated with PGV (McGarr 1984 [DIRS 163996], p. 206). PGV is appropriate for structural damage caused by sliding or impact under earthquake loads (Newmark and Rosenblueth 1971 [DIRS 151246], Sections 11.3.5 and 11.4). Finally, PGV is also appropriate for the response of a rock mass to dynamic loading because the change in stress across a weak compression wave is directly proportional to the particle velocity. The abstractions in this document therefore use the horizontal PGV as the measure of the amplitude of the ground motion. Alternate measures, such as peak ground acceleration or the spectral acceleration at a given frequency, are anticipated to give similar results.

In the PGV-scaling approach, the earthquake recordings are scaled such that the PGV matches the PGV determined in the site-response analysis for a location of interest. The records may be scaled such that both horizontal components match the target horizontal PGV and the vertical component matches the target vertical PGV. Alternatively, one horizontal component may be scaled to the target horizontal PGV and the scaling of the other components done in a manner to maintain the intercomponent variability of the original recordings. Both of these methods have been used at Yucca Mountain.

For each PGV level of interest, 17 sets of time histories are developed. Each set of time histories consists of acceleration, velocity and displacement in each of two horizontal component directions and in the vertical component direction. The site-specific time histories are based on actual recordings of strong ground motion from earthquakes in the western United States and around the world (McGuire et al. 2001 [DIRS 157510], Appendix B). Recordings are selected to represent those earthquakes that dominate the seismic hazard at a given annual probability of exceedance. In other words, the recordings used as a basis for the time histories are selected to have a range of magnitudes and distances that corresponds to the magnitudes and distances of earthquakes contributing to the seismic hazard at the given annual exceedance probability. By basing the time histories on actual earthquake recordings and choosing records consistent with the seismic hazard, the resulting time histories will exhibit realistic phase characteristics and durations.

A variation of the PGV-scaling approach involves spectral conditioning of the original strong-ground-motion records before using them to develop time histories. Spectral conditioning modifies the original strong motion records such that their response spectra reflect to a greater degree the site conditions at Yucca Mountain. Conditioning can be done with respect to the PSHA reference rock outcrop conditions or to the waste emplacement level conditions that reflect the site response. Conditioning can be thought of as a weak spectral match. A strong spectral match is not desired in this case because it would tend to reduce the random variability of the original recordings.

For the 2.44-m/s PGV ground motion level, two suites of 17 sets of time histories each were developed. The 17 sets of recorded strong ground motion that form part of the basis for the time histories were selected to represent the range of magnitudes and distances consistent with the range indicated by the PSHA. The first suite consists of time histories for which both horizontal

components were scaled to the site-specific horizontal PGV and the vertical component was scaled to the site-specific vertical PGV. The observed intercomponent variability is therefore not maintained for the first suite. Also, the records used to generate the time histories were not spectrally conditioned prior to scaling.

A second suite of time histories for the 2.44-m/s PGV ground motion level was developed by first spectrally conditioning the records to weakly match Yucca Mountain site conditions based on the response spectra for the PSHA reference rock outcrop. Specifically, the ratios between mean response spectra for average western U.S. conditions and mean response spectra for the PSHA reference rock outcrop at Yucca Mountain were determined. The western U.S. response spectra are considered typical of the strong motion records forming the basis for Yucca Mountain time histories. These ratios, or transfer functions, were then applied to the response spectrum for each of the strong ground motion records to be used in generating time histories. Finally, the modified response spectra formed targets for weak spectral matches of the original records. Following this conditioning, the records were scaled to the site-specific PGV. In this case, only one horizontal component was scaled to the PGV and the other components were scaled to preserve the intercomponent variability of the original records.

Two suites of 17 sets of time histories were also developed for the 5.35-m/s PGV ground motion level. For both of these suites, the records forming the basis for the time histories were spectrally conditioned prior to scaling. In one case, they were spectrally conditioned to weakly match the response spectra for the PSHA reference rock outcrop, similar to the approach for the second suite of ground motions for 10^{-6} annual exceedance probability. In the second case, they were conditioned to the site-specific response spectra for the waste emplacement area.

Kinematic analyses and analyses of waste package structural response used the most current suite of ground motions that were available when the calculations were performed. The waste package structural response calculations for the 2.44-m/s PGV ground motion level ground motions were performed with the first suite of ground motions, wherein the time histories are scaled to the known values of PGV in the horizontal and vertical directions; intercomponent variability was not preserved. The waste package structural response calculations for the 5.35-m/s PGV ground motion level ground motions were again performed with the first suite of ground motions that were spectrally conditioned to the reference rock outcrop and preserved the intercomponent variability of the original records.

1.3.3 Terminology for Ground Motion Level

The terminology for the ground motion hazard curves and for the suite of ground motions corresponding to a given exceedance frequency is explained here. A mean ground motion hazard curve defines the relationship between the mean estimate of the mean annual frequency of exceedance and the amplitude of the vibratory ground motion, measured by PGV. The mean annual exceedance frequency represents the mean value of the frequency in any year with which future seismic events will exceed a given value of the PGV or fault displacement. In more concrete terms, the mean hazard curve is an average of the distribution of hazard curves representing the full variability and uncertainty in the hazard at a site. The development of the distribution of hazard curves during the PSHA is discussed in Section 1.3.1.

The seismic scenario class for TSPA-LA uses the mean hazard curves for PGV and for fault displacement. The use of the mean hazard curves simplifies the Monte Carlo sampling process for TSPA. It is also appropriate for calculations of the mean dose to the reasonably maximally exposed individual, as required to demonstrate acceptable repository performance over 10,000 years (10 CFR 63.303 and 63.311 [DIRS 173273]).

The mean annual exceedance frequency spans many orders of magnitude, from a minimum of 10^{-8} per year to a maximum of 1 per year (or greater). The mean frequency is defined as the number of observed events, divided by the time interval of observation. It varies randomly from one observation to the next. We use the mean of this random number as a measure of how likely an event is over any future year. When the mean annual exceedance frequency of interest is much less than 1, as it is here, the mean annual exceedance frequency and the annual exceedance probability are essentially equal³. This report uses the term exceedance frequency because it is more general, although the annual exceedance frequency and annual exceedance probability are interchangeable for the very infrequent seismic hazards considered in this study. The ground motion hazard curve for this report is based on the mean annual exceedance frequency.

The effect of vibratory ground motion on the EBS components is assessed for a set of ground motions with a given value of the horizontal PGV. Sets of 15 three-component ground motions have been developed for a PGV of 2.44 m/s and for a PGV of 5.35 m/s. These ground motion sets are often referred to as the 10^{-6} per year and the 10^{-7} per year ground motions (respectively) because PGV values of 2.44 m/s and 5.35 m/s correspond to these frequency values on the mean unbounded hazard curve at the emplacement drifts. Unfortunately, this convenient terminology is misleading because a seismic event with a PGV of 2.44 m/s will not occur with a frequency of 10^{-6} per year. The correspondence of 2.44 m/s with 10^{-6} per year on the mean unbounded hazard curve means that all ground motion events with PGV greater than 2.44 m/s occur with a mean annual frequency of 10^{-6} per year. In other words, the ensemble of seismic ground motions with PGV exceeding 2.44 m/s will occur with a mean frequency of 10^{-6} per year. As an aside, the probability of encountering an earthquake with a PGV of exactly 2.44 m/s is infinitesimally small, and will certainly not occur with a frequency of 10^{-6} per year.

In this report, ground motions are identified by the appropriate value of PGV because the value of PGV provides a unique and unambiguous identifier for each set of ground motions, even when multiple hazard curves have been developed for a site. For the reader's convenience, the correspondence between values of PGV and the values of annual exceedance frequency on the unbounded curve at the emplacement drifts is identified as follows:

- PGV of 0.19 m/s corresponds to the 5×10^{-4} per year exceedance frequency.
- PGV of 0.384 m/s corresponds to the 10^{-4} per year exceedance frequency.
- PGV of 1.05 m/s corresponds to the 10^{-5} per year exceedance frequency.
- PGV of 2.44 m/s corresponds to the 10^{-6} per year exceedance frequency.

³ The probability of one or more events for a Poisson process with annual rate λ {1/year} over duration T {years} is given by $(1 - e^{-\lambda T})$. When λ is small enough, the probability that one or more events occur in an interval T becomes $(1 - e^{-\lambda T}) = 1 - (1 - \lambda T + (\lambda T)^2 - \dots) \approx \lambda T$, so the annual probability for one or more events is given by $(\lambda T)/T = \lambda$. A typical criterion for the accuracy of this expansion is for $\lambda T \leq 0.1$.

- PGV of 5.35 m/s corresponds to the 10^{-7} per year exceedance frequency.

The hazard curve used to develop the ground motion is unbounded, in the sense that PGV continues to increase (albeit more slowly) with decreasing values of the exceedance frequency. This general behavior leads to PGV values exceeding 5.35 m/s for annual exceedance frequencies below 10^{-7} per year. These PGV values are extremely large and may not be physically realizable for the seismic sources and geologic conditions in and around Yucca Mountain.

A recent study (BSC 2005 [DIRS 170137]) estimated the limits for maximum shear strain in the lithophysal rock based on existing large-core compression testing and on numerical analyses of fracturing limits using field-mapped lithophysae geometries. With this bounded hazard curve, the value of horizontal PGV never exceeds 4.07 m/s for annual exceedance frequencies greater than or equal to 10^{-8} per year (BSC 2005 [DIRS 170137]). It is important to realize that this bound is only applied to one horizontal component of the ground motion, called the H1 component, and the other horizontal (H2) and vertical (V) components are not constrained by this limitation.

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2. METHOD

The waste package calculations presented in this summary are conducted using commercial finite-element (FE) and distinct element (DE) software which has been validated for Project use. 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 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 engineered components within the emplacement drift. The boundary and initial conditions are a result of the constraints supplied by the emplacement drift, waste package and emplacement pallet and from the applied static and dynamic loading conditions. The explicit FE method with the central difference method of time integration was employed in all FE calculations. Results of the FE analysis are given in terms of the transient induced stresses, strains and displacements of the FE 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 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 (or rigid block) using an explicit numerical integration scheme, and are subject to the applied initial and boundary conditions.

The FE mesh is created by using TrueGrid V2.2.0b and TrueGrid V2.2. The FE calculations were then performed by using the commercially available LS-DYNA FE codes with various qualified versions as described in Section 4. 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 (BSC 2002 [DIRS 161949], STN: 10173-3.1-00). This software has integral mesh development and postprocessing graphical display capability.

The kinematic calculations represent the waste packages and emplacement pallets as coarsely-discretized bodies that can be used to simulate a large problem consisting of many waste packages and emplacement pallets. Two different numerical approaches, using the FE and DE representations respectively, are used to perform the kinematic calculations. The results of the calculations provide two sets of output impact parameters. This is done to provide a range of potential impact parameters that account for numerical analysis uncertainty as well as to increase confidence in results derived from two different analysis methods.

A lookup table for converting the kinematic impact parameters to damage area was created based on the detailed FE calculation of a waste package impacting a surface (Table 3-2). In the detailed FE calculation of a waste package impacting a surface, damaged area is estimated from the residual tensile stress distribution and a residual stress threshold for accelerated stress corrosion cracking of the Alloy 22 OCB. The residual stress threshold is defined as a fraction of the yield strength of the OCB material, Alloy 22 [SB-575 N06022], at a given temperature.

Lower and upper thresholds for Alloy 22 are based on 80 percent and 90 percent of the yield strength of Alloy 22 (see discussion in Section 5.3). The yield strength and other material properties are generally evaluated at a temperature of 150°C, which is considered a conservative assumption for the 10,000-year postclosure period (see Assumption 3.2.12).

3. ASSUMPTIONS

Assumptions used in the analyses documented in this document are described below. Assumptions used in the previously completed calculations are not included in this section since they are available in the original documents.

3.1 ASSUMPTIONS REQUIRING VERIFICATION

There are no assumptions that require verification for this document.

3.2 ASSUMPTIONS NOT REQUIRING VERIFICATION

- 3.2.1 The drip shield is represented by a boundary above the waste package that moves synchronously with the free field for the kinematic analyses and waste package-drip shield interaction analysis.

Rationale—Justification for this assumption is found in two documents: *Drift Degradation Analysis* (BSC 2004 [DIRS 166107]) and *Mechanical Assessment of the Drip Shield Subject to Vibratory Motion and Dynamic and Static Rock Loading* (BSC 2004 [DIRS 169753]). *Drift Degradation Analysis* (BSC 2004 [DIRS 166107], Sections 6.3 and 6.4) shows, for ground motions with annual exceedance frequencies of 10^{-6} (2.44 m/s PGV) and 10^{-7} (5.35 m/s PGV), emplacement drifts undergo substantial rockfall in the nonlithophysal rock and complete collapse in the lithophysal rock within seconds of the arrival of the incoming earthquake wave, and prior to substantial movement of the waste package and emplacement pallet. This rockfall pins the drip shield in place via both frictional resistance of the rubble against the drip shield outer surface (which develops forces that oppose the ground motion), and from the weight of the rubble bearing on the drip shield if fully covered. This is confirmed by the cross-drift analysis results reported in Section V-4. These forces result in synchronous motion of the drip shield and invert with the surrounding rock mass free field (BSC 2004 [DIRS 169753], Section 5.3.3.1).

Where Used: Sections 5.4.1 and 5.4.2 and Attachments I, II, VI and XI.

- 3.2.2 The invert is assumed to be rigid and moves synchronously with the free field.

Rationale—It has been demonstrated in Section 5.8 and Attachment VIII that amplification of the seismic waves as they pass through the crushed rock in the invert of the drift is negligible. The analyses results presented in Attachment VIII show that the resultant impacts from rigid invert are higher than the case for deformable invert (Table VIII-8). In addition, analyses with the invert represented as discontinuum blocks show that the invert does not lose integrity with the EBS components resting on the invert at the end of simulation (Figure VIII-37).

Where Used: Sections 5.4.1 and 5.4.2, and Attachments I, II, V, VIII, and XI.

- 3.2.3 The waste packages, drip shields, emplacement pallet, and inverts are approximate representations, with appropriate dimensions and mass in the FE or DE representation.

Rationale—Simplification of the geometry and material property representation is used in the numerical analyses which account for the important features and configuration for the analyzed problem. Detailed geometry in areas not directly relevant to the problem is simplified for numerical efficiency. This is consistent with engineering practice for numerical analysis. The description of the approximate representations for each analysis conducted for this study is provided in the numerical representation subsection.

Where Used: Sections 5.6.1 and 5.6.2, and Attachments I, II, V, and VI.

- 3.2.4 The friction coefficients for metal-to-metal contact and metal-to-rock contact are considered random parameters in the kinematic analyses. The range of values for both of these friction coefficients is 0.2 to 0.8.

Rationale—Coefficients of static and sliding friction for various metals and other materials are provided in various handbooks (e.g., Avallone and Baumeister 1987 [DIRS 103508], Table 3.2.1, p. 3-26).

However, the coefficients of friction for the specific materials in this calculation are not defined in this handbook. In addition, the potential for long-term corrosion to modify the sliding friction should also be considered in defining the friction coefficient. In this situation, the appropriate coefficients of friction for the repository components have high uncertainty and high spatial variability due to waste package-to-waste package variation in long-term corrosion and surface conditions. It is thus 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. It is also appropriate to represent the potential spatial variability between individual waste packages by multiple sampling of the distribution for friction coefficient. A distribution of values for the friction coefficient between 0.2 and 0.8 will achieve these goals (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). The appropriateness of this range is independently confirmed by seismic analyses for spent fuel storage racks (DiGrassi 1992 [DIRS 161539]). This distribution is also broad enough to represent a range of mechanical response for the waste package, emplacement pallet, and drip shield. A friction coefficient near 0.2 maximizes sliding of the waste package on the emplacement pallet, of the emplacement pallet on the invert, and of the drip shield on the invert. Similarly, a friction coefficient near 0.8 minimizes sliding among the various components.

Where Used: Sections 5.4 and 5.5, and Attachments I, II, III, IV, V, X and XI.

- 3.2.5 A large bulk and shear moduli of the blocks that represent the waste package and the emplacement pallet are assumed for the UDEC analyses.

Rationale—The objective of these analyses was to investigate impacts between the waste package and the drip shield. A detailed analysis of damage and deformation during the impact was beyond the scope of the analysis. To estimate the impact locations, velocities, and angles of impact, it is necessary to simulate correctly the rigid body motions of the waste package and the drip shield. Stiffness insignificantly affects rigid body motion. If the bulk and shear moduli of the bodies involved in the impact are large compared to the stiffness of the contact, the amount of impact energy converted into strain energy of internal oscillations is small. Consequently, the assumption that blocks representing the waste package and the emplacement pallet with large bulk and shear moduli (i.e., almost rigid) is conservative.

Where Used: Attachments II and V.

- 3.2.6 The density and Poisson's ratio are not available for Ti-7 (Titanium Grade 7 [SB-265 R52400]), Ti-24 (Titanium Grade 24 [SB-265 R56405]), 316 SS, and Alloy 22 except at room temperature (RT) (20 °C). (Note: In regard to UNS designation for Ti-24, note that Ti-24 has the same mechanical properties as Ti-5 since the compositions are almost identical; 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.

Rationale—The rationale for this assumption is that the material properties in question do not have a significant impact on the calculation results. The impact of using RT density and RT Poisson's ratio is anticipated to be negligible.

Where Used: Attachments VI and XI.

- 3.2.7 A downward pressure is applied to the top of the rubble pile in the FE representation. This pressure, which represents the weight of the rock, is included in the numerical representations. Two pressures are used for the two heights used in these analyses—127.86 kPa for the 1-m rubble height case and 25 kPa for the 7-m rubble height case (Figure 5-25).

Rationale—The average vertical pressure on the top of the drip shield as calculated from 6 realizations of drift collapse is 128 kPa (BSC 2004 [DIRS 169753], Table 5-28). This pressure is applied to the top of the 1 m rubble height. The pressure applied to the 7 m rubble height, 25 kPa, is calculated as the pressure applied to the 1 m height case (128 kPa) minus 7 m of rubble weight [$(7 \text{ m} \times 1,500 \text{ kg/m}^3 \times 9.81 \text{ m/s}^2) = 103 \text{ kPa}$] (density of the caved lithophysal rock is provided in Table 5-1). Combining the applied pressure and weight of the rock results in a combined pressure of 143 kPa and 128 kPa for the 1 m and 7 m height models, respectively. Considering 570 kPa of pressure results in 0.0099 volumetric strain on the Pressure vs. Volumetric Strain curve for the rubble material (Figure VI-12), a 15 kPa difference in combined pressure between the two model heights will not have an appreciable effect on the solution.

Where Used: Section 5.6.2 and Attachment VI.

- 3.2.8 RT material properties from the UDEC simulations (Section 5.2 and Attachment IX) are assumed for the rubble in the LS-DYNA representations of drip shield stability resulting from waste package impacts.

Rationale— The temperature-dependent material properties are not available for the rubble from the collapsed drift. The porosity of the rubble governs bulk behavior of the rubble more than temperature variation of the rock. With peak strains in the collapsed drift rubble of 10 percent, but low stress levels, the mechanism of compaction of the rubble is primarily the result of packing of particles. Effects resulting from rubble particle constituent material behavior are secondary.

Where Used: Section 5.6.2 and Attachment VI.

- 3.2.9 The dynamic (sliding) friction coefficient for the contact between the drip shield and invert is fixed as 0.4 in the LS-DYNA analyses for waste package-drip shield interaction under rockfill.

Rationale—The friction coefficient of 0.4 represents a reasonable estimate based on available range for metal-to-rock friction coefficients, which is from 0.3 to 0.7 (Beer and Johnston 1977 [DIRS 145138], Table 8.1, p. 306). The friction coefficient used in this calculation is somewhat below the range average and close to the lower bound for conservatism of the drip shield stability assessment.

Where Used: Attachment VI.

- 3.2.10 The dynamic (sliding) friction coefficient for the contact between the collapsed drift and upper and lower boundaries for intact rock is assumed as 0.8 in the LS-DYNA analyses for waste package-drip shield interaction in which the drip shield is confined by collapsed rock rubble.

Rationale— The friction angles of the host rock and crushed tuff are 35° and 45°, respectively (Table 5-1). A friction coefficient of 0.8 is obtained by averaging the lithophysal rock mass and crushed tuff friction angles and rounding to the nearest tenth.

Where Used: Attachment VI.

- 3.2.11 The functional friction coefficient and static friction coefficient are assumed as equal to the dynamic friction coefficient. The effect of relative velocity of the surfaces in contact is not considered in the analyses.

Rationale—This assumption maximizes the relative motion of the drip shield with respect to the invert by minimizing the friction coefficient. The calculated results are therefore conservative.

Where Used: Attachments I, VI, and XI.

- 3.2.12 A temperature of 150°C is appropriate and reasonable for evaluation of material properties at the time of the seismic event.

Rationale—This value (150°C) is reasonable for evaluation of material properties during 97 percent of the first 10,000 years after repository closure. The material properties considered in general show lower strength at elevated temperature compared with those at ambient condition. This result is based on a series of thermal analyses that account for uncertainty in host-rock thermal conductivity and percolation flux for an unfilled drift (BSC 2005 [DIRS 173944], Figure 6.3-67). Results are presented for peak waste package temperature, which also provides an upper bound for the peak drip shield temperature. The peak waste package temperature ranges from 102.0°C to 203.1°C (BSC 2005 [DIRS 173944], Table 6.3-38). The waste package temperature time histories demonstrate that temperature exceeds 150°C for, at most, about the first 270 years after ventilation ceases. In some cases, the temperature never exceeds 150°C for certain percolation fluxes and host rock thermal conductivities. Since the time period when temperature exceeds 150°C is not greater than 270 years, it follows that evaluating material properties such as the yield strength at 150°C is conservative for the regulatory period. Additionally, the residual stress damage area increases for increasing temperature (BSC 2003 [DIRS 162293], Table 4 through 10).

Where Used: Sections 5.4.3, 5.5, 5.6.2 and 5.7, and Attachments III, IV, VI, VIII, and XI.

- 3.2.13 The thickness of the Ti-7 and Ti-24 plates is reduced by 2 mm for degradation during the postclosure period in LS-DYNA analyses for waste package-drip shield interaction under collapsed drift.

Rationale—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, Tables 16 and 17; DTN: MO0408MWDGLCDS.002 [DIRS 171486]). For the inside and outside plates, the 95th percentile general corrosion rate values (a reasonably conservative estimate) are 8.59E-5 mm/yr and 1.12E-4 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 nm/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 *Aqueous Corrosion Rates for Waste Package Materials* (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.

Where Used: Attachment VI.

- 3.2.14 The emplacement pallet is not represented in LS-DYNA analyses for waste package-drip shield interaction under collapsed drift in order to simplify the numerical analyses.

Rationale—The omission of the emplacement pallet is considered to have a conservative impact on the solution. Without the emplacement pallet, the side drip shield plates are allowed to travel inward unconstrained (except for frictional contact with the invert), increasing the possibility for buckling. With the emplacement pallet represented, the drip shield would have extra lateral support from the inside. Exclusion of the emplacement pallet in the drip shield-waste package impact analyses is conservative in nature and allows simplification of the FE representation.

Where Used: Attachment VI.

- 3.2.15 The waste package emplacement pallets are represented using beam elements connecting the two support blocks in the LS-DYNA kinematic analysis for multiple waste packages. These beam connectors do not interact with the waste packages.

Rationale—The focus of the kinematic analyses is on waste package-to-waste package interactions and any potential interaction between waste packages and the emplacement pallet beam connectors is of secondary importance (waste package–emplacement pallet interaction is addressed using a refined LS-DYNA analysis as described in Section 5.5 and Attachment IV). Using beam elements allows for a computationally efficient kinematic analysis.

Where Used: Section 5.4 and Attachment I.

- 3.2.16 The waste packages and emplacement pallets are characterized with elastic properties in the LS-DYNA kinematic analysis for multiple waste packages.

Rationale—The use of elastic properties allows the kinematic analysis to be conservative and computationally efficient. Energy dissipation during contact is accounted for through contact damping, which is calibrated to produce conservative values of the coefficient of restitution (COR) for impact.

Where Used: Section 5.2 and Attachment I.

- 3.2.17 The LS-DYNA kinematic analysis for multiple waste packages uses a limited series of waste packages to reasonably represent the mechanical response of waste packages in a complete emplacement drift.

Rationale—A typical waste emplacement drift, 600 m in length, will contain roughly 100 waste packages that may be composed of various waste package types. It is desirable to reduce the analysis complexity and run time by representing the mechanical response of the emplacement drift with the minimum number of waste packages. The characteristics of the nominal waste package inventory is given in Table 3-1 (BSC 2005 [DIRS 173501]). The important aspects of this inventory, from a mechanical perspective,

are the dimensions and weight of the waste packages, as well as the total percentage of the particular type of waste package in the entire inventory. As seen in Table 3-1, the 21-PWR and the 44-BWR are the most prevalent types of waste packages (together comprising roughly 65 percent of the inventory), and they have approximately the same weight and dimensions. The 5-DHLW/DOE-Long (approximately 19 percent) and 5-DHLW/DOE-Short (approximately 10 percent) make up the majority of the remaining waste packages.

The LS-DYNA representative kinematic analyses described in Attachment I examine a series of 7 to 19 waste packages in an emplacement drift. It is assumed that a representative sequence of waste packages is obtained by including those with the greatest number in the inventory. These are the 21-PWR/44-BWR, which have approximately the same dimensions and weight, and the 5-DHLW/DOE-Long, which represents the largest waste packages in dimension and weight. The representative sequence is developed using the approximate percentage of 21-PWR and 5-DHLW/DOE-Long/Short waste packages as occurs in the inventory (i.e., 65 and 35 percent), respectively. The 5-DHLW/DOE-Long waste package is taken as representative of the combined 5-DHLW/DOE Short and Long waste packages due to its greater weight that results in more conservative impact damage effects. The sequence is defined (e.g., Figure I-23, Attachment I) in such a way that the heavy, larger 5-DHLW/DOE-Long waste packages are separated by at least three 21-PWR waste packages. In this way, the impacts on the center three 21-PWRs will reflect the confined effects of the bounding, large mass 5-DHLW/DOE-Long waste packages.

Table 3-1. Geometry and Weight Characteristics of the Nominal Waste Package Inventory for 70,000 MT

Waste Package Configuration	Inventory/% of Total Inventory (70,000 MT Nominal)	Nominal Loaded Weight (MT/lbs)	Nominal Length	Nominal Diameter
21-PWR Absorber Plate	4,299/(38.4%)	41.1/90,700	197.81"	67.65"
21-PWR-Control Rod	95/(0.9%)	41.1/90,700	197.81"	67.65"
12-PWR Absorber Plate	163/(1.4%)	29.3/64,500	218.91"	54.9"
44-BWR Absorber Plate	2,831/(25.3%)	41.7/91,900	197.81"	69.15"
24-BWR Absorber Plate	84/(0.8%)	28.0/61,800	197.81"	54.15"
5-DHLW/DOE Short	1,147/(10.3%)	36.1/79,600	135.94"	83.70"
5-DHLW/DOE-Long ¹	2,116/(18.9%)	53.1/117,000	199.19"	83.70"
2-MCO/2-2-DHLW/DOE	149/(1.3%)	47.0/104,000	199.19"	72.08"
Naval Short	144/(1.3%)	66.2/146,000	204.81"	76.58"
Naval Long	156/(1.4%)	68.5/151,000	229.82"	76.58"

Source: BSC 2005 [DIRS 173501], Tables 1 and 13.

Where Used: Attachments I and XI.

¹ The 5-DHLW/DOE-Long category combines all 5-DHLW/DOE-Long waste package types.

3.2.18 The material properties of crushed tuff are selected as:

Property	Value
Young's modulus	50 MPa
Poisson's ratio	0.25
Density	2,000 kg/m ³
Friction angle	45°
Friction angle between tuff and drift walls	35°

Rationale—Young's Modulus—Both the empirical data and the results of the numerical investigation using UDEC (discussed in Attachment IX, Section IX-5) show that the Young's modulus of crushed tuff at low confinement is in the range between 50 MPa and 200 MPa. Also, BSC (2004 [DIRS 168138], Section 7.15) estimate the initial shear modulus (before degradation) to be 40.1 MPa, resulting in Young's modulus of 98.4 MPa (Young's modulus = $2 \times \text{shear modulus} \times (1 + \text{Poisson's ratio})$). A lower bound of 50 MPa was used for Young's modulus in the calculation to account for nonlinear deformation during shaking.

Poisson's Ratio—BSC 2004 [DIRS 168138], Section 7.7, reports in Table 5 Poisson's ratio for crushed tuff in the range between 0.17 and 0.29, with an average of 0.23. The value of 0.25 was assumed in these calculations.

Internal Angle of Friction and Density—BSC 2004 [DIRS 168138], Sections 7.2 and 7.3, recommends 45 degrees as the angle of internal friction in tuff and average total density of 125 pcf (approximately 2,000 kg/m³). The friction angle between the crushed tuff and drift walls was assumed to be 35 degrees. It was assumed to be smaller than the internal friction angle in tuff for two reasons. The friction angle between the crushed tuff and the drift wall will most likely be smaller than the internal friction angle in crushed tuff because the drift wall will be relatively smooth as excavated by the tunnel boring machine. In addition, the smaller friction angle in the interface is a conservative assumption because it will result in greater potential for slip between the crushed tuff and the drift wall at lower accelerations. Therefore, 35 degrees is a reasonable, conservative assumption for the friction angle in the interface between the crushed tuff and the drift wall.

Where Used: Section 5.8 and Attachment VIII.

3.2.19 The material behavior of the caved rock rubble derived from UDEC numerical compression experiments (Attachment IX) is represented in the LS-DYNA calculations by Material Type 5 (mat_soil_and_foam in Livermore Software Technology 2003 [DIRS 166841]).

Rationale—The input parameters, calculated by fitting the Material Type 5 to the mechanical behavior of the synthetic representation of the broken rubble, were verified in simple, one-element calculations described in (Section VI-3.1).

Where Used: Section 5.6.2 and Attachment VI.

- 3.2.20 All properties of TSw2 rock (except friction; see Assumptions 3.2.4 and 3.2.10) used for Attachments VI and XI are obtained from *Drip Shield Structural Response to Rock Fall* (BSC 2004 [DIRS 168993], Section 5.1). TSw2 is used to represent the rigid invert and upper boundary constraint for the broken rubble.

Rationale—In Attachment VI, the invert is represented with a rigid material model, and all the invert nodes in Attachment XI move synchronously with the applied ground motion, essentially making them rigid. As such, the material properties are necessary only for the contact definitions. Although the material properties have been updated since the issuance of BSC (2004 [DIRS 168993]), the impact of using these material properties is anticipated to be negligible. The material properties of the invert (and upper boundary) do not have a significant impact on the calculation results.

Where Used: Section 5.2 and Attachments VI and XI.

- 3.2.21 The drip shield connector assembly, lifting feature, and base are excluded from the FE representation for simplicity in the waste package–drip shield interaction calculation.

Rationale—These drip shield components offer little to no support to the drip shield structure nor do they have appreciable effect on the response of the drip shield.

Where Used: Attachments VI and XI.

- 3.2.22 Symmetry was applied as a vertical plane along the emplacement drift for the LS-DYNA kinematic analysis for multiple waste packages. The FE representation of all components were restrained from moving cross drift, and ground motions were only applied in the vertical and longitudinal directions. Also, the UDEC kinematic analyses of waste package to waste package interactions are two-dimensional in nature, with the plane of analysis containing the vertical and drift longitudinal axes.

Rationale—The symmetric condition was imposed for the LS-DYNA analysis for direct comparison with the two-dimensional UDEC kinematic analysis results. The kinematic analyses were conducted for waste package end-to-end impact study. By exclusion of the cross-drift movement, a degree of freedom out-of-plane has been eliminated, forcing movement of waste packages along the drift axis, and thus promoting waste package interactions. This is also true for the two-dimensional UDEC analyses in which the out-of-plane movement is not allowed. This assumption results in analyses that are considered conservative for impacts.

Where Used: Attachments I and II.

- 3.2.23 The emplacement pallet tubes will continue to perform their intended function during the regulatory period.

Rationale—The assessment of the emplacement pallet tubes during seismic events has been evaluated and documented in Attachment XI. Based on the results of the assessment, the type 316 stainless steel (316 SS) emplacement pallet tubes will perform their intended function throughout the regulatory period.

Where Used: Attachment I.

- 3.2.24 In some of the calculations for the effect of crushed tuff invert on amplification of ground motions (i.e., approximate and continuum analyses in Sections VIII-2 and VIII-3, respectively) the effect of the engineered systems inside the emplacement drift (e.g., the waste package and emplacement pallet as well as potential collapsed rock rubble) was taken into account by applying a vertical confining pressure on the crushed tuff. The vertical confining pressure provides a reasonable approximation for the complex interactions between objects inside the emplacement drifts.

Rationale—This assumption is justified because of the weak coupling between the objects resting on the invert and the crushed tuff in the invert. The objects can freely separate from the invert and only frictional forces prevent the sliding of objects relative to the tuff in the invert. This assumption is validated in the UDEC analysis described in Section VIII-4.

Where Used: Section 5.8 and Attachment VIII.

- 3.2.25 In the continuum analysis for the effect of the crushed tuff invert on amplification of ground motions (Section VIII-3), it was assumed that there is 2 percent of energy dissipation, in addition to energy dissipated by the Mohr-Coulomb constitutive relation. This 2 percent energy dissipation is specified in the numerical calculation as Raleigh damping. The Mohr-Coulomb constitutive relation dissipates energy only when the yield limit of the material is exceeded.

Rationale—According to *Estimation of Mechanical Properties of Crushed Tuff for Use as Ballast Material in Emplacement Drifts* (BSC 2004 [DIRS 168138], Section 7.16), there is 2 percent of material damping in crushed tuff at approximately 0.002 percent of shear strain. A rough estimate of the yielding shear strain in crushed tuff is more than 0.1 percent. Thus, the 2 percent material damping occurs for strain levels below which damping through material yield occurs.

Where Used: Attachment VIII.

- 3.2.26 Porosity of the crushed tuff in the invert in the UDEC calculation or the effect of crushed tuff invert on amplification of ground motions is assumed to be zero.

Rationale—The crushed tuff in the invert will be compacted to approximately 30 percent porosity (BSC 2004 [DIRS 168138], Table 5). It is usually observed that granular materials with porosity in the range between 20 percent and 30 percent undergo additional irreversible compaction after shaking. (The irreversible volumetric strain of granular materials due to shaking is the reason for liquefaction of saturated granular materials during earthquakes.) However, the ground motions considered here have a relatively strong vertical component that tends to cause loosening and bulking of the material, as opposed to compaction caused by horizontal shaking. It is not clear what kind of irreversible volumetric deformation (compaction or bulking) this material would undergo as a result of strong ground shaking. The numerical representation, due to the idealization of no porosity in the initial configuration, certainly overestimates the bulking

of the invert. However, from the results of the calculations it does not seem that excessive bulking in the numerical representation has significant effect on the important aspect of this analysis, which is to examine the potential for amplification of seismic shaking through the invert.

Where Used: Attachment VIII.

- 3.2.27 The loaded weight for 21-PWR waste package is assumed as 41.7 MT (91,900 lb).

Rationale—The loaded weight for the waste package is necessary only to represent the correct inertia for the mass during the impacts for the kinematic analyses. The loaded weight for 21-PWR waste package is assumed as the same as the weight of the 44-BWR waste package—41.7 MT. Although the loaded weight for 21-PWR waste package is 41.1 MT (90,700 lb) in the current design (BSC 2005 [DIRS 173501], Table 1), the difference is less than 1.5 percent. The impact of using this value is anticipated to be negligible.

Where Used: Section 5.2 and Attachments I and II.

- 3.2.28 The COR for impact of metal-to-metal components (e.g., waste package to waste package or waste package to emplacement pallet) is assumed to be 0.6, and the COR for impact of metal to crushed tuff is assumed to be 0.2. These assumptions provide conservative (higher) estimates of the COR as the higher the value, the less energy dissipation that occurs in the impact, with subsequently greater impact velocities and number of impacts.

Rationale—Goldsmith (2001[DIRS 174360], Section 6.2) provides experimental results of the COR for impacts between objects of different materials and shapes, although most of the results are for solid metal spheres. Because the waste packages are not spherical or completely solid, more energy loss occurs upon impact, and thus the results reported by Goldsmith (2001 [DIRS 174360]) are certainly conservative estimates of COR for impact between waste packages or waste packages and emplacement pallets. Goldsmith (2001 [DIRS 174360], Figure 166) shows that, for impacts between spheres of the same material but of varying weights and weight ratios, the COR is less than 0.6 for the majority of the tested materials if the impact velocity is greater than 5.5 m/s. However, in the tests of impacts between spheres of the same size but different material (Goldsmith 2001 [DIRS 174360], Figure 167), the COR is measured to be less than 0.6 for the majority of tested cases if the impact velocity is greater than 1.8 m/s. Finally, the test results of a sphere dropped on a thick plate (Goldsmith 2001 [DIRS 174360], Figure 172), show that the majority of relevant metallic materials have a COR less than 0.6 for impact velocities greater than 0.3 m/s.

Richards et al. (2001) [DIRS 174362] investigated the COR during impacts between rock particles on debris planes of various inclination angle, Richards et al. (2001 [DIRS 174362], Table 4) summarize results of drop tests of solid basalt balls on debris and soil materials. These results included tests carried out on prepared beds of angular limestone, basalt particles and gravels, which are materials similar to the crushed tuff designed for the invert of the emplacement drifts. All measured CORs are less than 0.23.

The only two results (out of 19 reported) with the COR greater than 0.2 are for the inclined base. The fragmented materials are generally in the range between 0.1 and 0.2.

Where Used: Section 5.4.2 and Attachments I, II, V.

- 3.2.29 There is no significant damage for any waste package-waste package, waste package-emplacement pallet or waste package-drip shield impacts with relative velocity below 0.85 m/s.

Rationale—The long duration of the ground motions and the representation of multiple waste packages in the kinematic analyses (Attachments I and II) preclude the use of a highly refined FE or DE mesh. In this situation, it is more accurate and more computationally efficient to perform a set of very detailed “sidebar” calculations of the impact process using representative values for impact velocities and impact angles. These “sidebar” calculations, called end-on impacts, determine the damage to a 21-PWR waste package from a single end-on impact on an unyielding surface (BSC 2005 [DIRS 173178], Tables 2 and 3). The detailed results from the end-on impact calculations are provided in Attachment III. The rationale for using mean damaged areas, and the methodology for converting kinematic impact parameters into total damaged area using the table of mean damaged areas are discussed in BSC (2005 [DIRS 173247], Sections 6.5.1.2 and 6.5.1.3). Table 3-2 presents the mean damaged areas for residual stress thresholds of 80 percent and 90 percent of the yield strength of Alloy 22.

Table 3-2. Mean Damaged Areas for End-On Impacts of a 21-PWR Waste Package on an Unyielding Surface

Impact Velocity	Mean Damaged Area (m ²) for Stress Threshold of 80% of Yield Strength	Mean Damaged Area (m ²) for Stress Threshold of 90% of Yield Strength
1 m/s	0.0022	0.0014
2 m/s	0.0172	0.0046
4 m/s	0.0515	0.0209
6 m/s	0.0985	0.0404
10 m/s	0.1879	0.1002

Source: BSC 2005 [DIRS 173247], Table 6.5-4.

The mean damaged areas in Table 3-2 have nonzero values, even at the smallest impact velocity of 1 m/s. In order to use the results in Table 3-2 to determine damaged areas from the kinematic calculations, it is necessary to define a velocity threshold corresponding to no damage (zero damaged area). The velocity threshold is estimated by extrapolating the mean damaged curve for a residual stress threshold of 80 percent of yield strength. The mean damaged area curve is plotted in Figure 3-1 as a function of the impact velocity. A simple linear extrapolation of the points at 1 m/s and 2 m/s indicates that the x-intercept of the curve corresponds to 0.851 m/s. The velocity threshold has been rounded to 0.85 m/s for the purpose of calculating damaged areas from the kinetic impact data for adjacent waste packages.

Source: BSC 2005 [DIRS 173247], Figure 6.5-8.

Figure 3-1. Mean Damaged Areas as a Function of Impact Velocity for a Residual Stress Threshold of 80 Percent of Yield Strength

Where Used: Sections 5.4.1, 5.4.2, 5.4.4, 5.6.1 and Attachments I, II and V.

3.2.30 The 316 SS tubes are assumed to be 7.4 mm thick for emplacement pallet tube performance analysis.

Rationale—Thinning of the emplacement pallet tubes to 7.4 mm is based on vapor and aqueous corrosion rates available when the analysis (Attachment XI) was performed (BSC 2004 [DIRS 169898], Section 6.2.23). During the documentation process however, the corrosion rates were updated, indicating less corrosion than previously thought. Using the vapor phase corrosion rate (0.113 $\mu\text{m}/\text{year}$) for the first 2,000 years during the hot, dry period, and using the aqueous phase corrosion rate (0.154 $\mu\text{m}/\text{year}$ at 50°C) for the remaining 8,000 years, the depth of corrosion is calculated to be about 1.5 mm (BSC 2005 [DIRS 173781], Section 6.2.23). Based on the current design tube thickness of 9.5 mm (BSC 2005 [DIRS 173303], Table 6), and accounting for the reduction in thickness from corrosion, a thickness of 8.0 mm is conservative for the entire regulatory period. Because the new corrosion rates indicate thicker tubes than what was analyzed, the results presented in Attachment XI are considered conservative, and further support the survivability of the emplacement pallet tubes.

Where Used: Attachment XI.

- 3.2.31 For emplacement pallet tube performance analysis, the density of the 316 SS tubes is increased to calibrate the weight of the emplacement pallet to the appropriate mass (1,970 kg; BSC 2005 [DIRS 173303], Table 7). The density of six of the seven sets of stainless steel tubes is set to 11,631 kg /m³ to bring the emplacement pallet mass to exactly 1,970 kg. The density of the second set of 316 SS tubes (from the left in Figure XI-1) is set to 15,474 kg/m³ (this is the density necessary to bring the short emplacement pallet to the correct mass).

Rationale—Increasing the mass of the 316 SS tubes will have negligible effects on the solution. Additionally, the extra mass for the second emplacement pallet (increased to 2,212 kg; 11 percent difference) will have a minimal effect on the solution.

Where Used: Attachment XI.

- 3.2.32 The modulus of elasticity and Poisson's ratio are the same for all components in the LS-DYNA kinematic analyses.

Rationale: The focus of the analysis is the kinematic response of the waste packages. The material deformation and damage of the components are not the scope of the analyses. Therefore typical mechanical properties are adequate for this purpose.

Where Used: Attachment I.

- 3.2.33 The Poisson's ratio of Alloy 625 (SB-443 N06625) is assumed for Alloy 22.

Rationale—The Poisson's ratio of Alloy 22 is not available in literature. 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).

Where Used: Attachment VI and XI.

4. USE OF COMPUTER SOFTWARE

4.1 QUALIFIED COMPUTER SOFTWARE

All controlled and baselined software used in the development of the kinematic analysis and waste package–drip shield interaction results documented in this calculation is identified in Table 4-1, including the software tracking number, version, operating environment, and range of use. Table 4-1 also includes a discussion of why the software was selected and describes any limitations on outputs from the software. The software documented in this section is appropriate for the applications used in this calculation, and is consistent with its intended use. Each software item was obtained from Software Configuration Management in accordance with LP-SI.11Q-BSC, *Software Management*. All software was used only within the range of its validation as specified in the software qualification documentation, in accordance with LP-SI.11Q-BSC. The input and output files for each software item used in this calculation have been submitted to the Technical Data Management System (TDMS) as noted in Section 5.9. Detailed listing of the files is available in the *readme* instruction of the DTNs. Note that analyses associated with waste package–emplacement pallet impacts and dynamic effects on cladding are summarized in this document, and detailed in separate source documents. Where applicable, these documents are referenced in the text. A listing of the qualified software used in these calculations can be found directly in the source documents.

Table 4-1. List of Qualified Software Supporting the Calculations

Software Title/Version	Software Tracking Number	Operating Environment (Platform/Operating System)	Brief Description of Software (Range of Use/Selection/Limitations)
UDEC V3.1 (BSC 2002 [DIRS 161949])	10173-3.1-00	PC/Windows 2000	UDEC was used to analyze the kinematic end-to-end impacts (Section 5.4.2 and Attachment II), waste package and drip shield interaction for collapsed drift scenario (Section 5.6.1 and Attachment V), the study of the effect of crushed tuff invert on amplification of ground motion (Section 5.8 and Attachment= VIII), and the study of the deformability of the caved lithophysal rock (Attachment IX). UDEC was selected for its capability of modeling solid body interaction with computationally efficient algorithm. UDEC was used only within the range of its validation as specified in the software qualification report (BSC 2002 [DIRS 172041]). There are no known limitations on outputs.
FLAC V4.0 (BSC 2002 [DIRS 161953])	10167-4.0-00	PC/Windows 2000	FLAC was used to simulate the invert material during seismic shaking (Section 5.8 and Attachment VIII). FLAC was selected for its capability of modeling dynamic loading for the continuum with computationally efficient algorithm. FLAC was used only within the range of its validation as specified in the software qualification report (BSC 2002 [DIRS 168820]). There are no known limitations on outputs.

Table 4-1. List of Qualified Software Supporting the Calculations (Continued)

Software Title/Version	Software Tracking Number	Operating Environment (Platform/Operating System)	Brief Description of Software (Range of Use/Selection/Limitations)
LS-DYNA V970.3858 D MPP-00 (BSC 2003 [DIRS 166918])	10300-970.3858 D MPP-00	HP Itanium 2/HP-UX 11.22	LS-DYNA V970.3858 D MPP-00 was used to analyze the detailed analysis of the waste package-drip shield interaction (Section 5.6.2 and Attachment VI) and the assessment of the emplacement pallet tube during seismic events (Section 5.6.2 and Attachment XI). LS-DYNA was selected for its capability of modeling solid mechanics in dynamic loading conditions. LS-DYNA was used only within the range of its validation as specified in the software qualification report (DOE 2003 [DIRS 168558]). There are no known limitations on outputs.
LS-DYNA SMP D. V970.3858 (LLNL 2005 [DIRS 172926])	10300-970.3858-01	SGI INDIGIO 2/IRIX64 6.5	LS-DYNA SMP D. V970.3858 SGI INDIGIO was used to analyze the kinematic end-to-end impacts (Section 5.4.1 and Attachment I). LS-DYNA was selected for its capability of modeling solid mechanics in dynamic loading conditions. LS-DYNA was used only within the range of its validation as specified in the software qualification report (DOE 2005 [DIRS 174541]). There are no known limitations on outputs.
LS-DYNA SMP D. V970.3858 (LLNL 2005 [DIRS 172925])	10300-970.3858-02	DEC ALPHA/OSF1 V5.1	LS-DYNA SMP D. V970.3858 DEC ALPHA was used to analyze the kinematic end-to-end impacts (Section 5.4.1 and Attachment I). LS-DYNA was selected for its capability of modeling solid mechanics in dynamic loading conditions. LS-DYNA was used only within the range of its validation as specified in the software qualification report (DOE 2005 [DIRS 174542]). There are no known limitations on outputs.
GOLDSIM V.8.01 SP4 (BSC 2005 [DIRS 169695])	10344-8.01SP4-00	PC/Windows 2000	Goldsim was used to sample the coefficient of friction for metal-to-metal contacts and metal-to-rock contacts for multiple waste package kinematic analyses (Attachment X). GOLDSIM was used only within the range of its validation as specified in the software qualification report (DOE 2004 [DIRS 170241]). There are no known limitations on outputs.

4.2 OTHER SOFTWARE

In addition to the above listed items, the FE mesh generation and postprocessing programs, including TrueGrid V2.2.0b and TrueGrid V2.2 (XYZ Scientific Applications, Inc.), LS-PREPOST V1.0 (Livermore Software Technology Corporation), and SLIC Version 4.90i (Lawrence Livermore National Laboratory) were used. These software programs were used solely to mesh geometric representations of the domain (i.e., for the development of FE mesh)

and visual display and graphical representation of results, and are therefore exempt from the requirements defined in LP-SI.11Q-BSC, Paragraph 2.1.2. The operating environments for these software are listed in Table 4-2.

A MATLAB script was written to automate the post-processing of the results of the LS-DYNA kinematic analyses. The MATLAB script was designed to run on MATLAB V6.5 Release 13 on Tru64 UNIX. The MATLAB script is exempted from qualification based on the criteria in LP-SI.11Q-BSC, Paragraph 2.1.6. The algorithm is verifiable by hand calculations, and all of the input and output are readable text. In accordance with LP-3.12Q-BSC, Section 5.2, Heading 11, the actions performed in the script are documented in Attachment I, Section I- 5.

The standard functions of commercial off-the-shelf software, Microsoft Excel 97 SR-2, were used to process and summarize impact data and to provide graphical presentation of the calculation results. Microsoft Excel 97 SR-2 was run on personal computers with a Pentium microprocessor and Microsoft Windows 2000 operating system. Microsoft Excel 97 SR-2 is exempted software applications in accordance with LP-SI.11Q-BSC, Paragraph 2.1.6.

Table 4-2. Operating Environments for the Software Supporting Finite-Element Pre- and Postprocessing

Software Title/Version	Operating Environment (Platform/Operating System)
TrueGrid V2.20b	DEC ALPHA/OSF1 V5.1
TrueGrid V2.2	HP 9000/HP-UX 11.00
LS-PREPOST V1.0	HP Itanium 2/HP-UX 11.22 (in Attachment VI) DEC ALPHA/OSF1 V5.1(in Attachment I) SGI INDIGIO 2/IRIX64 6.5 (in Attachment I)
SLIC V4.90i	SGI INDIGIO 2/IRIX64 6.5

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5. CALCULATION

5.1 INTRODUCTION

As described in Section 1, the emplacement drift EBS consists of several primary components that will be affected by vibratory ground motion from a remote earthquake. These components are (Figure 1-1): (a) the invert, which is composed of crushed, graded and compacted tuff tunnel muck (BSC 2004 [DIRS 168138], Section 8.2); (b) the emplacement pallet, a platform constructed of Alloy 22 end piers and 316 SS connector tubes, which rests on the invert and supports the waste package; (c) the waste package; and (d) the drip shield, a structure constructed of Ti-7 (plates) and Ti-24 (or similar alloy support structure) that protects the waste package from seepage water and rockfall.

The analysis of vibratory motion of engineered barriers resulting from seismic shaking is a complex problem that may involve large displacements of free bodies and potential collisions and localized failure mechanisms of the waste packages and drip shields. Additionally, intense ground motions from low probability earthquakes may result in substantial rockfall or collapse of emplacement drifts for PGVs in excess of approximately 1.5 m/s (BSC 2004 [DIRS 166107], Section 6.4). Since substantial movement of waste packages or drip shields does not occur for ground motions with less than the 1.5-m/s PGV level, it is assumed that the drip shields will be confined by rubble and will subsequently move in synchronous motion with the free field rock mass (Assumption 3.2.1). Thus, the problem analyzed in this calculation can be reduced to a string of many waste packages¹ aligned end-to-end beneath a series of interlocked drip shields within an emplacement drift which has substantially collapsed.

During seismic-induced vibratory motion, the waste packages will move synchronously with the invert of the emplacement drift (or free-field rock mass) if the inertial forces acting on the waste package are insufficient to: (a) cause sliding of the waste package relative to the emplacement pallet (or sliding of both the emplacement pallet and the waste package relative to the invert); or (b) throw the waste package into free flight after the waste package separates from the emplacement pallet. As long as the waste packages move synchronously with the free field, they will not interact with each other, nor with any other object inside the emplacement drift except the emplacement pallet on which the waste package rests (the force fluctuation between the waste package and the emplacement pallet will be insignificant and insufficient to cause any damage of the waste package as long as the waste package does not separate from the emplacement pallet).

When the peak acceleration of the ground motion exceeds a critical value resulting in sliding and separation of the waste package relative to the emplacement pallet and the invert, interaction and impacts between the waste package and other objects inside the emplacement drift become possible. The horizontal acceleration normal to the axis of the emplacement drift could cause lateral impacts between the waste package and the drip shield. The vertical acceleration could be the cause of impacts between the waste package and the emplacement pallet and between the

¹ As described in Assumption 3.2.17, the waste package inventory consists of a number of different waste package types that have different dimensions and masses, however four specific types—the 21-PWR and 44-BWR, as well as the 5-DHLW/DOE-Long and Short waste packages compose the large majority.

waste package and the inner surfaces of the top of the drip shield. The horizontal acceleration along the axis of the emplacement drift could cause interaction and impacts between the neighboring waste packages.

The objective of this calculation is to present postclosure seismic analyses of engineered barriers and to provide estimates of impact parameters such as the number, location and relative velocity of the collisions. The approach taken to analysis of this problem is summarized in Figure 5-1. This logic diagram illustrates the individual analyses conducted and the sections within this document where they are found. The basic input data required for these calculations includes the postclosure ground motion time histories and material properties estimates for the waste package and drip shield materials. These inputs are described in Section 5.2 of this document. Additionally, analysis of drip shield stability under possible impact from the waste package during large amplitude ground motions assumes that the drift will already have collapsed, resulting in a drip shield surrounded by rock rubble. The mechanical constitutive behavior and properties of the rubble are required as input, and are developed in Attachment VIII of this document.

These inputs feed three basic sets of analyses that are new to this calculation:

- Analysis of waste package to waste package interactions (summarized in Section 5.4 and presented in detail in Attachments I and II)
- Analysis of waste package to drip shield interactions (summarized in Section 5.6 and presented in detail in Attachment VI)
- Analysis of stability of the drip shield under waste package impact (summarized in Section 5.6 and presented in detail in Attachment V).

Additionally, two sets of previous analyses are summarized in this calculation:

- Analysis of waste package to emplacement pallet interactions (summarized in Section 5.5 and presented in detail in Attachment IV)
- Analysis of maximum accelerations of fuel assemblies within a waste package (summarized in Section 5.7 and presented in detail in Attachment VII).

Waste Package-Waste Package Analysis—An analysis of waste package-to-waste package interaction was conducted previously and described in *Structural Calculations of Waste Package Exposed to Vibratory Ground Motion* (BSC 2004 [DIRS 167083]). To make the problem tractable, a single waste package was assumed to be located between two vertical walls that move synchronously with the free field. Impacts into the walls were considered as impacts into the neighboring waste packages. The calculation yielded conservative estimates of the number of impacts between the waste packages and the impact velocities.

In the following calculation, a revised approach to the analysis of waste package to waste package interactions is taken to reduce the conservatism inherent in the single waste package-between-walls approach. The problem has been broken down into two separate

analyses: (a) a series of kinematic numerical calculations to define the gross movements of the various engineered components, and to determine the parameters describing their impacts; and, (b) a series of detailed FE calculations of a single waste package impacting a surface (previously conducted and summarized in Section 5.4.3 and Attachment III) aimed at determining the details of damage induced to the engineering components as a function of impact parameters (e.g., velocities and angles of impact). The kinematic calculations represent the waste packages and emplacement pallets as coarsely-discretized bodies that can be used to simulate a large problem consisting of many waste packages and emplacement pallets without resorting to significant simplifications in the number of waste packages represented or the problem boundary conditions. The detailed FE representations of a waste package impacting a surface creates a lookup table that can then be used for conversion of the kinematic impact calculations directly to waste package damage estimates. Since the kinematic analyses are complex in nature, two different numerical approaches are used to perform the same set of calculations and thus provide two sets of output impact parameters. This is done to provide a range of potential impact parameters that account for numerical analysis uncertainty as well as to increase confidence in results derived from two different analysis methods.

Waste Package-Drip Shield Analysis—The UDEC kinematic analysis is used to conduct cross-drift simulations of waste package movement within the rubble-confined drip shield. The analysis is used to simulate the process of tunnel collapse, interaction of the rubble with the drip shield, and, finally, the waste package to drip shield impact parameters (number of impacts, location of impacts, velocity and angle of impact). The impact parameters are then used as input to a separate, detailed FE calculation of the waste package-drip shield impact to determine drip shield stability.

Waste Package-Emplacement Pallet and Maximum Acceleration of Fuel Assemblies Analyses—Analyses of the impact parameters associated with waste package-emplacement pallet interactions were conducted previously and reported in a separate document that is summarized here for completeness. Likewise, analysis of the maximum acceleration and damage to fuel assemblies in interacting waste packages has been completed previously and is summarized in this document.

The results of these calculations are given primarily in terms of the number of impacts, and impact velocities. This information is subsequently used as direct input to *Seismic Consequence Abstraction* (BSC 2005 [DIRS 173247]) in which damage is calculated either directly from the supporting calculation or from the velocities using damage area to impact velocity correlations derived from separate, supporting calculations (BSC 2004 [DIRS 167083]; BSC 2005 [DIRS 173178]).

NOTE: Previous calculations only summarized in this document are shown in shaded boxes.

Figure 5-1: General Document Organization and Outputs to the Seismic Consequence Abstraction

5.2 INPUT PARAMETERS

The input parameters used for this study include:

- Design specification
- Material properties
- Seismic ground motions.

These parameters are summarized in Table 5-1 and described below. Input parameters used in the previously completed calculations are not included in this section since they are available in the original documents.

5.2.1 Design Specification

The development of the numerical representation of the drip shields, waste packages, and emplacement pallets is based on the current design configuration (BSC 2004 [DIRS 168275], BSC 2004 [DIRS 170835], and BSC 2003 [DIRS 166181]). The detailed dimensions for these EBS components were obtained from the detailed design drawings (BSC 2005 [DIRS 173303] and BSC 2005 [DIRS 173501]).

5.2.2 Material Properties

Material properties used in the numerical analyses include those for (1) EBS components, (2) contact friction, (3) host rock (Category 3 lithophysal rock mass), (4) caved lithophysal rock surrounding the drip shield, and (5) the crushed tuff as invert ballast material. Description for each category is provided below.

5.2.2.1 Material Properties for EBS Components

The representations of the 21-PWR and 5-DHLW/DOE-Long waste packages are hollow cylinders with the density chosen so that they have the correct mass in the LS-DYNA kinematic analysis for multiple waste packages (Section 5.4.1 and Attachment I). The inputs include the weight of the 21-PWR waste package (41.7 MT), the weight of the 5-DHLW/DOE-Long waste package (53.1 MT) and the weight of the emplacement pallet (1.97 MT) (Table 5-1). These inputs were also used for the UDEC kinematic analysis for multiple waste packages (Section 5.4.2 and Attachment II). A linear elastic material model is used for both LS-DYNA and UDEC kinematic analyses. The elastic properties used in both analyses are fictitious values to simulate correctly the rigid body motions of the waste package and the drip shield (values presented in Tables I-4 and II-4, see Assumptions 3.2.3, 3.2.5, and 3.2.16 for rationale).

A more elaborate material model representation is used for the LS-DYNA analyses for waste package-drip shield interaction (Section 5.6.2 and Attachment VI) and for the assessment of the performance of the emplacement pallet tubes (Attachment XI). The material properties are evaluated for 150°C (Assumption 3.2.12). Some of the temperature-dependent material properties are not available for Alloy 22, SS, Ti-7, and Ti-24. Therefore, RT density and RT Poisson's ratio are used for Alloy 22, SS, Ti-7, and Ti-24 (see Assumption 3.2.6). Note that the tangent (hardening) modulus, listed in this section, is a parameter of the bilinear elastoplastic constitutive representation used for the drip shield materials as defined in Figure 5-2.

NOTE: σ_y = yield strength, E = modulus of elasticity, E_1 = tangent modulus.

Figure 5-2. Bilinear Elastoplastic Constitutive Representation

5.2.2.2 Contact Friction

In the analysis of vibratory ground motion for multiple waste package impacts (Sections 5.4.1 and 5.4.2), in which friction is essential for transfer of seismic ground motion from the invert to the waste package, in absence of more specific data the dynamic friction coefficients for all contacts are randomly sampled from uniform distribution between 0.2 and 0.8 as described in Attachment X. The rationale for the selected range of the contact friction is provided in Assumption 3.2.4.

5.2.2.3 Material Properties for Rock Mass at Emplacement Level

In the cross-drift analysis of interaction between the waste package and drip shield (Section 5.6.1), the simulations not only include the motion of the objects inside the emplacement drift, it also considers the response of the rock mass and the overall stability of the emplacement drift during strong seismic ground motion. The lithophysal rock mass is selected in the analysis since approximately 85 percent of the emplacement area is located in the lithophysal rock (BSC 2003 [DIRS 165572], Table I-2). The material model representation of the lithophysal rock mass is described in details in *Drift Degradation Analysis* (BSC 2004 Section 6.4 [DIRS 166107]). The material properties for Category 3 lithophysal rock mass include the micro-mechanical properties of bonded polygonal blocks and the contacts between the blocks (Attachment V).

In the LS-DYNA analyses for waste package-drip shield interaction (Section 5.6.2 and Attachment VI), the TSw2 rock is used to represent the rigid invert and the material properties are necessary only for the contact definitions.

5.2.2.4 Material Properties for Caved Lithophysal Rock

An estimate of deformability of the caved rock mass covering the drip shield is required for the analysis of the interaction between the waste package, the drip shield, and the surrounding rock

mass. The estimate is based on the numerical simulation of load testing on caved rock with corroborative empirical results (Duncan et al. 1980 [DIRS 161776] and Marachi et al. 1972 [DIRS 157883]) as described in Attachment IX.

A relatively general form of deviatoric (or shear) yield function with three constants a_0 , a_1 , and a_2 was used. The equation is expressed as:

$$\phi = J_2 - (a_0 + a_1 p + a_2 p^2) \quad (\text{Eq. 5.2-1})$$

where p is the mean stress or pressure; and J_2 is the second stress invariant defined in terms of principal stresses (see Attachment IX). The material properties of caved lithophysal rock are provided in Table 5-1.

5.2.2.5 Material Properties for Crushed Tuff

Deformation of the crushed tuff in the invert of the emplacement drifts during strong seismic ground motions was analyzed numerically as described in Section 5.8 and Attachment VIII. Although the crushed tuff in the invert of the emplacement drift is a granular material it is represented in these calculations as an elasto-plastic Mohr-Coulomb continuum. The material properties used in the calculations are mainly obtained from *Estimation of Mechanical Properties of Crushed Tuff for Use as Ballast Material in Emplacement Drifts* (BSC 2004 [DIRS 168138], Table 5 and Assumption 3.2.18). Young's modulus listed in Table 5-1 is derived from the shear modulus and Poisson's ratio. The maximum shear modulus ($G_{\max}$) of 40 MPa and the Poisson's ratio of 0.25 were selected to represent the invert material.

5.2.3 Seismic Ground Motions

The development of the ground motion time histories based in results of a probabilistic seismic hazard analysis and a Yucca Mountain site response model is described in *Development of Earthquake Ground Motion Input for Preclosure Seismic Design and Postclosure Performance Assessment of a Geologic Repository at Yucca Mountain, NV* (BSC 2004 [DIRS 170027], Section 6.3.2). The number of ground motion time histories (17) for postclosure performance assessment is obtained from the DTNs listed in Table 5-1. In that document, 17 sets of three-component time histories were developed for each annual probability of exceedance considered for postclosure analyses. The time histories selected were based on strong motion records chosen to represent the range of earthquake magnitudes and distances indicated by the PGV hazard analysis (BSC 2004 [DIRS 170027], Section 6.3.1.4). As explained in that document, 15 sets of input ground motions are recommended by NUREG/CR-6728 (McGuire et al. 2001 [DIRS 157510], p. 3-3) when using a suite of time histories to perform soil-structure interaction analysis that is consistent with a probabilistically-defined seismic hazard. Two extra sets were developed to allow for substitutions if any of the 15 sets were found to be inappropriate. For the analyses, the full suite of 17 three component ground motions is retained to provide the broadest range of variability in the kinematic response.

Table 5-1. Input Parameters

Input Parameters	Value	Source	Application
Design Specification			
Detailed dimensions for drip shield	See reference drawings	BSC 2005 [DIRS 173303], Directory, Interlocking Drip Shield, LA Drip Shield Assembly Drawings	Attachments V and VI
Detailed dimensions for 21-PWR waste package	See reference drawings	BSC 2005 [DIRS 173501], Table 1	Sections 5.4, 5.5, 5.6, 5.7, 5.8 and Attachments I, II, V, VI, and VIII
Detailed dimensions for 5-DHLW/DOE-Long waste package	See reference drawings	BSC 2005 [DIRS 173501], Table 1	Section 5.4.1 and Attachment I
Detailed dimensions for emplacement pallet	See reference drawings	BSC 2005 [DIRS 173303], Directory, Emplacement pallet, Emplacement Pallet General Configuration, Nominal Dimensions, and Weights	Sections 5.4.1, 5.4.2, 5.6.2 and Attachments I, II, and V
The height of invert	0.86 m	BSC 2004 [DIRS 169776], Section A Drawing	Attachment VIII
Waste package spacing	0.1 m	BSC 2004 [DIRS 168489], Table 1	Section 5.6.2, Attachments I, II, VI, and XI
Loaded weight for 21-PWR waste package	41.7 MT	Assumption 3.2.27	Sections 5.4.1 and 5.4.2, Attachments I and II
Loaded weight for 5-DHLW/DOE-Long package	53.1 MT	BSC 2005 [DIRS 173501], Table 1	Section 5.4.1 and Attachment I
Emplacement pallet weight	1.97 MT	BSC 2005 [DIRS 173303], Table 7	Sections 5.4.1 and 5.4.2, Attachments I and II
Residual stress threshold for initiation of stress corrosion cracking on a smooth surface of Alloy 22	90 percent of the yield strength of Alloy 22	BSC 2004 [DIRS 172203], Section 6.2.1, 2nd paragraph on p. 6-7	Section 5.3
Area, 6 x 6 x 3/8 inch 316 SS Tube	5,212.9 mm ²	AISC 1989 [DIRS 107536], p. 1-95	Attachment I
Rectangular moment of inertia, 6 x 6 x 3/8 inch 316 SS Tube	1.732x10 ⁷ mm ⁴	AISC 1989 [DIRS 107536], p. 1-95	Attachment I
Polar moment of inertia, 6 x 6 x 3/8 inch 316 SS Tube	2.851x10 ⁷ mm ⁴	AISC 1989 [DIRS 107536], p. 1-95	Attachment I
Material Properties for SB-265 R52400 (Ti-7)			
Density (at RT)	4,520 kg/m ³	DTN: MO0003RIB00073.000 [DIRS 152926]; p.1	Section 5.6.2, Attachments VI and XI
Yield strength (at 150°)	209 MPa	BSC 2004 [DIRS 168993]; Section 5.1.1	Section 5.6.2, Attachments VI, and XI
Poisson's ratio (at RT)	0.32	DTN: MO0003RIB00073.000 [DIRS 152926]; Section "Mechanical Properties"	Section 5.6.2, Attachments VI and XI
Modulus of elasticity (at 150°)	101 GPa	DTN: MO0003RIB00073.000 [DIRS 152926]; p.3	Section 5.6.2, Attachments VI, and XI

Table 5-1. Input Parameters (Continued)

Input Parameters	Value	Source	Application
Tangent (hardening) modulus	0.448 GPa	BSC 2004 [DIRS 168993]; Section 5.1.3	Section 5.6.2 and Attachment VI
True Ultimate Strength (at 150°)	347 MPa	BSC 2004 [DIRS 168993]; Section 5.1.2	Section 5.6.2 and Attachment VI
Material Properties for SB-265 R56405 (Ti-24)			
Density (at RT)	4430 kg/m ³	ASM International. 1990 [DIRS 141615]; p.620	Section 5.6.2 and Attachment VI
Yield strength (at 150°)	750 MPa	BSC 2004 [DIRS 168993]; Section 5.1.1	Section 5.6.2 and Attachment VI
Poisson's ratio (at RT)	0.34	ASM International. 1990 [DIRS 141615]; p.621	Section 5.6.2 and Attachment VI
Modulus of elasticity (at 150°)	108 GPa	BSC 2004 [DIRS 168993]; Section 5.1.1	Section 5.6.2 and Attachment VI
Tangent (hardening) modulus (at 150°)	1.52 GPa	BSC 2004 [DIRS 168993]; Section 5.1.3	Section 5.6.2 and Attachment VI
True Ultimate Strength (at 150°)	982 MPa	BSC 2004 [DIRS 168993]; Section 5.1.2	Section 5.6.2 and Attachment VI
Material Properties for SB-575 N06022 (Alloy 22)			
Density (at RT)	8,690 kg/m ³	DTN: MO0003RIB00071.000 [DIRS 148850], Table S04196_001	Attachments VI and XI
Yield strength (at 150°)	310 MPa	BSC 2004 [DIRS 167083]; Section 5.1.1	Attachments VI and XI
Poisson's ratio (at RT)	0.278	DTN: MO0003RIB00071.000 [DIRS 148850], Table S04196_001 and Assumption 3.2.33	Attachments VI and XI
Modulus of elasticity (at 150°)	199 GPa	BSC 2004 [DIRS 167083]; Section 5.1.1	Attachments VI and XI
Tangent (hardening) modulus (at 150°)	1.77 GPa	BSC 2004 [DIRS 167083]; Section 5.1.3	Attachments VI and XI
Material Properties for SA-240 S31600 (316 SS)			
Density (at RT)	7,980 kg/m ³	ASTM G 1-90 1999 [DIRS 103515], Table X1.1, p.7	Attachment XI
Yield strength (at 150°)	161 MPa	BSC 2004 [DIRS 167083]; Section 5.1.1	Attachment XI
True Ultimate Strength (at 150°)	644 MPa	BSC 2004 [DIRS 167083]; Section 5.1.2	Attachment XI
Poisson's ratio (at RT)	0.298	ASM 1980 [DIRS 104317], Figure 15, p. 755	Attachment XI
Modulus of elasticity (at 150°)	186 GPa	BSC 2004 [DIRS 167083]; Section 5.1.1	Attachment XI
Tangent (hardening) modulus (at 150°)	1.94 GPa	BSC 2004 [DIRS 167083]; Section 5.1.3	Attachment XI

Table 5-1. Input Parameters (Continued)

Input Parameters	Value	Source	Application
Contact Friction			
Metal-to-metal	0.2 – 0.8	Assumption 3.2.4	Sections 5.4.1 and 5.4.2, Attachments I, II, and XI
Metal-to-rock	0.2 – 0.8	Assumption 3.2.4	Sections 5.4.1 and 5.4.2, Attachments I, II, and XI
Material Properties for Host Rock			
Category 3 lithophysal rock mass, unconfined compressive strength	20 MPa	BSC 2004 [DIRS 166107], Table 6-41	Section 5.6.1 and Attachment V
Category 3 lithophysal rock mass, Young's modulus	10.8 GPa	BSC 2004 [DIRS 166107], Table 6-41	Section 5.6.1 and Attachment V
Category 3 lithophysal rock mass, friction angle	35 deg	BSC 2004 [DIRS 166107], Table 6-43	Section 5.6.1 and Attachment V
Category 3 lithophysal rock mass, residual friction angle	15 deg	BSC 2004 [DIRS 166107], Table 6-43	Section 5.6.1 and Attachment V
Category 3 lithophysal rock mass, cohesion	7.94 MPa	BSC 2004 [DIRS 166107], Table 6-43	Section 5.6.1 and Attachment V
Category 3 lithophysal rock mass, tension	3.18 MPa	BSC 2004 [DIRS 166107], Table 6-43	Section 5.6.1 and Attachment V
Category 3 lithophysal rock mass, normal stiffness	53.08 GPa/m	BSC 2004 [DIRS 166107], Table 6-43	Section 5.6.1 and Attachment V
Category 3 lithophysal rock mass, shear stiffness	26.57 GPa/m	BSC 2004 [DIRS 166107], Table 6-43	Section 5.6.1 and Attachment V
Category 3 lithophysal rock mass, block bulk modulus	51.37 GPa	BSC 2004 [DIRS 166107], Table 6-43	Section 5.6.1 and Attachment V
Category 3 lithophysal rock mass, block shear modulus	38.60 GPa	BSC 2004 [DIRS 166107], Table 6-43	Section 5.6.1 and Attachment V
TSw2 unit, density	2,370 kg/m ³	Assumption 3.2.20	Section 5.6.2 and Attachment VI
TSw2 unit, Poisson's ratio	0.21	Assumption 3.2.20	Section 5.6.2 and Attachment VI
TSw2 unit, modulus of elasticity	33 GPa	Assumption 3.2.20	Section 5.6.2 and Attachment VI
Material Properties for Caved Lithophysal Rock			
Density	1,500 kg/m ³	Derived in Attachment IX	Section 5.6.2 and Attachment VI

Table 5-1. Input Parameters (Continued)

Input Parameters	Value	Source	Application
Bulk modulus	335 MPa	Derived in Attachment IX	Section 5.6.2 and Attachment VI
Shear modulus	201 MPa	Derived in Attachment IX	Section 5.6.2 and Attachment VI
Yield function constant a_0	0	Derived in Attachment IX	Section 5.6.2 and Attachment VI
Yield function constant a_1	0	Derived in Attachment IX	Section 5.6.2 and Attachment VI
Yield function constant a_2	0.305	Derived in Attachment IX	Section 5.6.2 and Attachment VI
Material Properties for Crushed Tuff			
Young's modulus	50 MPa	Assumption 3.2.18, derived from Shear modulus and Poisson's ratio in BSC 2004 [DIRS 168138] Table 5	Section 5.8 and Attachment VIII
Poisson's ratio	0.25	Assumption 3.2.18, selected from the max and min range in BSC 2004 [DIRS 168138] Table 5	Section 5.8 and Attachment VIII
Density	2,000 kg/m ³	Assumption 3.2.18, selected based on BSC 2004 [DIRS 168138] Table 5	Section 5.8 and Attachment VIII
Friction angle	45°	Assumption 3.2.18, selected based on BSC 2004 [DIRS 168138] Table 5	Section 5.8 and Attachment VIII
Friction angle between crushed tuff and drift walls	35°	Assumption 3.2.18	Section 5.8 and Attachment VIII
Seismic Ground Motions			
PGV 1.05 m/s level (1×10^{-5} per year)	All ASCII files contained in vts.zip	MO0402AVDTM105.001 [DIRS 168890]	Sections 5.4.1, 5.4.2, 5.5, 5.6.1, 5.8 and Attachments I, II, IV, V, VIII
PGV 2.44 m/s level (1×10^{-6} per year)	All ASCII files contained in vts.zip	MO0403AVDSC106.001 [DIRS 168891]	Sections 5.4.1, 5.4.2, 5.5, 5.6.1, 5.8 and Attachments I, II, IV, V, VIII
PGV 5.35 m/s level (1×10^{-7} per year)	All ASCII files contained in vts.zip	MO0403AVTMH107.003 [DIRS 168892]	Sections 5.4.1, 5.4.2, 5.5, 5.6.1, 5.8 and Attachments I, II, IV, V, VIII, and XI

5.3 FAILURE MECHANISMS

Mechanical processes that occur during an extremely low probability seismic event may compromise the functionality of the waste packages and drip shields as barriers to radionuclide

release. These mechanical processes include impacts caused directly by vibratory ground motion during an earthquake and impacts caused by rockfall induced by vibratory ground motions.

Under vibratory ground motions, impacts can occur between adjacent waste packages and between the waste package and its emplacement pallet, the surrounding drip shield, and the invert. Impacts can also occur between the drip shield and the emplacement pallet, the invert, and even the drift wall. Rockfall induced by vibratory ground motions can result in impacts on the drip shield in the postclosure period and impacts on the waste packages in the preclosure period, when drip shields are not yet in place. Rockfall induced by vibratory ground motion in the lithophysal zones may collapse the drifts, resulting in static loads from the mass of rubblized rock surrounding the drip shield. Finally, mechanical loads may be generated by fault displacement within the repository block. In this case, EBS components may become pinned if the fault displacement is greater than the available clearances between components.

These mechanical processes are associated with a number of potential failure mechanisms for the waste package and fuel rod cladding under vibratory ground motions:

- Peak dynamic loads have the potential to result in immediate puncture or tearing of an EBS component if the failure criterion is exceeded. A puncture provides a potential pathway for flow into and radionuclide transport out of an EBS component.
- Impact-related dynamic loads may dent a component, resulting in permanent structural deformation with residual stress. High levels of residual tensile stress may lead to local degradation from accelerated corrosion processes. Areas that are breached from corrosion processes provide a potential pathway for flow into and radionuclide transport out of an EBS component.
- Impacts between adjacent waste packages, and other impacts involving the waste packages, impose dynamic loads on waste package internals. These dynamic loads may result in deformed fuel rods and perforated cladding. Failure of cladding provides a potential pathway for release of radionuclides from fuel rods.

The exterior of the waste packages is comprised of Alloy 22, which is very ductile. Immediate puncture or tearing of the waste package exterior would be accompanied by large distortions that produce high stresses and strains in a significant volume of material. Supporting calculations for waste package drops on the emplacement pallet were performed using a refined representation of a waste package. These calculations considered impact velocities similar to those observed in the vibratory ground motion calculations. The supporting calculations indicate that the maximum stress intensity¹ developed in the outer wall of the waste package is significantly below the true ultimate tensile strength of the material (BSC 2003 [DIRS 165497]). A localized puncture or tear due to impact processes caused by vibratory ground motions is very unlikely and is not included in the seismic scenario class.

¹ The stress intensity used hereinafter is defined as the difference between the algebraically largest principle stress and the algebraically smallest principal stress at a given point. In other words, the stress intensity is defined as twice the maximum shear stress. It should not be confused with the stress intensity factor used commonly in Fracture Mechanics.

On the other hand, the presence of high residual tensile stress has the potential to result in accelerated stress corrosion cracking. This combined mechanical-corrosion failure mechanism is expected to be the most likely cause of failure for the waste package and drip shield from impact processes caused by vibratory ground motions. The areas that exceed the residual tensile stress threshold are referred to throughout this document as the damaged area. The effective area for transport through the damaged areas will be substantially less than the damaged area because the cross-sectional area of the stress corrosion cracks is much less than the total surface area that exceeds the residual stress threshold (BSC 2005 [DIRS 173247], Section 6.3.5).

Application of a residual tensile stress threshold for seismic failures is nonmechanistic in the sense that detailed calculations with accelerated corrosion rates or crack propagation are not used to determine the actual failure time after a seismic event. Rather, the waste package is assumed to fail immediately once the residual tensile stress threshold is exceeded, providing potential pathways for transport through the areas exceeding the residual tensile stress threshold. The residual tensile stress threshold is often referred to as the residual stress threshold or more simply the stress threshold, with the understanding that the principal residual stress must always be tensile to initiate an accelerated corrosion process.

Figure 5-3 is a simplified illustration of how residual stress is generated by permanent (plastic) deformation in a simple uniaxial strain model. The loading path in Figure 5-3 has three phases: (1) elastic loading until reaching the elastic yield limit, (2) plastic loading above the elastic yield limit, and (3) elastic unloading when the external load reduces the local stress. Figure 5-3 also shows that plastic deformation does not always generate a damaged area because the final residual stress state may be compressive or, if tensile, may be below the threshold to initiate accelerated localized corrosion or stress corrosion cracking. It should be recognized that propagation of a once nucleated stress corrosion crack could be arrested by an encounter with the residual stress field that is unfavorable for further propagation.

Figure 5-3. Permanent Deformation from Plastic Yielding Generates Residual Stress

Accelerated stress corrosion cracking from high residual stress is expected to be the most likely cause of failure for the waste package from impact processes under vibratory ground motion.

The residual stress thresholds for seismic response are similar to the criteria for initiation of stress corrosion cracking on smooth surfaces of Alloy 22 (BSC 2004 [DIRS 172203], Section 6.2.1). The use of a stress corrosion cracking initiation criterion is appropriate for seismic analysis because regions where the residual stress from mechanical damage exceeds the tensile failure criterion are expected to be severely cold worked and, hence, potentially subject to enhanced stress corrosion cracking.

A residual stress threshold is a conservative failure criterion because detailed corrosion models will have a delay time until failure. A conservative approach is appropriate because it is consistent with other tensile failure criteria (BSC 2004 [DIRS 172203], Section 6.2.1), because the residual stress failure criterion is transparent, and because it is easily applied to the output from structural response calculations.

The residual stress threshold for failure of the waste package is represented by a uniform distribution with a lower bound of 80 percent of the yield strength of Alloy 22 and an upper bound of 90 percent of the yield strength of Alloy 22. The upper bound is based on experimental data and conservatively incorporates a safety factor of 2.2 because of the very long lifetime of the waste package (BSC 2004 [DIRS 172203], Section 6.2.1). The lower bound is introduced to evaluate the sensitivity of damaged area to potential uncertainty in the residual stress threshold. This residual stress criterion (80 percent to 90 percent of the yield strength) is also consistent with the failure criterion for initiation of stress corrosion cracking in other waste package analyses.

In practice, the damage to the waste package has been evaluated at the extremes of the uniform distribution. The results from each structural response calculation are post-processed to determine the elements in the OCB of the waste package whose residual stress exceeds 80 percent of the yield strength of Alloy 22 and to determine the elements in the OCB of the waste package whose residual stress exceeds 90 percent of the yield strength of Alloy 22. These elements are then converted into an area susceptible to accelerated stress corrosion cracking at the 80 percent and 90 percent criteria. The appropriate areas at intermediate values of the residual stress threshold can then be defined by linear interpolation between the extremes. The elements that exceed 90 percent of the yield strength are always a subset of the elements that exceed 80 percent of the yield strength. In other words, the damaged area for the 90 percent residual stress threshold is always less than the damaged area for the 80 percent residual stress threshold.

The dynamic loads on fuel rods from end-to-end impacts of adjacent waste packages and from impacts between waste package and emplacement pallet (and, to a smaller degree, the drip shield) have the potential to fail the cladding. In the former case, the direction of the fuel rods loading is predominantly axial while in the latter it is transverse. The primary cladding failure mechanism is perforation due to acceleration (g-loads) in the axial and transverse direction of the fuel rods (BSC 2005 [DIRS 173247], Section 6.5.6). The primary deformation mode of axially loaded fuel rods (end-to-end impact of adjacent waste packages) is buckling and the resulting cladding failure mechanism is the only one considered in this study. The g-loads required to buckle fuel rods are estimated from a simple analytic calculation based on Euler buckling of a column (Chun et al. 1987 [DIRS 144357]). It is estimated that the cladding fails when the

impact accelerations are in the range of 82 g to 252 g for axial impacts (and 63 g to 211 g for lateral impacts) (Chun et al. 1987 [DIRS 144357], Table 4).

5.4 WASTE PACKAGE–WASTE PACKAGE INTERACTION

5.4.1 LS-DYNA Kinematic Analyses with Multiple Waste Packages

Two suites of kinematic calculations have been performed with multiple waste packages to determine the kinematic impact parameters due to end-to-end impacts between adjacent packages. The two suites are based on different computational techniques with different numbers and types of waste packages. The two suites represent alternate technical approaches to the kinematic calculations, thereby providing a range of estimates for TSPA abstraction. The first suite is based on the LS-DYNA code (LLNL 2005 [DIRS 172925] STN: 10300-970.3858-02, LLNL 2005 [DIRS 172926] STN: 10300-970.3858-01), while the second suite is based on the UDEC code (BSC 2002 [DIRS 161949], STN 10173-3.1-00). This section describes the major features of the analyses and results for the first suite (LS-DYNA) relevant to *Seismic Consequence Abstraction* (BSC 2005 [DIRS 173247]). The UDEC calculations are described in Section 5.4.2. More detailed description of the analyses and results are provided in Attachment I.

5.4.1.1 Numerical Representation

The objective of this kinematic analysis is to determine the response of a series of emplaced spent nuclear fuel waste packages when subjected to seismic ground motion inputs. The scope of this calculation is limited to estimating end-to-end impact velocities between adjacent waste packages. The end-to-end impact velocities are used to estimate the damaged area, based on the damaged area incurred from end impacts documented in previous analyses (BSC 2004 [DIRS 173178]). A number of configurations were studied to determine a representative series of waste packages, varying the number of waste packages and the mix of package geometries in the series.

The kinematic analyses were performed using a FE representation of a series of waste packages. The FE calculation was performed with the commercially available LS-DYNA FE code (LLNL 2005 [DIRS 172925] STN: 10300-970.3858-02, LLNL 2005 [DIRS 172926] STN: 10300-970.3858-01). The FE representation includes waste packages, emplacement pallets, and a rigid representation of the invert and drip shield (Figure 5-4 and Assumption 3.2.2). The invert and drip shield were extended beyond the waste packages (by the length of 4 waste packages) to accommodate relative horizontal motion of the waste packages. Two waste package representations were created, approximating a 21-PWR waste package, and a 5-DHLW/DOE-Long waste package. The waste packages were characterized as hollow cylinders with end caps (Figure 5-5). The inner diameter and end cap thickness of the waste packages were selected as convenient dimensions to approximate the inner cavity of the waste packages and to produce material densities on the same order as the density of other components in the FE representation, with the intent of maintaining reasonable analytic time steps. The waste emplacement pallets were represented as two hollow shell structures connected with beams (Figure 5-6). The connecting beams are $6 \times 6 \times 3/8$ inch square tubes and were represented as non-interactive (no contact) elements (Assumption 3.2.15) using the LS-DYNA

Belytschko-Schwer resultant beam element. Detailed description of the geometry and configuration in LS-DYNA analyses are provided in Attachment I.

NOTE: The configuration consists of five 21-PWR packages and two 5-DHLW/DOE-Long waste packages. Impacts to the center three packages are considered representative of a typical repository waste package.

Figure 5-4. Finite-Element Representation of a Series of Waste Packages

NOTE: Adjacent waste packages are positioned 10 cm apart.

Figure 5-5. Geometry of 21-PWR and 5-DHLW/DOE-Long Packages, Shown from the Symmetry Plane Side

Figure 5-6. Finite-Element Representation of the Waste Package Emplacement Pallet

The invert and drip shield are represented by 10 in (254 mm) thick blocks, slightly wider than the emplacement pallet, and extended by the length of 4 waste packages (about 790 in/20,066 mm).

The drip shield is placed 31.73 in (806 mm) above the 21-PWR waste package (109.77 in/2788.2 mm above the invert). For the 5-DHLW/DOE-Long waste package, the drip shield is 14.20 in (361 mm) above the waste package.

There is a 0.5-second period for gravity initialization before ground motion time histories are applied. The force of gravity is ramped up to full strength over the first 0.2 seconds. During gravity initialization, every node of the invert and the drip shield is held fixed in the vertical direction, and the waste packages and emplacement pallets are free to settle. Global damping with a damping constant of 200.0 is applied over the first 0.4 seconds of the gravity initialization and then ramped down to 0.01 at 0.5 seconds. The global damping factor of 200 was selected as sufficient to allow the dynamic gravity initialization to be applied in 0.4 seconds, simulating a static solution. At 0.5 seconds, the vertical restraint is removed, and every node of the invert and the drip shield is prescribed to move with the input ground acceleration (Assumptions 3.2.1 and 3.2.2).

Ground motion is only applied in the Y and Z directions (vertical and horizontal along the axis of the emplacement drift). The H1 component of the ground motion is used for horizontal (i.e., the Z direction). Thus, the FE representation utilizes symmetry along the axis of the emplacement drift (Z axis in Figure 5-4). A symmetry boundary condition is prescribed for all nodes on the symmetry plane; translation perpendicular to the plane (X direction) and rotations out of the plane (about the Y and Z axes) are restrained.

Seventeen sets of ground motion time histories scaled to three different levels of horizontal PGV are used as input. The three PGV values are 1.05 m/s, 2.44 m/s, and 5.35 m/s. These three levels of PGV correspond to 10^{-5} , 10^{-6} , and 10^{-7} per year exceedance frequencies for the unbounded hazard curve. The 17 realizations referred to in this section and Attachment I correspond to the ground motions as shown in Table 5-2.

The representations of the 21-PWR and 5-DHLW/DOE-Long waste packages are hollow cylinders, as shown in Figure 5-5, with the density chosen so that they have the correct mass. The selected density and elastic material properties for each component are provided in Attachment I, Table I-4. The coefficients of friction for metal-to-metal and metal-to-rock contact are random parameters that differ for each waste package and emplacement pallet set. The independent sampling for the value of friction coefficient of the individual waste packages and pallets directly represents the uncertainty and spatial variability of friction coefficients through the inputs to the kinematic calculations. The static and dynamic friction coefficients are taken to be the same, and the values range between 0.2 and 0.8 (Assumption 3.2.4).

All interactions between components in the FE representation are defined using surface-to-surface contact. The contact interfaces for interaction between adjacent waste packages and for interaction between waste packages and the invert and drip shield are defined based on segment sets. This reduced the computational intensity of these well-defined contact interfaces by limiting the scope of the contact search algorithm. The contact interfaces involving the support pallet are less predictable and required using part-to-part contact, where the contact surfaces are determined by LS-DYNA based on all surfaces of the parts.

Two types of analysis were performed to evaluate analysis parameters, with a focus on parameters relating to contact. The first analysis involved dropping a waste package and the second analysis examined the effects of the sliding contact. Contact parameters included automatic contact, viscous contact damping, soft constraint option, and segment-based contact option. Automatic contact allows LS-DYNA to determine the order and orientation of surface normals for the master and slave surfaces of defined contact interfaces. Viscous contact damping can be used to approximate the effects of the COR of the contacting surfaces. The soft constraint option with segment-based contact sliding helps prevent node catching during sliding along an interface. Additionally, the general analysis parameter, hourglass control type, was also examined. It was determined that optimal parameters for reasonable contact behavior are automatic contact, 150 percent viscous contact damping, and pinball segment-based contact (soft 2) with the sliding option (sbopt 4) from these tests.

To confirm the applicability and conservatism in the seven waste package FE representation, a series of parametric studies was conducted to refine the LS-DYNA analysis solution parameters, and to investigate the effect of representation of larger numbers of waste packages. Comparison of the predicted damage levels from the eleven and seven waste package configurations for 17 ground motion realizations at 3 seismic hazard levels shows that the seven waste package results are conservative.

5.4.1.2 Results

The suite of 51 seismic ground motions was applied to the seven waste package configuration to calculate an update to the TSPA damage abstraction. Waste package-to-waste package impacts and impact velocities were extracted from the output. Waste package-to-waste package impact velocities were processed as the maximum relative horizontal (Z) velocity between the upper or lower corner nodes of adjacent waste packages at the simulation time just prior to the onset of contact.

The results of 51 simulations (i.e., 17 ground motions for each of 3 PGV levels) are summarized in Table 5-2. The results are presented for the 3 waste packages in the middle of the string of 7 waste packages. The table includes the number of impacts greater than 0.85^2 m/s and the maximum impact velocities for each realization. The 1.05-m/s PGV ground motions resulted in zero impact velocities above 0.85 m/s. Thus, the kinematic analysis predicts zero damage at this level. At the 2.44-m/s PGV level, impacts occurred in 9 realizations only. A large number of impacts for each realization and relatively large impact velocities are predicted at the 5.35-m/s PGV level.

² A number of impacts with impact velocity greater than 0.85 m/s (not the total number of impacts) is reported because it is assumed impacts will not damage the waste package if the impact velocity is lower than 0.85 m/s (Assumption 3.2.29).

Table 5-2. Summary of Impact Results from LS-DYNA Kinematic Analyses

Realiz.	Motion	1.05-m/s PGV Level						2.44-m/s PGV Level						5.35-m/s PGV Level					
		Number of Impacts ¹			Max. Velocity ² (m/s)			Number of Impacts ¹			Max. Velocity ² (m/s)			Number of Impacts ¹			Max. Velocity ² (m/s)		
		Left ³	Center ³	Right ³	Left ³	Center ³	Right ³	Left ³	Center ³	Right ³	Left ³	Center ³	Right ³	Left ³	Center ³	Right ³	Left ³	Center ³	Right ³
1	17	0	0	0	0.00	0.00	0.00	0	0	0	0.00	0.00	0.00	0	0	0	0.00	0.00	0.00
2	16	0	0	0	0.00	0.00	0.00	0	1	2	0.00	0.87	0.92	5	2	1	7.91	1.15	1.46
3	3	0	0	0	0.00	0.00	0.00	1	2	4	1.99	2.59	2.59	6	5	3	4.73	11.92	11.92
4	2	0	0	0	0.00	0.00	0.00	1	1	1	0.87	0.87	0.99	8	8	7	3.82	3.20	3.20
5	11	0	0	0	0.00	0.00	0.00	0	0	0	0.00	0.00	0.00	2	2	2	1.95	1.95	1.76
6	4	0	0	0	0.00	0.00	0.00	0	0	1	0.00	0.00	0.88	6	8	7	3.30	4.08	4.08
7	12	0	0	0	0.00	0.00	0.00	0	0	1	0.00	0.00	0.89	6	6	4	2.11	2.11	1.11
8	5	0	0	0	0.00	0.00	0.00	0	0	0	0.00	0.00	0.00	3	5	4	2.88	2.88	2.21
9	15	0	0	0	0.00	0.00	0.00	0	0	0	0.00	0.00	0.00	2	1	1	1.35	0.89	1.10
10	9	0	0	0	0.00	0.00	0.00	2	4	6	1.49	1.49	2.23	8	11	8	5.39	6.25	6.25
11	8	0	0	0	0.00	0.00	0.00	0	0	0	0.00	0.00	0.00	4	2	1	2.39	1.99	1.26
12	6	0	0	0	0.00	0.00	0.00	0	0	0	0.00	0.00	0.00	9	10	8	1.76	1.76	2.00
13	10	0	0	0	0.00	0.00	0.00	0	0	0	0.00	0.00	0.00	5	5	6	2.47	2.47	1.68
14	1	0	0	0	0.00	0.00	0.00	0	0	0	0.00	0.00	0.00	4	3	4	2.64	2.54	2.54
15	7	0	0	0	0.00	0.00	0.00	2	2	3	2.73	2.73	2.17	8	7	7	3.14	2.71	2.71
16	14	0	0	0	0.00	0.00	0.00	1	1	2	0.91	1.02	1.22	6	3	3	1.48	1.85	1.85
17	13	0	0	0	0.00	0.00	0.00	0	1	1	0.00	0.95	0.95	5	4	4	2.11	2.11	1.45

NOTES: ¹Number of impacts greater than 0.85 m/s.² If greater than 0.85 m/s.³ Left, Center, and Right refer to three waste packages at the center of the seven waste packages string

5.4.2 UDEC Kinematic Analyses with Multiple Waste Packages

Two suites of kinematic calculations have been performed with multiple waste packages to determine the kinematic impact parameters due to end-to-end impacts between adjacent waste packages. The first suite, based on the LS-DYNA code, is presented in Section 5.4.1 and Attachment I. The analyses for the second suite were carried out with UDEC version 3.1 (BSC 2002 [DIRS 161949], STN: 10173-3.1-00), which is a two-dimensional numerical code used to simulate the mechanical interaction of polygonal blocks. This section describes the major features of the analyses and results for the second suite relevant to *Seismic Consequence Abstraction* (BSC 2005 [DIRS 173247]). A complete and detailed description of the analyses and results are provided in Attachment II.

5.4.2.1 Numerical Representation

The objective of this analysis was to determine the number of impacts and impact velocities between the waste packages during strong seismic ground motions. Therefore, the important aspect of this calculation was to correctly simulate the rigid-body motion of the objects inside the drip shield. A two-dimensional approximation is used in analyzing impacts between the waste packages. The problem is analyzed in the plane of the vertical cross-section along the axis of the emplacement drift and the waste packages. Only two components of the ground motions were used in the analysis: one horizontal (H1) and vertical. Geometrical representation of the EBS components in the UDEC analysis is shown in Figure 5-7.

Figure 5-7. Detail of the Geometry in the Middle of the String of Waste Packages

The emplacement pallet and the waste package, located inside the drip shield covered by the caved rock mass, are represented as rectangular blocks. The dimensions (the length and the height) of the blocks that represent the waste package in the calculations are equal to the length and the diameter, respectively, of the waste package; the length of the block that represents the emplacement pallet is equal to the length of the emplacement pallet. Because of the approximation of the three-dimensional geometries of the waste package and emplacement pallet

with two-dimensional representation in the numerical analysis (shown in the cross-section in Figure 5-8), the height of the block that represents the emplacement pallet is modeled to be equal to the minimum height of the waste package above the invert. The masses assigned to the blocks in the numerical representation are equal (per unit out-of-plane thickness as indicated in Figure 5-8) to the masses of the bodies they represent. More detailed description of the numerical representation of the three-dimensional problem in the two-dimensional analysis is provided in Attachment II.

Figure 5-8. Comparison of the Actual Geometry and its Representation in the Numerical Analysis

Only the motion of the objects located inside the drip shield was simulated. All other objects and boundaries included in the analysis were assumed to move synchronously with the free field (Assumptions 3.2.1 and 3.2.2). The blocks in the calculations interact through interfaces or contacts. The contacts stresses and displacements are based on Hook's law with the induced displacement linearly proportional to the applied stress. Coulomb slip law is used to govern the limit to the shear stress (see Attachment II for more detailed description).

Energy dissipation was accounted for using contact damping, which is a computational tool used to dissipate a certain amount of energy during an impact between two bodies. Hysteretic damping is used as impact damping in UDEC analyses. Different normal stiffnesses are assigned for contact during the loading and unloading phases of deformation (Figure 5-9). The difference between the areas beneath the loading and unloading portions of the force-displacement curves is proportional to the energy dissipated during the impact. The unloading stiffness must be greater than the loading stiffness (as shown in Figure 5-9) for energy to be dissipated. The ratio of the unloading and loading stiffnesses (i.e., k_{nu} / k_{nl}) is the main parameter to control energy dissipation in hysteretic damping. This parameter was determined based on drop numerical tests for the COR. The target COR for metal-to-metal and metal-to-rock impacts was 0.6 and 0.2 respectively (Assumption 3.2.28). The numerical tests showed that stiffness ratios (i.e., k_{nu} / k_{nl}) of 2.7 and 50.0 resulted in the responses that closely matched the CORs of 0.6 and 0.2, respectively.

Figure 5-9. Contact Force-Displacement Response as a Result of Hysteretic Damping

The calculations were carried out with UDEC version 3.1 (BSC 2002 [DIRS 161949], STN: 10173-3.1-00). Twenty-one waste packages were included in the numerical simulation. The geometries of all the blocks representing the waste packages at the end of a simulation are shown in Figure 5-10. The distance between the waste packages at the end of the string of 21 waste packages and the vertical boundaries, which represent the ends of the emplacement drift, is equal to approximately five waste package lengths in the original configuration (before shaking begins). No restraint was assumed on either end of the string of 21 waste packages.

Information recorded for all 21 waste packages during the simulation include: (a) time of impact, (b) location of impact relative to the local coordinate system (with origin at the lower-left corner of the impacted block and x -axis along the length of the waste package), and (c) relative impact velocity decomposed in the normal and tangential directions relative to the impacted surface. Impacts between the waste packages, the waste package and the emplacement pallet, and the waste package and the drip shield (i.e., the upper boundary) were recorded. Although the impact information is recorded for all waste packages, only the information for three waste packages in the middle of the string were used to calculate the damage due to waste package-to-waste package impacts. Because the number of the waste packages included in the simulation is smaller than the number of waste packages designed to be emplaced in one drift (approximately 100), it is important that the number of waste packages included in the numerical simulation (i.e., 21) does not affect a number of impacts and impact velocities calculated for three waste packages in the middle of the string. Qualitative review of the results of the numerical simulations shows that, for the duration of strong seismic ground motions, the end effect propagates, at most, six to eight waste packages from both ends. The configuration of the blocks and the contours of horizontal displacements at the end of a simulation for one of the ground motions (i.e., ground motion #12 at the 5.35-m/s PGV level) are shown in Figure 5-10. Details of displacements at the string ends also are shown in the figure. Three waste packages on the left end and eight waste packages on the right end drifted away from the middle of the string as a result of shaking and conditions at the ends of the finite string. On the right side, the end waste package completely fell off the emplacement pallet. In this particular case, for one of the strongest ground motions, 10 waste packages in the middle of the string are unaffected by the

end conditions. It appears that using 21 waste packages is sufficient to simulate waste package-to-waste package interaction sufficiently far from the ends of the string of the waste packages. The three waste packages in the middle of the string certainly will be unaffected by the end conditions.

Figure 5-10. Contours of Displacements (m) at the End of Simulation for Ground Motion #12 at 5.35 m/s Peak Ground Velocity Level

Three sets of 17 ground motions were analyzed. Each set represents a different PGV level (i.e., 1.05 m/s, 2.44 m/s, and 5.35 m/s). A total of 51 simulations was carried out. Full duration of the ground motion was not simulated. Instead, the portion of the records of the ground motions between the points corresponding to 5 percent and 95 percent in the energy build up, as measured by the Arias intensity (Kramer 1996 [DIRS 103337], Section 3.3.4), was simulated. For each three-component set of ground motions (i.e., two horizontal and one vertical), these points were determined for each component; then, the earliest 5 percent point and the latest 95 percent point were used to define the duration of strong ground motion for that set of ground motions.

5.4.2.2 Results

The results of 51 simulations (i.e., 17 ground motions for each of 3 PGV levels) are summarized in Table 5-3. The results are presented for 3 waste packages in the middle of the string of 21 waste packages. The table includes the number of impacts greater than 0.85¹ m/s and the maximum impact velocities for each realization. Only two impacts into the middle waste package with velocity greater than 0.85 m/s are detected from all realizations at the 1.05-m/s PGV level. At the 2.44-m/s PGV level, impacts into the middle waste package occurred in 9 realizations only. A large number of impacts for each realization and relatively large impact velocities are predicted at the 5.35-m/s PGV level.

For additional confidence building of the UDEC analysis, the problem of a waste package between rigid boundaries is reanalyzed in a two-dimensional approximation with UDEC using hysteretic contact damping. This problem has been analyzed in a previous calculation (BSC 2004 [DIRS 167083]) as a three-dimensional problem using the LS-DYNA code as summarized in Attachment IV. Comparison between UDEC and LS-DYNA results show good agreement in the average values of both the number of impacts and the maximum impact velocities. The comparison also indicates that UDEC results are in general conservative for the prediction of impact parameters. Details of the analysis and the results are provided in Section II-5.1.

¹ A number of impacts with impact velocity greater than 0.85 m/s (not the total number of impacts) is reported because it is assumed impacts will not damage the waste package if the impact velocity is lower than 0.85 m/s. (Assumption 3.2.29).

Table 5-3. Summary of Impact Results from UDEC Kinematic Analyses

Realiz.	Motion	1.05-m/s PGV Level						2.44-m/s PGV Level						5.35-m/s PGV Level					
		Number of Impacts*			Max. Velocity ** (m/s)			Number of Impacts*			Max. Velocity** (m/s)			Number of Impacts*			Max. Velocity** (m/s)		
		Left	Center	Right	Left	Center	Right	Left	Center	Right	Left	Center	Right	Left	Center	Right	Left	Center	Right
1	17	0	0	0	0.00	0.00	0.00	0	0	0	0.00	0.00	0.00	5	5	7	1.73	1.71	1.86
2	16	0	0	0	0.00	0.00	0.00	0	0	0	0.00	0.00	0.00	17	13	12	2.29	3.11	3.24
3	3	2	1	0	0.96	0.87	0.00	2	2	2	1.13	1.64	1.75	11	9	12	4.17	6.06	6.16
4	2	0	0	0	0.00	0.00	0.00	4	2	5	2.23	2.23	1.55	26	24	22	4.62	4.61	5.89
5	11	0	0	0	0.00	0.00	0.00	0	0	0	0.00	0.00	0.00	11	13	7	1.99	2.04	2.42
6	4	0	0	0	0.00	0.00	0.00	3	1	0	0.90	0.90	0.00	27	31	32	3.93	3.87	2.96
7	12	0	0	0	0.00	0.00	0.00	0	0	0	0.00	0.00	0.00	28	24	22	3.04	3.18	3.17
8	5	0	0	0	0.00	0.00	0.00	0	0	0	0.00	0.00	0.00	11	12	12	2.93	4.27	4.48
9	15	0	0	0	0.00	0.00	0.00	0	0	1	0.00	0.00	1.76	9	8	9	1.80	1.82	2.09
10	9	0	1	1	0.00	1.15	1.15	7	8	9	2.40	2.91	2.92	28	29	28	4.35	5.40	7.30
11	8	0	0	0	0.00	0.00	0.00	0	1	1	0.00	0.95	0.95	14	14	9	4.42	2.99	2.91
12	6	0	0	0	0.00	0.00	0.00	0	1	2	0.00	1.43	1.41	26	26	24	6.76	6.42	6.67
13	10	0	0	0	0.00	0.00	0.00	0	0	0	0.00	0.00	0.00	9	14	12	3.37	2.54	2.21
14	1	0	0	0	0.00	0.00	0.00	0	1	1	0.00	0.91	0.92	17	14	17	5.76	5.74	3.89
15	7	0	0	0	0.00	0.00	0.00	6	8	8	5.22	2.71	4.37	26	27	28	5.10	7.08	6.12
16	14	0	0	0	0.00	0.00	0.00	0	0	0	0.00	0.00	0.00	9	6	9	3.15	3.19	1.78
17	13	0	0	0	0.00	0.00	0.00	4	1	0	1.16	1.24	0.00	28	28	26	5.72	5.72	5.18

NOTES: *Number of impacts greater than 0.85 m/s.

** If greater than 0.85 m/s.

5.4.3 Single 21-PWR Waste Package End-Impacts Calculation

The kinematic analyses, presented in Sections 5.4.1 and 5.4.2, do not use a refined FE mesh because it would result in prohibitively long calculations with multiple waste packages. Instead, the kinematic impact data are converted into damaged area using a “catalog” or lookup table based on highly refined FE calculations for end-on impact of a waste package on an unyielding surface. The highly refined FE calculations are reported in detail in *21-PWR Waste Package End Impacts—A Mesh Study* (BSC 2004 [DIRS 173178]). This section describes the major features of the calculations and summarizes the results relevant to *Seismic Consequence Abstraction* (BSC 2005 [DIRS 173247]). Additional information with more detailed description of the calculations and results is provided in Attachment III.

The study represents a parametric study of waste package impact as a function of five values of the impact velocity and up to four values of the impact angle (Figure 5-11). The use of an elastic unyielding surface is computationally efficient because it reduces the computational mesh by a factor of two and also provides a conservative representation of the damaged area. The damaged area with an unyielding surface will generally be greater than the damaged area with an adjacent waste package because the elastic and unyielding surface is on a rigid boundary that maximizes impact stresses and deformation of the waste package for a given impact velocity and impact angle.

Material properties are based on temperature at 150°C. As noted in Assumption 3.2.12, a temperature of 150°C is the base case for all calculations because it is conservative for 97 percent of the first 10,000 years and 98.5 percent of the first 20,000 years after repository closure (Assumption 3.2.12). The residual stress threshold is based on 80 percent and 90 percent of the yield strength for Alloy 22 at the various temperature values. The variations in residual stress threshold evaluate the sensitivity of damaged area to this parameter.

The initial conditions for the impacts are as follows:

Initial velocity is 1 m/s, 2 m/s, 4 m/s, 6 m/s, and 10 m/s; Initial angle between the axis of the waste package and the vertical (α in Figure 5-11) is 0 degrees, 1 degree, 5 degrees, and 8 degrees.

Source: BSC 2003 [DIRS 162293], Figure 2.

Figure 5-11. Initial Position of the Waste Package for the End Impacts

The selected impact velocities range from 1 m/s to 10 m/s and impact angles ranging from 0 to 8 degrees were anticipated to be sufficiently wide to encompass all velocities and angles encountered during simulations of waste package response to vibratory ground motion.

5.4.3.1 Numerical Representation

Following a standard engineering practice, the mesh of the OCB in the FE mesh is refined in the region where significant deformations and residual stresses are expected (i.e., region of interest). The remaining part of the mesh is coarser to reduce the simulation running time. The extent of the region of interest depends on the input parameters (the velocity and angle of impact). The configuration for 5-degree end impact of the 21-PWR waste package is illustrated in Figure 5-12. A three-dimensional FE representation of the waste package was developed using the dimensions provided in *21-PWR Waste Package Side and End Impacts* (BSC 2003 [DIRS 162293], Attachment I). Detail of the FE representation of 21-PWR waste package for ideal (0 degree) end impact is illustrated in Figure 5-13.

The thickness of the OCB was reduced by 2 mm on its outer side (BSC 2003 [DIRS 162293], Assumption 3.14). The target surface was conservatively assumed to be elastic and unyielding, and its density was rounded up to 8,000 kg/m³. A static and dynamic friction coefficient of 0.5 was taken into account between all parts. The value of 0.5 is an average value for the range of friction coefficient, 0.2 to 0.8, defined in Assumption 3.2.4 and used for the structural response calculations described in Section 5.2.1. The use of an average friction coefficient of 0.5 is reasonable here because this is a single, discrete impact on an unyielding surface, so frictional forces should have a very minor effect in determining damaged area on the waste package. Other simplifications of the internal structure of the waste package are described in Attachment III.

Source: BSC 2005 [DIRS 173178], Figure 1.

Figure 5-12. Schematic of the Configuration for 5-Degree End Impact of the 21-PWR Waste Package

Source: BSC 2005 [DIRS 173178], Figure 2(b).

Figure 5-13. Detail of the Finite-Element Representation of 21-PWR Waste Package for Ideal (0 Degree) End Impact

The duration for all the impact calculations, 0.05 seconds, was chosen to establish a stable residual first principal stress after the waste package impact. In order to calculate residual stresses efficiently, system damping (Hallquist 1998 [DIRS 155373], Section 28.2) is applied after the first impact between the waste package and the unyielding surface (i.e., after 0.03 seconds), until the termination of the simulation at 0.05 seconds. The value of the damping coefficient is 200. This value was determined by running 3 test cases: first with a damping coefficient of 0 (no system damping); second with a coefficient of 50; and third with a coefficient of 200 as described in Attachment III.

5.4.3.2 Results

Based on the results documented in *21-PWR Waste Package Side and End Impacts-A Mesh Study* (BSC 2005 [DIRS 173178]), Table 5-4 lists the damaged area for the end impacts at 150°C for residual stress thresholds of 80 percent and 90 percent of the yield strength. An illustration of the damaged area distribution on the OCB surface is provided in Attachment III.

Table 5-4. Catalog of Damaged Areas from End-On Impact of a 21-PWR Waste Package on an Unyielding Surface

Impact Velocity	Damaged Area (m ²) for Stress Threshold of 80 Percent of Yield Strength as Function of Impact Angle				Damaged Area (m ²) for Stress Threshold of 90 Percent of Yield Strength as Function of Impact Angle			
	0°	1°	5°	8°	0°	1°	5°	8°
1 m/s	0.0	0.0020	0.0027	0.0020	0.0	0.0017	0.0014	0.0012
2 m/s	0.0024	0.0282	0.0130	0.0105	0.0	0.0035	0.0052	0.0051
4 m/s	0.0122	0.0421	0.0651	0.0474	0.0122	0.0126	0.0288	0.0212
6 m/s	0.0264	0.0521	0.1466	0.0967	0.0124	0.0222	0.0655	0.0335
10 m/s	0.0419	0.0571	0.2822	0.2244	0.0377	0.0259	0.1542	0.1206

Source: BSC 2005 [DIRS 173178], Tables 2 and 3.

5.4.4 Damaged Area Calculations from Kinematic Impact Data

The kinematic analyses, presented in Sections 5.4.1 and 5.4.2, do not use a refined FE mesh because it would result in prohibitively long calculations with multiple waste packages. Instead, the kinematic impact data are converted into damaged area using a “catalog” or lookup table based on highly refined FE calculations for end-on impact of a waste package on an unyielding surface. This section summarizes the methodology for calculating damaged area from the kinematic impact data. Additional details on the damaged area catalog are available in the *Seismic Consequence Abstraction* report (BSC 2005 [DIRS 173247], Sections 6.5.1.2 and 6.5.1.3).

Table 5-4 presents the damaged areas from end-on impacts for the residual stress thresholds of 80 percent and 90 percent of the yield strength of Alloy 22 at 150°C. The damaged area data in Table 5-4 has a complex angular dependence that has been simplified for the purpose of determining damaged areas from kinematic impact data. The simplification is motivated by two factors:

- The kinematic calculations are two-dimensional analyses that exclude the transverse horizontal component of each ground motion. This transverse horizontal component may increase or decrease the relative impact angle between two adjacent waste packages. Given the uncertainty in impact angle, it is reasonable to simplify the dependence shown in Table 5-4.
- Interpolation of damaged areas at small relative impact angles may result in misleading results. More specifically, the damaged areas near zero degrees may be artificially low because the ideal alignment for a 0° impact is unlikely to be duplicated by two adjacent waste packages that potentially have different masses and differing orientations relative to the impact plane.

The catalog of damaged areas has been simplified by assigning the mean value of the damaged areas at 1°, 5°, and 8° as the damaged area at a given impact velocity. This approach eliminates interpolation for impact angles near 0°. This approach also eliminates the potential sensitivity to changes in impact angle generated by the transverse horizontal component of the ground motion. Equal weighting of the damaged areas at 1°, 5°, and 8° is a reasonable approximation because

there is wide variability in the impact angles between adjacent waste packages in the kinematic calculations. Table 3-2 in Assumption 3.2.29 presents the resulting mean values.

The mean damaged areas in Table 3-2 have nonzero values even at the smallest impact velocity of 1 m/s. In order to use the results in Table 3-2 to determine damaged areas from kinematic impact data, it is necessary to define a velocity threshold corresponding to no damage (zero damaged area). The velocity threshold is estimated by extrapolating the mean damaged curve for a residual stress threshold of 80 percent of yield strength. The mean damaged area curve is plotted in Figure 3-1 in Assumption 3.2.29 as a function of the impact velocity. A simple linear extrapolation of the points at 1 m/s and 2 m/s indicates that the x-intercept of the curve corresponds to 0.851 m/s. The velocity threshold has been rounded to 0.85 m/s for the purpose of calculating damaged areas from end-to-end impacts of adjacent waste packages.

The mean damaged areas in Table 3-2 and the velocity threshold of 0.85 m/s (corresponding to zero damage) provide the basis for determining damaged areas from kinematic impact data. The methodology for determining total damaged area uses the relative impact velocity between adjacent waste packages from the kinetic analyses as an interpolation parameter between the given impact velocities in Table 3-2. The total damaged area is then defined as the sum of the damaged areas from the individual impacts to a waste package in each realization. This methodology has two significant conservatisms:

- The relative impact velocity between adjacent waste packages from the kinematic calculations should be divided by two to get the equivalent end-on impact velocity for interpolation in Table 3-2. As a concrete example, a 1 m/s end-on impact of a single waste package onto an unyielding surface is equivalent to the impact of two adjacent waste packages with velocities of +1 m/s and -1 m/s, for a total relative velocity of 2 m/s. Stated differently, the unyielding surface provides a plane of symmetry for the end-on impact calculations, and this plane of symmetry implies that waste packages are moving in equal and opposite directions, resulting in the factor of two increase in relative velocity for equal waste packages.
- The simple summation of damage from individual impacts overestimates the damage if impacts occur in the same location or if the damaged areas from adjacent impacts overlap significantly.

The methodology for analyzing damaged area does not incorporate the factor of two between end-on impact velocity and relative impact velocity because of uncertainties in the kinematic parameters. For example, adjacent waste packages are not always equal in mass and in their geometric configuration, so the factor of two cannot always be applied exactly. In addition, the two-dimensional kinematic calculations may not represent the full variation in impact location and geometry for the three-dimensional response. The potential reduction by a factor of two has therefore been excluded until the quantitative impact of uncertainties in the impact process are better understood.

The damaged areas from the kinematic calculations have been analyzed for four different cases: (i) LS-DYNA calculations for 80 percent residual stress threshold, (ii) LS-DYNA calculations for 90 percent residual stress threshold, (iii) UDEC calculations for 80 percent

residual stress threshold, and (iv) UDEC calculations for 90 percent residual stress threshold. The damaged area calculations for each of the four cases are documented in Excel spreadsheets that are available in the *Seismic Consequence Abstraction* (BSC 2005 [DIRS 173247], Appendix G).

5.5 WASTE PACKAGE–EMPLACEMENT PALLET INTERACTION

The calculations and results for waste package–emplacement pallet interaction are reported in *Structural Calculations of Waste Package Exposed to Vibratory Ground Motion* (BSC 2004 [DIRS 167083]) and *Additional Structural Calculations of Waste Package Exposed to Vibratory Ground Motion* (BSC 2004 [DIRS 171717]). This section summarizes the major features of the calculations and summarizes the results relevant to *Seismic Consequence Abstraction* (BSC 2005 [DIRS 173247]). Additional information with more detailed description of the calculations and results is provided in Attachment IV.

5.5.1 Numerical Representation

The objective of the calculations is to determine the residual stress distribution in the OCB of a waste package under vibratory ground motion, and to estimate the area of the waste package OCB for which the residual first principal stress exceeds the residual stress threshold. This area is called the “damaged area” in this document.

A set of 15 calculations for dynamic waste package structural response was performed for the suite of ground motions with a PGV of 2.44 m/s (BSC 2004 [DIRS 167083], Section 6.1). A similar set of calculations is also performed for a PGV of 5.35 m/s (BSC 2004 [DIRS 167083], Section 6.2) and a PGV of 1.05 m/s (BSC 2004 [DIRS 171717], Section 6.3). These values for PGV correspond to the peak of the first horizontal velocity component, which is always in a horizontal plane and perpendicular to the longitudinal direction for the structural response calculations (the longitudinal direction runs along the centerline of the drift). The stochastic (uncertain) input parameters for the 15 simulations are 15 sets of three-component ground motion time histories, the metal-to-metal friction coefficient, and the metal-to-rock friction coefficient (Assumption 3.2.4). A Monte Carlo sampling scheme defines the appropriate combinations of ground motion and friction coefficients (BSC 2004 [DIRS 169999], Section 6.4) for each PGV level. The sampled values of these stochastic parameters are listed in Table 5-5, with the friction coefficients rounded to two significant figures.

Each FE simulation is performed in three steps. The first step calculates the transient vibratory motion and impacts. The second step of the simulation is the post-vibratory relaxation to obtain steady-state results at the end of the ground motions. The third step of the analysis is comparison of the first principal residual stress with the residual stress threshold for accelerated corrosion cracking of Alloy 22. The goal of this step is to determine the “damaged areas” wherein the first principal stress exceeds the residual tensile stress threshold for Alloy 22.

Table 5-5. Values of Randomly Sampled Input Parameters for Each Realization

Realization Number	Ground Motion Number	Friction Coefficient (-)	
		Metal to metal	Metal to rock
1	7	0.80	0.34
2	16	0.33	0.49
3	4	0.50	0.62
4	8	0.60	0.22
5	11	0.20	0.24
6	1	0.27	0.69
7	2	0.71	0.60
8	13	0.56	0.54
9	10	0.55	0.36
10	9	0.36	0.41
11	5	0.42	0.67
12	6	0.65	0.73
13	12	0.75	0.31
14	14	0.29	0.45
15	3	0.46	0.78

Source: BSC 2004 [DIRS 167083], Table 6.1-1.

5.5.1.1 Finite-Element Mesh

Figure 5-14 illustrates the components of the three-dimensional FE representation for the vibratory ground-motion simulations. Figure 5-15 presents a cut-away view (portions of various parts are removed to offer a more revealing outlook) showing details of the waste package and emplacement pallet. As shown in these figures, the FE representation consists of the waste package mounted on its emplacement pallet, the surrounding drip shield, the invert surface, and the lateral and longitudinal boundaries. The longitudinal boundary represents the neighboring waste package/emplacement pallet assembly, while the lateral boundary represents the drift walls. The FE representation is developed based on the dimensions provided in the detailed design drawings (BSC 2005 [DIRS 173303]), as described in *Structural Calculations of Waste Package Exposed to Vibratory Ground Motion* (BSC 2004 [DIRS 167083], Attachments I, II, and III). The FE representations are then used in LS-DYNA to perform a transient calculation of the waste package exposed to vibratory ground motion.

The average waste package skirt-to-skirt spacing is 0.1 meters in the high temperature operating mode (BSC 2004 [DIRS 168489], Table 1). Thus, the distance between the waste package (specifically, the trunnion collar sleeve [i.e., the skirt]) and the longitudinal boundary (representing the neighboring waste package and emplacement pallet) is 0.1 meters.

Three components of the acceleration time history are simultaneously applied on the platform representing the top surface of the invert for each ground motion. The same acceleration time history is applied to all platform nodes simultaneously, resulting in zero deformation of the invert. The invert surface is represented in LS-DYNA as an elastic material.

The externally applied momentum from the ground motion is transferred to the freestanding (unanchored) objects solely by friction and impact. The lateral and longitudinal boundaries move synchronously with the platform and are rigid. In effect, these boundaries act like rigid members that are fixed to the platform.

Both ends of the waste package are represented as the bottom-end configuration (BSC 2004 [DIRS 167083], Attachment I and BSC 2005 [DIRS 173303]). The details of the waste package top end, such as the extended OCB lid and closure lid, are not explicitly represented and their mass is taken into account by increasing the thickness of the OCB lid. The thickness of the waste package OCB is reduced by 2 mm (from 20 mm to 18 mm) to represent degradation of the OCB over a 10,000-year to 20,000-year period. The part of the OCB that can come in contact with the emplacement pallet (Figures 5-16 and 5-17; also identified by regions F and C in Figure 5-17) is the most important area for these calculations. The FE representation for this region of the OCB is finely meshed on one side of the waste package (region F in Figure 5-17). All damage resulting from the waste package–emplacement pallet interaction during the vibratory ground motion reported in this document are based on region F. The FE mesh is modified for the 5.35-m/s PGV level ground motions due to the much higher intensity of the movements. The detailed description of the FE meshes, FE types, and material models used is provided in Attachment IV.

Time = 0

Source: BSC 2004 [DIRS 167083], Figure 1.

Figure 5-14. Initial Configuration for Waste Package Vibratory Simulations for Ground Motions at the 2.44 m/s Peak Ground Velocity Level

Time = 0

Source: BSC 2004 [DIRS 167083], Figure 2.

Figure 5-15. Cut-Away View of Initial Configuration for Waste Package Vibratory Simulations

Time = 0

Source: BSC 2004 [DIRS 167083], Figure 3.

Figure 5-16. Emplacement Pallet and Two Regions on the Outer Surface of the Waste Package that Can Come in Contact with the Emplacement Pallet

Source: BSC 2004 [DIRS 167083], Figure 4.

Figure 5-17. Side View of OCB of Waste Package, Showing Variations in Finite-Element Grid

The mesh of the FE representation was appropriately generated and refined in the contact regions according to standard engineering practice. Thus, the accuracy and representativeness of the results of this calculation are deemed acceptable (BSC 2004 [DIRS 167083], Attachments V through IX for discussion of results). The uncertainties are taken into account by random sampling (from appropriate probability distributions) of the calculation inputs that are inherently stochastic (uncertain) and characterized by a large scatter of data (ground-motion time histories and friction coefficients).

5.5.1.2 Ground-Motion Time History Cutoff

The structural response calculations for the waste package are computationally intense due to several factors discussed in Attachment IV. It is attractive to reduce the duration of the calculations by considering only that portion of the ground-motion time history that causes changes in the damaged area. For the ground motions at the 2.44-m/s PGV level, the computational duration is usually restricted to the 5 percent to 95 percent levels of ground motion energy, measured by Arias Intensity. Arias Intensity is an estimate of energy delivered to structures (Kramer 1996 [DIRS 103337], Section 3.3.4). For brevity, the minimum time corresponding to the 5 percent level of the ground motion energy is called the “5 percent-time”, and the maximum time corresponding to the 95 percent level of the ground motion energy is called the “95 percent time”.

All simulations for ground motions at the 5.35-m/s PGV level are performed from the 5 percent-time to the 90 percent level of the ground motion energy, referred to as the "90 percent-time". Thus, the starting times for the 2.44-m/s and 5.35-m/s PGV level coincide with the 5 percent-time, while the ending time for the 5.35-m/s PGV level has been reduced to the 90 percent time. A sensitivity study of the ending time was conducted for the 2.44-m/s PGV level comparing the damage areas between the 90 percent ending time and 95 percent ending time (BSC 2004 [DIRS 167083], Attachment VII). The appropriateness of using the 90 percent time is confirmed by the sensitivity study.

5.5.1.3 System Damping

In order to obtain steady-state results (i.e., residual stresses) in a reasonable time, it is necessary to apply damping during the second post-vibratory relaxation step of the computational process. The system damping is strictly a numerical technique for accelerating convergence to the steady-state stress state after the transient simulation is completed. It is applied globally to all elements and nodes of the FE grid. Detailed description of the damping constant used in the calculation is provided in Attachment IV.

5.5.2 Results

The damaged area due to the waste package–emplacement pallet interaction is only evaluated on the half of the waste package with the finely meshed region (Figures 5-16 and 5-17, and the discussion in Section 5.5.1). The total damaged area from waste package–emplacement pallet interaction is calculated by multiplying the damaged area from the finely zoned region by two.

Table 5-6 presents the damaged area resulting from the waste package–emplacement pallet interactions during the vibratory ground motion with horizontal PGV values of 1.05 m/s, 2.44 m/s, and 5.35 m/s. The damaged area is based on the residual first principal stress plot, as computed by the postprocessor LSPOST V2.0. The results for Realization 8 at the 2.44-m/s PGV level is not presented in Table 5-6 because an input error¹ was discovered for this calculation during the checking process. The results for realization 2 at the 5.35-m/s PGV level are not presented in Table 5-6 because the impacts between waste package and emplacement pallet are outside the finely meshed region of the outer shell, thereby reducing the numerical accuracy of the damage calculation for this realization.

¹ The three initial velocity components do not correspond to the beginning of the acceleration time history for Realization 8 at the 2.44 m/s PGV level. Consequently, the velocity and displacement time histories are not appropriately specified, so the results from this realization are not included in the abstraction process.

Table 5-6. Damaged Area from Waste Package–Emplacement Pallet Impacts at 2.44 m/s, 5.35 m/s, and 1.05 m/s Peak Ground Velocity Levels

Realization Number	Ground Motion Number	Damaged Area on the Waste Package								
		Waste Package-Emplacement Pallet Damaged Area at 2.44 m/s PGV-Transverse Level (m ²)			Waste Package-Emplacement Pallet Damaged Area at 5.35 m/s PGV-Transverse Level (m ²)			Waste Package-Emplacement Pallet Damaged Area at 1.05 m/s PGV-Transverse Level (m ²)		
		PGV-Long. (m/s)	80% Yield Strength	90% Yield Strength	PGV-Long. (m/s)	80% Yield Strength	90% Yield Strength	PGV-Long. (m/s)	80% Yield Strength	90% Yield Strength
1	7	2.44	0.0029	0.0014	5.31	0.20	0.17	0.89	0	0
2	16 ^d	2.44	0	0	N/A ^c	N/A ^c	N/A ^c	0.67	0	0
3	4	2.43	0.0050	0	5.69	0.096	0.083	1.00	0	0
4	8	2.44	0.030	0.0064	8.81	0.12	0.096	1.52	0.0014	0
5	11	2.44	0.0015	0	5.61	0.093	0.071	1.26	0	0
6	1	2.43	0.025	0.0028	4.28	0.046	0.024	0.83	0.0015	0
7	2	2.44	0.017	0	5.89	0.038	0.028	1.25	0	0
8	13	N/A ^a	N/A ^a	N/A ^a	6.65	0.095	0.068	1.04	0	0
9	10	2.38	0.0035	0	1.72	0.0052	0.0035	0.32	0	0
10	9	2.44	0	0	17.91	0.16	0.14	3.58	0	0
11	5	2.43	0.012	0.0037	5.64	0.032	0.0070	1.67	0	0
12	6	2.43	0.0039	0	2.90	0.062	0.041	0.46	0.0040	0.0014
13	12	2.43	0	0	5.95	0.027	0.018	0.70	0	0

Table 5-6. Damaged Area from Waste Package-Emplacement Pallet Impacts at 2.44 m/s, 5.35 m/s, and 1.05 m/s Peak Ground Velocity Levels (Continued)

Realization Number	Ground Motion Number	Damaged Area on the Waste Package								
		Waste Package-Emplacement Pallet Damaged Area at 2.44 m/s PGV-Transverse Level (m ²)			Waste Package-Emplacement Pallet Damaged Area at 5.35 m/s PGV-Transverse Level (m ²)			Waste Package-Emplacement Pallet Damaged Area at 1.05 m/s PGV-Transverse Level (m ²)		
		PGV-Long. (m/s)	80% Yield Strength	90% Yield Strength	PGV-Long. (m/s)	80% Yield Strength	90% Yield Strength	PGV-Long. (m/s)	80% Yield Strength	90% Yield Strength
14	14	2.44	0.010	0.0043	2.75	0.020	0.016	0.41	0	0
15	3	2.43	0.0078	0.0015	14.09	0.0045	0	2.62	0.028	0.014
2 ^b	15'	1.53	0	0	3.36	0.0080 ^c	0.0020 ^c	(Additional calculations were not performed at the 1.05 m/s and 5.35-m/s PGV levels because these ground motions already included spectral conditioning and intercomponent variability.)		
3 ^b	4'	2.60	0.0014	0						
4 ^b	8'	4.02	0.0032	0						
6 ^b	1'	1.95	0.0081	0.0014						
15 ^b	3'	6.43	0.043	0.010						

Sources: BSC 2005 [DIRS 167083], Tables 6.1.1-1 and 6.2.1-1; BSC 2004 [DIRS 171717] Tables 6.1-4, 6.2-7, and 6.3-6; BSC 2004 [DIRS 166107], Appendix X, Tables X-2, X-3, X-4, and X-5.

- NOTES: ^a Results for realization 8 are not presented because of an error in the input file for this calculation.
- ^b Additional calculations were performed primarily to determine the sensitivity of damaged area to spectral conditioning and intercomponent variability of the ground motions at the 2.44-m/s PGV level (BSC 2004 [DIRS 171717], Sections 6.1 and 6.2). These ground motions are denoted as 2', 3', 4', 6', and 15' to indicate the differences in the ground motion time histories.
- ^c Results for realization 2 with ground motion 16 are not presented because the kinematics of the waste package are such that the impacts between waste package and emplacement pallet occur outside the finely meshed region of the outer shell. Results for realization 2 with ground motion 15' are not exact because the waste package-emplacement pallet impacts occur partly outside the finely zoned mesh on the outer shell, but are included in the statistical analyses because the data lie within the range of the other realizations at the 5.35-m/s PGV level (BSC 2004 [DIRS 171717], Section 6.1.3).
- ^d Calculations are performed with 15 ground motions numbered 1, 2, 3, ..., 14, and 16. Seventeen sets of ground motion time histories were initially developed from which 15 sets were selected for these postclosure analyses. Ground motion #16 was initially substituted for ground motion #15 because of concerns about its response spectrum. Subsequent analyses with ground motion #15' at the 2.44 m/s and 5.35-m/s PGV levels (fifth line from the bottom in the table) indicate that ground motion #15' does not result in anomalous behavior (BSC 2004 [DIRS 171717], Section 6.2).

The original set of calculations for the 2.44-m/s PGV level (BSC 2004 [DIRS 167083]) used ground motion time histories that do not preserve intercomponent variability. In other words, the variability between the three velocity components of a given ground motion is limited because each velocity component is scaled to a target value, rather than maintaining the intercomponent variability in the original ground motion records. In addition, the ground motions records were not spectrally conditioned to earthquake spectra typical of the western United States.

Five additional calculations at the 2.44-m/s PGV level have been performed with ground motions that do preserve intercomponent variability and do condition response spectra to be more typical of those found in the western United States (BSC 2004 [DIRS 171717]). These time histories were spectrally conditioned to have response spectra more typical of the Yucca Mountain site prior to being scaled. The five additional calculations correspond to realizations 2, 3, 4, 6, and 15. Realizations 3, 6, and 4 are characterized by the largest damaged areas (in the descending order) among the calculations documented in Table 5-6.

Two calculations have been performed to evaluate the damaged areas for single ground motions at the 0.19-m/s PGV level and at the 0.384-m/s PGV level. Both calculations demonstrate that there is no damage to the waste package. Detailed description of the results for the ground motions at the 0.384-m/s PGV level is provided in Attachment IV.

5.6 WASTE PACKAGE-DRIP SHIELD INTERACTION

5.6.1 Cross-Drift Analysis of Interaction between the Waste Package and the Drip Shield

Interactions between the waste packages, the waste package and the emplacement pallet, and the waste package and the drip shield during strong seismic ground motion were estimated in longitudinal representations in the vertical plane along the axis of the emplacement drift as described in Section 5.4 and Attachments I and II. The boundary above the waste package in these calculations represented the drip shield which was assumed to be pinned in place with caved rock rubble. Consequently, the drip shield moved synchronously with the free field. As a result of the two-dimensional nature of the analysis and orientation of the longitudinal plane in which all objects were assumed to move, the calculations could not yield predictions of side impacts between the waste package and the drip shield, only the impacts of the waste package into the crown of the drip shield.

The interaction between the objects inside the emplacement drift during strong seismic ground motions is a truly three-dimensional problem. A general analysis would require a three-dimensional representation of geometry of a number of waste packages and drip shields, and representation and simulation of drift collapse. Such a calculation, if possible, would be time consuming and computationally intensive. Drift collapse and interaction between the collapsed rock mass and the drip shield was analyzed as a two-dimensional problem in the cross-section normal to the axis of the emplacement drift (i.e., cross-drift analysis); the results are presented in the *Drift Degradation Analysis* (BSC 2004 [DIRS 166107], Section 6.4). In the original calculation, the waste package-drip shield interactions were not considered. The waste package and the emplacement pallet were simulated to move synchronously with the free field and the invert. Movements of the waste package and the emplacement pallet inside the drip shield do not affect collapse of the emplacement drift and insignificantly affect interaction

between the drip shield and the collapsed rock around the drip shield (i.e., the loads that the collapsed rock exert on the drip shield). The same cross-drift calculation, in which the waste package and the emplacement pallet were allowed to move freely according to their masses and forces acting on them, was used to analyze the waste package-drip shield interactions—particularly the side impacts of the waste package into the drip shield. The impacts of the waste packages into the top part of the drip shield are also analyzed in the longitudinal section as described in Section 5.4.2 and Attachment II. In addition, the analysis is carried out to provide a confirmation of the assumption that the collapsed rock will pin down the drip shield, forcing it to move almost synchronously with the invert and the free field (Assumption 3.2.1).

This section describes the major features of the analysis and results relevant to *Seismic Consequence Abstraction* (BSC 2005 [DIRS 173247]). A complete and detailed description of the analysis and results are provided in Attachment V.

5.6.1.1 Numerical Representation

Because of the nature of the ground motions (three mutually orthogonal components of the ground motion) and the geometry of the objects inside the emplacement drift, the problem of interaction between the waste package and the drip shield is truly three-dimensional. Simulation of drift collapse in a three-dimensional representation simultaneous with analysis of impacts between the objects located inside the emplacement drift is extremely complex. Instead, a two-dimensional analysis was carried out in the vertical plane perpendicular to the axis of the emplacement drift. In this cross-drift calculation, impacts of the waste package into the side and top part of the drip shield were analyzed. Only two components of the ground motion were used in the cross-drift simulations: one horizontal (H2) and vertical. Longitudinal calculations also were carried out for two components of the ground motions: one horizontal (H1) and vertical, and are described in detail in Attachments I and II.

The analyses were carried out with UDEC version 3.1 (BSC 2002 [DIRS 161949], STN: 10173-3.1-00), which is a two-dimensional numerical code used to simulate the mechanical interaction of polygonal blocks. The code has a general algorithm for automatic detection of contacts between blocks. Any two blocks in the calculation can interact with each other at any point of calculation. The geometry of the numerical representation of the analyzed problem is shown Figure 5-18. All objects inside the emplacement drift were considered to be linearly elastic. Only impacts and impact velocities between those objects were monitored. Damage of the rock mass and collapse of the emplacement drift were simulated in the analyses.

Figure 5-18. Geometry of the Numerical Representation of the Emplacement Drift and the Engineered Systems Located Inside the Drift

The analyses simulate not only the motion of the engineered systems located inside the emplacement drift (i.e., the drip shield, the waste package, the emplacement pallet, and the invert), they also simulate the response of the rock mass and the overall stability of the emplacement drift during strong seismic ground motion. The lithophysal rock mass is represented as an assembly of randomly shaped, bonded polygonal blocks with an average size of 0.3 m. The approach of using bonded polygonal blocks to represent the mechanical response of the lithophysal rock mass and to analyze degradation of the emplacement drifts for strong seismic ground motions are discussed in detail in *Drift Degradation Analysis* (BSC 2004 [DIRS 166107], Section 6.4.2). Details about the rock mass material model are also described in Attachment V.

Hysteretic damping was applied to impacts between all the objects inside the drip shield, including impacts into the drip shield (e.g., waste package-emplacment pallet, waste package-drip shield and emplacement pallet-invert impacts). Details of contact hysteretic damping, which accounts for energy dissipation during impact, are discussed in Attachment II, Section II-2.4. No contact damping was used for impacts between caved rock blocks, or between rock blocks and the drip shield. The ratio between unloading and loading normal stiffnesses for metal-to-metal and metal-to-rock contacts is assigned the values of 2.7 and 50.0, respectively. This ratio controls the amount of energy dissipated by hysteretic damping during impact. The selected values of the ratios are the same as the values used in the analysis of waste package interaction in the longitudinal section (Attachment II). Different drop tests were carried out to determine the actual response of the objects used in the cross-drift calculation; the details are provided in Attachment II, Section II-2.4.

Two sets of 17 ground motions, at 2.44-m/s and 5.35-m/s PGV levels, were analyzed. Ground motions at the 1.05-m/s PGV level do not result in impacts above the 0.85 m/s damage threshold (Assumption 3.2.29) between the waste package and drip shield. The full duration of the ground motions was not simulated. Instead, the portion of the records of the ground motions between the points corresponding to 5 and 95 percent in the energy build-up, as measured by the Arias intensity (Kramer 1996 [DIRS 103337], Section 3.3.4), was simulated. For each three-component set of ground motions (i.e., two horizontal and one vertical), these points were determined for each component; then, the earliest 5 percent point and the latest 95 percent point were used to define the duration of strong ground motion for that set of ground motions.

Geometry of the objects within the drift was simplified in the analyses to account for the important features related to the waste package-drip shield impact study (Assumption 3.2.3). The rationale of using the simplified geometry is provided in Attachment V, Section V-3.3. The mechanical properties used in the analyses are listed in Attachment V, Section V-3.4.

5.6.1.2 Results

Waste package-drip shield and waste package-emplacement pallet impacts were monitored during the dynamic simulations. Time of impact, location of impact (in the global coordinate system) and relative impact velocity were recorded for each impact. Snap-shots of the simulated geometry taken every 0.05 s during the simulation were used to generate animations showing evolution of the drift geometry (collapse) and interaction between the objects inside the drift. The relative impact velocities reported in the global coordinate system are calculated as the difference between the average velocities of the waste package and the drip shield.

The summary of the waste package-drip shield impact results is listed in Table 5-7. The table contains the number of impacts with impact velocity greater than 0.85 m/s (Assumption 3.2.29) and the magnitude of maximum impact velocities (if greater than 0.85 m/s). Snap-shots of the geometry of the simulated problem at 1-s time intervals for realization 10 at the 2.44-m/s and 5.35-m/s PGV levels are shown in Attachment V, Figures V-9 and V-10. As illustrated in Figure V-10 in the frame at 5 s, the waste package impacts the plates attached to the drip shield legs, but also, for ground motions with large vertical acceleration, impacts the waste package into the bulkhead region in the crown (from below) of the drip shield structure. At the 2.44-m/s PGV level, the waste package impacts (with impact velocity greater than 0.85 m/s) the drip shield in 4 of 17 realizations. In two cases, the maximum impact velocities are greater than 5 m/s; in the other two cases, the maximum impact velocities are less than 2 m/s. In only two realizations at the 5.35 PGV level does the waste package not impact the drip shield with impact velocity greater than 0.85 m/s. The maximum impact velocities at the 5.35-m/s PGV level vary significantly from one realization to another. The largest impact velocity of 13.4 m/s is recorded for realization 10

Table 5-7. Summary of Waste Package-Drip Shield Impact Results

Realization	Motion	2.44 m/s Peak Ground Velocity Level		5.35 m/s Peak Ground Velocity Level	
		Total Number of Impacts*	Max. Velocity** (m/s)	Total Number of Impacts*	Max. Velocity** (m/s)
1	17	0	0.00	3	1.70
2	16	0	0.00	4	3.41
3	3	4	5.35	22	12.60
4	2	0	0.00	18	6.48
5	11	0	0.00	7	3.91
6	4	0	0.00	20	6.48
7	12	0	0.00	11	3.82
8	5	0	0.00	7	5.00
9	15	0	0.00	7	3.35
10	9	7	5.41	21	13.40
11	8	1	1.27	8	4.77
12	6	0	0.00	16	10.80
13	10	0	0.00	0	0.00
14	1	0	0.00	1	2.12
15	7	1	1.85	7	10.80
16	14	0	0.00	0	0.00
17	13	0	0.00	68	5.68

NOTES: *Number of impacts greater than 0.85 m/s.

**If greater than 0.85 m/s.

5.6.2 Structural Stability of the Drip Shield Subjected to Waste Package Impacts

The results of the cross-drift analyses presented in Section 5.6.1 (Attachment V) as well as the longitudinal kinematic analyses described in Sections 5.4.1 and 5.4.2 (Attachments I and II) indicate that some of the 17 realizations of ground motions at the 2.44-m/s and 5.35-m/s PGV levels result in impact of the waste package to the drip shield sidewall plates or to the bulkhead support beams exposed in the interior crown of the drip shield. The objective of this study is to investigate structural stability of a drip shield subjected to waste package impacts. Waste package orientation, magnitude of velocity, direction of velocity, and location of impact are explored; the range of which is based on the results from kinematic analysis of multiple waste packages subjected to vibratory ground motion (Sections 5.4.1, 5.4.2, and 5.6.1). In the analyses presented herein, the drip shield is surrounded by rubble from a collapsed drift. The dimensions and mass of the waste package used for impacting the drip shield are those of the 21-PWR (BSC 2005 [DIRS 173501]). The scope is limited to reporting whether or not drip shield structural collapse occurs (i.e., the loss of structural stability). If the structural collapse does not occur, the scope is limited to reporting the results in terms of the final horizontal deflection of the drip shield side plate (inward displacement of the bottom of the plate) and maximum Von-Mises stress in the structural members (drip shield plates, bulkhead, and large support beams). The analyses were carried out using the FE program LS-DYNA V970.3858 D MPP-00 (BSC 2003 [DIRS 166918], STN: 10300-970.3858 D MPP-00). A three-dimensional representation is used

in this analysis. The following discussion provides a summary of the detailed discussion of the results of the analyses presented in Attachment VI.

5.6.2.1 Impact Parameters

In all, 25 analyses are performed to study the effects of boundary conditions, waste package orientation, magnitude of velocity, direction of velocity, and location of impact on structural stability of the drip shield. Throughout this section the following nomenclature is used to describe the analyses: cross-drift refers to the x-axis, vertical refers to the y-axis, and longitudinal refers to the z-axis (Figure 5-19).

Figure 5-19. Full Finite-Element Representation of the Drip Shield

Analyses were conducted in which the angle of the waste package relative to the drip shield side wall was varied from 0° to 4° . The angle of contact is largely limited by the length and diameter of the waste package, the spacing of waste packages (0.1 m) and the inside clear dimension of the drip shield. Since the kinematic analyses indicate that the waste package may contact the interior of the drip shield at virtually any location, a number of particularly vulnerable locations were chosen that could have the greatest impact on structural stability of the drip shield. These locations are illustrated in Figure 5-20. These locations include:

- Plate 2 directly supported by the large support beam (Segment 1, Direct)
- Plate 2 centered between two large support beams (Segment 2 impact location)
- The bulkhead from underneath (Segment 1, Vertical and Vertical Oblique)

- The bulkhead from the side (longitudinally; Bulkhead impact location), and
- A combination of those impacts.

NOTE: Segment 1 is the drip shield segment between lines A and B, Segment 2 is between lines C and D, and the Triple Segment (used to test symmetry conditions and longitudinal bulkhead impacts) runs the full length. Only half of the drip shield is shown (the mesh is cut along the yz-plane for clarity).

Figure 5-20. Waste Package Impact Locations

A constant, conservative impact velocity for all simulations was set at 6 m/s. The kinematic analyses described in Sections 5.4.1, 5.4.2 and 5.6.1 indicate mean resultant waste package-drip shield impact velocities for the 2.44-m/s PGV level of 3.87 m/s or less. The maximum observed impact velocities for these PGV levels was less than 6 m/s. Therefore, performing these detailed drip shield structural calculations for an impact velocity of 6 m/s is considered conservative. Although 6 m/s impact is considered to be a conservative case, a number of analyses were run using an 11 m/s impact to demonstrate the robustness of the drip shield to waste package impact.

The direction of impact—the motion of the waste package relative to the drip shield was examined. Table 5-8 summarizes the impact velocity direction parameters chosen for each of the contact locations. The impacts are classified as direct, glancing (impact to wall plates with large longitudinal velocity component), oblique (horizontal impact to walls with equal horizontal velocity components), falling and rising oblique (oblique, with upward or downward velocity component), vertical and vertical oblique directions.

Table 5-8. Impact Direction and Corresponding Velocity Values

Name	Directional Vector	Magnitude (m/s)	Vx	Vy	Vz
Direct	(1, 0, 0)	6.000	6.000	0	0
Glancing	(0.1, 0, -1)	6.000	0.572	0	5.720
Oblique	(1, 0, -1)	6.000	4.243	0	-4.243
Falling Oblique	(1, -1, -1)	6.000	3.464	-3.464	-3.464
Rising Oblique	(1, 1, -1)	6.000	3.464	3.464	-3.464
Vertical	(0, 1, 0)	6.000	0	6.000	0
Vertical Oblique	(1, 1, 0)	6.000	4.243	4.243	0

The above velocity component directions were combined with both the 0° and 4° angular orientations of the waste package. Thus, a 4° orientation combined with a glancing velocity can result in a potential tearing or gouging mode of deformation along the sidewall plates. Additionally calculations in which the waste package “clips” a bulkhead beam at velocities of 1.00 m/s and 2.25 m/s were analyzed (Figure 5-21). This highly unlikely case (see Attachment VI for explanation) is viewed as an extreme test of drip shield stability as a waste package can severely bend and potentially destroy the support function of a bulkhead beam in this manner.

Figure 5-21. Waste Package Position for the Longitudinal Bulkhead Impacts

Finally, a simulation involving multiple impacts was conducted based on the results of the cross-drift analyses as described in Attachment V. Table 5-9 and Figure 5-22 illustrate the impact sequence and locations for the multiple impact analysis.

Table 5-9. Impact Sequence for Multi-Impact Analysis

Sequence #	Waste Package Orientation	Velocity	
		Magnitude (m/s)	Direction
1	0°	1.3	Vertical
2	4°	1.3	Direct
3	0°	5.4	Vertical Oblique
4	0°	2.4	Falling Oblique
5	4°	5.2	Direct
6	0°	2.0	Direct
7	4°	1.0	Rising Oblique

NOTE: The numbers in this figure correspond to sequence numbers in Table 5-9.

Figure 5-22. Impact locations for Multi-Impact Analysis

5.6.2.2 Finite-Element Representation

The details of the LS-DYNA FE representation are presented in Attachment VI and only summarized here. A detailed, three-dimensional representation of a typical drip shield segment, including bulkhead, longitudinal stiffeners, legs, and plates is provided (Figure 5-23).

NOTE: Some drip shield parts are partially removed from Figure to improve visibility.

Figure 5-23. Details of Finite-Element Representation of the Drip Shield (Inside View)

All deformable elements are of the brick-type, including five elements across the thickness of the drip shield plate to improve estimates of stress and strain fields at impact sites. As described in Section 5.6.1 and Attachment V, the emplacement drift is modeled to have collapsed at the 2.44-m/s and 5.35-m/s PGV levels¹. The weight of the resulting rock rubble lies on the drip shield and must be accounted for in stability estimates. The rubble is included in the FE representation via continuum brick elements surrounding the drip shield (Figure 5-24). Two heights for the broken rubble pile are represented in these analyses (Assumption 3.2.7). For most analyses the height of the pile extends 1 m above the drip shield (y-axis); the other represented height of the broken rubble pile is 7 m (Figure 5-25). As explained in Section VI-2.2.2, computational efficiency is the reason for the different heights. *Drift Degradation Analysis* (BSC 2004 [DIRS 166107], Section 6.4) presents an analysis of the drift collapse process and the resulting static loads induced by the collapsed rubble. In total, 6 realizations of collapse were simulated and the distribution of loads around the drip shield were estimated. The average

¹ The cross-drift analyses presented in Attachment V indicate no waste package-drip shield interactions for the 1.05 m/s PGV level.

vertical pressure exerted by the rubble load, as defined in the Drift Degradation Analysis, is applied here as a vertical pressure of 128 kPa applied to the top of the 1-m rubble pile analysis (see Assumption 3.2.7). Because of the increase in weight from the added rubble elements in the 7 m analysis, only 25 kPa is applied to the top [$128 \text{ kPa} - (7 \text{ m} \times 1,500 \text{ kg/m}^3 \times 9.81 \text{ m/s}^2) = 25 \text{ kPa}$]. This vertical pressure also induces a lateral loading to the drip shield via the Poisson effect. Thus, when impacted, the drip shield is preloaded as a result of the quasistatic drip shield load. A previous calculation (BSC 2003 [DIRS 162601]) has shown that the drip shield is stable under all six loading realizations with a substantial safety margin.

NOTE: Sections of the collapsed drift have been removed for clarity.

Figure 5-24. Triple Segment Finite-Element Representation of the Drip Shield

Figure 5-25. Numerical Representation of the 1-m (Green) and 7-m (Green and Pink) Broken Rubble Pile (a) Dimensions (b) Mesh Discretization

The collapsed rubble is assigned a “double yield” material model (see Attachment IX for a detailed description of the yield model and derivation of properties). This model is an elasto-plastic material model with both a shear and hydrostatic yield surface, and is thus capable of representing the compaction of a granular media and the irreversible strains that result from compaction of pore volume. The material properties for the rubble are derived from empirical and numerical simulations of the compression of collapsed rubble (Attachment IX, Assumptions 3.2.8 and 3.2.19). The drip shield is represented by an elasto-plastic material with hardening modulus and a von Mises yield function. Material properties of Titanium Grades 7 (plates) and Grade 24 (support structures) are estimated at 150°C. Material properties determined at this temperature are considered to be conservative for 97 percent of the 10,000-year postclosure period (Assumption 3.2.12). The details of the material properties selection for Titanium can be found in Attachment VI.

The waste package in the simulations is a simplified cylindrical body that is given the proper dimensions and mass of the 21-PWR waste package (Figure 5-26, Assumption 3.2.3). The waste package is “thrown” against the drip shield according to the parameters described previously. After impact (or multiple impacts) the resulting deformation of the drip shield, the locked-in residual stresses in the drip shield members and the overall stability of the drip shield are determined as the FE representation is allowed to equilibrate under gravitational and applied boundary loads.

Waste Package Representation for 4 degree Impacts

Waste Package Representation for 0 degree Impacts

00584DC_063.ai

Figure 5-26. Discretization of the Waste Package for Impact Analyses

5.6.2.3 Summary of Results

Analysis was performed to demonstrate the suitability of the boundary conditions. Results from single element compression tests in LS-DYNA demonstrate the ability of Material Type 5 to capture the behavior of UDEC numerical compression experiments (Attachment IX) on caved rock rubble (Assumption 3.2.19). Additionally, symmetry conditions were tested to show conservatism in the analyses herein.

Examination of drip shield survivability when enshrouded in rubble and subject to waste package impacts has been performed. Impacts of varying speeds and locations were explored. Even under extreme impact scenarios, each of the drip shield components remained within their ultimate strengths through all but one of the impact scenarios. Stresses during a 2.25-m/s longitudinal impact to the bulkhead indicate that the bulkhead will fail at the location of impact, although a discussion is presented (Section VI-3.4.2) that the likely occurrence of such an impact is small enough to dissolve concern. This discussion highlights the limited configurations (constrained by dimensions, orientation and relative motion of the components) that permit a longitudinal impact to the side of the bulkhead as well as the limited impact velocity possible for ground motions within the 10^{-8} annual exceedance frequency on the bounded hazard curve.

5.7 MAXIMUM ACCELERATIONS ON THE FUEL ASSEMBLIES OF A 21-PWR WASTE PACKAGE DURING END IMPACTS

The mechanical response of the waste package to vibratory ground motion can produce dynamic impacts between adjacent waste packages, between the waste package and its emplacement pallet, and between the waste package and the drip shield. During each of these impacts, the waste package may experience very high acceleration in the axial and lateral directions. These accelerations can be “transmitted” to the fuel assemblies. The assemblies may impact the lid of a waste package due to the end-on (axial) impact of adjacent waste packages, or be pushed sideways, toward the sidewall of the waste package, during impact with the emplacement pallet or drip shield. Either of these impacts has the potential to fail the fuel rod cladding. The focus in this study is on single direction (axial) impacts because single direction loadings have the potential to fail the cladding. The calculations and results for the estimate of the maximum accelerations on the fuel assemblies of a 21-PWR waste package during end impacts waste package are reported in detail in *Maximum Accelerations on the Fuel Assemblies of a 21-PWR Waste Package During End Impacts* (BSC 2003 [DIRS 162602]). This section describes the major features of the calculations and summarizes the results relevant to *Seismic Consequence Abstraction* (BSC 2005 [DIRS 173247]). Additional information with more detailed description of the calculations and results is provided in Attachment VII.

5.7.1 Numerical Representation

The objective of this calculation is to determine the acceleration of the fuel assemblies contained in a 21-PWR waste package during impact on an unyielding surface. More specifically, the average acceleration and the maximum acceleration of the fuel assemblies are defined by two successive differentiations of the appropriate displacement time history. All accelerations are expressed in units of g , the acceleration of gravity ($= 9.81 \text{ m/s}^2$).

These calculations represent a parametric study for average and maximum fuel assembly accelerations in response to end-to-end impacts of waste packages. The calculations are performed for five impact velocities at a 1-degree impact angle. The impact calculations are performed with an elastic unyielding boundary, rather than a detailed FE representation of the adjacent waste package (similar to the single 21-PWR waste package end impacts calculation described in Section 5.4.3). The use of a elastic and unyielding surface is computationally efficient because it reduces the computational mesh by a factor of two. The use of an unyielding surface also provides a conservative representation of the damaged area. The damaged area with an unyielding surface will generally be greater than the damaged area with an adjacent waste package because the unyielding surface is on a rigid boundary, maximizing impact stresses and deformation of the waste package for a given impact velocity and impact angle.

Material properties are based on two temperatures: 150°C and 200°C (BSC 2003 [DIRS 162602], Section 5.1). A temperature of 150°C is the base case for all calculations because it is conservative for 97 percent of the first 10,000 years and 98.5 percent of the first 20,000 years after repository closure (Assumption 3.2.12). Two calculations for impact velocities of 1 m/s and 4 m/s are also performed with material properties at 200°C to evaluate the sensitivity of fuel assembly accelerations at temperature.

The initial conditions for the calculations are an initial velocity of 0.5 m/s, 1 m/s, 2 m/s, 4 m/s, or 6 m/s, and an initial angle between the axis of the waste package and the vertical of 1 degree (i.e. $\alpha = 1^\circ$ in Figure 5-11). Additional calculations at multiple impact angles were not performed because the g-loads from these initial calculations were generally sufficient to fail most if not all fuel rod cladding. Therefore, a subset of the calculations provided sufficient data for developing the damage abstraction for the fuel rod cladding.

5.7.1.1 Finite-Element Mesh

A half-symmetry, three-dimensional FE representation of the waste package was developed using the dimensions provided in *Maximum Accelerations on the Fuel Assemblies of a 21-PWR Waste Package During End Impacts* (BSC 2003 [DIRS 162602], Attachment I). The waste package OCB and lids, IV and lids, trunnion sleeves, and fuel assemblies were represented by solid (brick) elements. The constant-stress eight-node solid element (Livermore Software Technology Corporation 2003 [DIRS 166841], p. 26.30) with one-point Gaussian quadrature (Hallquist 1998 [DIRS 155373], Section 3) was used for all calculations. The FE mesh is illustrated in Figure 5-27.

The thickness of the OCB was reduced by 2 mm on its outer surface (BSC 2003 [DIRS 162602], Assumption 3.14). The target surface was conservatively assumed to be elastic and unyielding (BSC 2003 [DIRS 162602], Assumption 3.11), and its density was rounded up to $8,000 \text{ kg/m}^3$. A static and dynamic friction coefficient of 0.5 was taken into account between all parts (BSC 2003 [DIRS 162602], Assumptions 3.12 and 3.13). This value of friction coefficient represents the average value of the distribution (0.2 to 0.8) used in *Structural Calculations of Waste Package Exposed to Vibratory Ground Motion* (BSC 2004 [DIRS 167083], Assumption 3.11). The effect of the friction coefficients on the deceleration of the fuel assemblies is expected to be a second-order effect. Since the resulting fuel rod accelerations exceeded the cladding failure threshold, the more detailed inquiry was unnecessary. Finally, no system damping or contact damping are applied during the simulations. Other simplifications of the internal structure of the waste package are described in Attachment VII.

The fuel assembly accelerations may vary with the initial gap between the fuel assemblies and the bottom lid of the inner vessel. The sensitivity of acceleration to gap size is analyzed in *Maximum Accelerations on the Fuel Assemblies of a 21-PWR Waste Package During End Impacts* (BSC 2003 [DIRS 162602], Attachment II). These results show that the configuration with the minimum gap results in the highest maximum acceleration. Consequently, all cases were run with the minimum gap between the fuel assemblies and the bottom lid of the inner vessel.

Time = 0

Source: BSC 2003 [DIRS 162602], Figure III-4.

Figure 5-27. Standard Mesh for Determination of Fuel Assembly Accelerations

5.7.1.2 Output Period

Computational results are saved at a user-defined output period. This output period is small enough to accurately capture the maximum values of acceleration. An output period of one nanosecond ensures stable values for the maximum acceleration, as demonstrated in *Maximum Accelerations on the Fuel Assemblies of a 21-PWR Waste Package During End Impacts* (BSC 2003 [DIRS 162602], Attachment IV). This output period is used for all results reported in Section 5.7.2.

5.7.2 Results

The maximum peak accelerations (in the axial direction of the fuel assemblies) experienced by any of the fuel assemblies for material properties evaluated at 150°C are presented in Table 5-10. Table 5-11 presents the average peak acceleration for each impact. The average peak acceleration is obtained by averaging the peak values of acceleration time histories of all fuel assemblies. Details of these calculations and supporting figures are provided in *Maximum Accelerations on the Fuel Assemblies of a 21-PWR Waste Package During End Impacts* (BSC 2003 [DIRS 162602]), Attachment V). A low-pass filter with three different cutoff frequencies has been used to remove the high frequency response for all the results presented in this document. The choice of cutoff frequencies is discussed in Attachment VII.

Table 5-10. Maximum Peak Acceleration (g) for the Fuel Assemblies with Three Different Cutoff Frequencies

Cutoff Frequency (Hz)	Initial Velocity (m/s)				
	0.5	1	2	4	6
450	75	144	263	323	506
600	101	192	347	369	567
1,000	136	343	502	479	701

Source: BSC 2003 [DIRS 162602], Table 4.

Table 5-11. Average Peak Acceleration (g) for the Fuel Assemblies with Three Different Cutoff Frequencies

Cutoff Frequency (Hz)	Initial Velocity (m/s)				
	0.5	1	2	4	6
450	35	72	115	155	194
600	48	99	147	180	219
1,000	78	160	215	244	278

Source: BSC 2003 [DIRS 162602], Table 5.

Two additional cases were run at 200°C, one with an initial velocity of 1 m/s and the second with an initial velocity of 4 m/s. The results are presented in *Maximum Accelerations on the Fuel Assemblies of a 21-PWR Waste Package During End Impacts* (BSC 2003 [DIRS 162602]),

Attachment VI). The variation of 50°C for material properties has only a minor effect on the results.

5.8 EFFECT OF CRUSHED TUFF INVERT ON AMPLIFICATION OF GROUND MOTIONS

The invert of the emplacement drifts consists of a carbon steel framework in which crushed tuff has been infilled and mechanically compacted. The weight of the waste package and drip shield will initially be borne by the steel framework, but this will eventually corrode and the weight gradually transferred to the crushed tuff. In the analyses of the effects of the seismic ground motions on the vibratory motion of the drip shield and the waste package presented in Sections 5.4.1, 5.4.2, 5.6.1, and 5.6.2, the invert is represented as a rigid body and its motion is completely synchronous with the motion of the free-field rock mass (Assumption 3.2.2). There is a concern that seismic ground motions could be amplified when transmitted through the crushed rock in the drift invert, subjecting the drip shield, the emplacement pallet and the waste package to stronger ground motions than those of the free-field rock mass (for which the seismic analyses were carried out). The effects of crushed tuff in the invert of the emplacement drifts on seismic ground motions were analyzed, and the results of the analyses are presented in this section. More detailed discussion is provided in Attachment VIII.

The potential for magnification of seismic ground motion passing through the crushed tuff in the invert of the emplacement drift is investigated analytically and numerically. Three sets of analyses have been conducted to evaluate the effect:

1. Analytical method based on the amplitude of the response of a single-degree of freedom (SDOF) system to a harmonic loading (Clough and Penzien 1975, [DIRS 164683]) (see Attachment VIII-2 for details).
2. Continuum numerical analyses with crushed tuff represented as a cohesionless continuum material (see Attachment VIII-3 for details).
3. Discontinuum numerical analyses with crushed tuff represented as a discontinuum granular material (see Attachment VIII-4 for details).

A SDOF analysis shows that the natural frequency of the crushed tuff in the invert is much larger than the largest dominant frequency of the seismic ground motions (Attachment VIII-2). The magnification factor due to dynamic amplification is, therefore, close to 1 based on Equation VIII-2. Consequently, if the deformation of the invert is elastic during the ground motion, the crushed tuff in the invert would move synchronously with the free field ground motion.

Since the crushed tuff is a material of relatively low strength in shear and tension, inelastic deformation is expected during strong ground motion, particularly those from the 5.35-m/s PGV level. Continuum analyses using the software FLAC version 4.0 (BSC 2002 [DIRS 161953], STN: 10167-4.0-00) were conducted to investigate the effect of the inelastic deformation in the invert. The continuum analyses, in which crushed tuff is represented as a cohesionless continuum material, were carried out for all ground motions from the 2.44-m/s and 5.35-m/s PGV levels. The vertical confinement of 50 kPa and 100 kPa, on top of the crushed tuff,

representing the average weight of the objects resting on the invert and the pressure due to the caved rock mass, was used in the calculations (Assumption 3.2.24). The numerical simulations indicate that in most cases the strong ground motions will induce PGV on top of the crushed tuff practically the same or insignificantly larger (within 5 percent) than the PGV of the free field (Tables VIII-4 to VIII-7). The increase in PGV and the number of cases with increased PGV is smaller for larger confinement and for less intense ground motions (i.e., the 2.44-m/s PGV level). The amplification, when it occurs, is associated with the high frequency portion of a motion and occurs over a relatively short duration of time.

The continuum analyses use two approximations that can potentially affect the analysis results:

- The crushed tuff in the invert of the emplacement drift is represented as a continuum material.
- The effect of the engineered systems inside the emplacement drift was taken into account by applying the vertical confining pressure on the crushed tuff.

To investigate the effects of these approximation, additional discontinuum analyses using the software UDEC version 3.1 (BSC 2002 [DIRS 161949], STN: 10173-3.1-00) were carried out. The discontinuum analyses, which represent the invert as a granular material, include explicit representation of the waste package, the emplacement pallet and the drip shield, and simulate collapse of the drift, show that the invert: a) deforms practically as a rigid body during ground motions from the 2.44-m/s PGV level, and b) undergoes irreversible deformation during ground motions from the 5.35-m/s PGV level. The irreversible deformation of the invert is probably overestimated in the numerical analysis, which represents the crushed tuff in the invert as a material with no porosity in the initial configuration (porosity for the crushed tuff was estimated to be around 31 percent). For the cases analyzed (both PGV levels) the maximum impact velocity (between the waste package and the emplacement pallet and the invert) and number of impacts decrease or remain the same if a deformable invert is assumed in the calculations, compared to the cases when the invert is represented as a rigid body.

The approach of representing the invert as a rigid body has relatively small effect on the ground motions to which the objects inside the emplacement drift are subjected. With relatively small effect, the representation of the invert as a rigid body is considered as justified and reasonable.

5.9 CONCLUSIONS

This calculation presents the results of analyses of the mechanical effects of postclosure vibratory ground motions on waste packages within the emplacement drift, and the additional effects that waste package movement may have on other engineered barrier components. The analyses included examination of the following effects:

- Waste package-to-waste package interactions and resulting damage to the lid area of the waste package
- Waste package-to-emplacement pallet interactions and resulting damage to the sides of the waste package

- Waste package-to-drip shield interactions and resulting potential stability to the drip shield from impact
- Effect of the crushed tuff invert on potential amplification of the ground motion.

The emplacement drift and the included engineered components are subjected to postclosure ground motion time histories characterized by PGV levels of 1.05 m/s, 2.44 m/s, and 5.35 m/s (representative of 1×10^{-5} , 1×10^{-6} and 1×10^{-7} annual exceedance probabilities for the unbounded hazard curve). Numerical analysis has shown that no damaging impacts occur for ground motions at the 1.05-m/s PGV level. The emplacement drifts in the lithophysal rock mass (approximately 85 percent of the emplacement area) are predicted to undergo significant degradation at PGV levels in excess of 1.5 m/s and collapse at PGV threshold level of 2 m/s. This collapse was shown to occur rapidly—within a few seconds. Thus, for the 2.44-m/s and 5.35-m/s PGV levels, the string of waste packages (approximately 100 in a typical 600-m-long emplacement drift) in an emplacement drift are enclosed in interlocked drip shields that are substantially or completely surrounded by broken rubble. This rubble causes the drip shields to move in synchronous motion with the free field rock mass.

The methodology employed in analysis of mechanical effects on engineered components from vibratory motion was to first conduct relatively simple kinematic analyses of many waste packages within rubble-pinned drip shields to examine waste package to waste package impacts (Sections 5.4.1 and 5.4.2, Attachments I and II). A kinematic analysis represents the waste packages in a relatively crude manner, but allows simulation of many interacting bodies. The purpose of the kinematic calculations was to determine impact parameters (e.g., number, location, relative velocity, and angle of impact) for 17 realizations of ground motion time histories at the 3 PGV levels. In a separate, more detailed calculation, FE analyses of a single waste package forced to impact a boundary at various velocities and angles of impact, was used to create a correlation between the impact parameters and damage (Section 5.4.3 and Attachment III). Damage here takes the form of a dent which becomes the site for local stress corrosion cracking and enhanced corrosion. Puncture or tearing of the waste package is not indicated based on the level of induced strain and the mechanical characteristics of the Alloy 22 outer corrosion barrier. The problem of simulation of the vibratory response of many free, potentially impacting bodies to large amplitude ground motion is complex. Therefore, two distinctly different kinematic numerical codes were used in these calculations to provide a range of impact response that takes into account the uncertainty of different calculation approaches and parameters such as contact damping. Use of different calculation methodologies also enhances confidence in the results of the analyses. The LS-DYNA FE (Section 5.4.1 and Attachment I) and UDEC discrete element (Section 5.4.2 and Attachment II) codes were used to perform kinematic analyses, each using different contact damping methods and different numbers of waste packages. Impact parameters for 51 realizations of vibratory motion simulations from each of these approaches (i.e., 102 total realizations) show similarities in the number and velocity of impacts, the UDEC approach being more conservative as a result of its two-dimensional nature and the use of hysteretic contact damping versus viscous contact damping and the three-dimensional geometry of the waste package and emplacement pallet employed in the LS-DYNA approach. It is felt that these two approaches provide a reasonable range of potential impact parameters for the abstraction of waste package to waste package damage assessment. The analyses show that early, simplified analyses of a single waste package

between rigid end boundaries (BSC 2004 [DIRS 167083]) resulted in very conservative waste package to waste package impact numbers and velocities. The kinematic calculations showed that the waste packages move largely in synchronous motion, and make contact primarily when extreme ground motions at the 5.35-m/s PGV level cause the waste package to lift off the emplacement pallet. When this occurs, synchronicity breaks down and a more chaotic response results. In general, however, the kinematic analyses lead to greatly reduced impacts from the earlier, single waste package calculations.

The output from UDEC and LS-DYNA approaches is contained in two output DTNs:

- MO0503SPAUDCW.000, [DIRS 173337]. Kinematic Data from UDEC for End-to-End Impacts Between Adjacent Waste Packages. Submittal date: 03/08/2005
- MO0504SPALSDYN.000, [DIRS 173338]. Kinematic Data from LS-DYNA for End-to-End Impacts Between Adjacent Waste Packages. Submittal date: 04/07/2005.

These output DTNs contain impact parameters for impacts between adjacent waste packages for the three central waste packages in the simulations. Additionally, waste package to emplacement pallet damage is calculated directly using a detailed single waste package FE vibratory motion representation (Attachment IV). The data from both the kinematic and single waste package–emplacement pallet interaction calculations is used as direct input to Revision 2 of *Seismic Consequence Abstraction* (BSC 2005 [DIRS 173247]) where conversion is made from impact velocity to surface area damage to the outer corrosion barrier. An abstraction is then developed relating total waste package damage to PGV for use in the total system performance assessment for the license application model, Seismic Scenario Class.

A two-dimensional UDEC calculation representing a cross-drift section was performed in which the collapse of the drift, drip shield loading, and waste package vibratory motion was conducted (Section 5.6.1 and Attachment V). The simulation showed that the drip shield is “pinned” to the invert within seconds of the arrival of the strong ground motion, forcing it to move synchronously with the invert and free-field rock mass for the remainder of the ground motion. Waste package impact parameters to the interior of the drip shield sidewall plates and crown bulkheads were determined and used to develop inputs to a subsequent calculation of their effect on the structural stability of the drip shield (Section 5.6.2 and Attachment VI). In these stability calculations, the drip shield is initially statically loaded by a 7.5 m height of rock rubble. Vibratory analyses for the 1.05-m/s PGV level showed no impacts of the waste package and drip shield. A total of 34 analyses (17 realizations at two ground motion PGV levels) were conducted for the 2.44-m/s and 5.35-m/s PGV levels. Calculations of the structural stability of the drip shield during single and multiple impacts shows that drip shield maintains stability. This occurs as a result of the confinement afforded to the drip shield by the surrounding rubble, and the ability of the rubble to absorb energy from impacts without allowing major distortions of the drip shield plates or supporting structure.

A calculation that determines the average peak acceleration and the maximum peak acceleration on the fuel assemblies in the axial direction due to impacts between adjacent waste packages was summarized in Section 5.7 and discussed in Attachment VII. The average peak acceleration is obtained by averaging the peak values of acceleration time histories of all fuel assemblies. The

maximum peak acceleration varies between 75 g's and 701 g's. The average peak acceleration varies between 35 g's to 278 g's. These accelerations form the basis for estimating buckling failure of the cladding due to end-to-end impacts of adjacent waste packages for the seismic scenario class.

Finally, an analysis of the potential amplification of the seismic wave in the crushed tuff invert was examined (Attachment VIII). It was shown that the amplification is minimal, particularly since collapsed rock rubble provides a small confining pressure to the top surface of the crushed tuff.

Other than the outputs from the two kinematic analyses, the data developed and documented in this calculation report have been entered into an additional DTN: MO0508SPAMECHA.000 in the Technical Data Management System.

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MO0408MWDGLCDS.002. General Corrosion and Localized Corrosion of the Drip Shield for LA. Submittal date: 08/27/2004. 171486

6.4 SOFTWARE CODES

BSC 2002. *Software Code: FLAC*. V4.0. PC WINDOWS 2000/NT 4.0. 10167-4.0-00. 161953

BSC 2002. *Software Code: UDEC*. V3.1. PC WINDOWS 2000/NT 4.0. 10173-3.1-00. 161949

BSC 2002. *Software Implementation Report for FLAC Version 4.0*. Document Number: 10167-SIR-4.0-00. Las Vegas, Nevada: Bechtel SAIC Company. ACC: MOL.20020925.0376. 168820

BSC 2002. *Software Implementation Report for UDEC Version 3.1*. Document Number: 10173-SIR-3.1-00. Las Vegas, Nevada: Bechtel SAIC Company. ACC: MOL.20021105.0245. 172041

BSC 2003. *Software Code: LS-DYNA*. V.970.3858 D MPP. HP Itanium2, HP-UX 11.22. 10300-970.3858 D MPP-00. 166918

BSC 2004. *Software Code: GoldSim*. V8.01 Service Pack 4. PC, Windows 2000. 10344-8.01SP4-00. 169695

LLNL (Lawrence Livermore National Laboratory) 2005. *Software Code: LS-DYNA SMP D*. V970.3858. DEC ALPHA OSF1 V5.1. 10300-970.3858-02. 172925

LLNL 2005. *Software Code: LS-DYNA SMP D*. V970.3858. SGI IRIX. 10300-970.3858-01. 172926

ATTACHMENT I

**LS-DYNA KINEMATIC ANALYSES
WITH MULTIPLE WASTE PACKAGES**

I-1. INTRODUCTION

This attachment describes a kinematic analysis of waste packages and the emplacement pallet and their interactions with the drip shield and invert as determined through use of the LS-DYNA software code. The scope of this calculation is limited to estimating end-to-end impact velocities between adjacent waste packages. The end-to-end impact velocities are ultimately used to estimate the damaged area on the waste package for use in the *Seismic Consequence Abstraction* (BSC 2005 [DIRS 173247]). Each emplacement drift contains approximately 100 waste packages containing commercial, DOE and Naval fuel as described in Section 3.2.17. To reduce the analysis to a tractable problem, the minimum number of waste packages as well as the “mix” of waste package types that are representative of the entire emplacement drift need to be determined. A base case analysis consisting of 7 waste packages containing 21-PWR and 5-DHLW/DOE-Long waste packages was used for calculation of impact velocities for damage assessment in the *Seismic Consequence Abstraction* (BSC 2005 [DIRS 173247]). To confirm the 7 waste package assessment, a parametric study was performed in which the impact of the number and “mix” of waste packages were studied.

The computer files developed for this attachment can be accessed through the TDMS. Two DTNs have been created for this attachment. The first DTN: MO0504SPALSDYN.000 includes the output information for the seven waste package kinematic analysis and used as direct input in *Seismic Consequence Abstraction* (BSC 2005 [DIRS 173247]). The second DTN: MO0508SPAMECHA.000 includes complete inputs and outputs (files are located in *Attachment I* folder).

I-2. KINEMATIC ANALYSIS

The kinematic analyses were performed using a FE representation of a series of waste packages. The FE calculation was performed with the commercially available LS-DYNA FE code (LLNL 2005 [DIRS 172925] STN: 10300-970.3858-02, LLNL 2005 [DIRS 172926] STN: 10300-970.3858-01). The FE representations were created using TrueGrid Version 2.2.0b (XYZ Scientific Application Inc.) and SLIC Version 4.90i (Lawrence Livermore National Laboratory).

I-2.1 DESCRIPTION OF FINITE-ELEMENT REPRESENTATION

The FE representation includes waste packages, emplacement pallets, and a rigid representation of the invert and drip shield (Figure I-1). Justification for the representation of the drip shield as a rigid upper boundary that moves with the free field ground motion can be found in Assumption 3.2.1. Justification for representation of the invert as a rigid horizontal surface that moves in sync with the free field is provided in Assumption 3.2.2. The invert and drip shield were extended beyond the waste packages (by the length of 4 waste packages) to accommodate relative horizontal motion of the waste packages.

Figure I-1. Finite-Element Representation of a Series of Waste Packages

Two waste package representations were created, approximating a 21-PWR waste package, and a 5-DHLW/DOE-Long waste package. The waste packages were characterized as hollow cylinders with end caps (Figure I-2). The inner diameter and end cap thickness of the waste packages were selected as convenient dimensions to approximate the inner cavity of the waste packages and to produce material densities on the same order as the density of other components in the FE representation, with the intent of maintaining reasonable analytic time steps. The geometry and mass of these waste packages are listed in Table I-1. Adjacent waste packages are spaced 10 cm apart (BSC 2004 [DIRS 168489], Table 1).

Table I-1. Geometry and Mass of Waste Package Representations

Waste Package	21-PWR	5-DHLW/DOE-Long
Outer Diameter (mm/inches) ¹	1718.3/67.65	2133.6/84.0
Inner Diameter (mm/inches) ²	1219.2/48.0	1625.6/64.0
Length (mm/inches) ¹	5024.4/197.81	5024.4/197.81
End Cap Thickness (mm/inches) ²	438.3/17.255	438.3/17.255
Weight (kg/lb)	41685/91900 ³	53070/117000

NOTES: ¹ Source: BSC 2005 [DIRS 173501], Table 1

² selected as convenient dimensions to approximate the inner cavity of the waste packages and to produce material densities on the same order as the density of other components in the FE representation (Assumption 3.2.3)

³ Assumption 3.2.27.

Figure I-2. Geometry of 21-PWR and 5-DHLW/DOE-Long Waste Packages, Shown from the Symmetry Plane Side

The emplacement pallets were represented as two hollow shell structures connected with beams (Figure I-3). The shell thickness of the sides and ends are 0.69 inches (17.5 mm) and the shell thickness of the top and bottom surfaces are 0.88 inches (22.4 mm) (Table I-2). The connecting beams are 6x6x3/8 inch square tubes and were represented as non-interactive, or no contact, elements (Assumption 3.2.15) using the LS-DYNA Belytschko-Schwer resultant beam element. The emplacement pallet tubes are assumed to perform their intended function throughout the regulatory period (Assumption 3.2.23). The emplacement pallet geometry dimensions and parameters are listed in Table I-2 (Assumption 3.2.3). The shear area is calculated as the width of the tube (6 inches) times the total wall thickness of the walls in the direction in question ($3/8'' + 3/8'' = 3/4''$). Thus, the shear area is $6'' \times 3/4''$ or 4.5 in^2 . This applies in both directions because the tubes are square.

Table I-2. Emplacement Pallet Geometry Dimensions and Parameters

Geometry Dimensions	
Total Length (mm/inch) ¹	4147.9/163.3
Support Pad Length (mm/inch) ²	542.8/21.37
Width (mm/in) ¹	2150/84.65
Height at Center (mm/inch) ²	115.2/4.53
Support Pad Angle (degree) ²	30
Shell Thicknesses	
Sides and Ends (mm/inch) ³	17.5/0.69
Top and Bottom (mm/inch) ³	22.4/0.88
Connecting Beam Properties (6x6x3/8 inch Tube)	
Area (mm ² /in ²) ⁴	5212.9/8.08
Rectangular Moment of Inertia (mm ⁴ /in ⁴)	1.732x10 ⁷ /41.6
Polar Moment of Inertia (mm ⁴ /in ⁴) ⁴	2.851x10 ⁷ /68.5
Shear Area (mm ² /in ²) ⁵	2903.2/4.5

NOTES: ¹ Source: BSC 2005 [DIRS 173303], Table 7

² Source: BSC 2005 [DIRS 173303], Directory, Emplacement pallet, Emplacement Pallet General Configuration, Nominal Dimensions, and Weights

³ Source: BSC 2005 [DIRS 173303], Table 7

⁴ Source: AISC 1989 [DIRS 107536], p.1-95

⁵ Calculated as the width of the tube (6 inches) times the total wall thickness of the walls in the direction in question ($3/8" + 3/8" = 3/4"$). Thus, the shear area is $6" \times 3/4"$ or 4.5 in².

Figure I-3. Finite-Element Representation of the Waste Package Emplacement Pallet

The invert and drip shield are represented by 10 inch (254 mm) thick blocks, slightly wider than the emplacement pallet (50.79 inches/1290 mm), and extended by the length of 4 waste packages (about 790 inches/20066 mm). The drip shield is placed 31.73 inches (806 mm) above the 21-PWR waste package (BSC 2004 [DIRS 168489], Figure 1). For the 5-DHLW/DOE-Long waste package, the drip shield is 14.20 inches (361 mm) above the waste package.

I-2.2 BOUNDARY CONDITIONS

There is a 0.5-second period for gravity initialization before ground motion time histories are applied. The force of gravity is ramped up to full strength over the first 0.2 seconds. During gravity initialization, every node of the invert and the drip shield is held fixed in the Y (vertical) direction, and the waste packages and emplacement pallets are free to settle. Global damping with a damping constant of 200.0 is applied over the first 0.4 seconds of the gravity initialization and then ramped down to 0.01 at 0.5 seconds. The global damping factor of 200 was selected as sufficient to allow the dynamic gravity initialization to be applied in 0.4 seconds, simulating a static solution. At 0.5 seconds, the vertical restraint is removed, and every node of the invert and the drip shield is prescribed to move with the input ground acceleration (Assumptions 3.2.1 and 3.2.2).

Ground motion is only applied in the Y (vertical) and Z (drift-longitudinal) directions (Assumption 3.2.22). Thus, the FE representation utilizes symmetry along the axis of the emplacement drift (Figure I-4, Assumption 3.2.22). A symmetry boundary condition is prescribed for all nodes on the symmetry plane; translation perpendicular to the plane (X direction) and rotations out of the plane (about the Y and Z axes) are restrained.

NOTE: The letters A to S represent the naming convention of the waste packages, with J being the center waste package.

Figure I-4. Finite-Element Representation of a Series of Waste Packages with a Plane of Symmetry Along the Axis of the Emplacement Drift (Z)

I-2.3 GROUND MOTIONS

Seventeen sets of ground motion time histories scaled to three different levels of horizontal PGV are used as input. The three PGV values are 1.05 m/s, 2.44 m/s and 5.35 m/s. These three levels of PGV correspond to 10^{-5} , 10^{-6} and 10^{-7} annual exceedance frequencies for the unbounded hazard curve. Ground motion is applied to the FE representation in two components: vertical and horizontal along the axis of the emplacement drift. The H1 component of the ground motion is used for horizontal. The 17 realizations referred to in this document correspond to the ground motions as shown in Table I-3. Each realization includes a set of ground motion and contact frictions from random selection as described in Attachment X. A discussion of the PGV levels for each ground motion time history can be found in Section 5.2.

Table I-3. Relationship Between Realization Number and Ground Motion Number

Realization Number	Ground Motion Number
1	17
2	16
3	3
4	2
5	11
6	4
7	12
8	5
9	15
10	9
11	8
12	6
13	10
14	1
15	7
16	14
17	13

I-2.4 MATERIAL PROPERTIES

The representations of the 21-PWR and 5-DHLW/DOE-Long waste packages are hollow cylinders with the density chosen so that they have the correct mass of the actual waste package. The waste packages and emplacement pallets are characterized with elastic properties (Assumption 3.2.16). The weight of the 21-PWR waste package is assumed as 91,900 lbs (41.7 MT) (Assumption 3.2.27), and the weight of the 5-DHLW/DOE-Long waste package is 117,000 lbs (53.1 MT) (BSC 2005 [DIRS 173501], Table 1). The density of the emplacement pallets is also chosen to give the correct emplacement pallet mass. The emplacement pallet weight is 4,340 lbs (1.97 MT) (BSC 2005 [DIRS 173303], Table 7). The modulus of elasticity and Poisson's ratio are the same for all components (Assumption 3.2.32). The unit weight and linear elastic material properties for each component are summarized in Table I-4. The waste package densities were calculated as the waste package weight divided by the waste package volume.

Table I-4. Material Properties

	21-PWR Waste Package	5-DHLW/DOE-Long Waste Package	Emplacement Pallet Shells	Emplacement Pallet Beams
Unit weight (Mass density) ¹	0.2269 lbs/in ³ (6281 kg/m ³)	0.2103 lbs/in ³ (5821 kg/m ³)	0.2282 lbs/in ³ (6317 kg/m ³)	0.2828 lbs/in ³ (7828 kg/m ³)
Modulus of elasticity ²	29.0e+6 psi (200 GPa)	29.0e+6 psi (200 GPa)	29.0e+6 psi (200 GPa)	29.0e+6 psi (200 GPa)
Poisson's ratio ²	0.29	0.29	0.29	0.29

NOTES: ¹ The densities were calculated as the waste package weight divided by the waste package volume

² Assumption 3.2.32

The coefficients of friction for metal-to-metal and metal-to-rock contact are random parameters that differ for each waste package and emplacement pallet set. The static and dynamic friction coefficients are taken to be the same, and the values range between 0.2 and 0.8 (Assumptions 3.2.4 and 3.2.11). The waste packages and emplacement pallets are named A to S, as shown in Figure I-4. The coefficients of friction for each of the 17 realizations for metal-to-metal and metal-to-rock contact (Attachment X) are presented in Table I-5 and Table I-6, respectively. The values of the coefficients of friction were determined using random sampling from GoldSim V8.01 SP4 (BSC 2004 [DIRS 169695], STN: 10344-8.01SP4-00) based on uniform distribution with range from 0.2 to 0.8 (Attachment X). Metal-to-metal contact includes waste package to emplacement pallet, waste package to drip shield, waste package to waste package, emplacement pallet to emplacement pallet and emplacement pallet to drip shield. Metal-to-rock contact includes emplacement pallet to invert and waste package to invert. The coefficients of friction for the repository components have high uncertainty because the appropriate values for the EBS materials are not available in handbooks and because long-term corrosion or time-dependent settling of the emplacement pallet into the invert has the potential to significantly modify the time-dependent values of the coefficients. The broad range for friction coefficient, 0.2 to 0.8, is designed to encompass a range of materials and a range of mechanical response, from little sliding to substantial sliding between components. In addition, the friction coefficients are independently sampled for each waste package/emplacement pallet set in order to represent the potential variability between sets caused by long-term corrosion and settling of the emplacement pallet.

The coefficients of friction are defined such that if two waste packages are in contact, then the governing metal-to-metal coefficient of friction is the value associated with the waste package closer to the central waste package, which is waste package J. For example, if waste packages I and J are in contact then the coefficient of friction for J governs; and if waste packages K and L are in contact then the coefficient of friction for K governs. The same is true for two emplacement pallets in contact, and a waste package and a emplacement pallet in contact. The metal-to-metal friction coefficient associated with the part closer to the center always governs (Figure I-5). The friction tables provided in Attachment X addressed contact between a waste package and its associated pallet. Because the tables did not address contact between adjacent waste packages and pallets, we selected this method to apply the friction table values to adjacent contact as a straightforward and systematic approach.

Table I-5. Metal-to-Metal Coefficients of Friction

Realization #	A	B	C	D	E	F	G	H	I	J
1	0.65366	0.32093	0.41049	0.59397	0.62892	0.60661	0.75327	0.57638	0.76666	0.51524
2	0.29918	0.57656	0.22729	0.29634	0.37167	0.42698	0.58001	0.74702	0.71202	0.45004
3	0.2101	0.2978	0.4157	0.42111	0.21613	0.39713	0.64045	0.68395	0.38015	0.74051
4	0.24688	0.76289	0.77047	0.72159	0.46025	0.73011	0.6898	0.77928	0.59089	0.69082
5	0.75363	0.40389	0.70558	0.5344	0.26819	0.37264	0.25901	0.59054	0.5031	0.25947
6	0.71345	0.76851	0.54769	0.46224	0.27656	0.54725	0.35055	0.21888	0.63054	0.61473
7	0.4989	0.5181	0.24096	0.58065	0.30793	0.50815	0.39718	0.26039	0.46047	0.39442
8	0.5422	0.34158	0.29694	0.67685	0.55815	0.33421	0.54781	0.35253	0.3539	0.56025
9	0.3427	0.43203	0.68965	0.77302	0.59291	0.64669	0.22696	0.63342	0.25203	0.62505
10	0.55884	0.47415	0.44808	0.21811	0.4267	0.22592	0.61641	0.38865	0.67503	0.70393
11	0.39109	0.61478	0.73592	0.31189	0.48914	0.71904	0.27611	0.27828	0.5235	0.30831
12	0.77613	0.70504	0.32481	0.24897	0.74443	0.77381	0.44932	0.50972	0.28727	0.44546
13	0.41564	0.21201	0.51689	0.36124	0.67096	0.67343	0.7712	0.33653	0.75305	0.28574
14	0.66831	0.67482	0.61252	0.76417	0.38496	0.29131	0.32614	0.53427	0.21966	0.37392
15	0.46891	0.64929	0.3414	0.65683	0.71042	0.58101	0.48249	0.69819	0.43675	0.77906
16	0.32215	0.25919	0.57013	0.40938	0.54539	0.25453	0.44579	0.46026	0.57408	0.2031
17	0.61847	0.48698	0.65764	0.50213	0.7805	0.4677	0.72451	0.44673	0.31337	0.52999

Realization #	K	L	M	N	O	P	Q	R	S
1	0.75102	0.5157	0.35643	0.69366	0.73239	0.32978	0.45509	0.47652	0.33038
2	0.6042	0.54777	0.79724	0.4289	0.60267	0.66686	0.5569	0.53298	0.58714
3	0.30566	0.39408	0.72101	0.47896	0.62874	0.49866	0.39225	0.3118	0.76816
4	0.50778	0.63458	0.58404	0.56918	0.48607	0.75819	0.35277	0.41628	0.61648
5	0.25645	0.24232	0.2559	0.77613	0.7796	0.47424	0.7833	0.40907	0.2673
6	0.22337	0.67929	0.53094	0.33738	0.38909	0.63465	0.66789	0.36621	0.36401
7	0.47226	0.34823	0.20738	0.50467	0.20838	0.25892	0.28686	0.2363	0.29154
8	0.42133	0.33122	0.68088	0.20348	0.46616	0.54976	0.74678	0.51548	0.44214
9	0.56144	0.46093	0.44477	0.521	0.26916	0.41464	0.52274	0.76424	0.76228
10	0.31181	0.77204	0.76396	0.30025	0.36628	0.21822	0.2544	0.21257	0.52024
11	0.64231	0.30564	0.51383	0.26906	0.28635	0.77079	0.30623	0.64481	0.47137
12	0.53103	0.43039	0.29137	0.70908	0.71439	0.71873	0.6035	0.77892	0.68733
13	0.39125	0.55866	0.63641	0.38089	0.30884	0.59673	0.50447	0.58825	0.50157
14	0.69048	0.21786	0.6201	0.74224	0.44618	0.34999	0.44056	0.27381	0.6299
15	0.37143	0.59041	0.33604	0.63661	0.56526	0.55725	0.63521	0.71355	0.2114
16	0.79285	0.73881	0.38888	0.34412	0.68342	0.28076	0.20709	0.66586	0.6973
17	0.72249	0.70122	0.45875	0.61745	0.53808	0.38202	0.70639	0.58018	0.38288

NOTE: A, B, C, ...to S are for waste package A to S per Figure I-4.

Table I-6. Metal-to-Rock Coefficients of Friction

Realization #	A	B	C	D	E	F	G	H	I	J
1	0.42599	0.75925	0.49458	0.53287	0.31878	0.35173	0.74103	0.45704	0.69753	0.54255
2	0.30763	0.21838	0.26419	0.25372	0.21881	0.47556	0.62115	0.30541	0.78146	0.72809
3	0.70431	0.32817	0.52106	0.71835	0.46306	0.23268	0.54727	0.66563	0.47206	0.28081
4	0.29588	0.53062	0.7556	0.60512	0.70412	0.26512	0.50095	0.75224	0.31661	0.51729
5	0.25515	0.71205	0.67405	0.63946	0.51949	0.31998	0.21052	0.4118	0.54475	0.25932
6	0.60713	0.39082	0.21636	0.51602	0.59847	0.65986	0.58546	0.78554	0.63455	0.77163
7	0.46305	0.42466	0.30311	0.55353	0.36894	0.48884	0.37835	0.69816	0.57661	0.38194
8	0.49958	0.2369	0.63152	0.37594	0.68582	0.76938	0.64869	0.6382	0.24013	0.42889
9	0.76426	0.49614	0.57289	0.28445	0.40191	0.76276	0.34456	0.37726	0.30423	0.67262
10	0.66982	0.29126	0.72884	0.7718	0.64684	0.57507	0.33072	0.3751	0.60203	0.61763
11	0.53046	0.59736	0.44766	0.75096	0.73761	0.61313	0.2599	0.22524	0.74656	0.73279
12	0.23096	0.69271	0.6006	0.45188	0.27697	0.54717	0.69196	0.50715	0.40301	0.45438
13	0.6353	0.78792	0.3432	0.30981	0.2418	0.6487	0.79918	0.56208	0.49327	0.58555
14	0.39148	0.36413	0.76763	0.66907	0.5721	0.41082	0.72599	0.60736	0.22821	0.32038
15	0.36656	0.62453	0.39484	0.41988	0.42366	0.4285	0.4673	0.54813	0.35977	0.36674
16	0.77983	0.46813	0.44287	0.39528	0.50229	0.30264	0.4403	0.2652	0.44273	0.65572
17	0.55932	0.57103	0.31062	0.21597	0.7717	0.70299	0.29046	0.3228	0.66081	0.21857

Realization #	K	L	M	N	O	P	Q	R	S
1	0.38877	0.57453	0.79893	0.56298	0.34316	0.54326	0.52918	0.20182	0.51192
2	0.75214	0.32463	0.20062	0.60189	0.27448	0.6097	0.72886	0.76432	0.68681
3	0.60163	0.61272	0.25471	0.64311	0.72375	0.27107	0.78317	0.29239	0.78193
4	0.35038	0.43717	0.46407	0.26659	0.77564	0.34663	0.73924	0.36955	0.7167
5	0.69165	0.54699	0.35103	0.67948	0.50768	0.46019	0.24674	0.77885	0.21525
6	0.31924	0.72421	0.61791	0.79615	0.45665	0.41425	0.36236	0.60087	0.37303
7	0.48086	0.22705	0.73956	0.34598	0.3188	0.586	0.44123	0.72705	0.2458
8	0.72895	0.6255	0.28395	0.2151	0.57393	0.22714	0.60287	0.32736	0.43934
9	0.64526	0.23701	0.38195	0.44947	0.3943	0.26013	0.33219	0.66914	0.59323
10	0.27976	0.73971	0.72279	0.33801	0.68688	0.64201	0.48012	0.56923	0.28825
11	0.76485	0.39674	0.6633	0.51543	0.25447	0.72468	0.22319	0.43012	0.56685
12	0.41936	0.27781	0.52803	0.27384	0.21461	0.7963	0.50208	0.46139	0.32037
13	0.55591	0.7672	0.42402	0.53312	0.64854	0.68441	0.57084	0.54066	0.53606
14	0.53052	0.46441	0.64702	0.44138	0.6173	0.38265	0.68507	0.39297	0.63893
15	0.24573	0.51169	0.49723	0.72925	0.73842	0.50685	0.64582	0.51668	0.40874
16	0.21804	0.66316	0.31832	0.38214	0.52296	0.31738	0.39991	0.64781	0.75924
17	0.4937	0.37117	0.56647	0.73483	0.41704	0.75098	0.2781	0.24537	0.46195

NOTE: A, B, C, ...to S are for waste package A to S per Figure I-4.

NOTE: Arrows indicate which friction coefficients are used when units interact horizontally. The friction coefficients associated with the J waste package and emplacement pallet are used for interactions with I and K waste packages and emplacement pallets. The friction coefficients associated with the K waste package are used for interactions with the L waste package and emplacement pallet.

Figure I-5. Convention for Friction Coefficients between Waste Packages

All interactions between components in the FE representation are defined using surface-to-surface contact. The contact interfaces for interaction between adjacent waste packages and for interaction of waste packages with the invert and drip shield are defined based on segment sets. This reduced the computational intensity of these contact interfaces by limiting the scope of the contact search algorithm. The contact interfaces involving the emplacement pallet are less predictable and required using part-to-part contact, where the contact surfaces are determined by LS-DYNA based on all surfaces of the parts. Interface contact definitions and parameters are discussed in Hallquist 1998 [DIRS 155373], Section 23 and LS-DYNA Keyword User's Manual (Livermore Software Technology Corporation 2003 [DIRS 166841], Section 6).

I-3. ANALYSES AND RESULTS

The kinematic analysis effort involved developing a FE representation that would capture the kinematic motion of multiple waste packages and emplacement pallets, as well as the interactions between these components and the invert and drip shield boundaries. Preliminary analyses were focused on determining a reasonable waste package representation that would be applied to the suite of 51 total ground motions, with the ultimate objective of development of a revision to the damage abstraction for the *Seismic Consequence Abstraction* (BSC 2005 [DIRS 173247]). A series of preliminary kinematic simulations were performed for various configurations of waste packages, ranging in number from 5 to 13, containing primarily 21-PWR waste packages and one or two 5-DHLW/DOE-Long waste packages. These preliminary analyses were used to determine the minimum number of waste packages that provide a reasonable representation of the interactions of many waste packages in a typical emplacement drift. A seven waste package configuration (Figure I-6) was selected as representative of potential repository emplacement drift conditions (see Assumption 3.2.17), and a suite of 51 analyses was performed, one for each of the 17 ground motions at 3 different PGV (i.e., annual exceedance) levels. All waste package-to-waste package impacts and impact velocities were extracted from the output of these seven waste package configuration and used, along with the DE kinematic simulations described in Attachment II, to calculate waste package surface damage areas (BSC 2005 [DIRS 173247], Section 6.5.1). Subsequently, additional calculations were performed to examine the effect of various analysis parameters, in particular the contact

parameters, on the number of impacts and their velocities. Using the resulting updated analysis parameters, additional analyses were performed to further evaluate the number of waste packages required to minimize the end effects of the representation. Configurations were evaluated with 7 to 19 waste packages with a 5-DHLW/DOE-Long waste package between groups of three 21-PWR waste packages. From these analyses, an 11 waste package configuration (Figure I-7) was selected, and a suite of 51 analyses were performed to verify that the damage area results from the seven waste package configuration analyses were conservative.

NOTE: The configuration consists of five 21-PWR waste packages and two 5-DHLW/DOE-Long waste packages. Impacts to the center three waste packages are considered representative of a typical repository waste package.

Figure I-6. Seven Waste Package Configuration (Base-Case Analyses)

Figure I-7. Eleven Waste Package Configuration

I-3.1 PRELIMINARY ANALYSES

The focus of the preliminary analyses was to develop a reasonable FE representation of a series of waste packages that would be subjected to 51 seismic ground motions, resulting in estimates of the number and velocity of waste package end-to-end impacts. Generic friction coefficients and a single ground motion record (ground motion 1 at 5.35 m/s PGV) were used for these preliminary analyses (Figure I-8). The waste package representation was analyzed in a variety of configurations, which included a baseline representation of a single 21-PWR waste package between fixed adjacent waste packages, 5 to 13 waste packages with a single, central 5-DHLW/DOE-Long waste package, 13 waste packages with five 21-PWR waste packages between two 5-DHLW/DOE-Long waste packages (Figure I-9). These configurations were evaluated on the number of impacts between adjacent waste packages (Figure I-10), the maximum impact force between waste packages (Figure I-11) and animations of the analysis simulations (Figure I-12). Relative impact velocities were manually extracted for two impacts (shown in Figure I-11) and used to infer impact velocities prior to developing techniques to extract the relative impact velocities for all impacts directly from the analysis results. The single waste package case had the largest number of impacts and the highest impact forces. The 13 waste package case with two 5-DHLW/DOE-Long waste packages predicted a larger number of impacts and higher impact forces than configurations with a single 5-DHLW/DOE-Long waste package. The results from these analyses also indicated that use of multiple 5-DHLW/DOE-Long waste packages provides a “confinement” to the waste packages between them, thus preventing outer waste packages from translating away from the central waste package after a number of collisions. Additional analyses compared various configurations with two 5-DHLW/DOE-Long waste packages (Figure I-13). Based on comparisons of number of impacts (Figure I-14), maximum impact forces (Figure I-15), and simulation animations, the seven waste package configuration, case 7i with three 21-PWR waste packages between two 5-DHLW/DOE waste packages (Figure I-6), was selected as a reasonable configuration for

determination of the number and velocity of impacts for use in later damage abstractions (BSC 2005 [DIRS 173247]). Case 7i predicted representative numbers of impacts and impact forces, either typical of the other configurations, or larger. This seven waste package configuration (five 21-PWR waste packages and two 5-DHLW/DOE-Long waste packages) approximates the anticipated mix of emplaced waste package sizes and weights as described in Assumption 3.2.17.

NOTE: Ground motion 1 at 5.35-m/s PGV (10^{-7} exceedance frequency) was applied in two directions, H1 in the longitudinal horizontal direction (Z), and V in the vertical direction (Y).

Figure I-8. Application of Generic Friction Coefficients to Contact Interfaces

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Figure I-9. Preliminary Configurations of Waste Packages, Including Baseline Configuration with a Single Waste Package between Fixed Adjacent Waste Packages

NOTE: Case 13(2), with two 5-DHLW/DOE-Long waste packages (Figure I-9), generally predicted more impacts than did configurations with a single 5-DHLW/DOE-Long waste package.

Figure I-10. Comparison of Number of Impacts between Adjacent Waste Packages for Five Configurations

NOTE: Case 13(2), with two 5-DHLW/DOE-Long waste packages (Figure I-9), predicted higher impact forces than configurations with a single 5-DHLW/DOE-Long waste package.

Figure I-11. Comparison of Maximum Impact Force between Adjacent Waste Packages for Five Configurations, Including Inferred Velocity

Figure I-12. Typical Animation Snap Shots used to Evaluate Preliminary Configurations

Figure I-13. Additional Waste Package Configurations with Two 5-DHLW/DOE-Long Waste Packages

NOTE: Case 7i predicted a representative number of impacts for the center 3 waste packages, I, J, and K.

Figure I-14. Comparison of Number of Impacts between Waste Packages for Configurations with Two 5-DHLW/DOE-Long Waste Packages

NOTE: Case 7i predicted representative impact forces for the center 3 waste packages, I, J, and K.

Figure I-15. Comparison of Maximum Impact Force between Waste Packages for Configurations with Two 5-DHLW/DOE-Long Waste Packages

I-3.2 SEVEN WASTE PACKAGE CONFIGURATION

The suite of 51 seismic ground motions was applied to the seven waste package configuration (Case 7i in Figure I-13) to determine the number of and relative velocities of end-to-end impacts. A complete listing of the number of contacts, the angle of contact and relative impact velocity for each of the 51 seven waste package analyses can be found in DTN: MO0504SPALSDYN.000 [DIRS 173338] (*LLNL_Impact_Velocities_E-5.xls* for 1e-5 ground motion, *LLNL_Impact_Velocities_E-6 02-14-05.xls* for 1e-5 ground motion, *LLNL_Impact_Velocities_E-7 02-14-05.xls* for 1e-7 ground motion). Waste package-to-waste package impact velocities were processed as the maximum relative horizontal (Z) closing velocity between the upper or lower corner nodes of adjacent waste packages at the simulation time just prior to the onset of contact (Figure I-16). The onset of contact occurs when the contact force for the waste package-to-waste package interface becomes non-zero (a zero force indicates that no contact is taking place). The number of impacts and maximum impact velocities for the center three 21-PWR waste packages are summarized in Tables I-8 to I-13 for the 2.44 m/s and 5.35 m/s cases. Only those ground motion realizations that indicated impacts with velocities greater 0.85 m/s are given (Assumption 3.2.29). A relative velocity of 0.85 m/s is a reasonable level, below which, the waste packages suffer no surface damage (BSC 2005 [DIRS 173247], Section 6.5.1.2, Figure 6.5-8). As seen in these tables, the maximum impact velocity is approximately 2.7 m/s and 12 m/s for the 2.44-m/s and 5.35-m/s PGV cases. A significantly greater number of impacts occurs for the 5.35 m/s case, as expected.

Figure I-16. The Impact Velocity between Adjacent Waste Packages is the Maximum Relative Closing Velocity between Upper Corner Nodes TL and TR or Lower Corner Nodes BL and BR

For purposes of comparison of the seven waste package representation to representations with greater numbers of waste packages, the impact information is converted into end-to-end damage area. This conversion requires previously-completed calculations that established tables of damage area as functions of impact velocity, impact angle, temperature, and stress limit

(BSC 2005 [DIRS 173178], Tables 2 and 3¹ as summarized in Table 5-4 of this document). These damage lookup tables are also used in combination with the impact data in DTN: MO0504SPALSDYN.000 [DIRS 173338] (*LLNL_Impact_Velocities_E-5.xls* for 1e-5 ground motion, *LLNL_Impact_Velocities_E-6 02-14-05.xls* for 1e-6 ground motion, *LLNL_Impact_Velocities_E-7 02-14-05.xls* for 1e-7 ground motion) for determination of end-to-end waste package damage area in *Seismic Consequence Abstraction* (BSC 2005 [DIRS 173247]). For the purpose of these kinematic analyses, the damage tables were simplified by averaging the effects of impacts at angles of 1, 5, and 8 degrees (Table I-7). Damage areas, for both 80 percent and 90 percent yield strengths, were obtained for each impact characterized by a relative velocity above 0.85 m/s (Assumption 3.2.29), by linear interpolation based on velocity. The damage area results are presented in Tables I-8 to I-13. Each table lists the number of impacts, the maximum impact velocity, and the damage areas for both 80 percent and 90 percent yield strengths, as a function of realization number (1 to 17). Realizations that have zero predicted impacts above 0.85 m/s have been removed from the tables. The tables are organized by waste package (left-of-center, center, right-of-center) and ground motion level (2.44-m/s PGV, 5.35-m/s PGV). The 1.05-m/s PGV ground motions resulted in zero impact velocities above 0.85 m/s. Thus, the kinematic analysis predicts zero damage at this level.

Table I-7. Damage Areas as Function of Impact Velocity and Yield Strength

Impact Velocity (m/s)	Damage Area at 80% Yield Strength (m ²)	Damage Area at 90% Yield Strength (m ²)
0.85	0.000	0.0000
1.0	0.0022	0.0014
2.0	0.0172	0.0046
4.0	0.0515	0.0209
6.0	0.0985	0.0404
10.0	0.1879	0.1002

Table I-8. Damage Areas for Left-of-Center Waste Package I at 2.44 m/s PGV

Realization Number	Number of Impacts	Maximum Impact Velocity (m/s)	Damage Area at 80% Yield Strength (m ²)	Damage Area at 90% Yield Strength (m ²)
3	1	1.994	0.0171	0.0046
4	1	0.871	0.0003	0.0002
10	2	1.491	0.0098	0.0031
15	2	2.727	0.0444	0.0146
16	1	0.912	0.0009	0.0006

NOTE: The damage areas reported above have been rounded to 4 significant digits.

¹ The damage in Tables 2 and 3 designated as B-DA for the refined FE mesh are used to estimate damage as a function of velocity and impact angle.

Table I-9. Damage Areas for Center Waste Package J at 2.44 m/s PGV

Realization Number	Number of Impacts	Maximum Impact Velocity (m/s)	Damage Area at 80% Yield Strength (m ²)	Damage Area at 90% Yield Strength (m ²)
2	1	0.873	0.0003	0.0002
3	2	2.588	0.0311	0.0112
4	1	0.871	0.0003	0.0002
10	4	1.491	0.0141	0.0054
15	2	2.727	0.0498	0.0165
16	1	1.021	0.0026	0.0015
17	1	0.945	0.0014	0.0009

NOTE: The damage areas reported above have been rounded to 4 significant digits.

Table I-10. Damage Areas for Right-of-Center Waste Package K at 2.44 m/s PGV

Realization Number	Number of Impacts	Maximum Impact Velocity (m/s)	Damage Area at 80% Yield Strength (m ²)	Damage Area at 90% Yield Strength (m ²)
2	2	0.924	0.0014	0.0009
3	4	2.588	0.0371	0.0138
4	1	0.993	0.0021	0.0014
6	1	0.875	0.0004	0.0002
7	1	0.886	0.0005	0.0003
10	6	2.229	0.0319	0.0122
15	3	2.166	0.0400	0.0121
16	2	1.221	0.0081	0.0036
17	1	0.945	0.0014	0.0009

NOTE: The damage areas reported above have been rounded to 4 significant digits.

Table I-11. Damage Areas for Left-of-Center Waste Package I at 5.35 m/s PGV

Realization Number	Number of Impacts	Maximum Impact Velocity (m/s)	Damage Area at 80% Yield Strength (m ²)	Damage Area at 90% Yield Strength (m ²)
2	5	7.91	0.1545	0.0754
3	6	4.725	0.1521	0.0583
4	8	3.817	0.1867	0.0679
5	2	1.946	0.0180	0.0054
6	6	3.295	0.0958	0.0349
7	6	2.112	0.0496	0.0168
8	3	2.88	0.0584	0.0207
9	2	1.349	0.0080	0.0029
10	8	5.388	0.2602	0.1004
11	4	2.386	0.0437	0.0141
12	9	1.757	0.0552	0.0195
13	5	2.471	0.0443	0.0162
14	4	2.637	0.0409	0.0149
15	8	3.143	0.0743	0.0282
16	6	1.476	0.0288	0.0115
17	5	2.105	0.0326	0.0120

NOTE: The damage areas reported above have been rounded to 4 significant digits.

Table I-12. Damage Areas for Center Waste Package J at 5.35 m/s PGV

Realization Number	Number of Impacts	Maximum Impact Velocity (m/s)	Damage Area at 80% Yield Strength (m ²)	Damage Area at 90% Yield Strength (m ²)
2	2	1.149	0.0082	0.0037
3	5	11.923	0.3349	0.1687
4	8	3.196	0.1571	0.0576
5	2	1.946	0.0268	0.0076
6	8	4.079	0.1929	0.0704
7	6	2.112	0.0302	0.0108
8	5	2.88	0.0739	0.0259
9	1	0.888	0.0006	0.0004
10	11	6.253	0.2725	0.1024
11	2	1.992	0.0233	0.0068
12	10	1.757	0.0653	0.0224
13	5	2.471	0.0510	0.0176
14	3	2.539	0.0381	0.0134
15	7	2.71	0.0669	0.0233
16	3	1.85	0.0257	0.0083
17	4	2.105	0.0328	0.0111

NOTE: The damage areas reported above have been rounded to 4 significant digits.

Table I-13. Damage Areas for Right-of-Center Waste Package K at 5.35 m/s PGV

Realization Number	Number of Impacts	Maximum Impact Velocity (m/s)	Damage Area at 80% Yield Strength (m ²)	Damage Area at 90% Yield Strength (m ²)
2	1	1.458	0.0091	0.0029
3	3	11.923	0.2860	0.1495
4	7	3.196	0.0961	0.0326
5	2	1.759	0.0240	0.0070
6	7	4.079	0.1397	0.0493
7	4	1.109	0.0063	0.0034
8	4	2.205	0.0395	0.0131
9	1	1.098	0.0037	0.0017
10	8	6.253	0.2839	0.1119
11	1	1.26	0.0061	0.0023
12	8	2.003	0.0522	0.0174
13	6	1.683	0.0284	0.0109
14	4	2.539	0.0567	0.0183
15	7	2.71	0.0645	0.0228
16	3	1.85	0.0220	0.0070
17	4	1.454	0.0256	0.0088

NOTE: The damage areas reported above have been rounded to 4 significant digits.

I-3.3 VERIFYING THE SEVEN WASTE PACKAGE ANALYSES

The purpose of the multi-waste package kinematic analysis study was to produce a more realistic damage estimation, in comparison to previous single waste package analyses, while maintaining a certain level of conservatism. A two-step process was used to demonstrate that the seven waste package analyses are conservative. The first step was to refine analysis parameters, with a focus on parameters relating to contact. The second step was to perform analyses on a number of waste package configurations to reduce the end effects inherent in a representation utilizing fewer waste packages than may be emplaced. Previous configurations ranged from 5 to 13 waste packages with one or two 5-DHLW/DOE-Long waste packages, subjected to a single realization. This study encompassed configurations ranging from 7 to 19 waste packages with as many as four 5-DHLW/DOE-Long waste packages. Each configuration was subjected to six realizations at two ground motion levels, 2.44-m/s PGV and 5.35-m/s PGV.

I-3.3.1 Refining Analysis Parameters

Two types of analysis were performed to evaluate analysis parameters, with a focus on parameters relating to contact. The first analysis involved dropping a waste package from a height of 0.5 m onto a emplacement pallet resting on the invert, examining the level of rebound of the waste package COR. The second analysis examined the effects of the sliding contact between the waste package and emplacement pallet and between the emplacement pallet and invert. Contact parameters included automatic contact, viscous contact damping, soft constraint option, and segment-based contact option. Automatic contact allows LS-DYNA to determine the order and orientation of surface normals for the master and slave surfaces of defined contact

interfaces. Viscous contact damping can be used to approximate the effects of the COR of the contacting surfaces. The soft constraint option with segment-based contact sliding helps prevent node catching during sliding along an interface. Additionally, the general analysis parameter, hourglass control type, was also examined.

From these tests (summarized below), it was determined that optimal parameters for reasonable contact behavior are automatic contact, 150 percent viscous contact damping, and pinball segment-based contact (soft 2) with the sliding option (sbopt 4). The general analysis hourglass control parameter was set to type 2, viscous form hourglass control. This selects the Flanagan-Belytschko viscous form of hourglass control for solid elements (orthogonal to rigid body rotations) and the Belytschko-Tsay viscous form of hourglass control for shell element.

Waste Package Drop Analyses—Drop analyses of a single waste package on a emplacement pallet were performed to study contact parameters and to determine the COR for a vertical impact. The waste package was dropped from a height of 0.5 m above the emplacement pallet with gravity acting in the negative Y direction. Figure I-17 shows the initial condition of the analysis. All nodes of the invert were fixed in the vertical (Y) direction. A symmetry boundary condition was applied on the vertical plane along the axis of the waste package. Gravity was applied over the first 0.3 seconds with high global damping, allowing the emplacement pallet to settle on the invert before impact of the waste package.

Figure I-17. Representation of a Single Waste Package Prepared for a Drop Analysis from a Height of 0.5 m above an Emplacement Pallet

The COR of the waste package-to- emplacement pallet-to-invert impact was calculated by taking the ratio of peak rebound vertical velocity of the waste package to the velocity of the waste package at impact with the emplacement pallet. When the viscous damping parameter was set to high values, the rebound behavior of the waste package would become unrealistic. In some cases, the COR was larger than 1.0, implying that energy was being added to the system. Thus, viscous damping could not be increased without limit. Reasonable rebound behavior was achieved when the viscous contact damping parameter was set to 150. Stiffness form hourglass

control (type 4) produced a stiffer system than the viscous form hourglass control (type 1 or 2). Because the stiffness form yielded a higher COR, the viscous form (type 2) was selected. The default penalty formulation for contact (soft 0) produced reasonable rebound. In order to maintain reasonable behavior for sliding contact (discussed below in the sliding analysis), the pinball segment-based contact (soft 2) with the sliding option (sbopt 4) was selected.

After optimizing the contact and analysis parameters, the waste package drop analysis results predicted a COR of 0.65, based on a peak rebound velocity of 77.358 in/sec and an impact velocity of 118.45 in/sec. The predicted COR is close to the target COR for metal-to-metal contact (Assumption 3.2.28). The vertical rigid-body velocity of the waste package is shown in Figure I-18, and the vertical rigid-body displacement of the waste package is shown in Figure I-19.

Figure I-18. Vertical Velocity of the Waste Package for a 0.5-m Drop Analysis, Based on Optimized Contact and Analysis Parameters

Figure I-19. Vertical Displacement of the Waste Package for a 0.5 m Drop Analysis, Based on Optimized Contact and Analysis Parameters

Waste Package Sliding Analyses—A waste package sliding analysis was used to study the friction contact interface between the waste package and emplacement pallet, as well as the interface between the emplacement pallet and invert. The objective of this analysis was to define LS-DYNA-specific parameters that allow proper response of the sliding interfaces between waste package and emplacement pallet and emplacement pallet and invert. All nodes of the invert were fixed in the Y and Z directions, and a symmetry boundary condition was applied on the vertical plane along the axis of the waste package. Gravity was applied, with high global damping, over a period of 0.5 seconds, bringing the waste package to rest on the emplacement pallet under gravitational load. The analysis was performed by applying a linearly increasing point load to the waste package in the horizontal longitudinal direction (Z), as shown in Figure I-20. The static and dynamic coefficients of friction for the interface between the waste package and emplacement pallet were 0.2, and the coefficients of friction for the interfaces of the emplacement pallet with the invert and the waste package with the invert were 0.8. These values of the coefficient of friction were selected within the range of likely mechanical response of the EBS components (Assumptions 3.2.4, 3.2.10 and 3.2.11).

NOTE: A longitudinal (Z) point load was applied to the waste package to initiate sliding contact.

Figure I-20. Finite-Element Representation of a Waste Package on an Emplacement Pallet

Animations of the sliding contact showed that when contact was defined with the default penalty formulation for soft constraint (soft 0), a node of the waste package would catch on the emplacement pallet after the waste package has fallen off of one side of the emplacement pallet. Once the node caught, the waste package would drag the emplacement pallet along, as shown in Figure I-21. Since the coefficient of friction between the waste package and emplacement pallet is much smaller than the coefficient of friction between the emplacement pallet and invert, the expected behavior was for the emplacement pallet to have very little motion. The soft constraint option was changed to the pinball segment-based formulation (soft 2) with the sliding option (sbopt 4) to prevent the nodes from catching. With this set of parameters, the waste package slid over the emplacement pallet without significant movement of the emplacement pallet (Figure I-22), and this formulation was chosen for use in the kinematic analyses. For the waste package sliding analyses, the different types of hourglass control and level of viscous contact damping were not significant.

NOTE: The waste package nodes catch on the emplacement pallet once one end of the waste package has slid past the emplacement pallet support pad.

Figure I-21. Four Snapshots in Time of the Animation of the Sliding Analysis using the Penalty-Based Contact Formulation (soft 0)

Figure I-22. Four Snapshots in Time of the Animation of the Sliding Analysis using the Pinball Segment-Based Contact Formulation (soft 2) with the Sliding Option (sbopt 4)

I-3.3.2 Refined Waste Package Configuration Analyses

An updated FE representation of the series of waste packages was created using the updated analysis parameters (mostly from the waste package drop and sliding analyses) and a few small geometry changes. The contact parameters for contact interfaces involving emplacement pallets were updated to use the soft 2 and sbopt 4 options. Interfaces not involving an emplacement pallet use the soft 0 option. The most notable geometry change was that the inner diameter of the 5-DHLW/DOE-Long waste package was adjusted to 66.5029 inches (1689.2 mm), making the material density of the 5-DHLW/DOE-Long waste packages the same as the density for the 21-PWR waste packages as listed in Table I-4. Additional analyses were performed to further evaluate the number of waste packages required to minimize the effects of end conditions on the representation. Configurations were evaluated with 7 to 19 waste packages with a 5-DHLW/DOE-Long waste package between groups of three 21-PWR waste packages

(Figure I-23). Six realizations at 2.44-m/s PGV and six realizations at 5.35-m/s PGV were applied to the configurations. The end condition analyses with realizations at 2.44-m/s PGV were conducted with the same analysis parameters utilized in the seven waste package analyses, prior to completing analysis parameter studies. The end condition analyses with realizations at 5.35-m/s PGV were conducted with the full set of updated analysis parameters.

NOTE: Each configuration has a 5-DHLW/DOE-Long waste package between each three 21-PWR waste packages.

Figure I-23. Waste Package Configurations used to Evaluate the Effects of End Conditions

These configurations were evaluated on the cumulative damage areas, based on the number of impacts and the associated impact velocities above 0.85 m/s. The seven waste package analyses, used for the update to the TSPA damage assessment, conservatively used the relative velocity between adjacent waste packages to estimate the damage areas from the damage table (Table I-7). The table was created from analyses of waste packages impacting a rigid boundary (BSC 2005 [DIRS 173178], Tables 2 and 3). This could also be considered to be a symmetry boundary, implying that two waste packages were impacting with equal and opposite velocities. The relative velocity between the two symmetric waste packages (or closure velocity) is twice the velocity of a single waste package impacting the rigid symmetry plane. When considering this, and the momentum transfer that occurs when adjacent waste packages impact, it was determined that relative velocity divided by 2 should be used to determine the damage from Table I-7, producing a more realistic estimate of damage. In reviewing the relative nodal velocities obtained directly from the output files, it was observed that a few velocities appeared to be artificially high as a result of either high frequency vibration of the waste package representation, or artifacts of rubbing type contact conditions. For the latter condition, adjacent

waste packages were resting on the emplacement pallets and were in direct contact with one another when a single pair of nodes (one on each waste package) would react to one another, creating the appearance of large impact velocities, when the waste packages were actually moving in a synchronous fashion. Artificially high velocities were observed in less than one percent of waste package impacts. To address these issues, a technique was developed to infer the horizontal (Z) velocity at the corners of the waste package using the top and bottom nodes at the mid-length of the waste package. The average horizontal velocity for the two nodes was used to determine the overall horizontal velocity of the waste package and the difference between the two horizontal velocities was used to calculate the rotational velocity of the waste package. Based on the geometry and orientation of the waste package, the horizontal components of velocity (due to rotation) were calculated for each corner of the waste package, which were then summed with the overall waste package velocity to produce overall velocities at the corners. These inferred velocities were compared to the velocities computed directly from the end nodes and were observed to be almost identical, with the exception of the instances of the observation of artificially high velocities. This technique (shown graphically in Figures I-24 to I-26) effectively calculated more realistic relative impact velocities.

NOTE: TL is top left, TC is top center, TR is top right, BL is bottom left, BC is bottom center, and BR is bottom right.

Figure I-24. Horizontal Velocities at the Corner Nodes of a Waste Package are Related to Waste Package Velocity (V_P) and Waste Package Rotation (ω)

Figure I-25. Calculation of Waste Package Velocity (V_P), the Waste Package Rotation (ω), and Tangential Velocity (V_{Tan})

NOTE: TL is top left, TC is top center, TR is top right, BL is bottom left, BC is bottom center, and BR is bottom right. β and R are the waste package geometry, α is the orientation of the waste package.

Figure I-26. Calculation of the Velocities at the Corners of the Waste Package

The cumulative damage areas were calculated, based on inferred relative impact velocities above 0.85 m/s (Assumption 3.2.29), for six realizations at 2.44-m/s PGV (Figure I-27) and six

realizations at 5.35-m/s PGV (Figure I-28). The analyses with the six realizations at 2.44-m/s PGV predicted very few impacts and correspondingly low damage areas. The analyses with the six realizations at 5.35-m/s PGV predicted a much larger number of impacts and a range of damage areas. Upon reviewing the damage areas for the 5.35-m/s PGV realizations, it was determined that the 11 waste package configuration was a reasonable representation of an emplaced series of waste packages, and should be used to repeat the analysis of 51 ground motions.

Figure I-27. Damage Area Estimates for Waste Package Configurations with 7 to 19 Waste Packages, as a Result of Six Realizations at 2.44 m/s PGV

Figure I-28. Damage Area Estimates for Waste Package Configurations with 7 to 19 Waste Packages, as a Result of Six Realizations at 5.35 m/s PGV

I-3.3.3 Eleven Waste Package Configuration Analyses as Verification of Seven Waste Package Analyses

The suite of 51 seismic ground motions was applied to the refined eleven waste package configuration to verify that the seven waste package analyses impact parameters are conservative in nature. The seven waste package impact parameters were subsequently used in *Seismic*

Consequence Abstraction (BSC 2005 [DIRS 173247]) for calculation of waste package end-to-end damage. Waste package-to-waste package impacts and impact velocities were extracted from the LS-DYNA output (Section I-5) and damage areas were calculated. Waste package-to-waste package impact velocities were processed as the inferred relative horizontal (Z) velocity (Section I-3.3.2) between the upper or lower corner nodes of adjacent waste packages at the simulation time just prior to the onset of contact.

Damage areas, for both 80 percent and 90 percent yield strengths, were obtained for each impact above 0.85 m/s, by linear interpolation based on the inferred relative velocity. Damage areas were determined from tables relating impact velocity and angle of impact to damaged area provided in (BSC 2005 [DIRS 173178], Tables 2 and 3). The damage area results are presented in Tables I-14 to I-20. Each table lists the number of impacts, the maximum impact velocity, and the damage areas for both 80 percent and 90 percent yield strengths, as a function of realization number (1 to 17). Realizations that have zero predicted impacts above 0.85 m/s have been removed from the tables. The tables are organized by waste package (left-of-center, center, right-of-center) and ground motion level (1.05-m/s PGV, 2.44-m/s PGV, 5.35-m/s PGV). The 1.05-m/s PGV ground motions resulted in a single impact velocity above 0.85 m/s.

Table I-14. Damage Areas for Center Waste Package J and Right-of-Center Waste Package K for Ground Motions at 1.05-m/s PGV

Realization Number	Number of Impacts	Maximum Impact Velocity (m/s)	Damage Area at 80% Yield Strength (m ²)	Damage Area at 90% Yield Strength (m ²)
10	1	1.005	0.0023	0.0015

NOTE: The damage areas reported above have been rounded to 4 significant digits.

Table I-15. Damage Areas for Left-of-Center Waste Package I at 2.44 m/s PGV

Realization Number	Number of Impacts	Maximum Impact Velocity (m/s)	Damage Area at 80% Yield Strength (m ²)	Damage Area at 90% Yield Strength (m ²)
4	3	1.001	0.0042	0.0027
10	5	1.452	0.0193	0.0082
12	1	0.866	0.0002	0.0002
15	1	1.166	0.0047	0.0020

NOTE: The damage areas reported above have been rounded to 4 significant digits.

Table I-16. Damage Areas for Center Waste Package J at 2.44 m/s PGV

Realization Number	Number of Impacts	Maximum Impact Velocity (m/s)	Damage Area at 80% Yield Strength (m ²)	Damage Area at 90% Yield Strength (m ²)
4	1	1.001	0.0022	0.0014
10	5	1.452	0.0236	0.0097
12	1	0.866	0.0002	0.0002
15	2	1.166	0.0090	0.0038

NOTE: The damage areas reported above have been rounded to 4 significant digits.

Table I-17. Damage Areas for Right-of-Center Waste Package K at 2.44 m/s PGV

Realization Number	Number of Impacts	Maximum Impact Velocity (m/s)	Damage Area at 80% Yield Strength (m ²)	Damage Area at 90% Yield Strength (m ²)
4	1	1.032	0.0027	0.0015
10	4	1.168	0.0148	0.0070
15	3	1.139	0.0080	0.0037

NOTE: The damage areas reported above have been rounded to 4 significant digits.

Table I-18. Damage Areas for Left-of-Center Waste Package I at 5.35 m/s PGV

Realization Number	Number of Impacts	Maximum Impact Velocity (m/s)	Damage Area at 80% Yield Strength (m ²)	Damage Area at 90% Yield Strength (m ²)
2	5	1.355	0.0223	0.0094
3	4	1.799	0.0329	0.0104
4	19	2.512	0.1805	0.0622
5	2	1.061	0.0035	0.0018
6	3	1.531	0.0113	0.0038
7	6	1.379	0.0238	0.0095
8	5	1.229	0.0136	0.0062
9	1	1.093	0.0036	0.0017
10	21	5.118	0.4385	0.1610
11	3	1.546	0.0214	0.0074
12	3	2.293	0.0323	0.0108
13	5	1.148	0.0072	0.0035
14	6	1.145	0.0088	0.0047
15	15	1.514	0.0667	0.0266
16	3	1.277	0.0113	0.0046
17	9	1.646	0.0494	0.0180

NOTE: The damage areas reported above have been rounded to 4 significant digits.

Table I-19. Damage Areas for Center Waste Package J at 5.35 m/s PGV

Realization Number	Number of Impacts	Maximum Impact Velocity (m/s)	Damage Area at 80% Yield Strength (m ²)	Damage Area at 90% Yield Strength (m ²)
2	3	1.244	0.0091	0.0043
3	4	1.628	0.0338	0.0110
4	22	3.852	0.2638	0.0912
5	1	0.871	0.0003	0.0002
6	10	1.531	0.0379	0.0151
7	8	1.379	0.0250	0.0106
8	4	1.105	0.0079	0.0040
9	1	1.093	0.0036	0.0017
10	23	5.118	0.4741	0.1736
11	5	1.726	0.0424	0.0137
12	1	2.293	0.0223	0.0070
13	5	1.148	0.0101	0.0047
14	7	1.335	0.0213	0.0090
15	15	1.789	0.0804	0.0303
16	2	1.134	0.0047	0.0022
17	12	1.627	0.0581	0.0216

NOTE: The damage areas reported above have been rounded to 4 significant digits.

Table I-20. Damage Areas for Right-of-Center Waste Package K at 5.35 m/s PGV

Realization Number	Number of Impacts	Maximum Impact Velocity (m/s)	Damage Area at 80% Yield Strength (m ²)	Damage Area at 90% Yield Strength (m ²)
2	4	0.988	0.0056	0.0036
3	4	1.712	0.0393	0.0121
4	21	3.852	0.2477	0.0878
5	5	0.974	0.0047	0.0030
6	12	1.892	0.0580	0.0222
7	6	1.749	0.0219	0.0083
8	3	1.498	0.0107	0.0036
10	18	5.025	0.3680	0.1351
11	4	1.726	0.0378	0.0118
12	2	1.523	0.0119	0.0042
13	5	1.851	0.0246	0.0095
14	8	1.335	0.0330	0.0129
15	11	1.789	0.0632	0.0228
16	4	1.285	0.0117	0.0051
17	10	1.623	0.0365	0.0153

NOTE: The damage areas reported above have been rounded to 4 significant digits.

In addition to the waste package-to-waste package impact results, the impact velocities resulting from waste package-to-drip shield impacts (i.e., the impacts of the waste package to the upper boundary of the representation) were also recorded and are provided in Table I-21. A single realization at 1.05-m/s PGV level, three realizations at 2.44-m/s PGV level, and 15 realizations at 5.35-m/s PGV level indicated contacts. The mean (and maximum) relative vertical velocities of

these impacts are 3.65 m/s (3.77 m/s) at the 2.44-m/s PGV level and 7.91 m/s (26.56 m/s) at the 5.35-m/s PGV level.

Table I-21. Summary of Waste Package to Drip Shield Impact Velocities

Realization	1.05-m/s PGV Level Maximum Relative Vertical Y Velocity (m/s)	2.44-m/s PGV Level Maximum Relative Vertical Y Velocity (m/s)	5.35-m/s PGV Level Maximum Relative Vertical Y Velocity (m/s)
1	0	0	0
2	0	0	2.019
3	0	3.768	13.948
4	0	0	11.244
5	0	0	4.036
6	0	0	7.134
7	0	0	3.677
8	0	0	3.223
9	0	0	2.766
10	2.123	3.729	26.559
11	0	0	4.269
12	0	0	6.749
13	0	0	0
14	0	0	8.496
15	0	3.447	12.856
16	0	0	2.98
17	0	0	8.668
Mean	2.123	3.65	7.91
Std Dev	NA	0.18	6.42
Max	2.123	3.77	26.56
Min	2.123	3.45	2.02

I-3.3.4 Comparing the 7 and 11 Waste Package Configuration Analyses

The seven waste package configuration analysis is used for providing base case impact parameters for input to the *Seismic Consequence Abstraction* (BSC 2005 [DIRS 173247]) damage abstraction. After refining various analysis parameters and examining a broader set of waste package configurations ranging up to 19 waste packages, the eleven waste package configuration was selected as representative of a series of emplaced waste packages. Analyses were performed for 17 ground motion realizations (at each of three seismic hazard levels) and impact parameters and damage approximations calculated. The seven and eleven waste package configurations were compared using statistical metrics, based on the damage areas for the center three waste packages (left-of-center, center, and right-of-center). The mean damage value was calculated from the natural logarithm of the non-zero damage areas. The median damage value was calculated as the exponential of the mean value. The standard deviation was calculated from the natural logarithm of the non-zero damage areas. The fraction without damage was calculated as the number of waste package-realization damage areas that were zero, divided by 51 (the number of ground motion realizations (17) times the number of waste packages (3)). The results

of this comparison are listed in Table I-22. For the 1.05-m/s PGV and 2.44-m/s PGV seismic levels, the analyses of both configurations predict essentially the same damage levels. The 11 waste package analyses, at the 1.05 m/s level, predicted a single impact between the J and K waste package above 0.85 m/s, while the 7 waste package analyses predicted zero impacts on any of the central 3 waste packages (I, J, and K) above 0.85 m/s. The 11 and 7 waste package analyses at the 1.05 m/s level are considered to be essentially the same in terms of damage. In addition, the *Seismic Consequence Abstraction* model report (BSC 2005 [DIRS 173247]) also includes the predicted impact results from UDEC (Section 5.4.1 and Attachment II). The UDEC results predict higher impact frequencies and velocities and therefore prevent the potential for underrepresentation of impacts. For the 2.44-m/s PGV level, the eleven waste package configuration had a larger fraction-without-damage value. For the 5.35-m/s PGV seismic level, the seven waste package configuration analyses predicted about twice the median damage area as the eleven waste package configuration, with both analyses predicting essentially the same fraction-without-damage value.

Table I-22. Statistical Comparison of the Seven and Eleven Waste Package Configuration Analysis Damage Areas using 80 Percent Yield Strength

Seismic Level	Number of waste packages	Mean of Ln(DamageArea>0) (m ²)	Median damage area (m ²)	Standard Deviation of Ln(DamageArea>0) (m ²)	Fraction Without Damage
1.05 m/s PGV (10 ⁻⁵ exceedance)	7	0	0	0	1.000
	11	-6.068	0.0023	0	0.961
2.44 m/s PGV (10 ⁻⁶ exceedance)	7	-5.497	0.0041	1.841	0.588
	11	-5.542	0.0039	1.576	0.784
5.35 m/s PGV (10 ⁻⁷ exceedance)	7	-3.125	0.0439	1.264	0.059
	11	-3.728	0.0240	1.421	0.078

I-4. CONCLUSIONS

The multi-waste package configuration kinematic analyses have provided a reasonable assessment of waste package end-to-end impacts. Previous analyses (BSC 2004 [DIRS 167083]) using a single waste package between two restrained waste packages, were overly conservative with regard to end-to-end impacts. A seven waste package configuration was used to estimate impact parameters (number of impacts, their relative velocities and angle of impact) for 17 realizations of ground motion time histories at 3 seismic hazard levels (1.05, 2.44 and 5.35 m/s). These impact parameters were subsequently used to determine waste package damage to the Alloy 22 OCB, and for development of the *Seismic Consequence Abstraction* (BSC 2005 [DIRS 173247]). To confirm the applicability and conservatism in the seven waste package FE representation, a series of parametric studies were conducted to refine the LS-DYNA analysis solution parameters, and to investigate the effect of representation of larger numbers of waste packages. These analyses determined that eleven waste package grouping provided the smallest number of waste packages that provide reasonable comparisons to configurations containing larger numbers (up to 19) of waste packages. Comparison of the predicted damage levels from the eleven and seven waste package configurations for 17 ground motion realizations at 3 seismic hazard levels shows that the seven waste package results are conservative.

I-5. POST-PROCESSING LS-DYNA RESULTS

The seven and eleven waste package analyses produced output files that were processed to identify contact between adjacent waste packages and the relative velocities of those impacts. Because there were a large number of analyses (102 realizations between the seven and eleven waste package configurations) and as many as several hundred impacts per waste package interface, a MATLAB script was developed to automate the calculation of waste package relative impact velocities and damage area estimates.

MATLAB scripts are exempted from qualification based on the criteria in LP-SI.11Q-BSC, Paragraph 2.1.6. The algorithm is verifiable by hand calculations, and all of the input and output are readable text. In accordance with LP-3.12Q-BSC, Section 5.2, Heading 11, the post-processing of LS-DYNA results is documented in following sections.

Sections I-5.1 and I-5.2 describe the post-processing of LS-DYNA results for the seven waste package analyses and the eleven waste package analyses, respectively. While the procedure steps for post-processing both sets of analyses are similar, the details of these steps have some significant differences. The seven waste package analyses were post-processed from binary output files, relative impact velocities were determined directly from the end nodes of the waste packages, and damage area estimates were based on the full relative impact velocity. The eleven waste package analyses were post-processed from text output files, relative impact velocities were inferred from waste package velocities and rotations, and damage area estimates were based on half the relative impact velocity. Detailed descriptions of the post-processing steps are discussed in the following sections.

I-5.1 SEVEN WASTE PACKAGE ANALYSES

For the seven waste package analyses, LS-DYNA produced large binary output files containing the contact interface forces and FE results at each simulation output time. LS-PREPOST V1.0 was used to plot time histories of selected results and to save these time histories in text curve files as time-value pairs. Four curve files were created to post-process the relative impact velocity between waste packages: 1) normal interface force curve file for the six interfaces between the seven waste packages, 2) Y coordinate curve file for top and bottom waste package end nodes at each interface, 3) Z coordinate curve file for top and bottom waste package end nodes at each interface, and 4) Z velocity curve file for top and bottom waste package end nodes at each interface. Figure I-29 shows the nodes used for post-processing the relative impact velocity between two waste packages. Table I-23 lists the specific interface and node numbers corresponding to the waste package interfaces. Each curve file is organized as end-to-end time histories. For example, the interface force curve file contains the complete time history results for interface 9, followed by the complete time history results for interface 5, and so on for all six interfaces. The naming convention for the curve results files is as follows.

dprodRRLLL_RESULT.crv

where:

dprod = Base name for all seven waste package analysis results
 RR = Realization number (1, 2, ... 17)
 LLL = Ground motion level, one of:
 e-5 (for 1.05 m/s PGV)
 e-6 (for 2.44 m/s PGV)
 e-7 (for 5.35 m/s PGV)

RESULT = Result type, one of:
 iff (normal interface forces)
 Y_Coordinate
 Z_Coordinate
 Z_Velocity

.crv = File extension identifying this as a text time history curve file

Thus, the file dprod10e-7_Z_Velocity.crv is for a seven waste package analysis for Realization 10 at ground motion level 5.35-m/s PGV (e-7) and contains time history results for the Z velocity of selected nodes.

Figure I-29. Node Convention for Two Waste Packages

Table I-23. Waste Package, Interface Number and Node Number Relationship

Left Package	Right Package	Interface Number	1.05 m/s & 2.44 m/s PGV Analyses				5.35 m/s PGV Analyses			
			Node TL	Node BL	Node TR	Node BR	Node TL	Node BL	Node TR	Node BR
G	H	9	1839	1801	1928	1890	3	4	5	6
H	I	5	2290	2252	2331	2293	7	8	9	10
I	J	1	2693	2655	2734	2696	11	12	13	14
J	K	3	3096	3058	3137	3099	15	16	17	18
K	L	7	3499	3461	3540	3502	19	20	21	22
L	M	11	3902	3864	3943	3905	23	24	25	26

The damage areas for waste package-to-waste package impacts are determined using a four-step process. Step 1 is to identify an impact time for a waste package interface from the appropriate interface force history. Impacts are identified in the time history when a non-zero impact force occurs immediately following a zero impact force. The impact time is selected as the simulation time point immediately preceding the non-zero impact force. At the time point of the non-zero impact force, impact is already occurring and the relative impact velocity has already been reduced. Therefore, a better measure of relative impact velocity is obtained by “backing up” one time point in the time history. Step 2 is to extract (at the determined impact time) the Y and Z coordinates and Z velocity for the waste package nodes associated with the interface. This is accomplished by locating the appropriate node time history in the curve files and then extracting the value at the impact time. Step 3 is to calculate the relative impact velocity and angle, based on the waste package top nodes (TR and TL) and bottom nodes (BR and BL).

$$\begin{aligned} V_T &= V_{TR} - V_{TL} \\ V_B &= V_{BR} - V_{BL} \end{aligned}$$

A negative relative velocity indicates a closing velocity. The impact velocity is conservatively determined as

$$V_{imp} = | \min (V_T , V_B) |$$

The relative angle of impact between the waste packages is based on their orientations.

$$\begin{aligned} \text{ANGLE}_L &= \text{ARCTAN} [(Z_{BL} - Z_{TL}) / (Y_{TL} - Y_{BL})] \\ \text{ANGLE}_R &= \text{ARCTAN} [(Z_{BR} - Z_{TR}) / (Y_{TR} - Y_{BR})] \end{aligned}$$

The relative impact angle is computed as

$$\text{ANGLE}_{Rel} = | \text{ANGLE}_R - \text{ANGLE}_L |$$

Step 4 is to determine the damage area based on the relative impact velocity and linear interpolation of the damage values in Table I-7. For impact velocities above 10 m/s, the damage area is extrapolated.

Example of the Four-Step Process—Following is an example of the four-step process used to determine the damage area for a waste package-to-waste package impact.

Step 1. Identify the impact time.

Figure I-30 shows an excerpt from the interface force curve file, showing the curve file header, the header for interface #1 (between waste packages I and J), and the time-value points surrounding the second impact. The first column is time and the second column is the normal interface force. The interface force values are zero preceding the impact and non-zero during the impact. The impact time is selected as the time point immediately preceding the non-zero interface force value (1.7069946527e+00 sec).

NOTE: Shown is the curve file header, the header for interface #1, and the time-value points surrounding the second impact.

Figure I-30. Excerpt from the Interface Force Curve File

Step 2. Extract the interface node results at the impact time.

Table I-24 shows the interface node results extracted for the impact at time 1.7069946527e+00 sec.

Table I-24. Interface #1 Node Results at Time 1.7069946527e+00 sec.

Node Number (Location)	Y Coordinate (in)	Z Coordinate (in)	Z Velocity (in/sec)
11 (TL)	4.7491752625e+01	1.7097548828e+03	-1.2815286636e+01
12 (BL)	-1.9841634750e+01	1.7084116211e+03	-6.8784835815e+01
13 (TR)	3.4764186859e+01	1.7097083740e+03	-1.0789027405e+02
14 (BR)	-3.1839803696e+01	1.7201499023e+03	3.8655483246e+01

Step 3. Calculate the relative impact velocity and angle.

Using the formulas previously discussed, the relative impact velocity and angle are calculated.

$$V_T = (-1.0789027405e+02) - (-1.2815286636e+01) = -95.07498741 \text{ in/sec}$$

$$V_B = (3.8655483246e+01) - (-6.8784835815e+01) = 107.44031906 \text{ in/sec}$$

$$V_{imp} = | \min (-95.07498741, 107.44031906) | = 95.07498741 \text{ in/sec} * 0.0254 \text{ m/in} = 2.415 \text{ m/s}$$

$$ANGLE_L = ARCTAN [(1.7084116211e+03 - 1.7097548828e+03) / (4.7491752625e+01 - (-1.9841634750e+01))]$$

$$ANGLE_L = -1.143 \text{ degrees}$$

$$ANGLE_R = ARCTAN [(1.7201499023e+03 - 1.7097083740e+03) / (3.4764186859e+01 - (-3.1839803696e+01))]$$

$$ANGLE_R = 8.910 \text{ degrees}$$

$$ANGLE_{Rel} = | 8.910 - (-1.143) | = 10.053 \text{ degrees}$$

Step 4. Determine the damage area from the damage table (Table I-7).

The relative impact velocity is 2.415 m/s. Thus, the damage area is linearly interpolated between 2.0 m/s and 4.0 m/s, as shown in Table I-25 below.

Table I-25. Linear Interpolation of Damage Area

Impact Velocity (m/s)	Damage Area at 80% Yield Strength (m ²)	Damage Area at 90% Yield Strength (m ²)
2.0	0.0172	0.0046
2.415	0.0243	0.0080
4.0	0.0515	0.0209

MATLAB Script—A MATLAB script was written to automate the process described above. A MATLAB script is exempted from qualification based on the criteria in LP-SI.11Q-BSC, Paragraph 2.1.6. The algorithm is verifiable by hand calculations, and all of the input and output are readable text. In accordance with LP-3.12Q-BSC, Section 5.2, Heading 11, the actions performed in the script are documented below.

The algorithm is the 4-step process that was previously described in detail, and is summarized below:

1. Identify the impact time at an interface
2. Extract the interface node Y and Z coordinates and Z velocities at the impact time
3. Calculate relative impact velocity and angle
4. Determine the damage area by interpolation based on impact velocity from the damage table (Table I-7)

This algorithm is embedded in a loop over the time steps to record every impact, and a loop over all 6 interfaces between waste packages. The peak impact velocity for each of the middle three waste packages (I, J, K) is determined, and the total damage area for each of the middle three waste packages is summed from each individual impact.

The inputs to the algorithm are:

- Normal interface force time histories for the 6 interfaces between the waste packages
- Y coordinate time histories at 24 nodes (4 for each interface)
- Z coordinate time histories at 24 nodes (4 for each interface)
- Z velocity time histories at 24 nodes (4 for each interface)
- Damage area interpolation table (Table I-7)

The outputs from the algorithm are:

- Impact times for all 6 interfaces
- Relative impact velocities for all impacts
- Relative impact angles for all impacts
- Damage areas based on 80 percent yield strength for all impacts
- Damage areas based on 90 percent yield strength for all impacts
- Peak impact velocity for each of the middle three waste packages (I, J, K)
- Total damage area for each of the middle three waste packages (I, J, K) based on 80 percent yield strength
- Total damage area for each of the middle three waste packages (I, J, K) based on 90 percent yield strength

The MATLAB script was designed to run on MATLAB Version 6.5 Release 13 on Tru64 UNIX. The script is named *ImpactVelocity7WP.m* (DTN: MO0508SPAMECHA.000, *Attachment I\WP_7_Analyses* folder) and it requires the root name of the curve files, e.g. dprod10e-7, as an argument.

An excerpt of output from the script for the second impact at interface #1 is shown below. All coordinates are in inches and velocities are in in/sec, unless specified otherwise. Notice that the output results match those computed by the hand calculation example. This excerpt of output shows the values that are read in for nodal coordinates and velocities at the impact time and the damage area table values used for interpolation. This echo of the input allows for diagnostics to ensure that the script is using the correct input values.

Impact 2 at time = 1.7070 sec

```
-----  
Cask I - Right End Top Node, TL (Node 11)  
  z-vel = -1.2815E+01  
  y-coor = 4.7492E+01  
  z-coor = 1.7098E+03  
Cask I - Right End Bottom Node, BL (Node 12)  
  z-vel = -6.8785E+01  
  y-coor = -1.9842E+01  
  z-coor = 1.7084E+03
```

```

Cask J - Left End Top Node, TR (Node 13)
  z-vel = -1.0789E+02
  y-coor = 3.4764E+01
  z-coor = 1.7097E+03
Cask J - Left End Bottom Node, BR (Node 14)
  z-vel = 3.8655E+01
  y-coor = -3.1840E+01
  z-coor = 1.7201E+03
Angle of Cask I = -1.143 degrees
Angle of Cask J = 8.910 degrees
RELATIVE ANGLE = 10.053 degrees
Rel Vel Top Nodes = -9.5075E+01 ( -2.415 m/s)
Rel Vel Bottom Nodes = 1.0744E+02 ( 2.729 m/s)
RELATIVE VELOCITY = -2.415 m/s
Calculate damage area in m^2 at 80% YS
  vel = 2.000 m/s --> dam80%ys = 0.0172333
  vel = 2.415 m/s -----> interpolate -----> DAM80%YS = 0.024349
  vel = 4.000 m/s --> dam80%ys = 0.0515333
Calculate damage area in m^2 at 90% YS
  vel = 2.000 m/s --> dam90%ys = 0.0046000
  vel = 2.415 m/s -----> interpolate -----> DAM90%YS = 0.007975
  vel = 4.000 m/s --> dam90%ys = 0.0208667

```

The peak impact velocity is tracked for waste packages I, J and K and output for each waste package after all of the impact velocities are calculated. The damage areas for impacts on waste packages I, J and K are summed and the total damage area for each waste package is output after all of the damage areas are calculated.

I-5.2 ELEVEN WASTE PACKAGE ANALYSES

For the eleven waste package analyses, LS-DYNA produced large text output files containing the contact interface forces and nodal results at each simulation output time. LS-PREPOST V1.10 was used to plot time histories of selected results and to save these time histories in text curve files as time-value pairs. Four curve files were created to post-process the relative impact velocity between waste packages: 1) resultant interface force curve file for the six interfaces between the middle seven waste packages, 2) Y displacement curve file for the middle nodes at the top and bottom of the middle seven waste packages, 3) Z displacement curve file for the middle nodes at the top and bottom of the middle seven waste packages, and 4) Z velocity curve file for the middle nodes at the top and bottom of the middle seven waste packages. Figure I-31 shows the nodes used for post-processing the relative impact velocity between two waste packages. Table I-26 lists the specific interface numbers corresponding to the waste package interfaces, and Table I-27 lists the specific node numbers corresponding to the waste packages. Each curve file is organized as end-to-end time histories. For example, the interface force curve file contains the complete time history results for interface 5, followed by the complete time history results for interface 3, and so on for all six interfaces. The naming convention for the curve results files is as follows.

dp11cRLLLL_RESULT.crv

where:

dp11c = Base name for all eleven waste package analysis results

RR = Realization number (1, 2, ... 17)

LLL = Ground motion level, one of:
 e-5 (for 1.05 m/s PGV)
 e-6 (for 2.44 m/s PGV)
 e-7 (for 5.35 m/s PGV)

RESULT = Result type, one of:
 iff (resultant interface forces)
 Y_Displacement
 Z_Displacement
 Z_Velocity

.crv = File extension identifying this as a text time history curve file

Thus, the file `dp11c10e-7_Z_Velocity.crv` is for an eleven waste package analysis for Realization 10 at ground motion level 5.35 m/s PGV (e-7) and contains time history results for the Z velocity of selected nodes.

Figure I-31. Node Convention for a Waste Package

Table I-26. Waste Package and Interface Number Relationship

Left Package	Right Package	Interface Number
G	H	5
H	I	3
I	J	1
J	K	2
K	L	4
L	M	6

Table I-27. Waste Package and Node Number Relationship

Waste Package	Node TC	Node BC
G	29	30
H	31	32
I	33	34
J	35	36
K	37	38
L	39	40
M	41	42

The Y and Z displacements of the nodes are available in the curve files. Nodal Y and Z coordinates are needed to compute the angle of the waste package during an impact. Thus, the displacements are added to the initial Y and Z coordinates to get the updated coordinates at the time of impact. The initial Y and Z coordinates for the waste package nodes are stored in a file named mid_coords.dat.

The middle nodes of the waste packages are used for velocity calculations instead of the end nodes so that local effects at the contact interface can be removed. An inferred velocity at the ends of the waste packages is calculated using the average Z velocity of the waste package and the rotational velocity of the waste package. The impact velocity is determined as the relative velocity between two waste packages divided by 2. The reason for this is because the damage table (Table I-7) was created from analyses of waste packages impacting a rigid boundary. This is analogous to a situation where two waste packages impact with equal and opposite velocities. The relative velocity between the two waste packages (or closure velocity) is twice the velocity of a single waste package impacting the rigid boundary.

The damage areas for waste package-to-waste package impacts are determined using a four-step process. Step 1 is to identify an impact time for a waste package interface from the appropriate interface force history. Impacts are identified in the time history when a non-zero impact force occurs immediately following a zero impact force. The impact time is selected as the simulation time point immediately preceding the non-zero impact force. At the time point of the non-zero impact force, impact is already occurring and the relative impact velocity has already been reduced. Therefore, a better measure of relative impact velocity is obtained by "backing up" one time point in the time history. Step 2 is to extract (at the determined impact time) the Y and Z displacements and Z velocity for the middle nodes on the waste packages associated with the interface. This is accomplished by locating the appropriate node time history in the curve files and then extracting the value at the impact time. The initial Y and Z coordinates for the corresponding nodes are added to the Y and Z displacements to obtain the coordinates at the time of impact.

Step 3 is to calculate the relative impact velocity and angle, based on the waste package middle nodes (TC and BC). The calculation of the inferred velocities at the top and bottom end nodes of a waste package from the velocities at the middle nodes is described in Figures I-24 to I-26. Based on the geometry and orientation of the waste package, the Z components of velocity (due to rotation) are calculated for each end node of the waste package, which are then added to the

gross waste package Z velocity to produce Z velocities at the end nodes. This step is described in more detail below.

The diameter of the waste package is calculated from its nodal coordinates to determine the size of the waste package.

$$XDIA = [(Z_{TC} - Z_{BC})^2 + (Y_{TC} - Y_{BC})^2]^{0.5}$$

A 21-PWR waste package has a diameter of 67.65 inches, and 5-DHLW/DOE-Long waste package has a diameter of 84.0 inches (BSC 2005 [DIRS 173501], Table 1). The length of both waste packages is 197.81 inches (**LEN**). The nodal coordinates will not necessarily yield the exact diameter so the waste package is determined to be a 21-PWR waste package if **XDIA** is less than $1.1 * 67.65$, and a 5-DHLW/DOE-Long waste package otherwise. Once the waste package size is determined (**DIA** = 67.65 for 21-PWR, **DIA** = 84.0 for 5-DHLW/DOE-Long), the geometry parameters β and **R** (Figures I-25 and I-26) can be computed.

$$\beta = \text{ARCTAN} (DIA / LEN)$$

$$R = 0.5 * (DIA^2 + LEN^2)^{0.5}$$

The waste package rotation α and the height parameter **H** (Figures I-33 and I-34) are computed from the nodal coordinates.

$$\alpha = \text{ARCTAN} [(Z_{TC} - Z_{BC}) / (Y_{TC} - Y_{BC})]$$

$$H = 0.5 * (Y_{TC} - Y_{BC})$$

The remainder of the calculations to determine the inferred velocities at the end nodes of a waste package is shown in Figures I-25 and I-26.

If the waste package is to the left of the interface at which the impact is occurring, then the velocities on the right side of the waste package (TR and BR) are computed. If the waste package is to the right of the interface at which the impact is occurring, then the velocities on the left side of the waste package (TL and BL) are computed. The relative impact velocities at the top and bottom nodes are computed by

$$V_T = (V_{TL} - V_{TR}) / 2$$

$$V_B = (V_{BL} - V_{BR}) / 2$$

A negative relative velocity indicates a closing velocity. The impact velocity is conservatively determined as

$$V_{imp} = | \min (V_T , V_B) |$$

The relative angle of impact between the waste packages is based on their orientations. The angle for a waste package is computed as

$$\text{ANGLE} = \text{ARCTAN} [(Z_{BC} - Z_{TC}) / (Y_{TC} - Y_{BC})] = -\alpha$$

The relative impact angle between the right (R) and left (L) waste packages is computed as

$$ANGLE_{Rel} = |ANGLE_R - ANGLE_L|$$

Step 4 is to determine the damage area based on the relative impact velocity and linear interpolation of the damage values in Table I-7. For impact velocities above 10 m/s, the damage area is extrapolated.

Example of the Four-Step Process—Following is an example of the four-step process used to determine the damage area for a waste package-to-waste package impact.

Step 1. Identify the impact time.

Figure I-32 shows an excerpt from the interface force curve file, showing the curve file header, the header for interface #3 (between waste packages H and I), and the time-value points surrounding the second impact. The first column is time and the second column is the resultant interface force. The interface force values are zero preceding the impact and non-zero during the impact. The impact time is selected as the time point immediately preceding the non-zero interface force value (1.5679899454e+00 sec).

NOTE: Shown is the curve file header, the header for interface #3, and the time-value points surrounding the third impact.

Figure I-32. Excerpt from the interface Force Curve File

Step 2. Extract the middle node results at the impact time.

Table I-28 shows the middle node results extracted for the impact at time 1.5679899454e+00 sec.

Table I-28. Waste Package H and I Middle Node Results at Time 1.5679899454e+00 sec.

Node Number (location)	Y Displacement (in)	Z Displacement (in)	Z Velocity (in/sec)
31 (TC, H)	-1.2020999938e-01	6.7206001282e+00	-8.5620002747e+00
32 (BC, H)	-8.8248997927e-02	9.7929000854e+00	1.6014999390e+02
33 (TC, I)	-8.9914999008e+00	5.0925998688e+00	1.1743000031e+01
34 (BC, I)	-9.1078996658e+00	6.0039000511e+00	5.4751998901e+01

Table I-29 shows the initial Y and Z coordinates for the middle nodes.

Table I-29. Waste Package H and I Middle Node Initial Coordinates

Node Number (location)	Y Coordinate (in)	Z Coordinate (in)
31 (TC, H)	51.3589172	1412.22900
32 (BC, H)	-32.6410828	1412.22900
33 (TC, I)	33.8250008	1613.97607
34 (BC, I)	-33.8250008	1613.97607

The computed coordinates (initial coordinates plus displacements) at the time of impact are shown in Table I-30.

Table I-30. Waste Package H and I Middle Node Coordinates at Time 1.5679899454e+00 sec.

Node Number (location)	Y Coordinate (in)	Z Coordinate (in)
31 (TC, H)	51.2387072	1418.9496
32 (BC, H)	-32.7293318	1422.0219
33 (TC, I)	24.8335009	1619.06867
34 (BC, I)	-42.93290047	1619.97997

Step 3. Calculate the relative impact velocity and angle using inferred velocities.

Using the formulas previously discussed, the relative impact velocity and angle are calculated.

For waste package H:

$$XDIA = [(1418.9496 - 1422.0219)^2 + (51.2387072 - (-32.7293318))^2]^{0.5} = 84.02422627 \text{ in}$$

$$DIA = 84.0 \text{ in (5-DHLW/DOE-Long)}$$

$$\beta = \text{ARCTAN} (84.0 / 197.81) = 23.00850031 \text{ degrees}$$

$$R = 0.5 * (84.0^2 + 197.81^2)^{0.5} = 107.4532411 \text{ in}$$

$$\alpha = \text{ARCTAN} [(1418.9496 - 1422.0219) / (51.2387072 - (-32.7293318))] = -2.095456024 \text{ degrees}$$

$$H = 0.5 * (51.2387072 - (-32.7293318)) = 41.9840195 \text{ in}$$

$$V_p = (-8.5620002747e+00 + 1.6014999390e+02) / 2 = 75.79399681 \text{ in/sec}$$

$$\omega = (-8.5620002747e+00 - 75.79399681) / 41.9840195 = -2.009240613 \text{ rad/sec}$$

$$V_{TAN} = -2.009240613 * 107.4532411 = -215.899416 \text{ in/sec}$$

$$V_{TR} = 75.79399681 + (-215.899416) * \sin(23.00850031 - (-2.095456024)) = -15.8039109 \text{ in/sec}$$

$$V_{BR} = 75.79399681 - (-215.899416) * \sin(23.00850031 + (-2.095456024)) = 152.8594394 \text{ in/sec}$$

$$ANGLE_L = ARCTAN [(1422.0219 - 1418.9496) / (51.2387072 - (-32.7293318))] = 2.095456024 \text{ degrees}$$

For waste package I:

$$XDIA = [(1619.06867 - 1619.97997)^2 + (24.8335009 - (-42.93290047))^2]^{0.5} = 67.77252852 \text{ in}$$

$$DIA = 67.65 \text{ in (21-PWR)}$$

$$\beta = ARCTAN (67.65 / 197.81) = 18.88042346 \text{ degrees}$$

$$R = 0.5 * (67.65^2 + 197.81^2)^{0.5} = 104.5290852 \text{ in}$$

$$\alpha = ARCTAN [(1619.06867 - 1619.97997) / (24.8335009 - (-42.93290047))] = -0.7704481236 \text{ degrees}$$

$$H = 0.5 * (24.8335009 - (-42.93290047)) = 33.88320069 \text{ in}$$

$$V_p = (1.1743000031e+01 + 5.4751998901e+01) / 2 = 33.24749947 \text{ in/sec}$$

$$\omega = (1.1743000031e+01 - 33.24749947) / 33.88320069 = -0.6346655275 \text{ rad/sec}$$

$$V_{TAN} = -0.6346655275 * 104.5290852 = -66.341007 \text{ in/sec}$$

$$V_{TL} = 33.24749947 + (-66.341007) * \sin(18.88042346 + (-0.7704481236)) = 12.62593401 \text{ in/sec}$$

$$V_{BL} = 33.24749947 - (-66.341007) * \sin(18.88042346 - (-0.7704481236)) = 55.55717529 \text{ in/sec}$$

$$ANGLE_R = ARCTAN [(1619.97997 - 1619.06867) / (24.8335009 - (-42.93290047))] = 0.7704481236 \text{ degrees}$$

The relative impact velocity and angle are:

$$V_r = (12.62593401 - (-15.8039109)) / 2 = 14.21492246 \text{ in/sec}$$

$$V_B = (55.55717529 - 152.8594394) / 2 = -48.65113206 \text{ in/sec}$$

$$V_{imp} = | \min(14.21492246, -48.65113206) | = 48.65113206 \text{ in/sec} * 0.0254 \text{ m/in} = 1.236 \text{ m/s}$$

$$ANGLE_{Rel} = | 0.7704481236 - 2.095456024 | = 1.325 \text{ degrees}$$

Step 4. Determine the damage area from the damage table (Table I-7).

The relative impact velocity is 1.236 m/s. Thus, the damage area is linearly interpolated between 1.0 m/s and 2.0 m/s, as shown in Table I-31 below.

Table I-31. Linear Interpolation of Damage Area

Impact Velocity (m/s)	Damage Area at 80% Yield Strength (m ²)	Damage Area at 90% Yield Strength (m ²)
1.0	0.002233333	0.001433333
1.236	0.0057694	0.0021798
2.0	0.017233333	0.004600000

MATLAB Script—A MATLAB script was written to automate the process described above. A MATLAB script is exempted from qualification based on the criteria in LP-SI.11Q-BSC,

Paragraph 2.1.6. The algorithm is verifiable by hand calculations, and all of the input and output are readable text. In accordance with LP-3.12Q-BSC, Section 5.2, Heading 11, the actions performed in the script are documented below.

The algorithm is the 4-step process that was previously described in detail, and is summarized below:

1. Identify the impact time at an interface
2. Extract the middle node Y and Z displacements and Z velocities at the impact time and compute Y and Z coordinates
3. Calculate relative impact velocity and angle using inferred velocities at the end nodes
4. Determine the damage area by interpolation based on impact velocity from the damage table (Table I-7).

This algorithm is embedded in a loop over the time steps to record every impact, and a loop over the 6 interfaces between the middle seven waste packages. The peak impact velocity for each of the middle three waste packages (I, J, K) is determined, and the total damage area for each of the middle three waste packages is summed from each individual impact.

The inputs to the algorithm are:

- Resultant interface force time histories for the 6 interfaces between the middle 7 waste packages
- Y displacement time histories at 14 nodes (2 for each of the middle 7 waste packages)
- Z displacement time histories at 14 nodes (2 for each of the middle 7 waste packages)
- Z velocity time histories at 14 nodes (2 for each of the middle 7 waste packages)
- Initial Y and Z coordinates at 14 nodes (2 for each of the middle 7 waste packages)
- Damage area interpolation table (Table I-7)

The outputs from the algorithm are:

- Impact times for all 6 interfaces
- Relative impact velocities for all impacts
- Relative impact angles for all impacts
- Damage areas based on 80 percent yield strength for all impacts
- Damage areas based on 90 percent yield strength for all impacts

- Peak impact velocity for each of the middle three waste packages (I, J, K)
- Total damage area for each of the middle three waste packages (I, J, K) based on 80 percent yield strength
- Total damage area for each of the middle three waste packages (I, J, K) based on 90 percent yield strength

The MATLAB script was designed to run on MATLAB Version 6.5 Release 13 on Tru64 UNIX. The script is named *ImpactVelocity11WP.m* (DTN: MO0508SPAMECHA.000, *Attachment I\WP_11_Analyses* folder) and it requires the root name of the curve files, e.g., *dp11c10e-7*, as an argument.

An excerpt of output from the script for the third impact at interface #3 is shown below. All displacements and coordinates are in inches and velocities are in in/sec, unless specified otherwise. Notice that the output results match those computed by the hand calculation example. This excerpt of output shows the values that are read in for nodal displacements and velocities at the impact time, the initial coordinates, and the damage area table values used for interpolation. This echo of the input allows for diagnostics to ensure that the script is using the correct input values.

Impact 3 at time = 1.5680 sec

```
-----
Cask H - Middle Top Node (Node 31)
  z-vel = -8.5620E+00
  y-disp = -1.2021E-01  initial y-coor = 5.1359E+01
  z-disp = 6.7206E+00  initial z-coor = 1.4122E+03
--> y-coor = 5.1239E+01
--> z-coor = 1.4189E+03
Cask H - Middle Bottom Node (Node 32)
  z-vel = 1.6015E+02
  y-disp = -8.8249E-02  initial y-coor = -3.2641E+01
  z-disp = 9.7929E+00  initial z-coor = 1.4122E+03
--> y-coor = -3.2729E+01
--> z-coor = 1.4220E+03
Cask I - Middle Top Node (Node 33)
  z-vel = 1.1743E+01
  y-disp = -8.9915E+00  initial y-coor = 3.3825E+01
  z-disp = 5.0926E+00  initial z-coor = 1.6140E+03
--> y-coor = 2.4834E+01
--> z-coor = 1.6191E+03
Cask I - Middle Bottom Node (Node 34)
  z-vel = 5.4752E+01
  y-disp = -9.1079E+00  initial y-coor = -3.3825E+01
  z-disp = 6.0039E+00  initial z-coor = 1.6140E+03
--> y-coor = -4.2933E+01
--> z-coor = 1.6200E+03
Angle of Cask H = 2.095 degrees
Angle of Cask I = 0.770 degrees
RELATIVE ANGLE = 1.325 degrees
Inferred velocity calculation for Cask H (LEFT)
  xdia = 8.4024E+01
--> DHLW Long
    dia = 8.4000E+01
    len = 1.9781E+02
    beta = 2.3009E+01 degrees
```

```

      R      = 1.0745E+02
alpha = -2.0955E+00 degrees
      H      = 4.1984E+01
      vp     = 7.5794E+01
      omega  = -2.0092E+00
      vtan   = -2.1590E+02
      vtr    = -1.5804E+01
      vbr    = 1.5286E+02
Inferred velocity calculation for Cask I (RIGHT)
      xdia   = 6.7773E+01
--> 21-PWR
      dia    = 6.7650E+01
      len    = 1.9781E+02
      beta   = 1.8880E+01 degrees
      R      = 1.0453E+02
alpha = -7.7045E-01 degrees
      H      = 3.3883E+01
      vp     = 3.3247E+01
      omega  = -6.3467E-01
      vtan   = -6.6341E+01
      vtl    = 1.2626E+01
      vbl    = 5.5557E+01
Inferred Rel Vel Top Nodes    = 1.4215E+01 ( 0.361 m/s)
Inferred Rel Vel Bottom Nodes = -4.8651E+01 ( -1.236 m/s)
                        INFERRED RELATIVE VELOCITY = -1.236 m/s
Calculate damage area in m^2 at 80% YS
      vel = 1.000 m/s --> dam80%ys = 0.0022333
      vel = 1.236 m/s -----> interpolate -----> DAM80%YS = 0.0057694
      vel = 2.000 m/s --> dam80%ys = 0.0172333
Calculate damage area in m^2 at 90% YS
      vel = 1.000 m/s --> dam90%ys = 0.0014333
      vel = 1.236 m/s -----> interpolate -----> DAM90%YS = 0.0021798
      vel = 2.000 m/s --> dam90%ys = 0.0046000

```

The peak impact velocity is tracked for waste packages I, J and K and output for each waste package after all of the impact velocities are calculated. The damage areas for impacts on waste packages I, J and K are summed and the total damage area for each waste package is output after all of the damage areas are calculated.

ATTACHMENT II

**UDEC KINEMATIC CALCULATIONS WITH
MULTIPLE WASTE PACKAGES—LONGITUDINAL
SECTIONAL CALCULATIONS**

II-1. INTRODUCTION

This Attachment provides a kinematic analysis of waste package to waste package interactions subject to postclosure ground motions using the two-dimensional DE program UDEC (BSC 2002 [DIRS 161949], STN: 10173-3.1-00). There will be approximately 100 waste packages in a typical 600 m long emplacement drift. At both ends of this "string" of waste packages, there is an open space between the end waste package and the backfill in the turnouts connecting the emplacement drifts with the access mains. Simulation of the interaction of the entire string of 100 waste packages would be time-consuming and unnecessary. However, a sufficiently large number of waste packages to ensure that the end effects do not propagate throughout the entire string of waste packages for the duration of the ground motion must be included in the calculation. The end effect is manifested by a gradual drifting of the waste packages away from the center of the string toward the open spaces at the ends, resulting in an increase in spacing between the waste packages. This effect starts at the ends and propagates toward the middle of the string. Because of the stochastic nature of this problem (when seismic ground motion is sufficiently strong to cause free flight of the waste packages), it is necessary to conduct a large number of simulations to characterize the interactions between the waste packages properly. One objective of the calculation discussed in this attachment is to characterize the interaction between the waste packages by conducting a large number of relatively simple calculations (i.e., which execute in a short time) that capture the important aspects of the analyzed problem, allowing a large number of waste packages to be included in the simulations to avoid end effects.

Energy dissipation during impact is a complex process occurring on time and length scales that are practically impossible to consider when a large number of waste packages is included in the calculation. A pragmatic solution is that the energy dissipation during impact is represented by a certain type of impact damping. Another objective of the calculations presented here was to solve the problem using hysteretic damping, which is an alternative form of impact damping, as opposed to commonly used viscous damping. Using different types of impact damping (i.e., viscous and hysteretic) provides additional confidence that the results of the calculations bound the true solution.

The computer files developed for this attachment can be accessed through the TDMS. Two DTNs have been created for this attachment. The first DTN: MO0503SPAUDCW.000 includes the impact information from the kinematic analysis and used as the direct input in the *Seismic Consequence Abstraction* (BSC 2005 [DIRS 173247]). The second DTN: MO0508SPAMECHA.000 includes complete inputs and outputs (files are located in *Attachment II* folder).

II-2. METHODOLOGY AND APPROACH

II-2.1 TWO-DIMENSIONAL APPROXIMATION

The problem of the interaction between the waste packages during seismic ground motion is truly three-dimensional for two reasons: (a) the geometry of the waste package and the objects located inside the emplacement drift, and, (b) the three-dimensional character of the ground motions, which are specified by three orthogonal components. However, a two-dimensional approximation is used in analyzing impacts between the waste packages. The problem is

analyzed in the plane of the vertical cross-section along the axis of the emplacement drift and the waste packages. Only two components of the ground motions were used in the calculation: one horizontal (H1) and vertical. The geometrical representation of the problem used is shown in Figure II-1. Motion in the out-of-plane direction (normal to the plane of the vertical cross-section along the axis of the emplacement drift) is not considered (Assumption 3.2.22). This approximation is considered to be conservative since the additional degree of freedom of the out-of-plane motion increases the probability of large waste package displacements without impact (i.e., reduction in the number of degrees of freedom of motion in the numerical approximation “forces” the waste packages to interact).

Figure II-1. Detail of the Geometry in the Middle of the String of Waste Packages

The emplacement pallet and the waste package, located inside the drip shield covered by the caved rock mass (see Assumptions 3.2.1 and 3.2.2), are represented as rectangular blocks. The dimensions (the length and the height) of the blocks that represent the waste package in the calculations are equal to the length and the diameter, respectively, of the waste package; the length of the block that represents the emplacement pallet is equal to the length of the emplacement pallet. Because of approximation of the three-dimensional geometries of the waste package and emplacement pallet with a two-dimensional representation in the numerical analysis (shown in the cross-section in Figure II-2), the height of the block that represents the emplacement pallet is modeled to be equal to the minimum height of the waste package above the invert (Assumption 3.2.3). The masses assigned to the blocks in the numerical representation are equal (per unit out-of-plane thickness as indicated in Figure II-2) to the masses of the bodies they represent.

Figure II-2. Comparison of the Actual Geometry and its Representation in the Numerical Analysis

The objective of this calculation is to determine the number of impacts and impact velocities between the waste packages during strong seismic ground motion. Impact-related local deformation and related damage of the waste packages are determined separately in the *Seismic Consequence Abstraction* (BSC 2005 [DIRS 173247]). Therefore, the important aspect of this calculation is to correctly simulate the rigid-body motion of the objects inside the drip shield. For this type of calculation, it is important to represent the mass and geometry of the bodies correctly. Deformability of the bodies will have a second-order effect on their free flight and impact velocities. Consequently, the waste package and the emplacement pallet were represented in the calculation as *practically* rigid. One of the consequences of the approximation of a three-dimensional geometry by a two-dimensional representation, which could affect the simulation of the rigid-body motion, is an error in the moment of inertia relative to the horizontal axis in the vertical cross-section. As a result, when the block that represents the waste package in the numerical calculation is subject to a certain rotational velocity (in a kinematically controlled system) it will have a greater rotational energy than the actual waste package, resulting in an additional level of conservatism in the two-dimensional calculation of the interaction between the waste packages.

Representation of the three-dimensional problem in the two-dimensional numerical calculation also affects the contact between the emplacement pallet and the waste package, and the frictional resistance in that contact. The contact forces generated between the waste package and the emplacement pallet, and the representation in the numerical calculation, are illustrated in Figure II-3. When the waste package rests on the emplacement pallet in an equilibrium state (i.e., it is completely settled), there are two contacts between the waste package and the emplacement pallet. The total frictional resistance of the interface (accounting for forces in both contacts) as calculated in Equation II-1 for weight of the waste package, W , and angle of friction, ϕ , is about 15 percent greater than the frictional resistance of the interface in the numerical representation, as shown in Equation II-2. The difference in the frictional resistance of 15 percent was considered relatively small compared to uncertainties in the input parameters used in this calculation and to the inherent randomness of the analyzed problem. The friction coefficient between the waste package and the emplacement pallet is a random parameter in the calculations (i.e., each waste package-emplacement pallet pair was assigned a different friction coefficient), taken from a uniform distribution between 0.2 and 0.8 (Assumption 3.2.4). The difference of 15 percent is relatively small compared to the range of variability of the friction coefficient.

$$F = 2 \frac{W}{2 \cos 30^\circ} \tan \phi \cong 1.15W \tan \phi \quad \text{Eq. II-1}$$

$$F = W \tan \phi \quad \text{Eq. II-2}$$

Figure II-3. Comparison of the Contact Forces in the Actual Geometry and its Representation in the Numerical Analysis

II-2.2 BOUNDARY CONDITIONS

Only the motion of the objects located inside the drip shield was simulated. All other objects and boundaries included in the calculation were assumed to move synchronously with the free field (Assumptions 3.2.1 and 3.2.2). The lower boundary (i.e., the surface on which the emplacement pallets rest) represents the invert. The boundary above the waste package represents the drip shield. It has been demonstrated in Attachment VIII that amplification of the seismic waves as they pass through the crushed rock in the invert of the drift is negligible. The drip shield is resting by its own weight on the invert and can move relative to the invert during seismic ground motion when subjected to inertial forces of a certain magnitude. The analyses of emplacement drift stability during strong seismic ground motions (BSC 2004 [DIRS 166107], Sections 6.3 and 6.4) indicate total collapse of the drifts in the lithophysal rock mass if the PGV of the ground motion exceeds approximately 2 m/s. For the same levels of ground motion intensity, significant rockfall is predicted inside the drifts in the nonlithophysal rock mass. Although the rockfall in nonlithophysal units will not result in total collapse of the emplacements drifts, the drip shield will be covered with a caved rock mass in both the lithophysal and nonlithophysal units. Massive rockfall, which is observed to occur within a couple of seconds after the onset of strong ground motion, will cover the drip shield, restricting its subsequent motion. Although the drip shield covered by the caved rock will not move in perfect synchronicity with the free field (i.e., as observed in the cross-drift calculation, Attachment V, there will be an effect of wave propagation through the caved rock mass even after it completely covers the drip shield), the relative motion will not be significant. For the purpose of the calculation of waste package interaction, assuming synchronous motion of the drip shield with the free field is justifiable (Assumption 3.2.1).

II-2.3 CONTACT MODEL

The blocks representing the waste package and emplacement pallet interact through interfaces or contacts. Contact stresses, σ_n and σ_s , in the normal and shear directions, respectively, are generated as a result of the relative motion, u_n and u_s , of the blocks involved in the contact according to the simple relations (Itasca Consulting Group 2002 [DIRS 160331], UDEC Manual):

$$\begin{aligned}\sigma_n &= k_n u_n \\ \sigma_s &= k_s u_s\end{aligned}\tag{Eq. II-3}$$

where k_n and k_s are normal and shear contact stiffnesses, respectively. The contacts cannot sustain any tensile stresses in the normal direction, but the contact response in the normal direction in compression is linear (i.e., k_n is constant irrespective of σ_n or u_n). The limit to the shear stress, $\sigma_{s,\max}$, is governed by the Coulomb slip law, in which cohesive resistance to slip is always assumed to be zero (Itasca Consulting Group 2002 [DIRS 160331], UDEC Manual):

$$\sigma_{s,\max} = \sigma_n \tan \phi\tag{Eq. II-4}$$

where $\tan \phi$ is the friction coefficient, and ϕ is the friction angle.

II-2.4 HYSTERETIC DAMPING AT CONTACTS

During high-velocity impact of the waste packages, the outer shell of the waste package will deform plastically at the impact location. A consequence of the localized plastic deformation is dissipation of impact energy. If energy dissipation during impact were not considered in the calculation, the calculated predictions of the number of impacts and impact velocities would be unrealistic and excessively conservative. However, explicitly simulating localized impact and associated energy dissipation at the same time as rigid body motion and interaction of a large number of waste packages is computationally intractable. Instead, in the calculations presented here, energy dissipation was accounted for using contact damping, which is a computational tool used to dissipate energy during an impact between two bodies. There are two types of contact damping: viscous and hysteretic. Viscous contact damping (used in the LS-DYNA calculations described in Attachment I) is represented as a dashpot acting in parallel with a spring, which represents the elastic response of the contact. In general, constitutive behavior and the parameters that characterize that behavior are not the same for both normal and tangential deformations of the contact. Impact damping (either viscous or hysteretic) acts in the normal direction only. On the other hand, the frictional slider (another mechanism of energy dissipation during contact deformation) acts in the tangential direction only. The viscous damping force, which is a function of the relative normal velocity of the bodies involved in the contact, acts during any relative motion between the waste package and the emplacement pallet, even if that motion does not occur as a result of the impact. Hysteretic damping is used as impact damping in the calculations discussed in this attachment with UDEC calculations. It is implemented, based on the global force-displacement response of the contact, in such a way that the contact is assigned different normal stiffness during the loading and unloading phases of deformation

(Figure II-4). The difference between the areas beneath the loading and unloading portions of the force-displacement curves is proportional to the energy dissipated during the impact. The unloading stiffness must be greater than the loading stiffness (as shown in Figure II-4) for energy to be dissipated.

Figure II-4. Contact Force-Displacement Response as a Result of Hysteretic Damping

Sometimes the impact between two bodies involves more than one loading-unloading cycle. If the hysteretic damping (i.e., the change in the contact normal stiffness) is applied to each cycle (as shown in Figure II-5), a non-physical result may occur in which a continuous increase of normal displacement (with every loading-unloading cycle) and subsequent large overlap of the bodies involved in the contact results. In reality, the amount of energy dissipation is proportional to stress changes that occur during the loading-unloading cycle. There is also a limit of contact stress below which energy dissipation is negligibly small irrespective of the number of the cycles. The impact energy is dissipated mainly during the first loading-unloading cycle only. If subsequent cycles occur, energy dissipation is negligibly small. In the calculation presented here, hysteretic damping is applied in such a way that it acts during the first loading-unloading cycle only. All subsequent cycles use the same contact stiffness (equal to the unloading stiffness of the first loading-unloading cycle).

Figure II-5. Nonphysical Increase in Normal Displacements Caused by Relatively Small Stress Oscillations Due to Hysteretic Damping

II-3. CALIBRATION

The main parameter of hysteretic damping, which controls energy dissipation, is the ratio of the unloading and loading stiffnesses (i.e., k_{nu} / k_{nl}). The COR, which is defined as the ratio between the impact velocities after and before impact, is commonly used to characterize energy loss during inelastic impact of rigid, spherical (or cylindrical) bodies (or impact of such bodies into a rigid half-space). Under such conditions, it is possible to develop a unique relation between the stiffness ratio and the COR. The simple problem of a rigid ball dropped on rigid half-space is simulated in UDEC. Both the cylinder and the half-space have a finite stiffness in the numerical simulation, but those stiffnesses are very large compared to the stiffness of the contact between the cylinder and the half-space. Because most of deformation during impact takes place in the contact, the cylinder and the half-space behave as “practically rigid”. The geometry of the problem is shown in Figure II-6.

Figure II-6. Vertical Gravity Drop of a Cylinder Impacting a Half Space to Calibrate the Hysteretic Contact Damping Parameters Equivalent to a Given COR

The simulation was carried out for different values of the ratio between the loading and unloading stiffnesses. The COR is calculated based on the results of the numerical simulations and is plotted in Figure II-7 as a function of the stiffness ratio. The results obtained with UDEC are compared with the Particle Flow Code (PFC) results for the same problem reported in PFC2D Version 3.1 User's Manual (Itasca 2005 [DIRS 174198]). (PFC is a numerical code used for numerical simulation of the mechanical interaction of rigid spherical or cylindrical bodies.) The results obtained with the two different codes agree very well.

Figure II-7. COR as a Function of the Ratio Between Loading and Unloading Stiffnesses

In general, for arbitrary size, shape and stiffness of the bodies involved in the contact, the relationship between the COR (or the ratio between velocities after and before impact) and the stiffness ratio is not unique. Therefore, it was necessary to calibrate the stiffness ratio to the prescribed COR for the geometries and properties of the blocks used for the simulation of the waste package interaction. A simple drop test was conducted for the waste package and the emplacement pallet in which the waste package was lifted and then dropped on the emplacement pallet. The numerical representation of the drop test is shown in Figure II-8. In order to obtain the response of the contact between the waste package and the emplacement pallet (i.e., metal-to-metal contact) only, the base of the emplacement pallet was kept fixed—i.e., there was no interaction with the invert. The target COR for metal-to-metal impacts was 0.6 (see Assumption 3.2.28). This calibrated stiffness ratio was assigned to all metal-to-metal impacts in the simulations of waste package interactions during strong seismic ground motions. The stiffness ratio for the metal-to-rock impacts was calibrated in two tests in which the waste package and the emplacement pallet were dropped on the invert. The configuration of the drop test for the emplacement pallet is shown in Figure II-9. The target COR for metal-to-rock impacts was 0.2 (see Assumption 3.2.28).

Figure II-8. Configuration During the Simulation of the Drop Test for the Middle Waste Package

Figure II-9. Configuration During the Simulation of the Drop Test for the Middle Emplacement Pallet

The calculations showed that stiffness ratios (i.e., k_{nu}/k_{nl}) of 2.7 and 50.0 resulted in the responses that closely matched the CORs of 0.6 and 0.2, respectively. The displacement and the velocity histories of the tested objects, which were recorded during the simulations, were used to calculate the COR. All of the tested objects were lifted 0.5 m above their original configuration

before being dropped on the base. Only in the case of the waste package dropped on the invert was the initial height of the waste package above the base greater than 0.5 m. The displacements and the velocities of the waste package during the drop tests are shown in Figures II-10 and II-11, respectively. If the stiffness ratio is equal to 1.0, the impacts are practically elastic, with no energy loss. The ratio of the velocities after and before impact (or the square root of the rebound height after and before the impact) is approximately 0.6 (Figure II-11) if the stiffness ratio is 2.7. The drop test on the invert using the stiffness ratio of 50.0 results in different rebound heights for the waste package and the emplacement pallet (Figure II-12). The COR is 0.15 for the waste package and 0.24 for the emplacement pallet.

NOTE: In the case of the ratio equal to 50.0, the waste package is dropped on the invert directly with emplacement pallet removed – thus the negative height; otherwise, the waste package is dropped on the emplacement pallet.

Figure II-10. Displacement as a Function of Time for Different Values of the Ratio Between Unloading and Loading Stiffnesses

Figure II-11. Velocity as a Function of Time for Different Values of the Ratio between Unloading and Loading Stiffnesses

NOTE: Stiffness ratio is equal to 50.0. The emplacement pallet is removed prior to the waste package drop, resulting in a negative height value.

Figure II-12. Displacement as a Function of Time for Drop Tests Conducted on the Waste Package and the Emplacement Pallet

A proportion of the energy dissipated by hysteretic damping (for constant contact stiffnesses) is independent of the impact energy. The stress-displacement responses for two different impact energies are illustrated in Figures II-13a and II-13b. The gray arrows indicate the stress path followed in the numerical approximation of hysteretic damping. The ratio between the dissipated energy (equal to the area of the ODE triangle) and the total impact energy (equal to the area of the ODD' triangle) is independent of the total impact energy. A more realistic stress-displacement response during the impact is shown as the thick solid line. The black solid arrows follow that stress path for two levels of impact energies. In this case, the ratio between the dissipated energy (equal to the area of the OABC quadrilateral) and the total impact energy (equal to the area of the OABB' quadrilateral) changes as a function of the impact energy. The proportion of the dissipated energy increases as the impact energy increases. Because the proportion of the energy dissipated by hysteretic damping remains constant irrespective of the impact energy, it appears that conservatism of hysteretic damping increases as the impact energy increases.

Figure II-13. Contact Stress-Displacement Responses for Two Different Impact Energies

II-4. DESCRIPTION OF THE CALCULATIONS

The calculations were carried out with UDEC version 3.1 (BSC 2002 [DIRS 161949], STN: 10173-3.1-00). UDEC is a two-dimensional numerical code used to simulate the mechanical interaction of polygonal blocks. The code has a general algorithm for automatic detection of contacts between blocks — any two blocks in the calculation can interact with each other at any point of calculation. The contacts are detected based on the relative position and geometry of the blocks only. Although UDEC usually is applied to problems of deformation and stability of a fractured rock mass, it is well suited for the calculation of the mechanical interaction between waste packages during strong seismic ground motions.

II-4.1 NUMBER OF WASTE PACKAGES

Twenty-one waste packages were included in the numerical simulation. The geometries of all the blocks representing the waste packages at the end of a particular simulation are shown in

Figure II-14. The distance between the waste packages at the end of the string of 21 waste packages and the vertical boundaries, which represent the ends of the emplacement drift, is equal to approximately five waste package lengths in the original configuration (before shaking begins). No restraint was assumed on either end of the string of 21 waste packages: the end waste packages can interact with the other waste package on one side but are free to move to the other side. In no simulations did the end waste packages displace sufficiently to come in the contact with the drift ends. The following information is recorded for all 21 waste packages: (a) time of impact; (b) location of impact relative to the local coordinate system (with origin at the lower-left corner of the impacted block and x -axis along the length of the waste package); and (c) relative impact velocity decomposed in the normal and tangential directions relative to the impacted surface. Impacts between the waste packages, the waste package and the emplacement pallet, and the waste package and the drip shield (i.e., the upper boundary) were recorded.

Although the impact information is recorded for all waste packages, only the information for 3 waste packages in the middle of the string were used to calculate the damage due to waste package-to-waste package impacts in the *Seismic Consequence Abstraction* (BSC 2005 [DIRS 173247]). Because the number of the waste packages included in the simulation is smaller than the number of waste packages designed to be emplaced in one drift (approximately 100 for a typical 600 m long emplacement drift), it is important that the number of waste packages included in the numerical simulation (i.e., 21) does not affect a number of impacts and impact velocities calculated for 3 waste packages in the middle of the string. Qualitative review of the results of the numerical simulations shows that, for the duration of strong seismic ground motions, the end effect propagates, at most, 6 to 8 waste packages from both ends. The configuration of the blocks and the contours of horizontal displacements at the end of a simulation for one of the ground motions (i.e., ground motion #12 at the 5.35-m/s PGV level) are shown in Figure II-14. Details of displacements at the string ends also are shown in the figure. Three waste packages on the left end and 8 waste packages on the right end drifted away from the middle of the string as a result of shaking and conditions at the ends of the finite string. On the right side, the end waste package completely fell off the emplacement pallet. In this particular case, for one of the strongest ground motions, 10 waste packages in the middle of the string are unaffected by the end conditions. It appears that using 21 waste packages is sufficient to simulate waste package-to-waste package interaction sufficiently far from the ends of the string. The three waste packages in the middle of the string certainly will be unaffected by the end conditions.

Figure II-14. Contours of Displacements (m) at the End of Simulation for Ground Motion #12 at 5.35-m/s PGV Level

II-4.2 GROUND MOTIONS

Three sets of 17 ground motions were analyzed (Section 5.2.3). Each set represents a different PGV level—i.e., 1.05 m/s, 2.44 m/s and 5.35 m/s. A total of 51 simulations were carried out. Full duration of the ground motion was not simulated; instead, the portion of the records of the ground motions between the points corresponding to 5 and 95 percent in the total energy of the time history, as measured by the Arias intensity, was simulated. For each three-component set of

ground motions (i.e., two horizontal and one vertical), these points were determined for each component; then, the earliest 5 percent point and the latest 95 percent point were used to define the duration of strong ground motion for that set of ground motions.

II-4.3 GEOMETRY

The simulations were carried out using only 21-PWR waste packages in the emplacement drift - the effect of variability in the mass of the waste packages was not considered as described in Attachment I. The specifications (mass and dimensions) for the 21-PWR and the emplacement pallet are listed in Tables II-1 and II-2, respectively. The dimensions of the waste package block in the numerical simulation are the same as the dimensions of the waste package in the vertical cross-section along the axis of the emplacement drift. The dimensions of the emplacement pallet in the cross-section and the height of the waste package above the invert, which was used as the height of the emplacement pallet in the calculations (Figure II-2), are indicated in Figure II-15. Different dimensions as used in the calculations are listed in Table II-3 (Assumption 3.2.3). In the numerical simulation, the waste package rests on the end parts of the emplacement pallet (shown with dark brown color in Figure II-1). A stiff block (light brown color in Figure II-1) connects the emplacement pallet end uprights that support the waste package. This stiff interconnecting block interacts with the end uprights of the emplacement pallet only. The waste package can overlap (without generation of the interaction forces) the connecting emplacement pallet block freely should the waste package slide off the end uprights.

Table II-1. Dimensions and Mass for the 21-PWR

Length¹	197.81"	5024.4 mm
Diameter¹	67.65"	1718.3 mm
Mass²	91,900 lb	41685 kg

NOTES: ¹ BSC 2005 [DIRS 173501], Table 1

² Assumption 3.2.27

Table II-2. Dimensions and Mass for the Emplacement Pallet

Length¹	163.3"	4147.9 mm
Width¹	21.37"	2150.1 mm
Height²	28.59"	726.3 mm
Mass¹	4,340 lb	1970 kg

NOTES: ¹ BSC 2005 [DIRS 173303], Table 7

² BSC 2005 [DIRS 173303], Directory, Emplacement pallet, Emplacement Pallet General Configuration, Nominal Dimensions, and Weights

NOTE: Dimensions are approximated based on BSC 2005 [173303] and BSC 2005 [173501].

Figure II-15. Dimensions of the Emplacement Pallet used to Calculate the Representation in the Numerical Calculation

Table II-3. Dimensions Used in the Numerical Simulations

Waste package height	1.727 m
Waste package length	5.029 m
Spacing between waste packages	0.1 m
Emplacement pallet height	0.247 m
Emplacement pallet length	4.140 m
Length of the emplacement pallet end parts	0.543 m
Drip shield height	2.78 m
Clearance between the drip shield and the waste package	0.806 m

NOTE: Approximated dimensions are used in the analyses (Assumption 3.2.3)

II-4.4 MECHANICAL PROPERTIES

The mechanical properties listed in Table II-4 were used in all simulations. These properties have a secondary effect on the results of the calculations. To ensure that the blocks behave as practically rigid materials, the bulk and shear moduli of the blocks that represent the waste package and the emplacement pallet are assumed to be very large relative to the contact normal stiffness (Assumption 3.2.5).

Table II-4. Mechanical Material Properties

Contact normal stiffness	10^9 Pa/m
Contact shear stiffness	10^9 Pa/m
Waste package bulk modulus	$16.29 \cdot 10^{12}$ Pa
Waste package shear modulus	$8.04 \cdot 10^{12}$ Pa
Emplacement pallet bulk modulus	$1.99 \cdot 10^{12}$ Pa
Emplacement pallet shear modulus	$0.98 \cdot 10^{12}$ Pa

NOTE: Material properties are assumed values to ensure correct estimate of impact information (Assumption 3.2.5).

The mechanical parameters that have a significant effect on the results of the calculations are the ratio of the contact stiffnesses (used in hysteretic damping) and the friction coefficients. The ratio of contact stiffnesses of 2.7 was used for all metal-to-metal impacts (i.e., waste package-emplacement pallet, waste package-waste package, waste package-drip shield, emplacement pallet-emplacement pallet); the ratio of contact stiffness of 50.0 was used for all metal-to-rock impacts (e.g., emplacement pallet-invert). No spatial variability of impact damping was considered in the calculations. The same impact damping was used in all simulations.

The metal-to-metal and metal-to-rock friction coefficients were considered to be random variables selected from the uniform distribution ranging between 0.2 and 0.8 (see Assumption 3.2.4 and Attachment X). Both friction coefficients (metal-to-metal and metal-to-rock) vary along the string of the waste packages. For a single waste package set (including the waste package and the emplacement pallet), the friction coefficient between the waste package and the emplacement pallet (metal-to-metal) was different from the friction coefficient between the emplacement pallet and the invert (metal-to-rock). Seventeen sets of 21 metal-to-metal friction coefficients and 17 sets of 21 metal-to rock friction coefficients were used for all three PGV levels (i.e., a different set of friction coefficients for each ground motion from a given PGV level). For example, ground motions #1 from all three PGV levels used the same sets of 21 metal-to-metal friction coefficients and 21 metal-to-rock friction coefficients.

II-5. CALCULATION OF A SINGLE WASTE PACKAGE BETWEEN RIGID BOUNDARIES

The problem of mechanical interaction between waste packages was analyzed in a previous calculation (BSC 2004 [DIRS 167083]) as a three-dimensional problem using the LS-DYNA code. A single waste package located between two vertical rigid boundaries was considered in the calculations. The vertical boundaries, which were 0.1 m from the edges of the waste package, represented rigid neighboring waste packages fixed to the invert. This calculation yielded a very conservative estimate of the number of impacts and impact velocities between the waste packages because the motion of neighboring waste packages relative to the free-field ground motion was not considered. A relatively fine grid was used to represent the geometry of the waste package. Elasto-plastic, bi-linear constitutive behavior was used to represent the response of Alloy 22 to deformation. Consequently, energy dissipation during impact was accounted for automatically by inelastic material deformation.

II-5.1 COMPARISON BETWEEN UDEC AND LS-DYNA RESULTS OF ANALYSIS OF THE WASTE PACKAGE BETWEEN VERTICAL, RIGID BOUNDARIES

The problem of a waste package between rigid boundaries is reanalyzed in a two-dimensional approximation with UDEC using hysteretic contact damping. The objective of the calculation was to compare the results of different numerical codes, assumptions of problem dimensionality and approaches of representing energy dissipation during high-velocity impacts. The configuration of the waste package blocks at a state during the UDEC simulation of the single waste package between the vertical boundaries is shown in Figure II-16. UDEC simulations were carried out for the same realizations and ground motions as simulated originally, at 2.44 m/s and 5.35-m/s PGV levels, referred to in Section 6.1 of *Structural Calculations of Waste Package Exposed to Vibratory Ground Motion* BSC (BSC 2004 [DIRS 167083]) as ground motions with 10^{-6} and 10^{-7} probability of annual recurrence.

The numbers of impacts with impact velocity greater than 1 m/s and maximum impact velocities as calculated with two different codes and approaches are listed in Table II-5. Because the analyzed problem involves simulating the free flight of rectangular blocks, their impacts and rebounds after impacts, the evolution of the problem is very sensitive to initial and boundary conditions. A very small variation of the initial or boundary conditions could result in significantly different trajectory of the block and, consequently, a different number of impacts and impact velocities. For example, if the waste package hits a surface with an edge, a very small change in the angle of impact relative to the normal of the impacted surface can drastically affect both the velocity and the direction of the waste package motion after impact. Consequently, because of the stochastic nature of the analyzed problem, comparison of the simulation results cannot be done based on results of a single realization. The statistical descriptions of the results of the multiple realizations were compared. Although the agreement between UDEC and LS-DYNA is not particularly good on case-by-case basis, there is a very good agreement in the average values of both the number of impacts and the maximum impact velocities for the 2.44-m/s PGV level. Histograms of the number of impacts and the maximum impact velocities, shown in Figures II-17 and II-18, respectively, also show agreement between UDEC and LS-DYNA results. The comparison demonstrates that, despite all of the simplifying assumptions used, the UDEC calculation accounts for the important aspects of the analyzed problem; consequently, the UDEC results are very similar to the LS-DYNA results, in which the problem is treated as three-dimensional, representing details of geometry and complex constitutive behavior.

For the 5.35-m/s PGV level, UDEC predicts a greater number of impacts and impact velocities than LS-DYNA (Table II-5). One explanation for the discrepancy between UDEC and LS-DYNA results at the 5.35-m/s PGV level is that, with an increase in the intensity of ground motion, the proportion of energy dissipation during impact increases (captured by the elasto-plastic constitutive model of the waste package outer barrier), while the hysteretic damping dissipates the same proportion of the energy irrespective of the intensity of the ground motion. This discrepancy is acceptable, as it indicates that UDEC results are conservative for the 5.35-m/s PGV level.

Figure II-16. Configuration During Simulation of a Single Waste Package

Table II-5. Comparison Between UDEC and LS-DYNA of Impact Results for a Single Waste Package

Realization	2.44-m/s PGV level				5.35-m/s PGV level			
	Number of impacts*		Max. velocity** (m/s)		Number of impacts*		Max. velocity** (m/s)	
	UDEC	LS-DYNA	UDEC	LS-DYNA	UDEC	LS-DYNA	UDEC	LS-DYNA
1	12	3	2.32	1.50	26	10	4.11	4.50
2	0	3	0.00	1.80	11	7	2.64	1.90
3	9	9	2.89	3.90	57	34	7.42	4.70
4	5	4	4.15	4.10	11	11	3.65	3.00
5	9	14	1.89	4.40	21	19	3.19	3.40
6	8	7	1.98	4.00	31	16	8.51	6.40
7	10	7	3.59	4.50	40	18	8.04	6.00
8	10	5	2.39	1.90	50	33	4.82	4.10
9	0	10	0.00	2.80	12	5	4.22	1.80
10	21	3	4.25	1.60	35	15	7.24	6.50
11	1	7	1.52	2.80	17	22	5.84	4.60
12	9	7	2.16	3.00	27	14	4.40	3.50
13	6	5	2.22	2.00	32	18	4.48	2.40
14	0	3	0.00	1.40	9	1	1.60	1.30
15	7	1	4.49	2.00	9	12	5.78	8.60
Average	7.13	5.87	2.26	2.78	25.87	15.67	5.06	4.18
St. dev.	5.6	3.38	1.48	1.13	15.13	9.15	2.04	2.04

NOTES: * Number of impacts greater than 1 m/s.

** If greater than 1 m/s.

Figure II-17. Number of Impacts for the 2.44-m/s PGV Level Calculated with UDEC and LS-DYNA

Figure II-18. Histograms of Maximum Impact Velocities for the 2.44-m/s PGV Level Calculated with UDEC and LS-DYNA

II-5.2 EFFECT OF HYSTERETIC DAMPING

To further investigate the effect of hysteretic damping as a function of the PGV level (i.e., the intensity of ground motion), the problem of a waste package between rigid boundaries is

simulated for the 2.44-m/s and 5.35 m/s PGV levels, with no contact damping. The results are compared with the results obtained with UDEC using calibrated hysteretic damping (Table II-6). Approximately the same reduction in the number of impacts (60 percent) and maximum impact velocity (30 percent) for both the 2.44-m/s and 5.35-m/s PGV levels as a result of hysteretic damping is in agreement with observation that hysteretic damping dissipates the same proportion of impact energy irrespective of the magnitude of impact energy. The LS-DYNA results indicate that the proportion of the dissipated energy increases with increase in impact energy.

Table II-6. Number of Impacts and Maximum Impact Velocities Calculated using Calibrated Hysteretic Damping (COR 0.6) and Assuming no Damping (COR 1.0)

Realization	2.44-m/s PGV level				5.35-m/s PGV level			
	Number of impacts*		Max. velocity** (m/s)		Number of impacts*		Max. velocity** (m/s)	
	COR 0.6	COR 1.0	COR 0.6	COR 1.0	COR 0.6	COR 1.0	COR 0.6	COR 1.0
1	12	28	2.32	3.55	26	75	4.11	5.34
2	0	0	0.00	0.00	11	28	2.64	2.21
3	9	22	2.89	4.16	57	67	7.42	6.35
4	5	9	4.15	2.74	11	36	3.65	8.22
5	9	12	1.89	2.34	21	31	3.19	3.43
6	8	31	1.98	5.08	31	64	8.51	8.56
7	10	39	3.59	8.37	40	54	8.04	7.46
8	10	37	2.39	3.99	50	174	4.82	9.69
9	0	1	0.00	1.01	12	19	4.22	5.69
10	21	58	4.25	6.40	35	141	7.24	13.40
11	1	5	1.52	3.96	17	22	5.84	5.13
12	9	9	2.16	2.06	27	46	4.40	6.19
13	6	7	2.22	1.80	32	56	4.48	3.97
14	0	0	0.00	0.00	9	20	1.60	3.21
15	7	6	4.49	3.06	9	86	5.78	17.50
Average	7.13	17.60	2.26	3.23	25.87	61.27	5.06	7.09

NOTES: * Number of impacts greater than 1 m/s.

** If greater than 1 m/s.

II-6. RESULTS OF SIMULATIONS

The results of 51 simulations (i.e., 17 ground motions for each of 3 PGV levels) are summarized in Table II-7. The results are presented for 3 waste packages in the middle of the string of 21 waste packages. The table includes the number of impacts greater than 0.85¹ m/s and the maximum impact velocities for each realization. Only two impacts with velocity greater than 0.85 m/s into the middle waste package are detected from all realizations at the 1.05-m/s PGV level. At the 2.44-m/s PGV level, impacts into the middle waste package occurred in 9

¹ A number of impacts with impact velocity greater than 0.85 m/s (not the total number of impacts) is reported because impacts will not damage the waste package if the impact velocity is lower than 0.85 m/s (Assumption 3.2.29).

realizations. A large number of impacts for each realization and relatively large impact velocities are predicted at the 5.35-m/s PGV level.

Table II-7. Summary of Impact Results

Realiz.	Motion	1.05-m/s PGV Level						2.44-m/s PGV Level						5.35-m/s PGV Level					
		Number of impacts*			Max. velocity** (m/s)			Number of impacts*			Max. velocity** (m/s)			Number of impacts*			Max. velocity** (m/s)		
		left	center	right	left	center	right	left	center	right	left	center	right	left	center	right	left	center	right
1	17	0	0	0	0.00	0.00	0.00	0	0	0	0.00	0.00	0.00	5	5	7	1.73	1.71	1.86
2	16	0	0	0	0.00	0.00	0.00	0	0	0	0.00	0.00	0.00	17	13	12	2.29	3.11	3.24
3	3	2	1	0	0.96	0.87	0.00	2	2	2	1.13	1.64	1.75	11	9	12	4.17	6.06	6.16
4	2	0	0	0	0.00	0.00	0.00	4	2	5	2.23	2.23	1.55	26	24	22	4.62	4.61	5.89
5	11	0	0	0	0.00	0.00	0.00	0	0	0	0.00	0.00	0.00	11	13	7	1.99	2.04	2.42
6	4	0	0	0	0.00	0.00	0.00	3	1	0	0.90	0.90	0.00	27	31	32	3.93	3.87	2.96
7	12	0	0	0	0.00	0.00	0.00	0	0	0	0.00	0.00	0.00	28	24	22	3.04	3.18	3.17
8	5	0	0	0	0.00	0.00	0.00	0	0	0	0.00	0.00	0.00	11	12	12	2.93	4.27	4.48
9	15	0	0	0	0.00	0.00	0.00	0	0	1	0.00	0.00	1.76	9	8	9	1.80	1.82	2.09
10	9	0	1	1	0.00	1.15	1.15	7	8	9	2.40	2.91	2.92	28	29	28	4.35	5.40	7.30
11	8	0	0	0	0.00	0.00	0.00	0	1	1	0.00	0.95	0.95	14	14	9	4.42	2.99	2.91
12	6	0	0	0	0.00	0.00	0.00	0	1	2	0.00	1.43	1.41	26	26	24	6.76	6.42	6.67
13	10	0	0	0	0.00	0.00	0.00	0	0	0	0.00	0.00	0.00	9	14	12	3.37	2.54	2.21
14	1	0	0	0	0.00	0.00	0.00	0	1	1	0.00	0.91	0.92	17	14	17	5.76	5.74	3.89
15	7	0	0	0	0.00	0.00	0.00	6	8	8	5.22	2.71	4.37	26	27	28	5.10	7.08	6.12
16	14	0	0	0	0.00	0.00	0.00	0	0	0	0.00	0.00	0.00	9	6	9	3.15	3.19	1.78
17	13	0	0	0	0.00	0.00	0.00	4	1	0	1.16	1.24	0.00	28	28	26	5.72	5.72	5.18

NOTES: *Number of impacts greater than 0.85 m/s (Assumption 3.2.29).

** If greater than 0.85 m/s.

The impact velocities for waste package to drip shield impacts for the 1.05 m/s, 2.44 m/s and 5.35-m/s PGV levels are given in Table II-8. As seen, only one realization at 1.05 m/s level shows an impact with absolute velocity greater than 0.85 m/s (Assumption 3.2.29). Three realizations at the 2.44-m/s PGV level indicate waste package-drip shield contacts with a mean absolute velocity of 3.87 m/s, and 15 realizations indicate contacts at the 5.35-m/s PGV level, with a mean absolute contact velocity of 6.51 m/s.

Table II-8. Summary of Waste Package to Drip Shield Impact Velocities

Realization	1.05-m/s PGV Level Absolute Velocity (m/s)	2.44-m/s PGV Level Absolute Velocity (m/s)	5.35-m/s PGV Level Absolute Velocity (m/s)
1	NI*	NI	NI
2	NI	NI	3.76
3	1.44	3.43	14.33
4	NI	NI	10.49
5	NI	NI	4.86
6	NI	NI	6.24

Table II-8. Summary of Waste Package to Drip Shield Impact Velocities (Continued)

Realization	1.05-m/s PGV Level Absolute Velocity (m/s)	2.44-m/s PGV Level Absolute Velocity (m/s)	5.35-m/s PGV Level Absolute Velocity (m/s)
7	NI	NI	3.69
8	NI	NI	2.70
9	NI	NI	2.77
10	NI	3.01	14.71
11	NI	NI	NI
12	NI	NI	2.118
13	NI	NI	1.698
14	NI	NI	1.237
15	NI	5.16	2.310
16	NI	NI	0.251
17	NI	NI	1.695
Mean	NA**	3.87	6.51
Std Dev	NA	1.14	4.19
Max	NA	5.16	14.71
Min	NA	3.01	1.29

NOTES: * NI – no impact, ** NA – not applicable

II-7. CONCLUSION

Interaction of waste packages during strong seismic ground motions was analyzed in a relatively simple calculation. The problem was analyzed as two-dimensional in which the waste package and the emplacement pallet were represented as nearly rigid rectangular blocks. The drip shield, which was represented as the boundary above the waste package, was assumed to be covered with collapsed rock rubble and was assumed to move synchronously with the free field. Energy dissipation during high-velocity impacts was accounted for by hysteretic damping at contacts. The ratio between unloading and loading normal stiffnesses, which is a parameter that controls the amount of energy dissipation by hysteretic damping, was calibrated against a drop test to match the COR of 0.6 for metal-to-metal impacts and approximately 0.2 for metal-to-rock impacts. The hysteretic damping was assumed to be the same in all simulations for all contact of the same type (i.e., metal-to-metal or metal-to-rock). The friction coefficients (both metal-to-metal and metal-to-rock) were assumed to be random variables, selected from a uniform distribution ranging between 0.2 and 0.8. The vibratory motion of twenty-one waste packages (21-PWRs) were analyzed in the calculations. This number of waste packages was sufficient to adequately represent the mechanical response of 100 (approximate) waste packages in a typical emplacement drift. The calculations were carried out for 17 ground motions at each of three PGV levels: 1.05 m/s, 2.44 m/s and 5.35 m/s (i.e., a total of 51 simulations). These PGV levels correspond to annual exceedance probabilities of 1×10^{-5} , 1×10^{-6} and 1×10^{-7} per year for the unbounded hazard curve.

Results from simulating waste package interaction in a two-dimensional simulation with UDEC were compared with the LS-DYNA results for the problem of a single waste package between two vertical walls, obtained using the fully three-dimensional, detailed representation of waste package geometry and detailed constitutive behavior of Alloy 22. The comparison shows a good

agreement of predictions of the number of impacts greater than 1 m/s and maximum impact velocities for the 2.44-m/s PGV level obtained by two calculations. At the 5.35-m/s PGV level, UDEC predictions of a number of impacts and maximum impact velocities are conservative. Hysteretic damping is the main reason for the large conservatism in the UDEC result at this PGV level.

During the simulations of interaction between 21 waste packages, the times and locations of impacts and impact velocities were monitored and recorded for every impact and every waste package in the calculation. The results are reported for three waste packages in the middle of the string. Only two impacts for the middle waste package with a maximum impact velocity greater than 0.85 m/s were detected in all 17 realizations for the 1.05-m/s PGV level. There are nine realizations at the 2.44-m/s PGV level with impact velocities greater than 0.85 m/s. At the 5.35-m/s PGV level, impacts with impact velocities greater than 0.85 m/s are detected in each realization. Maximum impact velocities in excess of 7 m/s are predicted at this PGV level. These impact parameters are used in *Seismic Consequence Abstraction* (BSC 2005 [DIRS 173247]) for determination of the damage abstraction for the waste package from end-to-end waste package impacts.

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ATTACHMENT III

**ADDITIONAL INFORMATION FOR THE SINGLE 21-PWR
WASTE PACKAGE END IMPACTS CALCULATION**

III-1. INTRODUCTION

The structural response calculations for end-on impacts (BSC 2005 [DIRS 173178]) are based on a relatively detailed FE mesh to determine damaged areas more accurately than is possible in *Structural Calculations of Waste Package Exposed to Vibratory Ground Motion* (BSC 2004 [DIRS 167083]). In effect, it is more accurate and more computationally efficient to perform very detailed calculations of the (brief) impact process because the long duration of ground motions and the complexity of the FE representation in *Structural Calculations of Waste Package Exposed to Vibratory Ground Motion* (BSC 2004 [DIRS 167083]) precludes such a detailed analysis.

These calculations represent a parametric study of waste package impact as a function of five values of the impact velocity and up to four values of the impact angle (Figure III-1). The use of an elastic unyielding surface is computationally efficient because it reduces the computational mesh by a factor of two and also provides a conservative representation of the damaged area. The damaged area with an unyielding surface will generally be greater than the damaged area with an adjacent waste package because the unyielding surface is infinitely stiff, maximizing impact stresses and deformation of the waste package for a given impact velocity and impact angle.

Material properties are based on temperature at 150°C. As noted in Assumption 3.2.12, a temperature of 150°C is the base case for all calculations because it is conservative for 97 percent of the first 10,000 years and 98.5 percent of the first 20,000 years after repository closure (Assumption 3.2.12). The residual stress threshold is based on 80 percent and 90 percent of the yield strength for Alloy 22 at the various temperature values. The variations in residual stress threshold evaluate the sensitivity of damaged area to this parameter.

The initial conditions for the impacts are: initial velocity is 1 m/s, 2 m/s, 4 m/s, 6 m/s, and 10 m/s; initial angle between the axis of the waste package and the vertical (α in Figure III-1) is 0 degrees, 1 degree, 5 degrees, and 8 degrees.

The selected impact velocity ranges from 1 m/s to 10 m/s and impact angle range from 0 to 8 degrees. The ranges are sufficiently wide to encompass all velocities and angles encountered during simulations of the vibratory ground motion, as confirmed by the results of the vibratory ground motion simulations (BSC 2004 [DIRS 167083], Tables 6.1.2-1 through 6.1.2-15 and Tables 6.2.2-1 through 6.2.2-15).

Source: BSC 2003 [DIRS 162293], Figure 2.

Figure III-1. Initial Position of the Waste Package for the End Impacts

III-2. FINITE-ELEMENT REPRESENTATION

There are ten different variations of the FE mesh (BSC 2003 [DIRS 162293], Table III-1 for a complete list) for an essentially same FE representation. The different meshes are used for the purpose of computational economy. Following a standard engineering practice, the mesh of the OCB is refined in the region where significant deformations and residual stresses are expected (i.e., "region of interest"). The remaining part of the mesh is coarser to reduce the simulation running time. The extent of the region of interest depends on the input parameters (the velocity and angle of impact). For example, B and C (BSC 2003 [DIRS 162293], Table III-1) have the same angle of impact (one degree), but C has more extended fine-mesh region than B to account for the greater damaged area extension due to the greater impact velocity. The initial configuration for 5-degree end impact of the 21-PWR waste package is illustrated in Figure III-2.

A three-dimensional FE representation of the waste package was developed using the dimensions provided in *21-PWR Waste Package Side and End Impacts* (BSC 2003 [DIRS 162293], Attachment I). The waste package OCB and lids, IV and lids, trunnion sleeves, and fuel assemblies were represented by solid (brick) elements. The constant-stress 8-node solid element (Livermore Software Technology Corporation 2003 [DIRS 166841], p. 26.30) with one-point Gaussian quadrature (Hallquist 1998 [DIRS 155373], Section 3) was used for all end and side impact calculations. Detail of the FE representation of 21-PWR waste package for ideal (0 degree) end impact is illustrated in Figure III-3.

1. The 21-PWR fuel assemblies were reduced to bars of square cross Section of uniform mass density, and assumed to be constructed of 304 SS.
2. The geometric dimensions of the fuel assemblies were modified to keep the value of the gap between the fuel assemblies and the nearest element consistent with the gap defined using the elements found in *21-PWR Waste Package Side and End Impacts* (BSC 2003 [DIRS 162293], Attachment I).
3. The mass density of the fuel assemblies was modified so that the total mass of the loaded waste package equals the mass given in *21-PWR Waste Package Side and End Impacts* (BSC 2003 [DIRS 162293], Attachment I).

4. The fuel basket tubes were not represented in the FE mesh for end impacts.
5. The thickness of the OCB was reduced by 2 mm on its outer surface. The target surface was conservatively assumed to be unyielding, and its density was rounded up to $8,000 \text{ kg/m}^3$. A static and dynamic friction coefficient of 0.5 was taken into account between all parts. The value of 0.5 is an average value for the range of friction coefficient, 0.2 to 0.8, defined in Assumption 3.2.4 and used for the structural response calculations. The use of an average friction coefficient of 0.5 is reasonable here because this is a single, discrete impact on an unyielding surface, so frictional forces should have a very minor effect in determining damaged area on the waste package.

As shown in the detailed design drawings (BSC 2005 [DIRS 173501]), a tight fit between the IV and the OCB is indicated. However, Plinski (2001 [DIRS 156800], Section 8.1.8) describes the fit between the two shells as "loose". In order to determine which configuration was more conservative for this study, two of the cases (end impacts, $\alpha = 5^\circ$, $v = 4 \text{ m/s}$ and $\alpha = 1^\circ$, $v = 2 \text{ m/s}$, material properties for 150°C) were each run with a tight fit and the maximum loose fit for the gap. The results are presented in 21-PWR Waste Package Side and End Impacts (BSC 2003 [DIRS 162293], Attachment II) and show that the configuration with a 4-mm gap is conservative. Consequently, all other cases were run with a 4-mm gap between the IV and the OCB.

Source: BSC 2005 [DIRS 173178], Figure 1.

Figure III-2. Schematic of the Configuration for 5-Degree End Impact of the 21-PWR Waste Package

Source: BSC 2005 [DIRS 173178], Figure 2(b).

Figure III-3. Detail of the Finite-Element Representation of 21-PWR Waste Package for Ideal (0 degree) End Impact

III-3. SYSTEM DAMPING

The duration for all the impact calculations, 0.05 seconds, was chosen to establish a stable residual first principal stress after the waste package impact. In order to calculate residual stresses efficiently, system damping (Hallquist 1998 [DIRS 155373], Section 28.2) is applied after the first impact between the waste package and the unyielding surface (i.e., after 0.03 seconds), until the termination of the simulation at 0.05 seconds. The value of the damping coefficient is 200. This value was determined by running 3 test cases: first with a damping coefficient of 0 (no system damping); second with a coefficient of 50; and third with a coefficient of 200. The variation of maximum first principal stress with time is presented in Figure III-4. Based on these results, a damping coefficient of 200 was considered adequate for this calculation.

Source: BSC 2003 [DIRS 162293], Figure 4.

NOTE: Time in seconds.

Figure III-4. Variation of Maximum First Principal Stress with Time for Different Values of the Damping Coefficient

III-4. POST-PROCESSING

An element where the residual first principal stress is above the residual stress threshold is called a damaged element. If an element has its first principal stress below this threshold, it is referred to as an undamaged element.

In order to determine the damage, the results obtained in the last time step of each simulation are post-processed with LS-POST V2 as follows: the undamaged elements of the OCB are “blanked out” (dark blue color in Figure III-5). The damage on the OCB outer surface is estimated by calculating the area of each damaged element’s face that coincides with the OCB outer surface. Since the number of damaged elements can be very large, the area of neighboring elements is calculated as the area of a rectangle containing these elements. However, if the damaged elements do not form a perfect rectangle, outside elements can be accounted for as shown in Figure III-5 (count these 2 elements/do not count these 2 elements).

Once the damage on the outer surface of the OCB is calculated, the inner surface of the OCB is treated in the same way. If the damaged area on the outer and inner surfaces overlap, the corresponding area is counted only once.

Finally, in the area where the OCB and the OCB bottom lid join, only the more damaged side of the junction is taken into account. For example, in Figure III-6, the damaged area in region A is larger than the damaged area in region B. Thus, only the damaged area in region A will be taken into account to avoid excessive conservatism.

Source: BSC 2003 [DIRS 162293], Figure 5.

NOTE: Color is irrelevant; graphic appears for reference only.

Figure III-5. Determination of Damaged Area Example

Source: BSC 2003 [DIRS 162293], Figure 6.

NOTE: Color is irrelevant; graphic appears for reference only.

Figure III-6. Determination of the Damaged Area for the Bottom Lid Junction of the OCB

III-5. RESULTS

Based on the results documented in *21-PWR Waste Package Side and End Impacts-A Mesh Study* (BSC 2005 [DIRS 173178]), Table III-1 lists the damaged area for the end impacts at 150°C for residual stress thresholds of 80 percent and 90 percent of the yield strength.

Table III-1. Catalog of Damaged Areas from End-On Impact of a 21-PWR Waste Package on an Unyielding Surface

Impact Velocity	Damaged Area (m ²) for Stress Threshold of 80 percent of Yield Strength as Function of Impact Angle				Damaged Area (m ²) for Stress Threshold of 90 percent of Yield Strength as Function of Impact Angle			
	0°	1°	5°	8°	0°	1°	5°	8°
1 m/s	0.0	0.0020	0.0027	0.0020	0.0	0.0017	0.0014	0.0012
2 m/s	0.0024	0.0282	0.0130	0.0105	0.0	0.0035	0.0052	0.0051
4 m/s	0.0122	0.0421	0.0651	0.0474	0.0122	0.0126	0.0288	0.0212
6 m/s	0.0264	0.0521	0.1466	0.0967	0.0124	0.0222	0.0655	0.0335
10 m/s	0.0419	0.0571	0.2822	0.2244	0.0377	0.0259	0.1542	0.1206

Source: BSC 2005 [DIRS 173178], Tables 2 and 3.

The damaged area distribution on the OCB surface is illustrated in Figure III-7(a) and III-7(b), based on end impact calculations with a finely zoned FE grid (BSC 2005 [DIRS 173178], Attachment I, Figures I-3 and I-4). Figure III-7 presents plots of the first principal stress with the number of stress fringe levels reduced to three and adjusted to emphasize the amount and distribution of the damaged area; the stress unit in Figure III-7 is Pascal [Pa = N/m²]. The stress thresholds of 248 MPa and 279 MPa correspond, respectively, to the residual stress thresholds for 80 percent and 90 percent of yield strength of Alloy 22 at 150°C. All elements with residual first principal stress below 248 MPa are blue. All elements with residual first principal stress from 248 MPa to 279 MPa are green. Finally, all elements with residual first principal stress exceeding 279 MPa are red. All other colors, if present, outline the waste package parts other than the OCB (most importantly, the trunnion collar sleeve is brown) to improve the clarity of the figure.

Figure III-7 illustrates two important points regarding the damage from end impacts. First, the majority of the damaged area is covered by the trunnion sleeve. In this situation, the sleeve helps to prevent radionuclide transport out of the waste package, although the damage abstraction for TSPA does not take credit for this effect. Second, the impact load in the OCB is transferred from the trunnion sleeve via the trunnion sleeve welds during the impact process. In effect, the trunnion sleeve acts to spread the deformation over a much larger area than would occur with a point impact on the OCB.

(a) Residual First Principal Stress Plot (in Pa) for 1-degree 4-m/s End Impact

(b) Residual First Principal Stress Plot (in Pa) for 8-degree 6-m/s End Impact

Source: BSC 2005 [DIRS 173178], Attachment I, Figures I-3 and I-4.

Figure III-7. Spatial Distribution of Residual First Principal Stress

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ATTACHMENT IV

**ADDITIONAL INFORMATION FOR CALCULATIONS
RELATED TO WASTE PACKAGE-EMPLACEMENT PALLET INTERACTION**

IV-1. INTRODUCTION

The calculations and results for waste package–emplacement pallet interaction are reported in detail in *Structural Calculations of Waste Package Exposed to Vibratory Ground Motion* (BSC 2004 [DIRS 167083]) and *Additional Structural Calculations of Waste Package Exposed to Vibratory Ground Motion* (BSC 2004 [DIRS 171717]). Section 5.5 provides a condensed summary for the major features of the calculations and the results. Additional information with more detailed descriptions of the calculations and results is provided in this Attachment. The objective of these calculations is to determine the residual stress distribution in the OCB of a waste package under vibratory ground motion, and to estimate the area of the waste package OCB for which the residual first principal stress exceeds the residual stress threshold. This area is called the “damaged area” in this document.

A set of 15 calculations for dynamic waste package structural response are performed for the suite of ground motions with a PGV of 2.44 m/s (BSC 2004 [DIRS 167083], Section 6.1). A similar set of calculations is also performed for a PGV of 5.35 m/s (BSC 2004 [DIRS 167083], Section 6.2) and a PGV of 1.05 m/s (BSC 2004 [DIRS 171717], Section 6.3). These values for PGV correspond to the peak of the first horizontal velocity component, which is always in a horizontal plane and perpendicular to the longitudinal direction for the structural response calculations (the longitudinal direction runs along the centerline of the drift). The stochastic (uncertain) input parameters for the 15 simulations are 15 sets of three-component ground motion time histories, the metal-to-metal friction coefficient, and the metal-to-rock friction coefficient. A Monte Carlo sampling scheme defines the appropriate combinations of ground motion and friction coefficients (BSC 2004 [DIRS 169999], Section 6.4) for each PGV level. The sampled values of these stochastic parameters are listed in Table IV-1, with the friction coefficients rounded to two significant figures.

Each FE simulation is performed in three steps. The first step calculates the transient vibratory motion and impacts. The goal of this step is to compute the deformation of the waste package during the dynamic impacts between waste package and emplacement pallet. During this computational phase the three components of ground-motion acceleration time history are simultaneously applied to all invert nodes. The stochastic (uncertain) input parameters for 15 simulations corresponding to the 2.44-m/s PGV level and for 15 simulations corresponding to the 5.35-m/s PGV level are listed in Table IV-1 (DTN: MO0301SPASIP27.004 [DIRS 161869], Table I-4). No system damping or contact damping is applied during the transient vibratory simulations. This admittedly conservative approach is used in order to prevent unwanted influence of damping on the rigid-body motion of unanchored structures.

Table IV-1. Values of Randomly Sampled Input Parameters for Each Realization

Realization Number	Ground Motion Number	Friction Coefficient (-)	
		Metal to metal	Metal to rock
1	7	0.80	0.34
2	16	0.33	0.49
3	4	0.50	0.62
4	8	0.60	0.22
5	11	0.20	0.24
6	1	0.27	0.69
7	2	0.71	0.60
8	13	0.56	0.54
9	10	0.55	0.36
10	9	0.36	0.41
11	5	0.42	0.67
12	6	0.65	0.73
13	12	0.75	0.31
14	14	0.29	0.45
15	3	0.46	0.78

Source: BSC 2004 [DIRS 167083], Table 6.1-1.

The second step of the simulation is the post-vibratory relaxation. The goal of this step is to obtain steady-state results (i.e., residual stresses) at the end of the ground motion. During this computational phase, the motion of the invert nodes is fixed in all three directions, and the only load applied to freestanding objects is the acceleration of gravity. In addition, system damping is applied globally (to all objects) to accelerate the convergence to steady-state results (Section IV-4 for details). The specified duration of this post-vibratory relaxation part of simulation is such to allow for the steady-state stresses to establish; most of the time a duration of 0.5 s suffices.

The third step of the analysis is comparison of the first principal residual stress with the residual stress threshold for accelerated corrosion cracking of Alloy 22. The goal of this step is to determine the “damaged areas” wherein the first principal stress exceeds the residual tensile stress threshold for Alloy 22. If an element on the surface of the waste package OCB exceeds this threshold, then its area is included in the total damaged area, independent of the stress state through the thickness of the waste package OCB. This is a conservative approach because it ignores the potential for a compressive stress profile through the thickness of the OCB to arrest crack propagation.

IV-2. FINITE-ELEMENT REPRESENTATION

Figure IV-1 illustrates the components of the three-dimensional FE representation for the vibratory ground-motion simulations. Figure IV-2 presents a cut-away view (portions of various parts are removed to offer a more revealing outlook) showing details of the waste package and emplacement pallet. As shown in these figures, the FE representation consists of the waste package mounted on its emplacement pallet, the surrounding drip shield, the invert surface, and

the lateral and longitudinal boundaries. The longitudinal boundary represents the neighboring waste package/emplacement pallet assembly, while the lateral boundary represents the drift walls. The FE representation is developed based on the dimensions provided in detailed design drawings (BSC 2005 [DIRS 173303]), and the *Structural Calculations of Waste Package Exposed to Vibratory Ground Motion* report (BSC 2004 [DIRS 167083], Attachments I, II, and III). The FE representations are then used in LS-DYNA to perform a transient calculation of the waste package exposed to vibratory ground motion.

The average waste package skirt-to-skirt spacing is 0.1 meters in the high temperature operating mode (BSC 2004 [DIRS 168489], Table 1). Thus, the distance between the waste package (specifically, the trunnion collar sleeve [i.e., the skirt]) and the longitudinal boundary (representing the neighboring waste package and emplacement pallet) is 0.1 meters.

Three components of the acceleration time history are simultaneously applied on the platform representing the top surface of the invert for each ground motion. The same acceleration time history is applied to all platform nodes simultaneously, resulting in zero deformation of the invert. The invert surface is represented in LS-DYNA as an elastic material.

The externally applied momentum from the ground motion is transferred to all freestanding (unanchored) objects solely by friction and impact. The lateral and longitudinal boundaries move synchronously with the platform and are rigid. In effect, these boundaries act like rigid members that are fixed to the platform.

Both ends of the waste package are represented as the bottom-end configuration (BSC 2004 [DIRS 167083], Attachment I). The details of the waste package top end, such as the extended OCB lid and closure lid, are not explicitly represented and their mass is taken into account by increasing the thickness of the OCB lid. The thickness of the waste package OCB is reduced by 2 mm to represent degradation of the OCB over a 10,000 year to 20,000 year period. It needs to be emphasized that this is not a rigorous evaluation of shell thickness due to corrosion or potential corrosion-acceleration effects. Rather, a thickness reduction of 2 mm is a reasonable conservatism within the stated objective of this calculation.

The waste package OCB, the trunnion collar sleeve, and the boundary walls are represented by 8-node solid (brick) elements. The constant-stress 8-node solid element (Livermore Software Technology Corporation 2003 [DIRS 166841], p. 26.30) with one-point Gaussian quadrature (Hallquist 1998 [DIRS 155373], Section 3) is used for all vibratory ground motion calculations. The part of the OCB that can come in contact with the emplacement pallet (Figures IV-3 and IV-7; also identified by regions F and C in Figure IV-4) is the most important area for these calculations. The FE representation for this region of the OCB is finely meshed on one side of the waste package (region F in Figure IV-4), with four layers of brick elements across the OCB thickness and a relatively dense in-plane mesh. The corresponding OCB region on the other side (region C in Figure IV-4) is more coarsely meshed with only two layers of brick elements across the thickness (Figures IV-3 and IV-4). These two parts of the waste package OCB are represented as elastoplastic, with linear kinematic hardening.

Time = 0

Source: BSC 2004 [DIRS 167083], Figure 1.

Figure IV-1. Initial Configuration for Waste Package Vibratory Simulations for Ground Motions at the 2.44-m/s PGV Level

Time = 0

Source: BSC 2004 [DIRS 167083], Figure 2.

Figure IV-2. Cut-Away View of Initial Configuration for Waste Package Vibratory Simulations

Source: BSC 2004 [DIRS 167083], Figure 3.

Figure IV-3. The Emplacement Pallet and Two Regions on the Outer Surface of the Waste Package That Can Come in Contact with the Emplacement Pallet

All damage resulting from the waste package–emplacement pallet interaction during the vibratory ground motion reported in this document is based on the part of the OCB designated by region F in Figure IV-4. The part of the OCB designated by region C (Figure IV-4), although coarsely meshed compared to region F, is still relatively finely meshed compared to the remaining part of the OCB (regions P and R in Figure IV-4) in order to ensure proper waste package–emplacement pallet interaction and the resulting rigid-body motions. The main purpose of the coarsely zoned parts of the mesh, designed P and R in Figure IV-4, is to provide appropriate boundary conditions for the more finely zoned F and C parts of the mesh. The main difference between parts of the OCB designated as P and R is that P is represented as elastoplastic (linear kinematic hardening) while R is rigid. The waste package components (excluding IV and IV lids) represented as rigid bodies are presented in Figures IV-5 and IV-7b.

Region F is especially important for the vibratory ground motion calculations because the stress state and damaged area are evaluated only for this region on the cylindrical surface of the waste package OCB. The two regions of the OCB that can contact the emplacement pallet, F and C, are connected to the remaining part of the OCB (P and R) by tied-interface contacts (Hallquist 1998 [DIRS 155373], Section 23.9; and Livermore Software Technology Corporation 2001 [DIRS 159166], p. 6.29).

Source: BSC 2004 [DIRS 167083], Figure 4.

Figure IV-4. Side View of OCB of Waste Package, Showing Variations in Finite-Element Grid

The waste package IV and its lid, emplacement pallet, and drip shield are represented by shell elements. Shell elements provide an adequate representation of these components because their dominant mode of deformation is bending. Additionally, this calculation is focused on the waste package OCB, so the stress states in the IV, emplacement pallet, and drip shield are of secondary importance. The IV and IV lids, and drip shield are represented as rigid bodies (BSC 2004 [DIRS 167083], Attachment VI) in order to reduce the computer execution time while preserving all the features relevant for the solution. The shell element used for representation of the emplacement pallet is the fully-integrated 4-node shell element with Gauss integration and three integration points through the shell thickness (Livermore Software Technology Corporation 2003 [DIRS 166841], p. 26.22).

The emplacement pallet is represented as elastoplastic but it is very coarsely meshed for the calculations at the 2.44-m/s PGV level (Figure IV-6). The coarse mesh of the emplacement pallet, necessitated by computer-execution-time considerations, results in an artificial increase of the emplacement pallet stiffness. In other words, the emplacement pallet is not as flexible as in reality and some of the cushioning effect of the emplacement pallet on the waste package is lost. The ultimate consequences of the coarse emplacement pallet mesh are an increase in the relative motion between the waste package and emplacement pallet, and an increase in deformation and residual stress in the OCB. Both of these effects are conservative for this calculation. Nonetheless, the emplacement pallet mesh has been refined (Figure IV-6b) for the calculations for the 5.35-m/s PGV level to prevent excessive relative motion and ensure more realistic results.

This change is motivated by the much higher intensity of the ground motion at the 5.35-m/s PGV level in comparison to the 2.44-m/s PGV level.

Source: BSC 2004 [DIRS 167083], Figure 5.

NOTE: IV and IV lids excluded.

Figure IV-5. Parts of the Waste Package Represented as Rigid Bodies

Source: BSC 2004 [DIRS 167083], Figure 6.

NOTE: (a) 2.44-m/s PGV calculations, (b) 5.35-m/s PGV calculations.

Figure IV-6. Front View of Pallet Mesh

The internal structure of the 21-PWR waste package is simplified by representing the IV and all waste package internals, including the fuel assemblies, as a thick-wall cylinder of circular cross

Section and uniform density. The outside diameter of the IV is kept unchanged. The thickness of the IV is determined by using the material properties (including density) of 316 SS, and matching the total mass of the IV and internals as presented in *Structural Calculations of Waste Package Exposed to Vibratory Ground Motion* (BSC 2004 [DIRS 167083], Attachment I). The benefit of this approach is a reduction in the computer execution time while preserving all features of the problem relevant to the structural response.

The FE representation of the 21-PWR waste package maximizes the loose-fit gap between the IV and OCB to 4 mm (Plinski 2001 [DIRS 156800], Section 8.1.8). Consequently, the IV is free to move within the OCB. This maximized gap provides a conservatively bounding set of results, as demonstrated in *21-PWR Waste Package Side and End Impacts* (BSC 2003 [DIRS 162293], Attachment II).

The drip shield has a simplified FE representation. The drip shield is represented as a rigid shell structure following the contour of the actual drip shield presented in *Structural Calculations of Waste Package Exposed to Vibratory Ground Motion* (BSC 2004 [DIRS 167083], Attachment III). All of the structural details of the drip shield are not considered. The drip shield is assumed to be made completely of Ti-7 and the density of Ti-7 is modified to match the total mass of the drip shield. These simplifications make it possible to capture the essential kinematics of freestanding components in the drift, while reducing the computer execution time. The impact of these simplifications in representation of the drip shield on the computational results presented in this document is anticipated to be negligible.

The most notable differences (in addition to the emplacement pallet mesh shown in Figure IV-6) between the two FE representations for the 2.44-m/s and 5.35-m/s PGV levels are that (1) the finely-meshed region is fully extended in the circumferential direction, and that (2) the configuration of the rigid OCB parts is changed for the 5.35-m/s PGV level calculations, as illustrated by Figure IV-7. These modifications are necessitated by the much more intense ground motion, causing much more relative (rigid-body) motion between the unanchored repository components, at the 5.35-m/s PGV level than at the 2.44-m/s PGV level. Figures IV-7(a) and IV-7(b) for the 5.35-m/s PGV calculations correspond to Figure IV-5 for the 2.44-m/s PGV calculations¹.

Contacts are specified between the OCB and IV, the OCB and emplacement pallet, the waste package (i.e., trunnion collar sleeve) and longitudinal and lateral boundaries, the emplacement pallet and invert, and the emplacement pallet and longitudinal and lateral boundaries, plus other components. The dynamic friction coefficients for all contacts are randomly sampled from a uniform distribution between 0.2 and 0.8 (see Assumption 3.2.4). One metal-to-metal friction coefficient and one metal-to-rock friction coefficient are sampled for each realization (Table IV-1), and applied to all metal-to-metal and metal-to-rock contacts. In other words, the friction coefficients vary from realization to realization (random sampling) but all metal-to-metal

¹ Notice that Realization 6 was the only realization at the 2.44-m/s PGV level that was, due to high intensity of the ground motion and resulting rigid body kinematics, performed with the FE representation with the finely-meshed region fully extended in the circumferential direction.

contacts have the same friction coefficient in a specific realization regardless of the contact pair; the same applies to metal-to-rock contacts.

Source: BSC 2004 [DIRS 167083], Figure 7.

NOTE: (a) Extended finely-meshed OCB region; (b) Rigid parts.

Figure IV-7. Modifications in Finite-Element Representation for the 5.35-m/s PGV Calculations

The functional friction coefficient used by LS-DYNA is defined in terms of static and dynamic friction coefficients, and relative velocity of the surfaces in contact (Livermore Software Technology Corporation 2001 [DIRS 159166], p. 6.9). The effect of relative velocity between contact surfaces is represented by a fitting parameter, called the exponential decay coefficient. However, this parameter cannot be defined for these calculations because the variation of static and dynamic friction coefficients are not available for Alloy 22 and Ti-7. In this situation, the effect of the relative velocity between contact surfaces is not considered by assuming that the functional friction coefficient and the static friction coefficient are equal to the dynamic friction coefficient. This approach maximizes the relative motion of the unanchored repository components by minimizing the friction coefficient within the given FE analysis framework. The friction coefficient affects the onset of sliding and dissipation of energy for the engineered barrier system components as a function of the ground motion intensity. However, the importance of friction is anticipated to diminish with increasing ground motion level because the engineered barrier system components begin to slide almost immediately for high-amplitude ground motions.

The mesh of the FE representation was appropriately generated and refined in the contact regions according to standard engineering practice. Thus, the accuracy and representativeness of the results of this calculation are deemed acceptable (BSC 2004 [DIRS 167083], Attachments V through IX for discussion of results). The uncertainties are taken into account by random sampling (from appropriate probability distributions) of the calculation inputs that are inherently stochastic (uncertain) and characterized by a large scatter of input data (ground-motion time histories and friction coefficients).

IV-3. GROUND-MOTION TIME HISTORY CUTOFF

The structural response calculations for the waste package are computationally intense because:

- (1) The FE representation is quite detailed (Section IV-2)
- (2) The calculations are highly nonlinear, with large deformation plasticity, friction, and impacts
- (3) The computational time step is quite small to ensure numerical stability of the conditionally-stable explicit FE method (typically one microsecond or less)
- (4) The ground motion duration is quite long, typically 30 to 40 seconds, relative to the time step.

Given these factors, it is attractive to reduce the duration of the calculations by considering only that portion of the ground-motion time history that causes changes in the damaged area.

For the ground motions at the 2.44-m/s PGV level, the computational duration is usually restricted to the 5 percent to 95 percent levels of ground motion energy, where energy is based on all three components of the ground motion measured by Arias Intensity (Kramer 1996 [DIRS 103337], Section 3.3.4)—an estimate of energy delivered to structures. For brevity, the minimum time corresponding to the 5 percent level of the ground motion energy is called the “5 percent-time”, and the maximum time corresponding to the 95 percent level of the ground motion energy is called the “95 percent time”.

All simulations for ground motions at the 5.35-m/s PGV level are performed from the 5 percent-time to the 90 percent level of the ground motion energy, referred to as the “90 percent-time”. Thus, the starting times for the 2.44-m/s and 5.35-m/s PGV level coincide with the 5 percent-time, while the ending time for the 5.35-m/s PGV level has been reduced to the 90 percent-time.

Table IV-2 presents the characteristic times for the 2.44-m/s PGV level calculations (BSC 2004 [DIRS 167083], Table 5.2.1.1). Table IV-2 lists the 5 percent-time, 95 percent-time, the start time and end time for the simulations (denoted as FE Start time and FE End time), and the duration of the FE simulations. The FE Start time is equal to the 5 percent-time for most simulations, and the FE End time is nominally the 95 percent-time. The duration of a specific simulation is determined by subtracting the FE End time from the FE Start time.

In five realizations, the starting time is ahead of the 5 percent-time to encompass some pertinent feature of the ground motion (Table IV-2). Similarly, the FE End time has been varied from the 95 percent-time in a few realizations to examine the sensitivity of damage to cutoff time. Specifically, realizations 1, 2, 4, 9, and 12 are extended for a short time after the 95 percent-time for the purpose of examining the evolution of damage after the nominal cutoff (BSC 2004 [DIRS 167083], Attachment VII). On the other hand, realizations 3, 8, 13, and 14 are not run up to the 95 percent-time since—as indicated in *Structural Calculations of Waste Package Exposed to Vibratory Ground Motion* (BSC 2004 [DIRS 167083], Table VII-1)—it was unnecessary because damaged area becomes constant before the 95 percent-time.

Table IV-2. Characteristic Times and Duration of Simulations for 2.44-m/s PGV Ground Motion Level

Ground Motion Number	5%-Time (s)	FE Start Time (s)	95%-Time (s)	FE End Time (s)	Durations (s)		Realization Number
					5% to 95% Time	FE Run Time	
1	0.85	0.85	7.05	7.05	6.2	6.2	6
2	0.58	0.41	8.13	8.41	7.6	8.0	7
3	1.7	1.5	5.04	5.00	3.4	3.5	15
4	1.3	1.1	15.0	13.9	13.7	12.8	3
5	2.0	2.0	10.3	10.3	8.3	8.3	11
6	2.3	2.3	9.96	11.2	7.7	8.9	12
7	4.0	4.0	11.6	12.9	7.6	8.9	1
8	1.1	1.1	5.99	6.80	4.9	5.7	4
9	0.79	0.6	8.18	7.90	7.4	7.3	10
10	1.6	1.6	10.8	11.9	9.2	10.3	9
11	2.1	2.1	10.3	10.3	8.2	8.2	5
12	1.4	1.4	13.6	12.9	12.2	11.5	13
13	1.9	1.85	17.0	15.4	15.1	13.5	8
14	7.2	7.2	21.5	18.2	14.3	10.9	14
16	3.8	3.8	11.8	12.8	8.0	9.0	2

Source: BSC 2004 [DIRS 167083], Table 5.2.1.1.

Table IV-3 presents the characteristic times for the 2.44-m/s PGV level ground motions with a cutoff based on the 90 percent level of ground motion energy (BSC 2004 [DIRS 167083], Table 5.2.1.2). The durations in the fourth column (Duration of Simulation to 90 percent-time) represent the relative time in the simulation when the 90 percent level for ground motion energy is reached for all three components of ground motion. These data are used in *Structural Calculations of Waste Package Exposed to Vibratory Ground Motion* (BSC 2004 [DIRS 167083], Attachment VII, Table VII-5) to examine the sensitivity of damaged area to the time-history cutoff.

Table IV-3. Characteristic Times and Duration of Simulations for the 5 Percent-90 Percent Energy Range at the 2.44-m/s PGV Ground Motion Level

Ground Motion Number	FE Start Time (s)	90% Time (s)	Duration of Simulation to 90% Time (s)	Realization Number
1	0.85	5.21	4.36	6
2	0.41	6.05	5.47	7
3	1.5	3.64	1.94	15
4	1.1	10.2	8.90	3
5	2.0	7.46	5.46	11
6	2.3	9.20	6.90	12
7	4.0	11.1	7.10	1
8	1.1	5.12	4.02	4
9	0.6	6.98	6.19	10

Table IV-3. Characteristic Times and Duration of Simulations for the 5 Percent-90 Percent Energy Range at the 2.44-m/s PGV Ground Motion Level (Continued)

Ground Motion Number	FE Start Time (s)	90% Time (s)	Duration of Simulation to 90% Time (s)	Realization Number
10	1.6	7.66	6.06	9
11	2.1	8.30	6.20	5
12	1.4	12.2	10.8	13
13	1.85	12.7	10.8	8
14	7.2	19.8	12.6	14
16	3.8	9.57	5.77	2

Source: BSC 2004 [DIRS 167083], Table 5.2.1.2.

Table IV-4 presents the characteristic times for the 5.35-m/s PGV level calculations (BSC 2004 [DIRS 167083], Table 5.2.1.3). Table IV-4 lists the 5 percent time, the 90 percent time, and the duration of the FE simulations based on these times. Finally, Table IV-4 presents the duration of each simulation and characteristic times used to define the duration for the 5.35-m/s PGV level ground motions (BSC 2004 [DIRS 167083], Table 5.2.1.3). In this case, as discussed previously, the starting time presented in the second column coincides with the 5 percent time, rounded to two significant digits. The most pronounced difference between 2.44-m/s PGV and the 5.35-m/s PGV level ground motions is that the latter are run only up to the maximum of 90 percent energy of ground motion (i.e., the ending time coincides with the 90 percent time). The rationale is to reduce the simulation running time without significantly affecting the damaged area. This rationale is based on the results for the 2.44-m/s PGV level realizations (BSC 2004 [DIRS 167083], Attachment VII), and its appropriateness is confirmed by the results of the 5.35-m/s PGV level realizations.

Table IV-4. Characteristic Times and Duration of Simulations for 5.35-m/s PGV Ground Motion Level

Ground Motion Number	5%-Time (s)	90% Time (s)	Duration of Simulation (s)		Realization Number
			5% to 95% Time	FE Run Time	
1	1.3	6.5	5.2	5.2	6
2	0.80	5.8	5.0	5.0	7
3	1.75	3.45	1.7	1.7	15
4	1.5	11.8	10.3	10.3	3
5	1.7	9.3	7.6	7.6	11
6	2.4	9.2	6.8	6.8	12
7	3.6	11.4	7.8	7.8	1
8	1.2	5.1	3.9	3.9	4
9	0.70	6.7	6.0	6.0	10
10	1.6	7.2	5.6	5.6	9
11	2.1	8.5	6.4	6.4	5
12	2.0	12.7	10.7	10.7	13
13	1.9	15.2	13.3	13.3	8
14	5.3	21.0	15.7	15.7	14
16	3.4	9.0	5.6	5.6	2

Source: BSC 2004 [DIRS 167083], Table 5.2.1.3.

IV-4. SYSTEM DAMPING

In order to obtain steady-state results (i.e., residual stresses) in a reasonable time, it is necessary to apply damping during the second post-vibratory relaxation step of the computational process. The system damping is strictly a numerical technique for accelerating convergence to the steady-state stress state after the transient simulation is completed. It is applied globally to all elements and nodes of the FE grid.

As discussed in Hallquist (1998 [DIRS 155373], Section 28.2), the most appropriate damping constant for the system is usually the critical damping constant. Therefore,

$$DC = 2 \cdot \omega_{\min} = 2 \cdot 350 \text{ rad/s} = 700 \text{ rad/s},$$

where $\omega_{\min} = 2 \cdot \pi \cdot 56 \approx 350 \text{ rad/s}$ is the minimum non-zero frequency of the waste package OCB (BSC 2004 [DIRS 167083], Attachment X [*Modal Analysis/wpp6Bmod.out*, line #6517]). Since the engineered barrier system components are unanchored in these calculations, the damping constant is reduced to $DC = 200 \text{ rad/s}$ to avoid over-damping the system. Furthermore, the parametric study of various damping constants presented in *21-PWR Waste Package Side and End Impacts* (BSC 2003 [DIRS 162293]), confirms the appropriateness of this choice. The system is obviously not over-damped, and a steady state is reached in reasonable time (BSC 2003 [DIRS 162293], Figure 4, p. 21).

IV-5. ALTERNATE GROUND MOTIONS AT 2.44-M/S PGV LEVEL

The original set of calculations for the 2.44-m/s PGV level (BSC 2004 [DIRS 167083]) used ground motion time history that do not preserve intercomponent variability. In other words, the variability between the three velocity components of a given ground motion is limited because each velocity component is scaled to a target value, rather than maintaining the intercomponent variability in the original ground motion records. In addition, the ground motions records were not spectrally conditioned to earthquake spectra typical of the western United States.

The five additional calculations at the 2.44-m/s PGV level have been performed with ground motions that do preserve intercomponent variability and do condition response spectra to be more typical of those found in the western United States (BSC 2004 [DIRS 171717]). These time histories were spectrally conditioned to have response spectra more typical of the Yucca Mountain site prior to being scaled.

Five additional calculations correspond to realizations 2, 3, 4, 6, and 15. Realizations 3, 6, and 4 are characterized by the largest damaged areas (in the descending order) among the calculations documented in Table 5-6. The changes in the PGV between the ground motion sets are illustrated in Table IV-5 for the longitudinal (along the tunnel; H2) and vertical (V) directions. The input data and results labeled hereinafter as “Old” and “New” refer to the original ground motion time histories and the modified ground motion time histories, respectively.

Table IV-5. Change of PGV between Two Ground Motion Sets

Realization	Ground Motion	Longitudinal (H2) PGV			Vertical (V) PGV		
		Old	New	Change	Old	New	Change
3	4	2.43 m/s	2.60 m/s	+7%	2.28 m/s	2.97 m/s	+30%
4	8	2.44 m/s	4.02 m/s	+65%	2.30 m/s	1.54 m/s	-33%
6	1	2.43 m/s	1.95 m/s	-20%	2.30 m/s	1.11 m/s	-52%
15	3	2.43 m/s	6.43 m/s	+165%	2.28 m/s	6.09 m/s	+167%

Source: BSC 2004 [DIRS 171717], Table 5.3-4

Realizations 3, 6, and 4, in addition to being characterized by the largest damaged areas, are also typical regarding the ground motion change between the two sets. Ground motion 4 (realization 3) is representative of a small PGV increase in the longitudinal and a moderate PGV increase in the vertical direction. Ground motion 1 (realization 6) is representative of a moderate decrease in the PGV in both the longitudinal and vertical directions. Ground motion 8 (realization 4) is representative of a moderate PGV increase in the longitudinal and a moderate PGV decrease in the vertical direction. Finally, ground motion 3 (realization 15) is characterized by a dramatic PGV increase in both directions.

IV-6. RESULTS

IV-6.1 GROUND MOTIONS AT THE 1.05-M/S, 2.44-M/S AND 5.35-M/S PGV LEVELS

The damaged area due to the waste package–emplacement pallet interaction is only evaluated on the half of the waste package with the finely-meshed region (Figures IV-3 and IV-4). The total damaged area from waste package–emplacement pallet interaction is calculated by multiplying the damaged area from the finely zoned region by two.

Table IV-6 presents the damaged area resulting from the waste package–emplacement pallet interactions during the vibratory ground motion with horizontal PGV values of 1.05 m/s, 2.44 m/s and 5.35 m/s. The damaged area is based on the residual first principal stress plot, as computed by the postprocessor LSPOST V2.0. The results for Realization 8 at the 2.44-m/s PGV level is not presented in Table IV-6 because an input error¹ was discovered for this calculation during the checking process. The results for realization 2 at the 5.35-m/s PGV level are not presented in Table IV-6 because the impacts between waste package and emplacement pallet are outside the finely meshed region of the outer shell, thereby reducing the numerical accuracy of the damage calculation for this realization.

The original set of calculations for the 2.44-m/s PGV level (BSC 2004 [DIRS 167083]) used ground motion time history that do not preserve intercomponent variability. In other words, the variability between the three velocity components of a given ground motion is limited because each velocity component is scaled to a target value, rather than maintaining the intercomponent

¹ The three initial velocity components do not correspond to the beginning of the acceleration time history for Realization 8 at the 2.44 m/s PGV level. Consequently, the velocity and displacement time histories are not appropriately specified, so the results from this realization are not included in the abstraction process.

variability in the original ground motion records. In addition, the ground motions records were not spectrally conditioned to earthquake spectra typical of the western United States.

The damaged-area from waste package–emplacement pallet interactions for the alternate ground motions is illustrated in Figures IV-8 through IV-11. These figures present the first principal stress plots with the number of stress fringe levels reduced to three and adjusted to emphasize the amount and distribution of the damaged area. The stress unit in Figures IV-8 through IV-11 is *Pascal* ($Pa = N/m^2$). Note that the stress thresholds of 248 *MPa* and 279 *MPa* correspond, respectively, to 80 percent and 90 percent of the yield strength for Alloy 22 at 150°C.) Thus, all elements with residual first principal stress below 248 *MPa* are blue and are not damaged. All elements with residual first principal stress from 248 *MPa* to 279 *MPa* are green. Finally, all elements with residual first principal stress exceeding 279 *MPa* are red and are always damaged.

Table IV-6. Damaged Area from Waste Package–Emplacement Pallet Impacts at 2.44 m/s, 5.35 m/s, and 1.05-m/s PGV Levels

Realization Number	Ground Motion Number	Damaged Area on the Waste Package								
		Waste Package–Emplacement Pallet Damaged Area at 2.44 m/s PGV-Transverse Level (m ²)			Waste Package–Emplacement Pallet Damaged Area at 5.35 m/s PGV-Transverse Level (m ²)			Waste Package–Emplacement Pallet Damaged Area at 1.05 m/s PGV-Transverse Level (m ²)		
		PGV-Long. (m/s)	80% Yield Strength	90% Yield Strength	PGV-Long. (m/s)	80% Yield Strength	90% Yield Strength	PGV-Long. (m/s)	80% Yield Strength	90% Yield Strength
1	7	2.44	0.0029	0.0014	5.31	0.20	0.17	0.89	0	0
2	16 ^d	2.44	0	0	N/A ^c	N/A ^c	N/A ^c	0.67	0	0
3	4	2.43	0.0050	0	5.69	0.096	0.083	1.00	0	0
4	8	2.44	0.030	0.0064	8.81	0.12	0.096	1.52	0.0014	0
5	11	2.44	0.0015	0	5.61	0.093	0.071	1.26	0	0
6	1	2.43	0.025	0.0028	4.28	0.046	0.024	0.83	0.0015	0
7	2	2.44	0.017	0	5.89	0.038	0.028	1.25	0	0
8	13	N/A ^a	N/A ^a	N/A ^a	6.65	0.095	0.068	1.04	0	0
9	10	2.38	0.0035	0	1.72	0.0052	0.0035	0.32	0	0
10	9	2.44	0	0	17.91	0.16	0.14	3.58	0	0
11	5	2.43	0.012	0.0037	5.64	0.032	0.0070	1.67	0	0
12	6	2.43	0.0039	0	2.90	0.062	0.041	0.46	0.0040	0.0014
13	12	2.43	0	0	5.95	0.027	0.018	0.70	0	0
14	14	2.44	0.010	0.0043	2.75	0.020	0.016	0.41	0	0

Table IV-6. Damaged Area from Waste Package–Emplacement Pallet Impacts at 2.44 m/s, 5.35 m/s, and 1.05-m/s PGV Levels (Continued)

Realization Number	Ground Motion Number	Damaged Area on the Waste Package								
		Waste Package—Emplacement Pallet Damaged Area at 2.44 m/s PGV-Transverse Level (m ²)			Waste Package—Emplacement Pallet Damaged Area at 5.35 m/s PGV-Transverse Level (m ²)			Waste Package—Emplacement Pallet Damaged Area at 1.05 m/s PGV-Transverse Level (m ²)		
		PGV-Long. (m/s)	80% Yield Strength	90% Yield Strength	PGV-Long. (m/s)	80% Yield Strength	90% Yield Strength	PGV-Long. (m/s)	80% Yield Strength	90% Yield Strength
15	3	2.43	0.0078	0.0015	14.09	0.0045	0	2.62	0.028	0.014
2 ^b	15'	1.53	0	0	3.36	0.0080 ^c	0.0020 ^c	(Additional calculations were not performed at the 1.05 m/s and 5.35-m/s PGV levels because these ground motions already included spectral conditioning and intercomponent variability.)		
3 ^b	4'	2.60	0.0014	0						
4 ^b	8'	4.02	0.0032	0						
6 ^b	1'	1.95	0.0081	0.0014						
15 ^b	3'	6.43	0.043	0.010						

Sources: BSC 2004 [DIRS 167083], Tables 6.1.1-1 and 6.2.1-1; BSC 2004 [DIRS 171717] Tables 6.1-4, 6.2-7, and 6.3-6; BSC 2004 [DIRS 166107], Appendix X, Tables X-2, X-3, X-4, and X-5.

NOTES: ^a Results for realization 8 are not presented because of an error in the input file for this calculation.

^b Additional calculations were performed primarily to determine the sensitivity of damaged area to spectral conditioning and intercomponent variability of the ground motions at the 2.44-m/s PGV level (BSC 2004 [DIRS 171717], Sections 6.1 and 6.2). These ground motions are denoted as 2', 3', 4', 6', and 15' to indicate the differences in the ground motion time histories.

^c Results for realization 2 with ground motion 16 are not presented because the kinematics of the waste package are such that the impacts between waste package and emplacement pallet occur outside the finely meshed region of the outer shell. Results for realization 2 with ground motion 15' are not exact because the waste package–emplacement pallet impacts occur partly outside the finely zoned mesh on the outer shell, but are included in the statistical analyses because the data lie within the range of the other realizations at the 5.35-m/s PGV level (BSC 2004 [DIRS 171717], Section 6.1.3)

^d Calculations are performed with 15 ground motions numbered 1, 2, 3, ..., 14, and 16. Seventeen sets of ground motion time histories were initially developed from which 15 sets were selected for these postclosure analyses. Ground motion #16 was initially substituted for ground motion #15 because of concerns about its response spectrum. Subsequent analyses with ground motion #15' at the 2.44-m/s and 5.35-m/s PGV levels (fifth line from the bottom in the table) indicate that ground motion #15' does not result in anomalous behavior (BSC 2004 [DIRS 171717], Section 6.2).

Source: BSC 2004 [DIRS 171717], Figure 6.2-4.

NOTE: Units in Pascals

Figure IV-8. Residual First Principal Stress Plot in OCB (Bottom View) for Realization 3

Source: BSC 2004 [DIRS 171717], Figure 6.2-6.

NOTE: Units in Pascals.

Figure IV-9. Residual First Principal Stress Plot in OCB (Bottom View) for Realization 4

Source: BSC 2004 [DIRS 171717], Figure 6.2-8.

NOTE: Units in Pascals.

Figure IV-10. Residual First Principal Stress Plot in OCB (Bottom View) for Realization 6

Source: BSC 2004 [DIRS 171717], Figure 6.2-10.

NOTE: Units in Pascals.

Figure IV-11. Residual First Principal Stress in OCB (Bottom View) for Realization 15

IV-6.2 GROUND MOTIONS AT THE 0.384-M/S PGV LEVEL

Two calculations have been performed to evaluate the damaged areas for single ground motions at the 0.19-m/s PGV level and at the 0.384-m/s PGV level. Both calculations demonstrate that there is no damage to the waste package from either waste package–emplacement pallet interactions or from waste package-to-waste package interactions. In fact, the static load from the weight on the waste package on the emplacement pallet generates the observed stresses in the waste package and emplacement pallet. Given this similarity, the results for the calculation at the 0.384-m/s PGV level are described here because they are most relevant to damage abstractions for the seismic scenario class (the largest amplitude ground motion that does not damage the waste package or its internals is most relevant to the damage abstractions). The results for the calculation at the 0.19-m/s PGV level are available in the original calculation report (BSC 2004 [DIRS 167083], Section 6.3).

The single calculation with the 0.384-m/s PGV level ground motion is based on the FE representation previously used for most of the ground motions at the 2.44-m/s PGV level. The single simulation is performed with material properties based on a temperature of 150°C. The simulation started at 9.7 s of the ground motion time history (corresponding to the 5 percent energy point of the ground motion), and the ending time was 34.9 s (corresponding to 65 percent

of the energy of the ground motion) (BSC 2004 [DIRS 167083], Section 6.4). This duration covered the most intense period of this ground motion time history. Further extension of the simulation is considered unnecessary based on the results presented in this Section (see, as an example, Figures IV-13 and IV-14).

The ground motion for 0.384-m/s PGV level is much less intense than for the 2.44-m/s PGV level. Consequently, the resulting rigid-body motion is very small. Specifically, the relative motion of the waste package with respect to the emplacement pallet in longitudinal (Y) and vertical (Z) direction is practically nonexistent. Figure IV-12 indicates that once the initial gap between waste package and emplacement pallet is closed the relative displacement of two typical waste package and emplacement pallet nodes (the locations of nodes number 20 and 18007 are depicted in *Structural Calculations of Waste Package Exposed to Vibratory Ground Motion* (BSC 2004 [DIRS 167083], Figure 17) is less than ± 0.07 mm even for the unfiltered data. The filtered plot is more meaningful since the high-frequency noise—very pronounced due to the high-frequency excitation and the absence of damping—is eliminated. A low pass filter with cutoff frequency of 1,000 Hz is used for that purpose throughout this section.

The relative displacement in vertical (Z) direction of the waste package with respect to the emplacement pallet is also small, as indicated in Figure IV-13. Most of the time, it varies within the range from 0 mm to 0.03 mm (Note the spikes in Figures IV-12 and IV-13 at the onset of simulations).

Source: BSC 2004 [DIRS 167083], Figure 20.

Figure IV-12. Relative Longitudinal (Y) Displacement (Raw and Filtered) of Waste Package with Respect to the Emplacement Pallet for the 0.384-m/s PGV Level

Source: BSC 2004 [DIRS 167083], Figure 21.

Figure IV-13. Relative Vertical (Z) Displacement (Raw and Filtered) of Waste Package with Respect to the Emplacement Pallet for the 0.384-m/s PGV Level

As a consequence of the limited rigid-body motion, there is no contact between the waste package and the longitudinal boundary or between the waste package and the drip shield during the simulation for the 0.384-m/s PGV level. The only remaining interaction that is relevant for this calculation is that between the waste package and the emplacement pallet.

The waste package–emplacement pallet interactions for this simulation are characterized by extremely small impact velocities due to the limited rigid-body motion in the vertical direction. As shown in Figure IV-14, the impact velocity between the waste package and the emplacement pallet rarely exceeds 0.005 m/s (for the filtered data; see blue curve in Figure IV-14) and the maximum impact velocity for the filtered data is less than 0.006 m/s. It seems appropriate to emphasize that the vibratory part of the simulation is performed without system damping or contact damping (Section IV-4). The statement that the rigid-body motion is negligible for this simulation is well supported by the results presented in Figures IV-12 through IV-14.

Source: BSC 2004 [DIRS 167083], Figure 22.

Figure IV-14. Relative Vertical (Z) Velocity (Raw and Filtered) of Waste Package with Respect to the Emplacement Pallet for the 0.384-m/s PGV Level

Figure IV-15 presents the residual first principal stress intensity plot for the vibratory part of the simulation. The maximum residual first principal stress (87 MPa) is below the stress limit (80 percent to 90 percent of yield strength) by a large margin. Note that the stress unit in Figure IV-15 is Pascals. The maximum residual stress is not caused by the dynamic response to the ground motion. The deformation of the waste package OCB is elastic during the transient, so the residual stress is zero from the ground motion. Rather, this residual stress results from the static load of the waste package on the emplacement pallet.

In summary, it can be concluded that the waste package OCB remains undamaged throughout the dynamic response to the 0.384-m/s PGV level ground motion; that is, the OCB area exceeding the residual stress thresholds is zero.

Source: BSC 2004 [DIRS 167083], Figure 23.

NOTE: Units in Pascals.

Figure IV-15. Residual First Principal Stress Plot in OCB (Top View) for the 0.384-m/s PGV Level

ATTACHMENT V
CROSS-DRIFT CALCULATION OF INTERACTION
BETWEEN THE WASTE PACKAGE
AND THE DRIP SHIELD

V-1. INTRODUCTION

Interactions between the waste packages, the waste package and the emplacement pallet, and the waste package and the drip shield during strong seismic ground motion were estimated in longitudinal representations in the vertical plane along the axis of the emplacement drift as described in Section 5.4 and Attachments I and II. The boundary above the waste package in these calculations represented the drip shield which was assumed to be pinned in place with caved rock rubble. Consequently, the drip shield moved synchronously with the free field. As a result of the two-dimensional nature of the calculation and orientation of the longitudinal plane in which all objects were assumed to move, the calculations could not yield predictions of side impacts between the waste package and the drip shield, only the impacts of the waste package into the crown of the drip shield.

The interaction between the objects inside the emplacement drift during strong seismic ground motions is a truly three-dimensional problem. A general analysis would require a three-dimensional representation of geometry of a number of waste packages and drip shields, and representation and simulation of drift collapse. Such a calculation, if possible, would be time consuming and computationally intensive. Drift collapse and interaction between the collapsed rock mass and the drip shield was analyzed as a two-dimensional problem in the cross-section normal to the axis of the emplacement drift (i.e., cross-drift analysis); the results are presented in the *Drift Degradation Analysis* (BSC 2004 [DIRS 166107], Section 6.4). In the original calculation, the waste package-drip shield interactions were not considered. The waste package and the emplacement pallet were simulated to move synchronously with the free field and the invert. Movements of the waste package and the emplacement pallet inside the drip shield do not affect collapse of the emplacement drift and insignificantly affect interaction between the drip shield and the collapsed rock around the drip shield (i.e., the loads that the collapsed rock exerts on the drip shield). The same cross-drift calculation, in which the waste package and the emplacement pallet were allowed to move freely according to their masses and forces acting on them, was used to analyze the drip shield-waste package interactions—particularly the side impacts of the waste package into the drip shield. The impacts of the waste packages into the top part of the drip shield are also analyzed in the longitudinal section as described in Section 5.4.2 and Attachment II. In addition, the calculation is carried out to provide a confirmation of the assumption that the collapsed rock will pin down the drip shield, forcing it to move almost synchronously with the invert and the free field.

The results of the calculations, carried out for two PGV levels, are provided in the form of the number of impacts between the waste package and the drip shield for those impacts with velocity greater than 0.85 m/s¹ and the maximum impact velocity. The impact velocities, location and number of impacts are used as input to calculation of their effects on drip shield structural stability (Attachment VI).

¹ The number of impacts with impact velocity greater than 0.85 m/s (not the total number of impacts) is reported because impacts will not damage the waste package if the impact velocity is lower than 0.85 m/s (Assumption 3.2.29).

The computer files developed for this attachment can be accessed through the TDMS. DTN: MO0508SPAMECHA.000 includes the inputs and outputs for this attachment (files are located in *Attachment V* folder).

V-2. METHODOLOGY AND APPROACH

V-2.1 TWO-DIMENSIONAL APPROXIMATION

Because of the nature of the ground motions (three mutually orthogonal components of the ground motion) and the geometry of the objects inside the emplacement drift, the problem of interaction between the waste package and the drip shield is truly three-dimensional. Simulation of drift collapse in a three-dimensional representation simultaneous with analysis of impacts between the objects located inside the emplacement drift is extremely complex and could not be completed in a reasonable time frame. Instead, a two-dimensional calculation was carried out in the vertical plane perpendicular to the axis of the emplacement drift. In this cross-drift calculation, impacts of the waste package into the side and top part of the drip shield were analyzed. Only two components of the ground motion were used in the cross-drift simulations: one horizontal (H2) and vertical. (The longitudinal calculations also were carried out for two components of the ground motions: one horizontal (H1) and vertical.)

A limitation of the two-dimensional cross-drift calculation is that the cross-drift approximation does not consider rotation of the objects about the vertical axis. Considering the relatively elongated shape of the waste packages in the direction along the axis of the emplacement drift, the rotational component about the vertical axis can be significant, resulting in an increased number of impacts and impact velocities compared to the situation when that rotation is prevented (as simulated in the cross-drift approximation).

V-2.2 HYSTERETIC DAMPING

Hysteretic damping was applied to impacts between all the objects inside the drip shield, including impacts into the drip shield (e.g., waste package-emplacement pallet, waste package-drip shield and emplacement pallet-invert impacts). Details of contact hysteretic damping, which accounts for energy dissipation during impact, are discussed in Attachment II, Section II-2.4. No contact damping was used for impacts between caved rock blocks, or between rock blocks and the drip shield. The ratio between unloading and loading normal stiffnesses for metal-to-metal and metal-to-rock contacts is assigned the values of 2.7 and 50.0, respectively. This ratio controls the amount of energy dissipated by hysteretic damping during impact. The selected values of the ratios are the same as the values used in the calculation of waste package interaction in the longitudinal section (Attachment II). Different drop tests were carried out to determine the actual response of the objects used in the cross-drift calculation: (a) the waste package was dropped on the emplacement pallet while the base of the emplacement pallet was fixed (i.e., deformation of the contact between the emplacement pallet and the invert was not allowed), shown in Figure V-1; (b) the waste package and the emplacement pallet were dropped on the invert, shown in Figure V-2; and (c) only the emplacement pallet was dropped on the invert, shown in Figure V-3. The histories of the displacements of the tested objects are shown in Figure V-4 for all of the analyzed cases. The resulting coefficients of restitution (CORs) are calculated and listed in Table V-1. The target CORs for metal-to-metal and metal-to-rock

impacts were 0.6 and 0.2, respectively (Assumption 3.2.28). The values of 0.59 and 0.17 are reasonably close matches.

Table V-1. Calculated Effective Coefficient of Restitutions

Case	Effective COR
Waste package dropped on emplacement pallet	0.59
Waste package and emplacement pallet dropped on invert	0.43
Emplacement pallet dropped on invert	0.17

Figure V-1. Configuration During the Drop Test of the Waste Package on the Emplacement Pallet

Figure V-2. Configuration During the Drop Test of the Waste Package and the Emplacement Pallet on the Invert

Figure V-3. Configuration During the Drop Test of the Emplacement Pallet on the Invert

Figure V-4. Displacement as a Function of Time for Different Drop Tests

V-3. DESCRIPTION OF THE CALCULATIONS

The calculations were carried out with UDEC version 3.1 (BSC 2002 [DIRS 161949], STN: 10173-3.1-00), which is a two-dimensional numerical code used to simulate the mechanical interaction of polygonal blocks. The code has a general algorithm for automatic detection of contacts between blocks. Any two blocks in the calculation can interact with each other at any point of calculation. Although UDEC usually is applied to problems of deformation and stability of a fractured rock mass, it is well suited for the analysis of the mechanical interaction of the objects that undergo large displacements (e.g., blocks after rockfall or impact between the waste package and the drip shield). The geometry of the numerical representation of the analyzed problem is shown Figure V-5. All objects inside the emplacement drift were considered to be linearly elastic. Only impacts and impact velocities between those objects were monitored. Damage of the rock mass and collapse of the emplacement drift were simulated in the calculations.

Figure V-5. Geometry of the Numerical Representation of the Emplacement Drift and the Objects Located Inside the Drift

V-3.1 REPRESENTATION OF THE ROCK MASS

The calculations simulate not only the motion of the objects located inside the emplacement drift (i.e., the drip shield, the waste package, and the emplacement pallet), they also simulate the response of the rock mass and the overall stability of the emplacement drift during strong seismic ground motions. The lithophysal rock mass is represented as an assembly of randomly-shaped, bonded, polygonal blocks with an average size of 0.3 m. The approach of representation of the rock mass with many randomly-shaped and bonded blocks to analyze degradation of the emplacement drifts in the lithophysal rock mass and the results of the analysis for strong seismic ground motions are discussed in detail in the *Drift Degradation Analysis* (BSC 2004 [DIRS 166107], Section 6.4.2). The micro-mechanical properties of the blocks and the contacts between the blocks must be calibrated to ensure that macro-mechanical properties (i.e., stiffness and strength) of the assembly of the block in the numerical calculation is representative of the (macro) mechanical properties of the rock mass. The block contact planes do not represent pre-existing fractures as they are bonded using the rock mass strength properties. However, should the forces dictate, fractures may propagate along these boundaries if the tensile or shear strength is overcome. In that way, the rock mass may fracture into blocks in response to stressing and these blocks may become dislodged and fall into the emplacement drift under gravitational or seismic accelerations. In all the simulations presented here, the micro-mechanical properties for Category 3 lithophysal rock mass were used. Five categories characterize the variability of the quality of the lithophysal rock mass. Category 3 was selected in these calculations as the median category, which represents a relatively large volume of the lithophysal rock mass at the repository level. The mechanical properties of the lithophysal rock mass and representation of the lithophysal rock mass in UDEC calculations are discussed in *Drift Degradation Analysis* (BSC 2004 [DIRS 166107], Sections 6.4.1 and 6.4.2). The macro- and

micro-mechanical properties of the lithophysal rock mass Category 3, used in the analyses discussed here, are listed in Table V-2.

Table V-2. Macro- and Micro-Mechanical Properties of Category 3 Lithophysal Rock Mass

Rock mass unconfined compressive strength	20.0 MPa
Rock mass Young's modulus	10.8 GPa
Friction angle	35 deg
Residual friction angle	15 deg
Cohesion	7.94 MPa
Tension	3.18 MPa
Normal stiffness	53.08 GPa/m
Shear stiffness	26.57 GPa/m
Block bulk modulus	51.37 GPa
Block shear modulus	38.60 GPa

Source: see Table 5-1.

The geometry of the representation of the rock mass, the extent of the simulated domain of the rock mass, and the initial and boundary conditions are the same as those described in detail in *Drift Degradation Analysis* (BSC 2004 [DIRS 166107], Sections 6.4.2.2). The invert was represented as a rigid slab that is moving synchronously with the free field (Assumption 3.2.2). It was demonstrated in Section 5.8 and Attachment VIII that such an approximation is reasonable, as magnification of the seismic waves after passing through the crushed rock in the drift invert will be insignificant for most of the ground motions.

V-3.2 GROUND MOTIONS

Two sets of 17 ground motions, at 2.44-m/s and 5.35-m/s PGV levels, were analyzed. The 1.05-m/s PGV level was not fully analyzed as the ground motion amplitudes are too small to result in waste package-drip shield interactions. The full duration of the ground motions was not simulated. Instead, the portion of the records of the ground motions between the points corresponding to 5 and 95 percent in the energy build-up, as measured by the Arias intensity, was simulated. For each three-component set of ground motions (i.e., two horizontal and one vertical), these points were determined for each component; then, the earliest 5 percent point and the latest 95 percent point were used to define the duration of strong ground motion for that set of ground motions.

V-3.3 GEOMETRY OF THE OBJECTS INSIDE THE DRIFT

V-3.3.1 Drip Shield

The drip shield is a three-dimensional structure with support beams and bulkheads spaced (center-to-center) at approximately 1.07 m, with 15-mm thick plates spanning between support beams and bulkheads. Representation of the drip shield in a two-dimensional calculation (UDEC) and calculation of the equivalent dimensions and properties for the numerical representation of the drip shield are discussed in Appendix Y of *Drift Degradation Analysis* (BSC 2004 [DIRS 166107]).

Material properties used in the calculations discussed here are the same as those used in the *Drift Degradation Analysis*, and a small modification was made to the geometrical representation of the drip shield as shown in Figure V-6. In the original representation of the drip shield, discussed in Appendix Y of *Drift Degradation Analysis* (BSC 2004 [DIRS 166107]), the legs of the drip shield have uniform thickness. In reality, the width of the support beam in the legs of the drip shield increases with height from the invert. A uniform thickness was assumed in the *Drift Degradation Analysis* because it resulted in a stiffer numerical representation of the drip shield and, consequently, more conservative estimates of the rubble loads on the drip shield structure. In reality, there is a design 14-cm horizontal clearance between the emplacement pallet and the legs of the drip shield. Because of the increased thickness of the legs in the numerical representation (i.e., 0.183 m), the clearance was maintained by a reduction in emplacement pallet width. This simplification was acceptable in the original calculation because motions of the waste package and the emplacement pallet were not considered. In the calculations presented here, a correct representation of the dimensions of the waste package and the emplacement pallet is important. In order to have a reasonable approximation of the clearance between the emplacement pallet and the drip shield, and the correct representation of the stiffness of the drip shield legs, a tapered shape with maximum thickness of 0.183 m is at the intersection with the top arch and minimum thickness of 0.079 m at the base was calculated using the approach described in Appendix Y of *Drift Degradation Analysis* (BSC 2004 [DIRS 166107]). The horizontal cross-section at the base of the drip shield leg (shown in Figure V-7) is approximated with a 0.079-m thick rectangular cross-section, based on the condition that the flexural stiffness of the numerical representation is equal to the flexural stiffness of the drip shield leg at the base. The Young's modulus of 108 GPa (Section 5.2.2.1 for Ti-24) is used for drip shield. Although the Ti-7 material is also part of drip shield, the difference of Young's modulus is minor and is therefore not accounted for. In order to avoid very thin cross-sections and small zone sizes, the Young's modulus of the numerical representation of the drip shield was selected to be 3.22 GPa (BSC 2004 [DIRS 166107], Appendix Y). The flexural stiffness was matched by adjusting the thickness of the cross-section. The resulting clearance of 0.12 m between the emplacement pallet and the drip shield in the numerical representation (indicated in Figure V-8) is approximately 15 percent smaller than the actual clearance. Considering uncertainties in input parameters and the stochastic nature of the analyzed problem, the difference in the clearance size should not have a significant effect on the predictions of the calculations.

The effect of change in geometry of the drip shield in the numerical representation on deformability is investigated by simulating a simple problem of elastic deformation of the drip shield for a uniform load of 300 kPa applied to its crown (BSC 2004 [DIRS 166107], Appendix Y). The same problem was analyzed for the original two-dimensional representation with UDEC and for the fully three-dimensional representation with LS-DYNA. The results of those calculations are presented in Appendix Y of *Drift Degradation Analysis* (BSC 2004 [DIRS 166107]). The vertical displacement of 2.47 cm in the middle of the top of the drip shield calculated with UDEC for the new geometry compares well with 2.40 cm calculated with LS-DYNA.

NOTE: All dimensions are approximated based on design drawing (BSC 2005 [DIRS 173303]), unit in m.

Figure V-6. Geometry of Drip Shield Representation in the UDEC Numerical Calculation

NOTE: All dimensions are approximated based on design drawing (BSC 2005 [DIRS 173303]), unit in m.

Figure V-7. Horizontal Cross-Section through the Support Beam and Plate at the Base of the Drip Shield

V-3.3.2 Waste Package and Emplacement Pallet

The geometries of the waste package and the emplacement pallet as represented in the numerical calculation are shown in Figure V-8. The calculations were carried out for the 21-PWR waste package only. Because the objective of the calculations was not to analyze local deformation and damage of the waste package and the emplacement pallet, details of their complicated geometry were not included (Assumption 3.2.3). Instead, only the outlines of the outside contours in the vertical cross-section normal to the drift axis are represented.

NOTE: All dimensions are approximated based on design drawings (BSC 2005 [DIRS 173303] and BSC 2005 [DIRS 173501]), unit in m.

Figure V-8. Geometries of the Waste Package and the Emplacement Pallet in the UDEC Numerical Calculation

V-3.4 MECHANICAL PROPERTIES

The mechanical properties that were kept constant in all of the calculations are listed in Table V-3. No attempt was made to represent the stiffness of the waste package and the emplacement pallet. Instead, they were assumed to be almost rigid (Assumption 3.2.5). The stiffnesses of the waste package and the emplacement pallet are relatively large compared to the stiffnesses of the contacts between the objects inside the emplacement drift, suggesting that most deformation occurring during the impact takes place in the contact. Consequently, the relatively small amount of energy during the impacts is transformed into vibrational energy of the waste package and the emplacement pallet. Densities of the waste package and the emplacement pallet are calculated by averaging their total masses (i.e., 41,700 kg and 1,970 kg for the waste package and the emplacement pallet, respectively, see Table 5-1) over the areas in the cross-section (defined by the dimensions shown in Figure V-8) and the 5.129 m length along the drift, which is the center-to-center spacing between the 21-PWR waste packages along the drift (includes the waste package length of 5.029 m (Table II-3) and a nominal 10 cm waste package spacing²).

² The 10 cm nominal waste package spacing can be found in (BSC 2004 [DIRS 168489], Table 1).

Table V-3. Mechanical Properties Used in the Calculations

Contact normal stiffness	10^9 Pa/m
Contact shear stiffness	10^9 Pa/m
Waste package bulk	$3.33 \cdot 10^{10}$ Pa
Waste package shear	$1.63 \cdot 10^{10}$ Pa
Waste package density	$3,470 \text{ kg/m}^3$
Pallet bulk modulus	$2.57 \cdot 10^{10}$ Pa
Pallet shear modulus	$1.05 \cdot 10^{10}$ Pa
Pallet density	418 kg/m^3

NOTE: Material properties are assumed values to ensure correct estimate of impact information (Assumption 3.2.5)

Different friction coefficients were assigned to metal-to-metal (e.g., waste package-drip shield, waste package-emplacement pallet, emplacement pallet-drip shield contacts) and metal-to-rock contacts (i.e., contacts with the invert) (Assumption 3.2.4). In addition, a different pair of friction coefficients (i.e., metal-to-metal and metal-to-rock) was used for each ground motion from the set of 17 ground motions for a given PGV level (i.e., the 2.44-m/s or 5.35-m/s PGV level). The friction angles and friction coefficients as used in the calculations are listed in Table V-4. These friction angles are taken from values provided in Attachment X, Tables X-1 and X-2, waste package number 1.

Table V-4. Friction Angles and Friction Coefficients Used in the Calculations

Realization	Metal-to-metal		Metal-to-rock	
	Friction angle (deg)	Friction coefficient	Friction angle (deg)	Friction coefficient
1	13.05	0.23	35.67	0.72
2	36.42	0.74	29.24	0.56
3	27.24	0.51	12.14	0.22
4	28.44	0.54	18.29	0.33
5	33.81	0.67	33.06	0.65
6	32.41	0.63	30.87	0.60
7	38.64	0.80	25.33	0.47
8	13.58	0.24	19.45	0.35
9	29.64	0.57	14.66	0.26
10	19.55	0.36	22.35	0.41
11	15.68	0.28	34.52	0.69
12	18.53	0.34	16.03	0.29
13	30.91	0.60	28.88	0.55
14	24.00	0.45	36.31	0.73
15	25.54	0.48	22.54	0.42
16	34.91	0.70	26.17	0.49
17	21.95	0.40	37.88	0.78

Source: Attachment X, Tables X-1 and X-2 (n=1).

NOTE: friction angle = $\text{atan}(\text{friction coefficient})$.

V-4. RESULTS OF SIMULATIONS

Waste package-drip shield and waste package-emplacement pallet impacts were monitored during the simulations. The time, location (in the global coordinate system) and relative velocity were recorded for each impact. Snap-shots of the simulated geometry taken every 0.05 s during the simulation were used to generate animations showing evolution of the drift geometry and interaction between the objects inside the drift. Because the main objective of the calculations was investigation of the waste package-drip shield impacts, only those impacts are reported here. Because impact location does not provide a reliable criterion for classification of impacts (i.e., distinguishing between waste package-drip shield and waste package-emplacement pallet impacts), the impacts were classified by visual inspection of the animations, followed by confirmatory comparison with the impact records. The relative impact velocities reported in the global coordinate system are calculated as the difference between the average velocities of the waste package and the drip shield.

Examples of snap-shots of the geometry of the simulated problem at 1-s time intervals for realization 10 at the 2.44-m/s and 5.35-m/s PGV levels are shown in Figures V-9 and V-10, respectively. This realization was chosen as it is characterized by some of the largest levels of PGV of all of the components. The figures illustrate that the emplacement drift collapses soon after onset of strong ground shaking. For the 5.35-m/s PGV level, the drift collapsed within 1 s after the onset of simulation. The drip shield is covered completely by the collapsed rock rubble, which significantly constrains motion of the drip shield. Despite strong ground shaking and impacts by the waste package, the drip shield is never overturned or displaced in such a way as to expose the waste package to direct impacts by the loose rocks. This conclusion is drawn by visual inspection of the animations for all 34 simulations carried out for ground motions at the 2.44-m/s and 5.35-m/s PGV levels. The drip shield is covered by the collapsed rock mass whenever the waste package impacts it. Broken rubble provides additional support to the drip shield (preventing large rigid body displacement of the drip shield and reducing damage in vicinity of impact location) when impacted by the waste package.

Table V-5 shows the relationship between the waste package-drip shield impact velocities and the peak ground velocities for the 2.44-m/s PGV level ground motions. The data in Table V-5 demonstrate that a waste package-drip shield impact velocity above 1 m/s only occurs for realizations number 3, 10, 11 and 15. Each of these realizations has a ground motion component with a PGV greater than 4 m/s (Table V-5). However, ground motion components with PGV greater than 4 m/s are extremely large and may not be physically realizable for the seismic sources and geologic conditions in and around Yucca Mountain. A recent study (BSC 2005 [DIRS 170137]) has estimated the limits for maximum shear strain in the lithophysal rock, based on existing large-core compression testing and on numerical analyses of fracturing limits using field-mapped lithophysae geometries. With these limits, the maximum value of PGV on the hazard curve is 4.07 m/s for annual exceedance frequencies greater than or equal to 10^{-8} per year (BSC 2005 [DIRS 170137]). In other words, the ground motions that create waste package-drip shield impact velocities above 1 m/s are probably not physically realizable at the emplacement drifts.

A summary of the waste package-drip shield impact results is listed in Table V-6 for the 2.44-m/s and 5.35-m/s PGV levels. The table contains the number of impacts with impact

velocity greater than 0.85 m/s (Assumption 3.2.29) and the magnitude of maximum impact velocities (if greater than 0.85 m/s). Analyses presented in *Seismic Consequence Abstraction* (BSC 2005 [DIRS 173247], Section 6.5.1.2) have shown that no damage is sustained by the waste package for impact velocities below about 0.85 m/s. As illustrated in Figure V-10 in the frame at 5 s, the waste package does not impact only the legs of the drip shield. Ground motions with large vertical acceleration also cause impact of the waste package into the crown (from below) of the drip shield structure. In only two realizations at the 5.35-m/s PGV level does the waste package not impact the drip shield with impact velocity greater than 0.85 m/s. The maximum impact velocities at the 5.35-m/s PGV level vary significantly from one realization to another. The largest impact velocity of 13.4 m/s is recorded for realization 10 (illustrated in Figure V-10).

Also included in Table V-6 is the information for the time the rubble covers the drip shield and the time the impacts occur for each simulation. Both the time of first impact and the time with maximum impact velocity are included. Almost all the simulations show that the time the rubble covers the drip shield occurs earlier than the first impact except Case 11 for 2.44-m/s PGV level (case with single impact of relatively low velocity). Notice that the observed time for the rubble covers the drip shield is at the time for complete coverage. The drip shield could be pinned by the rubble with substantially less rockfall. This confirms the rationale for Assumption 3.2.1.

Figure V-9. Evolution of the Analyzed Geometry for Realization 10 at the 2.44-m/s PGV Level

Figure V-10. Evolution of the Analyzed Geometry for Realization 10 at the 5.35-m/s PGV Level

Table V-5. Comparison of Maximum Waste Package-Drip Shield Impact Velocities from the Cross-Drift Calculations with PGV Values for the Transverse and Vertical Components at the 2.44-m/s PGV Level

Realization No.	Ground Motion No.	PGV-Transverse (m/s)	PGV-Vertical (m/s)	Max. Impact Velocity (m/s)
1	17	1.60	1.75	0
2	16	1.58	2.12	0
3	3	6.43	6.09	5.35
4	2	2.69	2.33	0.193
5	11	2.56	1.28	0
6	4	2.60	2.97	0.669
7	12	2.71	1.95	0.195
8	5	2.57	1.14	0
9	15	1.53	4.54	0
10	9	8.17	4.57	5.41
11	8	4.02	1.54	1.27
12	6	1.32	2.71	0
13	10	0.78	0.84	0
14	1	1.95	1.11	0
15	7	2.42	6.37	1.85
16	14	1.26	2.46	0
17	13	3.04	3.37	0

Table V-6. Summary of Waste Package-Drip Shield Impact Results

Case	Ground Motion	2.44-m/s PGV level*						5.35-m/s PGV level*					
		Time When Rubble Covers Drip Shield*** (sec)	Time at First Impact (sec)	Velocity at First Impact (m/s)	Time at Max Velocity Impact (sec)	Velocity at Max Impact (m/s)	Total Number of Impacts	Time When Rubble Covers Drip Shield*** (sec)	Time at First Impact (sec)	Velocity at First Impact (m/s)	Time at Max Velocity Impact (sec)	Velocity at Max Impact (m/s)	Total Number of Impacts
1	17	8.60	NI**	NI	NI	NI	0	2.15	5.11	1.34	5.35	1.70	3
2	16	5.15	NI	NI	NI	NI	0	2.05	5.19	1.40	7.44	3.41	4
3	3	1.05	2.12	2.67	2.48	5.35	4	0.3	1.85	12.58	1.85	12.58	22
4	2	6.05	NI	NI	NI	NI	0	2.1	2.30	4.26	4.12	6.48	18
5	11	4.25	NI	NI	NI	NI	0	1.45	2.56	1.48	3.89	3.91	7
6	4	2.25	NI	NI	NI	NI	0	1.15	3.80	2.82	8.38	6.48	20
7	12	4.35	NI	NI	NI	NI	0	2.4	4.74	3.82	4.74	3.82	11
8	5	5.75	NI	NI	NI	NI	0	2.7	4.11	1.45	4.25	5.00	7
9	15	12.15	NI	NI	NI	NI	0	5.6	12.76	1.12	19.27	3.35	7
10	9	3.70	4.31	1.29	6.01	5.41	7	0.55	1.14	9.12	5.96	13.42	21
11	8	4.85	3.96	1.27	3.96	1.27	1	2.1	3.46	1.22	4.14	4.77	8
12	6	5.60	NI	NI	NI	NI	0	0.4	2.56	10.77	2.56	10.77	16
13	10	No Collapse	NI	NI	NI	NI	0	3.5	NI	NI	NI	NI	0
14	1	6.00	NI	NI	NI	NI	0	2.75	2.82	2.12	2.82	2.12	1
15	7	5.00	9.28	1.85	9.28	1.85	1	2.9	4.93	1.65	8.25	10.81	7
16	14	7.10	NI	NI	NI	NI	0	6.15	NI	NI	NI	NI	0
17	13	2.70	NI	NI	NI	NI	0	1.45	2.55	0.87	4.96	5.68	68
Mean resultant velocity for cases with impact velocity > 0.85 m/s (based on velocity at max impact)		3.47						6.29					

NOTES: *Impact accounts only with Velocity > 0.85 m/s

** No impact

*** The time when the rubble covers the drip shield was determined by visual observation of the graphical results (.pcx files) in DTN: MO0508SPAMECHA.000 (Attachment V folder)

V-5. CONCLUSION

Interaction and impacts between the waste package and the drip shield were investigated in a two-dimensional approximation in the vertical cross-section normal to the axis of the emplacement drift. Damage in the rock mass, subsequent collapse of the emplacement drift and motion and interaction between the objects located inside the emplacement drift were simulated concurrently. The rock mass was represented as an assembly of bonded, irregular, polygonal blocks. Dynamic simulations were carried out only for the strength Category 3 lithophysal rock mass. The drip shield is represented as a linearly elastic, two-dimensional structure with properties and geometry calibrated to match bending stiffness of the actual drip shield. The waste package and the emplacement pallet are represented as nearly rigid blocks with correct mass and geometry of the outline. Energy dissipation during impacts between the objects located inside the emplacement drift was accounted for by hysteretic contact damping. The simulations were carried out for 17 ground motions at both the 2.44-m/s and 5.35-m/s PGV levels.

The results of the simulation show that the drift collapses before the waste package impacts the drip shield. The broken rock mass, which backfills the space between the drip shield and the drift walls, provides additional support to the drip shield during impact by the waste package and constrains the motion of the drip shield. In all of the simulated cases the drip shield maintains its function as the shield for the waste package against the impacts by the loose rock blocks. The waste package impacts the legs and the crown of the drip shield. In only four realizations at the 2.44-m/s PGV level was waste package-drip shield impact velocity greater than 0.85 m/s. At the 5.35-m/s PGV level, the waste package-drip shield impacts (with impact velocity greater than 0.85 m/s) are not observed in two realizations only. There is a significant increase in the number of impacts and the maximum impact velocity for the 5.35 m/s PGV level compared to the 2.44-m/s PGV level. The maximum recorded impact velocity at the 5.35-m/s PGV is 13.4 m/s.

ATTACHMENT VI

**STRUCTURAL STABILITY OF A DRIP SHIELD
SUBJECTED TO WASTE PACKAGE IMPACTS**

VI-1. INTRODUCTION

The objective of this study is to investigate structural stability of a drip shield subjected to waste package impacts using the FE program LS-DYNA V970.3858 D MPP-00 (BSC 2003 [DIRS 166918], STN: 10300-970.3858 D MPP-00). Waste package orientation, magnitude of velocity, direction of velocity, and location of impact are explored; the range of which is based on the results from kinematic analysis of waste packages subjected to vibratory ground motion (Attachments I, II, and V). In the analyses presented herein, the drip shield is surrounded by rubble from a collapsed drift. The dimensions and mass of the waste package used for impacting the drip shield are those of the 21-PWR (BSC 2005 [DIRS 173501]). The scope is limited to reporting whether or not drip shield structural collapse occurs (i.e., the loss of structural stability). If the structural collapse does not occur the scope is limited to reporting the results in terms of the final horizontal deflection of the drip shield side plate (inward displacement of the bottom of the plate) and maximum Von-Mises stress¹ in the drip shield plates, bulkhead and large support beams.

The information provided by the current design configurations (BSC 2005 [DIRS 173303] and BSC 2005 [DIRS 173501]) are that of the potential designs of the drip shield and waste package considered in this study and provides the potential dimensions and materials for those designs. All obtained results are valid for these designs only.

The computer files developed for this attachment can be accessed through the TDMS. DTN: MO0508SPAMECHA.000 includes the inputs and outputs for this attachment (files are located in *Attachment VI* folder).

VI-2. ANALYSIS DESCRIPTION

VI-2.1 IMPACT SCENARIOS

In all, 25 analyses are performed to study the effects of boundary conditions, waste package orientation, magnitude of velocity, direction of velocity, and location of impact on structural stability of the drip shield. Throughout this attachment the following nomenclature is used to describe the analyses: cross-drift refers to the x-axis, vertical refers to the y-axis, and longitudinal refers to the z-axis (Figure VI-1).

VI-2.1.1 Waste Package Orientation

During seismic events, the waste package movement within the drip shield is restricted to a finite space. The emplacement pallet as a bottom boundary and the drip shield as a top and side boundaries define this finite space. For impacts into the sides of the drip shield, the waste package can make contact at angles from 0° (flat impact) to 6.8° (corner impact). Figure VI-2 illustrates how 6.8° was calculated. The width of the drip shield in this figure (W) accounts for the inward slope of the drip shield walls and the minimum height at which the emplacement pallet will allow the waste package to hit the drip shield (the maximum angle would be larger if

¹ Von-Mises stress criterion is a commonly used to predict failure of ductile materials.

the waste package was allowed to impact the drip shield at its base where the distance between the sides is greatest).

Two waste package orientations are considered for these analyses: 0° (flat impact) and 4° (corner impact). At maximum articulation (6.8°), a waste package can not translate cross-drift relative to the drip shield, therefore 4° is selected (as half of 6.8 rounded upward) for side impacts. Additionally, 4° is a reasonable value considering the initial space between waste packages: at 0.1 m between waste packages (BSC 2004 [DIRS 168489], Table 1), contact with adjacent waste packages will also restrict the maximum angle achievable by a waste package.

Figure VI-1. Full Finite-Element Representation of the Drip Shield

Source: (Dimensions are from BSC 2005 [DIRS 173303] and BSC 2005 [DIRS 173501]).

Figure VI-2. Maximum Articulation of the 21-PWR Waste Package

VI-2.1.2 Impact Location

While examining the kinematic analyses of multiple waste packages subjected to vibratory ground motion, it becomes obvious that just about any location inside the drip shield may be subjected to a waste package impact. From side (cross-drift) impacts to vertical impacts, the waste package is free to move around. Therefore, it is important to consider the most vulnerable locations where the waste package may hit. Locations of impacts considered (referring to Figures VI-3 and VI-7) are at Plate 2 directly supported by the large support beam (Segment 1, Direct impact location), Plate 2 centered between two large support beams (Segment 2 impact location), the bulkhead from underneath (Segment 1, vertical and vertical oblique), the bulkhead from the side (longitudinally; Bulkhead impact location), and a combination of those impacts. Due to the need for computational efficiency, different segments of the drip shield are modeled depending on the impact location. Segment 1 (between lines A and B in Figure VI-3) was used for impacts centered on the large support beam, vertical impacts to the bulkhead, and multiple impacts. Segment 2 (between lines C and D in Figure VI-3) was used for impacts centered between two large support beams. A triple segment FE representation (from end to end in Figure VI-3) was created for the simulation of longitudinal impacts to the bulkhead. The numerical representations of these segments are discussed at length in Section VI-2.2.

NOTE: Only half of the drip shield is shown (the mesh is cut along the yz-plane for clarity).

Figure VI-3. Waste Package Impact Locations

VI-2.1.3 Magnitude of Impact

For the parametric analyses, the velocity magnitude remains constant at 6 m/s. This velocity is considered conservative for the following reasons. Three sets of vibratory kinematic calculations were conducted to define impact velocities for both waste package to waste package and waste package to drip shield interactions. Two longitudinal representations (LS-DYNA-Attachments I and UDEC-Attachment II) and one cross-drift representation (UDEC -Attachment V) were used and analyses performed for 1.05, 2.44 and 5.35-m/s PGV cases. The analyses showed that, at the 2.44-m/s PGV level, the mean resultant velocity at impact to the drip shield was 3.87 m/s, 3.65 m/s and 3.47 m/s for the UDEC analysis (see Attachment II, Table II-8), 11 waste package LS-DYNA (see Attachment I, Table I-21), and cross-drift calculations (see Attachment V, Table V-6), respectively. The maximum impact velocities were 5.16 m/s, 3.77 m/s and 5.41 m/s for the UDEC, 11 waste package LS-DYNA, and cross-drift calculations, respectively.

Therefore, impacts with resultant velocity greater than 6 m/s is considered unlikely, making it an appropriate upper bound. As the direction of the velocity vector changes (as explained in the next section), the velocity in a given direction changes, but the resultant magnitude remains constant.

VI-2.1.4 Direction of Impact

The final parameter considered was the direction the waste package is moving prior to impact. Seven directions are considered as listed in Table VI-1. The listed directions were chosen because of the potential they may have in causing unique stress loads causing collapse of the drip shield. The unit vector column, which corresponds to the model orientation in Figure VI-3, indicates which way the waste package is headed. The V_x , V_y , and V_z columns indicate the velocity in a given direction for the corresponding unit vector. As stated before, the resultant magnitude is held constant while the velocity in a given direction changes with the direction of the vector.

Table VI-1. Impact Direction and Corresponding Velocity Values

Name	(Directional Vector)	Magnitude (m/s)	V_x	V_y	V_z
Direct	(1,0,0)	6.000	6.000	0	0
Glancing	(0.1,0,-1)	6.000	0.572	0	5.720
Oblique	(1,0,-1)	6.000	4.243	0	-4.243
Falling Oblique	(1,-1,-1)	6.000	3.464	-3.464	-3.464
Rising Oblique	(1,1,-1)	6.000	3.464	3.464	-3.464
Vertical	(0,1,0)	6.000	0	6.000	0
Vertical Oblique	(1,1,0)	6.000	4.243	4.243	0

NOTE: Because of segment symmetry conditions, the 0° waste package orientation for Segment 1 and 2 provides the same loading conditions (repeated the length of the drift). Therefore, analysis for 0° orientation is not necessary for Segment 2. The corner of the waste package (i.e. 4° orientation) impacting the underside of drip shield is considered an extraneous possibility therefore not considered in the parametric analyses.

VI-2.1.5 Parametric Analysis Summary

Table VI-2 couples the waste package orientation, impact location, and velocity direction in one matrix. In total there are 16 scenarios analyzed for the parametric study. It should be noted that the stress and displacement results for the glancing cases of Segment 1 were small enough not to need consideration for Segment 2.

Table VI-2. Parametric Analysis Matrix

	Segment 1		Segment 2	
	0°	4°	0°	4°
Direct	x	x	-	x
Glancing	x	x	-	-
Oblique	x	x	-	x
Rising-Oblique	x	x	-	x
Falling-Oblique	x	x	-	x
Vertical	x	-	-	-
Vertical-Oblique	x	-	-	-

NOTE: Because of segment symmetry conditions, the 0° waste package orientation for Segment 1 and 2 provide the same loading conditions (repeated the length of the drift). Therefore, analysis for 0° orientation is not necessary for Segment 2.

VI-2.1.6 Additional Analyses

In addition to the 16 parametric analyses, two boundary condition analyses, three 11 m/s impacts, one multi impact scenario, and two longitudinal (along the drift) bulkhead side impacts were analyzed. These additional analyses were performed to verify the appropriateness of the boundary conditions, demonstrate the robustness of the design, and to cover extraneous possibilities.

VI-2.1.6.1 Boundary Condition

Two separate analyses were performed to test the suitability of the boundary conditions. The first analysis compares the broken rubble material model used for these analyses to UDEC numerical experiments (Attachment IX). The second analysis examines the effect of symmetry conditions on the solution.

VI-2.1.6.2 Impacts with 11 m/s Velocity

Three additional simulations were performed to examine structural stability under extreme impact velocities (11 m/s). This impact velocity is considered extreme in comparison to the mean resultant impact velocities determined from the 5.35-m/s PGV level longitudinal and cross-drift analyses presented in Attachments I, II and V. These analyses showed absolute impact velocities of 6.51 m/s, 7.91 m/s and 6.29 m/s from the UDEC (see Attachment II, Table II-8), 11 waste package LS-DYNA (see Attachment I, Table I-21) and the cross-drift (see Attachment V, Table V-6) representations, respectively. The 5.35-m/s PGV level exceeds the bounding PGV of 4.07 m/s representative of the 1×10^{-8} per year probability level. The use of an extreme 11 m/s impact velocity was chosen to demonstrate the robustness of the drip shield design and to cover impact velocity uncertainties from the kinematic analyses (e.g., not capturing rotational velocities components from using a two dimensional approximation; see Section V-2.1). Stress and displacement values from the parametric study were considered when selecting which cases to examine further. A direct impact with the waste package oriented at 4°, a vertical impact, and a vertical oblique impact were chosen because of their high displacement and stress values in the parametric study. For the direct impact, a 4° orientation was chosen over

0° to include one analysis with the corner of the waste package impacting the drip shield at this high velocity.

VI-2.1.6.3 Multiple Impacts

The multiple impact scenario was based on UDEC results for realization 10 cross-drift analysis with a PGV of 2.44 m/s (see Attachment V and DTN: MO0508SPAMECHA.000, *Attachment V\calculation files\cross-drift results\1e-6\results* folder). This particular realization has the most number of impacts above 0.85 m/s and has the highest magnitude impact for the 2.44-m/s PGV level (including two near the upper bound of possible impacts during the regulatory period). Table VI-3 lists the impacts in sequence and Figure VI-4 illustrates the impact locations. The impact magnitudes in Table VI-3 match the UDEC impact magnitudes above 0.85 m/s for realization 10 (DTN: MO0508SPAMECHA.000, *Attachment V\calculation files\cross-drift results\1e-6\results* folder).

Table VI-3. Impact Sequence for Multi-Impact Analysis

Sequence #	Waste Package Orientation	Velocity	
		Magnitude	Direction
1	0°	1.3	Vertical
2	4°	1.3	Direct
3	0°	5.4	Vertical Oblique
4	0°	2.4	Falling Oblique
5	4°	5.2	Direct
6	0°	2.0	Direct
7	4°	1.0	Rising Oblique

NOTE: The numbers in Figure VI-4 correspond to sequence numbers in Table VI-3.

Figure VI-4. Impact locations for Multi-Impact Analysis

VI-2.1.6.4 Longitudinal Bulkhead Impacts

Longitudinal impacts to the side of the bulkhead were also considered. The position of the waste package prior to impact can be found in Figure VI-5. The velocities of the waste package were chosen as 1 m/s and 2.25 m/s in the longitudinal direction. As discussed in the following paragraphs, a 2.25 m/s impact velocity is considered conservative for bounding ground motions, based on an analysis of data from cross-drift calculations discussed in Section 5.6.1.2 and Attachment V (Section V-4) of this report.

The potential impact velocities between the waste package and drip shield, referred to here as waste package-drip shield impacts, has been evaluated with two-dimensional cross-drift calculations for a waste package and drip shield that is surrounded by rubble from a collapsed drift (Section 5.6.1 and Attachment V). The results for 17 ground motions at the 2.44-m/s PGV level are summarized in Table VI-4. This PGV level is appropriate because it is centrally located between the minimum PGV value of 0.4019 m/s and the maximum PGV value of 4.07 m/s for TSPA (BSC 2005 [DIRS 173247], Section 6.9). The cross-drift calculations are useful for evaluating waste package-drip shield impact velocities because they can represent both lateral and vertical impacts between the waste package and the drip shield and because they represent the confinement from rubble induced by drift collapse on the motion of the drip shield. Section 5.6.1 has a general description of the cross-drift calculations and results.

Table VI-4 demonstrates that many realizations have no waste package-drip shield impacts. The data in Table VI-4 also demonstrate that a waste package-drip shield impact velocity above 1 m/s

only occurs for ground motions with a PGV component greater than 4 m/s, approximately the maximum PGV value at 10^{-8} annual exceedance frequency on the bounded hazard curve. For example, realization numbers 3, 10, 11, and 15 have maximum waste package-drip shield impact velocities above 1 m/s, and the corresponding maximum PGV value for either component is 6.43 m/s, 8.17 m/s, 4.02 m/s, and 6.37 m/s, respectively. On the other hand, all other ground motions result in maximum waste package-drip shield impact velocities below 0.669 m/s. These results indicate that waste package-drip shield impact velocities should be less than 1 m/s when ground motion components are at or below a PGV of 4 m/s. Note that ground motions with a PGV component greater than 4 m/s are extremely large, may not be physically realizable, and exceed the maximum PGV on the bounded hazard curve at the 10^{-8} annual exceedance frequency (Section 1.3.3). In this situation, the impact velocity of 2.25 m/s for the structural response calculation is an extreme case that is unlikely with bounded ground motion time histories.

Table VI-4. Comparison of Maximum Waste Package-Drip Shield Impact Velocities from the Cross-Drift Calculations with PGV Values for the Transverse and Vertical Components at the 2.44-m/s PGV Level

Realization No.	Ground Motion No.	PGV-Transverse (m/s)	PGV-Vertical (m/s)	Max. Impact Velocity (m/s)
1	17	1.60	1.75	0
2	16	1.58	2.12	0
3	3	6.43	6.09	5.35
4	2	2.69	2.33	0.193
5	11	2.56	1.28	0
6	4	2.60	2.97	0.669
7	12	2.71	1.95	0.195
8	5	2.57	1.14	0
9	15	1.53	4.54	0
10	9	8.17	4.57	5.41
11	8	4.02	1.54	1.27
12	6	1.32	2.71	0
13	10	0.78	0.84	0
14	1	1.95	1.11	0
15	7	2.42	6.37	1.85
16	14	1.26	2.46	0
17	13	3.04	3.37	0

Sources: Attachment V; BSC 2004 [DIRS 166107], Appendix X, Table X-3

Figure VI-5. Waste Package Position for the Longitudinal Bulkhead Impacts

VI-2.2 NUMERICAL REPRESENTATION

VI-2.2.1 Drip Shield

The full three-dimensional FE representation of the drip shield is illustrated in Figure VI-1. This representation was broken into segments to reduce the mesh size for parametric analysis. Segment 1 consists of the large support beam flanked on both sides by drip shield plates (between lines A and B in Figure VI-1). Segment 2 consists of the drip shield plates with a large support beam on both sides (between lines C and D in Figure VI-1). Boundary conditions, which are discussed later in this section, are applied at the ends of the segments to account for the removed parts of the drip shield (Lines A and B for Segment 1, C and D for Segment 2; Figure VI-1). Analyses were also performed combining three Segment 1 representations, which is referred to as the Triple Segment (Figure VI-3). The Triple Segment was used to analyze a longitudinal impact to the bulkhead (Section VI-3.4) and to examine the effects on results obtained by using the single-segment FE representation.

The drip shield connector assembly, lifting feature, and base are excluded from the FE representation (Assumption 3.2.21). The benefit of this simplification is to reduce the computer execution time while preserving the features of the problem most relevant to the structural response of the drip shield (Assumption 3.2.3).

The thickness of the drip shield components is reduced by 2 mm for all components except the internal and external support plates (Assumption 3.2.13). Because only one surface of the internal and external support plates is exposed, the thickness of these components is reduced by 1 mm (half of 2 mm). Moreover, the overall thickness of the sections of the drip shield plates covered by the internal and external support plates is conservatively reduced by 3 mm. The extra reduction of 1 mm in these areas simplifies the development of the finite element representation,

implying the thickness reduction of 2 mm per drip shield plate despite being covered on one side by a support plate.

NOTE: Some drip shield parts are partially removed to improve visibility.

Figure VI-6. Details of Finite-Element Representation of the Drip Shield (Inside View)

NOTE: Sections of the Collapsed Drift have been removed for clarity.

Figure VI-7. Segment 1 Finite-Element Representation of the Drip Shield

Figure VI-8. Segment 2 Finite Element Representation of the Drip Shield (Collapsed Drift Not Shown)

All drip shield nodes belonging to end-sections (i.e., nodes along lines A, B, C, and D in Figure VI-1) were constrained from translating in the longitudinal (z-) direction and from rotating about the x-axis and y-axis. The rationale for this boundary condition is the drip shield (as represented in Figure VI-1) has a plane of longitudinal symmetry and its geometry for the most part consists of the repeating segments. The asymmetric loading conditions from the waste package are discussed in Sections VI-2.2.3 and VI-3.1.2.

The FE representations were developed using solid (brick) elements for all drip shield and collapsed drift parts. The invert and upper boundary constraint were represented using shell elements. The details of the FE representation are illustrated in Figures VI-6 to VI-9. Constant-stress eight-node solid elements (Livermore Software Technology Corporation. 2003, p. 26.30 [DIRS 166841]), and fully integrated four-node shell elements (Livermore Software Technology Corporation. 2003, p. 26.22 [DIRS 166841]) are used for all analyses. Gaussian quadrature were used for the solid elements (Hallquist 1998 [DIRS 155373], Section 3); Gauss integration and four through-thickness integration points (Livermore Software Technology Corporation 2003 [DIRS 166841], p. 26.23), were specified for the shell elements.

NOTE: Sections of the Collapsed Drift have been removed for clarity.

Figure VI-9. Triple-Segment Finite-Element Representation of the Drip Shield

VI-2.2.2 Collapsed Drift

One of the major assumptions used in these analyses is the drip shield surrounded by rubble of the collapsed drift (Assumption 3.2.1). The numerical representation of the rubble includes solid hexahedral (brick) elements with Material Type 5 in LS-DYNA (*MAT_SOIL_AND_FOAM in Livermore Software Technology Corporation, 2003 [DIRS 166841]). This isotropic material model allows a user-defined pressure–volumetric strain curve (Figure VI-12). The values used to represent the rubble were obtained from numerical experiments (Attachment IX; Assumption 3.2.19). To verify the LS-DYNA material model was behaving as expected, single element uni-axial strain tests were performed and compared to UDEC analyses in Section VI-3.1.

The broken rubble pile was constrained on all outer surfaces in the analysis. A horizontal plane of shell elements just above the height of the rubble allows the rubble to settle any amount, but will stop the rubble from rising above the original position. All nodes on the outside surfaces of the rubble were constrained not to leave their respective vertical planes. The invert shell elements constrain the rubble from underneath. Both of these aforementioned horizontal planes of shell elements use a elastic material model with properties of TSw2 rock (Assumption 3.2.20)

Two heights for the broken rubble pile were represented in these analyses. For most analyses the height of the pile extends 1 m above the drip shield (y-axis). These analyses include Segment 1 and Segment 2 direct, glancing, oblique, rising-oblique, and falling-oblique as well as the bulkhead impacts (Figure VI-10 for 1 m rubble height). The other represented height of the broken rubble pile was 7 m in Figure VI-10 (Attachment V, Figure V-9). This height is used for vertical and vertical-oblique impacts. Computational efficiency is the reasoning for the different heights. In impacts to the side of the drip shield, the solution is not sensitive to the upper boundary constraint. Therefore, the extra elements necessary to extend the rubble pile from 1 m to 7 m were not included in the numerical analyses. In upward impacts to the crown of the drip shield, the behavior of the drip shield is more sensitive to the height of the broken rubble pile. If the height is too small the response of the rubble will be artificially stiff. Seven meters is chosen as a typical height the broken rubble pile will extend after collapse of the drift (BSC 2004 [DIRS 166107], Figure 6-173). The cross-drift dimension of the broken rubble pile (x-axis) extends to the diameter of the drift (before collapse). The longitudinal dimension (z-axis) of the rubble is set to match the length of the drip shield segment it is surrounding.

A downward pressure is applied to the top of the rubble pile to represent the weight of the rubble not included in these FE representations (128 kPa and 25 kPa for the 1 m and 7 m heights respectively; Assumption 3.2.7). The pressure is applied to the rubble from time zero until completion, and is allowed to equilibrate before impact from a waste package occurs. During the equilibrium period the horizontal pressure applied to the drip shield via the Poisson effect of the compressed rubble is approximately 35 to 50 kPa averaged across the side of the drip shield.

Figure VI-10. Numerical Representation of the 1-m (Green) and 7-m (Green and Pink) Broken Rubble Pile (a) Dimensions (b) Mesh Discretization

VI-2.2.3 Waste Packages

Two representations for the 21-PWR waste package (Figure VI-11) were used for the parametric analyses: one for 0° (flat) impacts, the second for 4° (angle) impacts. The mesh of the waste packages are refined in the areas of impact to ensure proper contact. For the 4° waste package, the outer diameter and length dimensions are those in the design drawing provided in BSC 2005 [DIRS 173501]. The inner diameter of the 4° waste package is selected so that the overall mass is consistent with the design drawing using the density of Alloy 22 (the *d3hsp* files in DTN: MO0508SPAMECHA.000 *Attachment IV* folder confirm mass of waste package in the FE representation is within 1.5 percent difference of the design mass in BSC 2005 [DIRS 173501]). The symmetric boundary conditions applied to the drip shield and the asymmetric loading of the waste package create a line-loading condition for the drip shield the entire length of the drift. With these boundary conditions, at a 0° orientation, the waste package is effectively one continuous waste package that runs the length of the drift. Therefore, the outer and inner diameters remain the same for the 0° orientation, but the length is shortened to match the length of the segment. The emplacement pallet is not represented in LS-DYNA analyses in order to simplify the numerical analyses (Assumption 3.2.14).

Waste Package Representation for 4 degree Impacts

Waste Package Representation for 0 degree Impacts

00584DC_063.ai

Figure VI-11. Discretization of the Waste Package for Impact Analyses

VI-2.2.4 Contact and Friction

Contacts were specified between the drip shield and the collapsed drift, waste package, and invert. In absence of more specific data, the friction coefficient for all contacts is assumed to be 0.4 with the exception of collapsed drift to invert contact, which is assumed to be 0.8 (see Assumptions 3.2.9 and 3.2.10). Furthermore, the functional friction coefficient, static friction coefficient, and dynamic friction coefficient are assumed to be equal (Assumption 3.2.11).

VI-2.3 MATERIAL PROPERTIES

Material properties used in these analyses are described in Section 5.2.2. The material properties were evaluated for 150°C (Assumption 3.2.12). Some of the temperature-dependent material properties were not available for Alloy 22, Ti-7, Ti-24, and TSw2 rock. Therefore, RT density and RT Poisson's ratio were used for Alloy 22, Ti-7, and Ti-24 (see Assumption 3.2.6). The RT material properties are used for TSw2 rock. Note that the tangent (hardening) modulus, listed in this section, is a parameter of the bilinear elastoplastic constitutive representation used for the drip shield materials in this calculation.

All material properties for the rubble were obtained from Attachment IX (Assumptions 3.2.8 and 3.2.19). The pressure–volumetric strain curve input into LS-DYNA can be found in Figure VI-12. Figure VI-12 displays the pressure–volumetric strain curve and corresponding

values used for the LS-DYNA collapsed drift material model. Ten points along the mean stress curve from UDEC simulations were chosen as input for the pressure–volumetric strain curve in LS-DYNA; the first nine points are taken directly from the data and the last point is extrapolated out to 60 percent strain.

Volumetric Strain	Pressure
0.0000	0.00
0.0099	0.57
0.0203	1.42
0.0383	3.45
0.0571	6.53
0.0701	8.84
0.0800	11.02
0.1000	16.08
0.1187	20.83
0.6000	109.01

Figure VI-12. Pressure versus Volumetric Strain Input Curve for LS-DYNA

VI-2.3.1 Constitutive Representation of the Drip Shield Materials

The LS-DYNA FE code requires input in terms of true stress and strain definitions (for the true stress and strain definitions see Dieter 1976 [DIRS 118647], Chapter 9). Also, the results of this simulation are required to include elastic and plastic deformations of the drip shield materials. When the materials are driven into the plastic range, the slope of the stress-strain curve continuously changes. Thus, a simplification for the stress-strain curve is needed to incorporate plasticity into the FE analysis. A simple approximation often used in engineering is to use a straight line that connects the yield strength point and the ultimate strength point of the material (bilinear elastoplastic constitutive representation, Figure VI-13). The tangent (hardening) modulus represents the slope of the stress-strain curve in the plastic region.

NOTE: (Notation: σ_y = yield strength, E = modulus of elasticity, E_1 = tangent modulus).

Figure VI-13. Bilinear Elastoplastic Constitutive Representation

VI-3. RESULTS

VI-3.1 BOUNDARY CONDITION EFFECTS

VI-3.1.1 Single Element Compression Simulation

The material behavior of the caved rock rubble observed in the UDEC numerical experiments (Attachment IX) is represented in the LS-DYNA calculations by Material Type 5 (Section `mat_soil_and_foam` in Livermore Software Technology Corporation, 2003 [DIRS 166841]) (Assumption 3.2.19). The input parameters, calculated by fitting the Material Type 5 to the mechanical behavior of the synthetic representation of the broken rubble, are verified in simple, one element calculations. As seen in Figure VI-14, the uni-axial strain test in LS-DYNA correlates well with the results from a similar numerical test carried out on a synthetic sample of broken rubble, extracted from the analysis of collapsed drift (see UDEC analyses in Attachment IX). The top five curves in the legend are from the UDEC simulations and the last four curves are from the LS-DYNA simulations. There are several aspects of Figure VI-14 that demonstrate the suitability of the LS-DYNA material model for capturing the bulk behavior of the broken rubble filling the collapsed drift. The LS-DYNA-1st curve in Figure VI-14 is the first principle stress from the LS-DYNA simulation, which matches the vertical stress from the UDEC analyses. The 2nd and 3rd principle stresses (LS-DYNA-2nd and LS-DYNA-3rd respectively) also correlate strongly with the wall (side) stress of the UDEC analysis.

Figure VI-14. UDEC and LSDYNA Uniaxial Compression Simulation Stress-Strain Curves

Broken rubble, as most of granular materials with relative density less than 100 percent, will undergo irreversible volumetric strain during compression as a result of rearrangement of blocks and some damage at sharp edges and corners of the blocks. Consequently, the unloading stiffness will be greater than the loading stiffness. Although the unloading portion of stress-strain curves simulated in UDEC is not shown in Figure VI-14, the unloading bulk modulus was calculated to be 335 MPa (Table IX-2). The LS-DYNA results shown in Figure VI-14 match well the unloading bulk modulus of 335 MPa.

VI-3.1.2 Symmetry Conditions

Results for Segment 1 and the Triple Segment subjected to a direct impact with the waste package at 4° are discussed in this section. This section is necessary to understand the effects the repeating waste package load has on the solution. As mentioned in Section VI-2.2.3 with symmetric boundary conditions the load of the waste package impact is repeated for each segment the length of the drift. For a flat impact (0°), the waste package is effectively one continuous waste package that runs the length of the drift. For a 4° impact, the load is repeated in the center of each segment the entire length of the drift (if the drift is 50 segments long, this would equate to 50 simultaneous impacts equally spaced apart). Comparing the results from a single segment impact to a triple segment impact is necessary to examine the effects of the repeated load. Repeating the triple segment analysis the length of the drift would equate to a waste package impact every third "single" segment. The maximum Von-Mises stresses and final displacements for the two analyses can be found in Tables VI-5 and VI-6 respectively. Figure VI-15 is a plot of the maximum Von-Mises stress in the drip shield plates, bulkhead and large support beams.

Table VI-5. Maximum Von-Mises Stress (MPa) for Direct 4° Impacts

	Plate 1	Plate 2	Large Support Beam	Bulkhead
One Segment	212	270	825	742
Triple Segments	215	310	822	759
% Difference	1.40	12.9	0.49	2.24

Table VI-6. Final Displacement (m) for Direct 4° Impacts

	Absolute		Relative to Rubble	
	Left	Right	Left	Right
One Segment	0.000	0.081	0.000	0.055
Triple Segments	0.000	0.014	0.000	0.007
% Difference	0.0	479	0.0	686

Figure VI-15. X-Direct Impact: Maximum Von-Mises Stress (Pa) in the Drip Shield Plates, Bulkhead and Large Support Beams Drip Shield Structural Members (a) Segment 1 (b) Triple Segment

Most of the values in Tables VI-4 and VI-5 have small percent differences between the two segments; the values that deviate are the maximum stress for plate 2 and the final displacement for the right side of the drip shield. Examining the displacement contours of the drip shield (Figures VI-16 and VI-17) gives insight to the phenomena causing these differences. These figures show the drip shields segments at their maximum displacements. Notice the displacement contours span the entire length for Segment 1, and remain localized for the Triple Segment. The line-loading conditions in Segment 1 cause displacement across the entire segment, which causes the bottom of plate 2 to lift off of the invert. When the bottom of plate 2 lifts off the invert, higher displacements occur because the plate no longer has to overcome frictional forces with the invert to move. This phenomenon explains the two orders of magnitude difference between the displacement of Segment 1 and the Triple Segment. Also, with the entire segment displacing, the stresses in Segment 1 are distributed across plate 2, where the triple segment experiences more localized stresses (which explains the higher maximum stress in the Triple Segment).

Figure VI-16. X-Displacement Contours for Segment 1 During a 6 m/s Direct 4^o Impact

Figure VI-17. X-Displacement Contours for the Triple Segment During a 6 m/s Direct 4° Impact

Although some differences are seen between the Segment 1 analysis and the Triple Segment analysis, the boundary conditions are appropriate considering the objectives of this study: structural stability of the drip shield. The drip shield will collapse when one of the sides collapse or one of the structural components fail. With the symmetry conditions causing more displacement in plate 2, collapse of the structure is more likely to occur, making the results more conservative. Although a 13 percent increase is seen in the maximum stress of plate 2, the stress is localized, indicating the results of the single segment analyses are adequate.

VI-3.2 PARAMETRIC ANALYSIS RESULTS

All 16 parametric analyses indicate that the drip shield reaches equilibrium after waste package impact without the loss of structural stability. Figures VI-18(a) to VI-33(a) illustrate the final drip shield configurations. The maximum Von-Mises stress plots presented in Figures VI-18 (a) to VI-32(a) demonstrate that the stress values in bulkhead, large support beam, plate 1, and plate 2) remain within their respective material's true ultimate strength (Table 5-1). Tables VI-7 to VI-10 report the maximum Von-Mises Stress of plate 1, plate 2, the large support beam, and the bulkhead for each of the impact analyses. Table VI-11 reports the final horizontal displacement of the bottom of plate 2.

Table VI-7. Maximum Von-Mises Stress in Drip Shield Plate 1 (MPa)

Von-Mises Stress (MPa)	Segment 1		Segment 2
	0°	4°	4°
Direct	210	212	211
Glancing	56	61	-
Oblique	209	209	209
Rising-Oblique	205	211	214
Falling-Oblique	206	209	207
Vertical	216	-	-
Vertical-Oblique	235	-	-

Table VI-8. Maximum Von-Mises Stress in Drip Shield Plate 2 (MPa)

Von-Mises Stress (MPa)	Segment 1		Segment 2
	0°	4°	4°
Direct	220	270	223
Glancing	195	210	-
Oblique	216	251	225
Rising-Oblique	214	252	215
Falling-Oblique	213	251	217
Vertical	209	-	-
Vertical-Oblique	213	-	-

Table VI-9. Maximum Von-Mises Stress in the Large Support Beam (MPa)

Von-Mises Stress (MPa)	Segment 1		Segment 2
	0°	4°	4°
Direct	811	825	801
Glancing	247	250	-
Oblique	774	778	756
Rising-Oblique	762	768	749
Falling-Oblique	762	772	749
Vertical	526	-	-
Vertical-Oblique	488	-	-

Table VI-10. Maximum Von-Mises Stress in the Bulkhead (MPa)

Von-Mises Stress (MPa)	Segment 1		Segment 2
	0°	4°	4°
Direct	613	742	625
Glancing	136	133	-
Oblique	430	556	317
Rising-Oblique	665	753	763
Falling-Oblique	327	451	261
Vertical	768	-	-
Vertical-Oblique	790	-	-

The final horizontal displacements of the drip shield side plate (plate 2) are presented in Table VI-11. The nodes used for displacement measurements are located on the bottom surface of plate 2, centered in the segment. Keeping a consistent location (i.e. center of each segment) for horizontal displacement makes the displacement values comparable between all analyses (instead of chasing localized maximums). The final configuration figures (Figures VI-18 (b) through VI-32 (b)²) show that for the most part, relative horizontal displacements along the axis (z) of the drift remains minimal. The absolute column in Table VI-11 reports the final displacement of the bottom center of plate 2; the relative column reports the final displacement between the bottom center of plate 2 and the collapsed drift. For the "Vertical" and "Vertical Oblique" rows of Table VI-11, only 0° impacts are analyzed for those impact directions. The vertical and vertical-oblique impact directions are the only ones to show appreciable displacement to the left side (-x side in Figure VI-7). Therefore, the displacement values for all other impact directions are for the right side, and indication is made for left and right displacement values for the vertical and vertical-oblique directions.

Table VI-11. Final Horizontal Displacement (m) of Drip Shield Side Plate Bottom

	Segment 1				Segment 2			
	Absolute		Relative to Rubble		Absolute		Relative to Rubble	
	0 deg	4 deg	0 deg	4 deg	0 deg	4 deg	0 deg	4 deg
Direct	0.088	0.081	0.060	0.055	-	0.112	-	0.080
Glancing	0.000	0.000	0.000	0.000	-	-	-	-
Oblique	0.029	0.081	0.013	0.058	-	0.044	-	0.029
Rise-Oblique	0.057	0.052	0.039	0.038	-	0.058	-	0.040
Fall-Oblique	0.003	0.005	0.000	0.000	-	0.004	-	0.000
	Left	Right	Left	Right	Left	Right	Left	Right
Vertical	0.315	0.344	0.210	0.264	-	-	-	-
Vertical-Oblique	0.152	0.187	0.103	0.141	-	-	-	-

² For all Von-Mises stress plots in this attachment, curve A is plate 1, curve B is plate 2, curve C is the large support beam, curve D is the bulkhead, and E is the bulkhead flange.

(a)

(b)

Figure VI-18. Segment 1, 0° Direct Impact: (a) Final Drip Shield Configuration, and (b) Maximum Von-Mises Stress (Pa) in the Drip Shield Plates, Bulkhead and Large Support Beams

Figure VI-19. Segment 1, 4° Direct Impact: (a) Final Drip Shield Configuration, and (b) Maximum Von-Mises Stress (Pa) in the Drip Shield Plates, Bulkhead and Large Support Beams

Figure VI-20. Segment 1, 0° Oblique Impact: (a) Final Drip Shield Configuration, and (b) Maximum Von-Mises Stress (Pa) in the Drip Shield Plates, Bulkhead and Large Support Beams

(a)

(b)

Figure VI-21. Segment 1, 0° Glancing Impact: (a) Final Drip Shield Configuration, and (b) Maximum Von-Mises Stress (Pa) in the Drip Shield Plates, Bulkhead and Large Support Beams

Figure VI-22. Segment 1, 4° Glancing Impact: (a) Final Drip Shield Configuration, and (b) Maximum Von-Mises Stress (Pa) in the Drip Shield Plates, Bulkhead and Large Support Beams

(a)

(b)

Figure VI-23. Segment 1, 4° Oblique Impact: (a) Final Drip Shield Configuration, and (b) Maximum Von-Mises Stress (Pa) in the Drip Shield Plates, Bulkhead and Large Support Beams

Figure VI-24. Segment 1, 0° Rising Oblique Impact: (a) Final Drip Shield Configuration, and (b) Maximum Von-Mises Stress (Pa) in the Drip Shield Plates, Bulkhead and Large Support Beams

Figure VI-25. Segment 1, 4° Rising Oblique Impact: (a) Final Drip Shield Configuration, and (b) Maximum Von-Mises Stress (Pa) in the Drip Shield Plates, Bulkhead and Large Support Beams

Figure VI-26. Segment 1, 0° Falling Oblique Impact: (a) Final Drip Shield Configuration, and (b) Maximum Von-Mises Stress (Pa) in the Drip Shield Plates, Bulkhead and Large Support Beams

Figure VI-27. Segment 1, 4° Falling Oblique Impact: (a) Final Drip Shield Configuration, and (b) Maximum Von-Mises Stress (Pa) in the Drip Shield Plates, Bulkhead and Large Support Beams

Figure VI-28. Segment 1, Vertical Impact: (a) Final Drip Shield Configuration, and (b) Maximum Von-Mises Stress (Pa) in the Drip Shield Plates, Bulkhead and Large Support Beams

Figure VI-29. Segment 1, Vertical-Oblique Impact: (a) Final Drip Shield Configuration, and (b) Maximum Von-Mises Stress (Pa) in the Drip Shield Plates, Bulkhead and Large Support Beams

Figure VI-30. Segment 2, 4° Direct Impact: (a) Final Drip Shield Configuration, and (b) Maximum Von-Mises Stress (Pa) in the Drip Shield Plates, Bulkhead and Large Support Beams

Figure VI-31. Segment 2, 4° Oblique Impact: (a) Final Drip Shield Configuration, and (b) Maximum Von-Mises Stress (Pa) in the Drip Shield Plates, Bulkhead and Large Support Beams

Figure VI-32. Segment 2, 4° Rising Oblique Impact: (a) Final Drip Shield Configuration, and (b) Maximum Von-Mises Stress (Pa) in the Drip Shield Plates, Bulkhead and Large Support Beams

Figure VI-33. Segment 2, 4° Falling Oblique Impact: (a) Final Drip Shield Configuration, and (b) Maximum Von-Mises Stress (Pa) in the Drip Shield Plates, Bulkhead and Large Support Beams

VI-3.3 EXTREME IMPACT VELOCITIES

Three additional simulations are performed to examine structural stability under extreme impact velocities (11 m/s). It should be emphasized that the probability of impacts of this magnitude is

far lower than 10^{-8} per year, but were chosen to demonstrate the robustness of the drip shield design. Stress and displacement results are reported in Tables VI-12 and VI-13. Figure VI-34 shows the final position of the drip shield with the surrounding rubble. Figures VI-35 to VI-37 show the final position of the drip shield without the surrounding rubble and the maximum Von-Mises stress histories for plate 1, plate 2, the large support beam, and the bulkhead.

Table VI-12. Maximum Von-Mises Stress (MPa) for 11 m/s Impacts

	Plate 1	Plate 2	Large Support Beam	Bulkhead
Direct (4°)	216	274	830	762
Vertical	226	212	768	838
Vertical-Oblique	259	238	773	775

Table VI-13. Final Horizontal Displacement (m) for 11 m/s Impacts

	Absolute		Relative to Rubble	
	Left	Right	Left	Right
Direct (4°)	0.000	0.211	0.000	0.141
Vertical	0.344	0.315	0.264	0.210
Vertical-Oblique	0.367	0.274	0.330	0.186

Figure VI-34. Final Position of the Drip Shield After an 11 m/s Vertical Impact

None of the 11 m/s impacts cause catastrophic failure nor do any of the components exceed their material's true ultimate strength. It is important to note that the surrounding rubble plays a big

role to the survivability of the drip shield: the rubble limits drip shield motion during waste package impacts, absorbs some of the impact energy, and acts as a support for the side plates during and after impacts.

(a)

(b)

Figure VI-35. Segment 1, 11 m/s 4° Direct Impact: (a) Final Drip Shield Configuration, and (b) Maximum Von-Mises Stress (Pa) in the Drip Shield Plates, Bulkhead and Large Support Beams

Figure VI-36. Segment 1, 11 m/s Vertical Impact: (a) Final Drip Shield Configuration, and (b) Maximum Von-Mises Stress (Pa) in the Drip Shield Plates, Bulkhead and Large Support Beams

Figure VI-37. Segment 1, 11 m/s Vertical-Oblique Impact: (a) Final Drip Shield Configuration, and (b) Maximum Von-Mises Stress (Pa) in the Drip Shield Plates, Bulkhead and Large Support Beams

VI-3.4 LONGITUDINAL IMPACTS TO THE BULKHEAD

Among the results presented in this attachment, this is the only scenario that causes a component of the drip shield to exceed its true ultimate strength. Two impact speeds were considered (1 m/s

and 2.25 m/s, see Section VI-2.1.6.4), with the impact at 2.25 m/s causing the bulkhead flange to exceed the materials true ultimate strength. Tables VI-14 and VI-15 summarize the maximum stresses and final displacements respectively. Table VI-14 shows the maximum Von-Mises stress histories for the 1 m/s and 2.25 m/s impacts; Table VI-15 shows the final horizontal displacements of the side plates. For longitudinal bulkhead impacts, the bulkhead flange plays a significant role in the analysis, and is therefore included in the Von-Mises stress plots in Figures VI-38 and VI-39. The Von-Mises stress contours are presented in Figure VI-40 for the 2.25 m/s impact. No appreciable displacements (Table VI-15) were seen in the side plate, so final configuration plots are not presented.

Table VI-14. Maximum Von-Mises Stress (MPa) for Bulkhead Longitudinal Impacts

Impact Speed	Plate 1	Plate 2	Large Support Beam	Bulkhead	Bulkhead Flange
1 m/s	214	214	372	787	932
2.25 m/s	232	231	732	979	1,323

Table VI-15. Final Horizontal Displacement (m) of the Drip Shield Side Plates for Bulkhead Longitudinal Impacts

Impact Speed	Absolute		Relative to Rubble	
	Left	Right	Left	Right
1 m/s	0.000	0.000	0.000	0.000
2.25 m/s	0.000	0.006	0.000	0.002

Figure VI-38. Longitudinal Bulkhead Impact (1 m/s) Maximum Von-Mises Stress (Pa)

Figure VI-39. Longitudinal Bulkhead Impact (2.25 m/s) Maximum Von-Mises Stress (Pa)

Figure VI-40. Von-Mises Stress Contours (Pa) Resulting from a 2.25 m/s Longitudinal Impact to the Bulkhead (Internal Support Plate Not Shown; time = 0.08 seconds)

The maximum stress occurs at the juncture where a longitudinal stiffener meets the bulkhead (Figure VI-40). This is also the location where the waste package makes contact with the flange.

The combination of a locally stiff area from the longitudinal stiffener and the impact of the edge of the waste package acts as a shear to the bulkhead and flange. The maximum Von-Mises stress of the bulkhead is just within the true ultimate strength, but with the flange exceeding the true ultimate strength, the load would likely transfer to the bulkhead causing it to fail³. Although detrimental to the bulkhead, the drip shield would likely remain structurally stable missing a section of one bulkhead (there are four bulkheads and two peripheral bulkheads per drip shield; see the following section).

VI-3.4.1 Direct 4° Impact Missing Part of a Bulkhead

To show the structural stability of the drip shield while missing a section of a bulkhead, subsequent analysis using a triple segment FE representation missing part of the center bulkhead and subjected to a 6 m/s Direct 4° impact was performed. The section of bulkhead removed from the model ran from where the bulkhead meets the longitudinal stiffener to the plane where the ends of plate 1 and plate 2 meet (Figure VI-41). The section removed is approximately the same section of bulkhead (and flange) that comes in contact with the waste package during the longitudinal bulkhead impacts (Figure VI-5). As with all analyses presented in this attachment the drip shield is allowed to equilibrate from the weight of the rubble before the impact occurs. The location of the Direct 4° impact is in the same plane (XY) and side (positive x-axis) as the missing bulkhead section. The drip shield remains structurally stable through loading of the rubble weight and subsequent waste package impact. As shown in the Von-Mises maximum stress history plot (Figure VI-42), the stress levels remain below the true ultimate strength of the material.

³ Recall the material model used for the drip shield materials is a bilinear stress-strain curve without a failure criteria, so although the flange exceeds the true ultimate strength of the material it is still contributing to the strength of the structure.

Figure VI-41. Von-Mises Stress Contours (Pa) Resulting From a 6 m/s Direct 4° Impact to the Triple Segment Analysis Missing a Section of the Center Bulkhead (Internal Support Plate Not Shown; time = 0.25 seconds)

Figure VI-42. Direct 4° Impact (6 m/s) to the Triple Segment Analysis Missing a Section of the Center Bulkhead Maximum Von-Mises Stress (Pa)

VI-3.4.2 Limiting Factors for Bulkhead Impacts

It is important to recognize the factors limiting the number and intensity of longitudinal impacts to the bulkheads. The analysis of the cross-drift calculations (Table VI-4) at the 2.44-m/s PGV level indicate that impact velocities are less than 0.669 m/s for ground motions whose horizontal transverse and vertical components are bound at 4 m/s, the maximum PGV value for 10^{-8} annual exceedance frequency on the bounded hazard curve. Other factors limit the number and intensity of longitudinal impacts to the bulkheads. For example, most waste package impacts to the drip shield occur to the sides of the drip shield, to the longitudinal stiffeners along the crown of the drip shield, or to the underside of the bulkheads rather than to the sides of the bulkheads (longitudinal impact). In effect, a longitudinal bulkhead impact requires a specific alignment and motion of the waste package in order for the edge of the waste package to contact the side of the bulkhead.

From the results of the parametric analyses (Section V-3.2) compared to the bulkhead impact analysis, impacts to the bulkhead from underneath are not as severe as impacts to the side. Examining the maximum stresses of a 6 m/s vertical or vertical oblique impact (Table VI-10) show the stresses are much lower than a 2.25 m/s longitudinal impact. Severe impacts only occur when a surface or end of the waste package is able to clip the side of a bulkhead (Figure VI-43). This orientation can only occur when the waste package hits the bulkhead on the same end as the direction it is traveling. If only impacts that can clip the bulkhead are considered, the probability of a significant impact velocity above 0.669 m/s becomes even smaller.

Another factor that should be considered is the geometry of the waste package and drip shield. The waste package is limited in the number of configurations to make contact with the side of the bulkhead. The longitudinal stiffeners make it difficult for the waste package to contact the bulkhead near the apex of the drip shield. Additionally, the spacing between bulkheads (1.047 m, BSC 2005 [DIRS 173303]) limit the angles at which the waste package can “reach-in” to clip the bulkhead (although the “Severe” side in Figure VI-43 is not to scale, the ratio between waste package length and bulkhead spacing is a reasonable approximation).

Figure VI-43. Bulkhead Impact Scenarios (Not To Scale)

VI-3.5 MULTIPLE IMPACTS

Maximum Von-Mises stresses and final displacements of the drip shield from the multi-impact scenario can be found in Tables VI-16 and VI-17 respectively. Figure VI-44 shows the final position of the drip shield without the surrounding rubble and the maximum Von-Mises stress histories for plate 1, plate 2, the large support beam, and the bulkhead.

Table VI-16. Maximum Von-Mises Stress (MPa) for Multiple Impacts

Plate 1	Plate 2	Large Support Beam	Bulkhead
229	352	810	770

The time-maximum Von-Mises stress in plate 2 exceeds the true ultimate strength of the material (Table VI-16). Results show the offending element is a surface element in direct contact with the waste package during impact number 5 (Table VI-3; 4o 5.2 m/s Direct Impact). This element is being pinched between the waste package and large support beam. Examining the x, y, and z directional stresses show all compressive stresses. The wall average of the elements through the thickness of the plate at this location shows a maximum average Von-Mises stress of 249 MPa (Figure VI-44). These directional and average stress values indicate that localized denting will occur, but tearing through the thickness of the plate is not indicated thereby validating the FE representation and confirming structural stability of the drip shield.

Table VI-17. Final Horizontal Displacement (m) of the Drip Shield Side Plates for Multiple Impacts

Absolute		Relative to Rubble	
Left	Right	Left	Right
0.149	0.205	0.108	0.146

Figure VI-44. Multiple Impact Scenario: (a) Final Drip Shield Configuration, and (b) Maximum Von-Mises Stress (Pa) in the Drip Shield Plates, Bulkhead and Large Support Beams

Figure VI-45. Wall-Averaged Von-Mises Stress (Pa) in Plate 2

VI-3.6 MESH OBJECTIVITY

The purpose of this section is to verify the objectivity of the mesh (i.e., that the calculation results are not mesh-sensitive). An approach used to achieve this goal is presented in detail in Meham 2004 ([DIRS 170673], Section 6.2.3). The maximum Von-Mises stress of the bulkhead is presented in this section for two different meshes (Figure VI-46 for the element locations). The obtained results are considered mesh-objective (i.e., mesh-insensitive) if the relative difference of results between the first and the second mesh are much smaller (approximately an order of magnitude smaller) than the relative difference of volumes of their representative (average, typical) elements.

The first mesh is obtained by following the guidance in Meham 2004 ([DIRS 170673], Section 6.2.3). The second mesh is a refined version of the first mesh. The first mesh is refined in all three directions in the areas of high stress. The volumes of the typical elements for the bulkhead are presented in Table VI-18. The numbers presented in Table VI-18 in parentheses represent the element numbers that are considered typical (Figure VI-46).

The mesh sensitivity is studied for the vertical-oblique impact at 6 m/s. This scenario was chosen because it experiences the highest stresses for two (plate 1 and bulkhead) of the four components listed in Tables VI-7 through VI-10. The direct 4° impact experiences the highest stresses in drip shield plate 2 and the large support beam, but with the stresses more localized (Section VI-3.5 for discussion), the vertical-oblique impact is considered more severe. The results are presented in Table VI-19. (Numbers of divisions in the axial, tangential, and thickness directions in the first mesh and the second mesh directions are available in DTN: MO0508SPAMECHA.000, see folders *Attachment VI\Mesh-Refinement\square.tg* and *Attachment VI\Seg1-VerticalOblique-0\square.tg*).

According to results presented in Tables VI-18 and VI-19, the calculation results are not mesh-sensitive.

Table VI-18. Volume of Typical Element for Two Different Finite-Element Meshes

Location	Volume of Typical Element ($1 \cdot 10^{-6} \text{ m}^3$)		
	First Mesh	Second Mesh	Difference (%)
Top Side of Bulkhead	0.685 (e# 54034)	0.266 (e# 94464)	158
Bottom Side of Bulkhead	0.732 (e# 53497)	0.142 (e# 91165)	415

Table VI-19. Maximum Von-Mises Stress for Two Different Finite-Element Meshes

Location	Maximum Von-Mises Stress (MPa)		
	First Mesh	Second Mesh	Difference (%)
Top Side of Bulkhead	759 (e# 54034)	768 (e# 94464)	1.17
Bottom Side of Bulkhead	792 (e# 53497)	723 (e# 91165)	9.54

Figure VI-46. Details of Finite-Element Representation of the Drip Shield Support Beam: (a) First Mesh, and (b) Second Mesh

VI-3.7 CONCLUSIONS

Results from single element compression tests in LS-DYNA demonstrate the ability of Material Type 5 to capture the behavior of UDEC numerical compression experiments on caved rock rubble. Additionally, symmetry conditions were tested to show conservatism in the analyses: the “line-load” created by the symmetry conditions causes an increase in side plate displacement.

Impacts of varying speeds and locations were explored. From the parametric study direct, vertical, and vertical-oblique impacts showed the highest stresses and displacements. The higher stresses caused by these impacts correlate more to the closing speed of the waste package than the direction of impact. Even under extreme impacts, each of the drip shield components remained within their true ultimate strengths through all but one of the impact scenarios. Stresses during a 2.25 m/s longitudinal impact to the bulkhead indicate that the bulkhead will fail at the location of impact, although a discussion is presented (Section VI-3.4.2) that the likely occurrence of such an impact is small enough to dissolve concern. This discussion highlights the limited configurations (constrained by dimensions, orientation and relative motion of the components) that permit a longitudinal impact to the side of the bulkhead as well as the limited

impact velocity possible for ground motions within the 10^{-8} annual exceedance frequency on the bounded hazard curve.

ATTACHMENT VII

**ADDITIONAL INFORMATION FOR THE STUDY
OF THE MAXIMUM ACCELERATIONS ON THE FUEL
ASSEMBLIES OF A 21-PWR WASTE PACKAGE DURING END IMPACTS**

VII-1. INTRODUCTION

The objective of this calculation is to determine the acceleration of the fuel assemblies contained in a 21-PWR waste package during impact on an unyielding surface. More specifically, the average acceleration and the maximum acceleration of the fuel assemblies are defined by two successive differentiations of the appropriate displacement time history. All accelerations are expressed in units of g , the acceleration of gravity ($= 9.81 \text{ m/s}^2$).

The maximum waste package velocities from end-on impacts with the 15 ground motions at the 2.44-m/s PGV level vary between 1.0 to 4.5 m/s (BSC 2004 [DIRS 167083], Tables 6.1.2-1 through 6.1.2-15). In other words, each realization with ground motions with 2.44-m/s PGV has an end-to-end impact velocity of at least 1.0 m/s. Similarly, the maximum waste package velocities for end-on impacts at the 5.35-m/s PGV level vary between 1.0 m/s and 6.5 m/s (BSC 2004 [DIRS 167083], Tables 6.2.2-1 through 6.2.2-15). That is, realizations for ground motions with 5.35-m/s PGV have an impact velocity of at least 1.0 m/s. (The minimum value for the 5.35-m/s PGV level is less than that for the 2.44-m/s PGV level because substantial stochastic variability in the 15 ground motions leads to substantial variability in waste package response).

The resulting fuel assembly accelerations due to this range of impact velocities have been analyzed using a FE representation of the fuel assemblies. These calculations represent a parametric study for average and maximum fuel assembly accelerations in response to end-to-end impacts of waste packages. The calculations are performed for five impact velocities at a 1-degree impact angle. The impact calculations are performed with an elastic and unyielding boundary, rather than a detailed FE representation of the adjacent waste package. The use of an elastic unyielding surface is computationally efficient because it reduces the computational mesh by a factor of two. The use of an elastic and unyielding surface also provides a conservative representation of the damaged area. The damaged area with an elastic surface backed by a rigid boundary will generally be greater than the damaged area with an adjacent waste package because the unyielding surface is infinitely stiff, maximizing impact stresses and deformation of the waste package for a given impact velocity and impact angle.

Material properties are based on two temperatures: 150°C, and 200°C (BSC 2003 [DIRS 162602], Section 5.1). A temperature of 150°C is the base case for all calculations because it is conservative for 97 percent of the first 10,000 years and 98.5 percent of the first 20,000 years after repository closure (BSC 2004 [DIRS 167083], Assumption 3.20). Two calculations for impact velocities of 1 m/s and 4 m/s are also performed with material properties at 200°C to evaluate the sensitivity of fuel assembly accelerations at temperature.

The initial conditions for the calculations are an initial velocity of 0.5 m/s, 1 m/s, 2 m/s, 4 m/s, or 6 m/s, and an initial angle between the axis of the waste package and the vertical of 1 degree (i.e., $\alpha = 1^\circ$ in Figure VII-1). Additional calculations at multiple impact angles were not performed because the g -loads from these initial analyses were generally sufficient to fail most if not all fuel rod cladding. Therefore, a subset of the calculations provided sufficient data for developing the damage abstraction for the fuel rod cladding.

Source: BSC 2003 [DIRS 162293], Figure 2.

Figure VII-1. Initial Position of the Waste Package for the End Impacts

VII-2. FINITE-ELEMENT REPRESENTATION

VII-2.1 FINITE-ELEMENT MESH

A half-symmetry, three-dimensional FE representation of the waste package was developed using the dimensions provided in *Maximum Accelerations on the Fuel Assemblies of a 21-PWR Waste Package During End Impacts* (BSC 2003 [DIRS 162602], Attachment I). The waste package OCB and lids, IV and lids, trunnion sleeves, and fuel assemblies were represented by solid (brick) elements. The constant-stress 8-node solid element (Livermore Software Technology Corporation 2003 [DIRS 166841], p. 26.30) with one-point Gaussian quadrature (Hallquist 1998 [DIRS 155373], Section 3) was used for all calculations. The FE mesh is illustrated in Figure VII-2.

Time = 0

Source: BSC 2003 [DIRS 162602], Figure III-4.

Figure VII-2. Standard Mesh for Determination of Fuel Assembly Accelerations

The internal structure of the waste package was simplified in several ways:

1. The 21-PWR fuel assemblies were reduced to bars of square cross section of uniform mass density, and assumed to be constructed of 304 SS.

2. The geometric dimensions of the fuel assemblies were modified to keep the value of the gap between the fuel assemblies and the nearest element consistent with the gap defined using the elements found in *Maximum Accelerations on the Fuel Assemblies of a 21-PWR Waste Package During End Impacts* (BSC 2003 [DIRS 162602], Attachment I).
3. The mass density of the fuel assemblies was modified so that the total mass of the loaded waste package equals the mass given in *21-PWR Waste Package Side and End Impacts* (BSC 2003 [DIRS 162293], Attachment I).
4. The fuel basket tubes and fuel basket plates are not represented in the FE mesh for end impacts.
5. The mass density of the basket stiffeners is modified so that the total mass of the loaded waste package equals the mass given in *Maximum Accelerations on the Fuel Assemblies of a 21-PWR Waste Package During End Impacts* (BSC 2003 [DIRS 162602], Attachment I).
6. The thickness of the OCB was reduced by 2 mm on its outer surface. The target surface was conservatively assumed to be elastic and unyielding, and its density was rounded up to $8,000 \text{ kg/m}^3$. A static and dynamic friction coefficient of 0.5 was taken into account between all parts. This value of friction coefficient represents the average value of the distribution (0.2 to 0.8) used in *Structural Calculations of Waste Package Exposed to Vibratory Ground Motion* (BSC 2004 [DIRS 167083]). The effect of the friction coefficients on the deceleration of the fuel rods is expected to be a second-order effect. Since the resulting fuel rod accelerations exceeded the cladding failure threshold, the more detailed inquiry was unnecessary. Finally, no system damping or contact damping is applied during the simulations.

VII-2.2 INITIAL GAP BETWEEN THE FUEL ASSEMBLIES AND THE IV BOTTOM LID

The fuel assembly accelerations may vary with the initial gap between the fuel assemblies and the bottom lid of the inner vessel. The sensitivity of acceleration to gap size is analyzed in *Maximum Accelerations on the Fuel Assemblies of a 21-PWR Waste Package During End Impacts* (BSC 2003 [DIRS 162602], Attachment II). These results show that the configuration with the minimum gap results in the highest maximum acceleration. Consequently, all cases were run with the minimum gap between the fuel assemblies and the bottom lid of the inner vessel.

VII-2.3 MESH REFINEMENT STUDY

The FE mesh was generated and refined in the contact region according to standard engineering practice. This mesh was then further refined in the region of contact (fuel assemblies and the bottom lid of the inner vessel) to verify that the results are not mesh sensitive. The variation in volume of a representative element and the variation in acceleration of the fuel assemblies are compared in *Maximum Accelerations on the Fuel Assemblies of a 21-PWR Waste Package During End Impacts* (BSC 2003 [DIRS 162602], Attachment III), based on the method described

in Mecham (2004 [DIRS 170673], Section 6.2.3). The accuracy and mesh representativeness are deemed acceptable for this calculation because the criterion in Mecham (2004 [DIRS 170673], Section 6.2.3) is met.

VII-2.4 OUTPUT PERIOD

Computational results are saved at a user-defined output period. This output period is small enough to accurately capture the maximum values of acceleration. An output period of one nanosecond ensures stable values for the maximum acceleration, as demonstrated in *Maximum Accelerations on the Fuel Assemblies of a 21-PWR Waste Package During End Impacts* (BSC 2003 [DIRS 162602], Attachment IV). This output period is used for all results reported in Section VII-3.

VII-2.5 CUTOFF FREQUENCY

The FE calculations for the fuel assembly accelerations do not include any damping. Impact calculations with no damping often produce acceleration time histories with peak values that are influenced by the spatial and temporal discretization of the calculations. In this situation, the output is typically filtered through a low-pass filter to determine a more realistic acceleration time history. The cutoff frequency for the filter is a compromise between damping the extraneous numerical noise while leaving the fundamental modes of the structure intact. Filtering the output below 400 Hertz dampens the fundamental modes of waste package and fuel assembly, potentially leading to erroneous results. Filtering the output at greater than 1,000 Hertz preserves computational noise and can also lead to misleading results. A cutoff frequency of 450 Hertz dampens the numerical noise but has minimal impact on the fundamental modes of fuel assembly and waste package (BSC 2003 [DIRS 162602], Attachment III). The peak and average accelerations from the structural response calculations have been evaluated for cutoff frequencies of 450 Hertz, 600 Hertz, and 1,000 Hertz.

VII-3. RESULTS

The maximum peak accelerations (in the axial direction of the fuel assemblies) experienced by any of the fuel assemblies for material properties evaluated at 150°C are presented in Table VII-1. Table VII-2 presents the average peak acceleration for each impact. The average peak acceleration is obtained by averaging the peak values of acceleration time histories of all fuel assemblies. Details of these calculations and supporting figures are provided in *Maximum Accelerations on the Fuel Assemblies of a 21-PWR Waste Package During End Impacts* (BSC 2003 [DIRS 162602]), Attachment V). A low pass filter with three different cutoff frequencies has been used to remove the high frequency response for all the results presented in this document.

Table VII-1. Maximum Peak Acceleration (g) for the Fuel Assemblies with Three Different Cutoff Frequencies

Cutoff Frequency (Hz)	Initial Velocity (m/s)				
	0.5	1	2	4	6
450	75	144	263	323	506
600	101	192	347	369	567
1000	136	343	502	479	701

Source: BSC 2003 [DIRS 162602], Table 4 and Attachment V.

Table VII-2. Average Peak Acceleration (g) for the Fuel Assemblies with Three Different Cutoff Frequencies

Cutoff Frequency (Hz)	Initial Velocity (m/s)				
	0.5	1	2	4	6
450	35	72	115	155	194
600	48	99	147	180	219
1000	78	160	215	244	278

Source: BSC 2003 [DIRS 162602], Table 5 and Attachment V.

Two additional cases were run at 200°C, one with an initial velocity of 1 m/s and the second with an initial velocity of 4 m/s. The results are presented in *Maximum Accelerations on the Fuel Assemblies of a 21-PWR Waste Package During End Impacts* (BSC 2003 [DIRS 162602], Attachment VI). The variation of 50°C for material properties has only a minor effect on the results.

ATTACHMENT VIII

**EFFECTS OF CRUSHED TUFF INVERT ON
AMPLIFICATION OF GROUND MOTION**

VIII-1. INTRODUCTION

The invert of the emplacement drifts consists of a carbon steel framework in which crushed tuff has been infilled and mechanically compacted. The weight of the waste package and drip shield will initially be borne by the steel framework, but this will eventually corrode and the weight gradually transferred to the crushed tuff. In the analyses of the effects of the seismic ground motions on the vibratory motion of the drip shield and the waste package, it was assumed that the invert is rigid and its motion completely synchronous with the motion of the free field rock mass (Assumption 3.2.2). The seismic ground motions could possibly be amplified when transmitted through the crushed rock in the drift invert, subjecting the drip shield, the emplacement pallet and the waste package to stronger ground motions than those of the free field rock mass (for which the seismic analyses were carried out). The effects of crushed tuff in the invert of the emplacement drifts on seismic ground motions were analyzed, and the results of the analyses are discussed in this Attachment.

The computer files developed for this attachment can be accessed through the TDMS. DTN: MO0508SPAMECHA.000 includes the inputs and outputs for this attachment (files are located in *Attachment VIII* folder).

VIII-2. APPROXIMATE ANALYSIS

Initially, a simplified, analytical approximate analysis of the potential for dynamic amplification of the invert material is given. This analysis, assuming elastic response of the invert, is presented as an initial scoping study.

The amplitude of the response of a lumped single degree of freedom (SDOF) system to harmonic loading can be written (Clough and Penzien 1975 [DIRS 164683]) as:

$$d_{\max} = \frac{p_{\max}}{k} \frac{1}{1 - (\bar{\omega}/\omega)^2} \quad (\text{Eq. VIII-1})$$

where $d_{\max}$ is the amplitude of displacement, $p_{\max}$ is the amplitude of the applied harmonic loading, k is the stiffness of the system, $\bar{\omega}$ is the circular frequency of the applied harmonic load, and ω is the natural free-vibration circular frequency of SDOF. The term:

$$\beta = \frac{1}{1 - (\bar{\omega}/\omega)^2} \quad (\text{Eq. VIII-2})$$

is the magnification factor due to dynamic amplification of the applied load. This simple representation can be applied to the mechanical behavior of the crushed tuff in the invert of the emplacement drift. The height of the invert, h , is modeled to be equal to the maximum thickness of the crushed tuff in the middle of the drift, i.e., 0.86 m (BSC 2003 [DIRS 169776], Section A drawing). The stiffness, k , of the invert representation in response to the horizontal dynamic force perpendicular to the drift axis can be approximated as:

$$k = \frac{G}{h} \quad (\text{Eq. VIII-3})$$

for a one-dimensional element of unit width in two horizontal, mutually orthogonal directions (i.e., normal to the drift axis and along the drift axis). In Equation VIII-3, G is the shear modulus of the crushed tuff, selected in the analysis to be 20 MPa. The shear modulus is conservatively set as half of the value assumed for the continuum analysis (Section VIII-1 and Assumption 3.2.18). The lower shear modulus results in lower natural frequency and hence higher amplification factor. If the mass, m , of this element is lumped on its top, the natural free-vibration frequency of the crushed tuff in the drift invert can be estimated as:

$$f = \frac{\omega}{2\pi} = \frac{1}{2\pi} \sqrt{\frac{G}{hm}} = 18.5 \text{ Hz} \quad (\text{Eq. VIII-4})$$

The mass is calculated using the density of the crushed tuff of 2000 kg/m³ (Assumption 3.2.18).

Power spectral densities for a number of ground motions from the 2.44-m/s and 5.35-m/s PGV levels are shown in Figures VIII-1 through VIII-4 (DTN: MO0508SPAMECHA.000, *Attachment VIII\calculation files\invert effect\analytical folder 1e-6power.xls* and *1e-7power.xls*). The cases shown here are representative of the spectral contents of all other cases from the 2.44-m/s and 5.35-m/s PGV levels. The spectral content of the ground motions varies from one case to another, but it is clear that the dominant frequencies are between 0 and 10 Hz. For example, the magnification factor, β , for the applied frequency $\bar{f} = \bar{\omega}/2\pi = 5 \text{ Hz}$, is 1.07. This implies that dynamic amplification is small, and the problem is practically static in nature.

If the motion of the rigid base is harmonic with maximum acceleration $\ddot{u}_{s,\max}$, the maximum dynamic force acting on the SDOF is $m\ddot{u}_{s,\max}$ and the relative deformation of the SDOF relative to the base is

$$d(t) = \beta \frac{m\ddot{u}_{s,\max}}{k} \sin \bar{\omega}t = -\beta \left(\frac{\bar{\omega}}{\omega} \right)^2 u_s(t) \quad (\text{Eq. VIII-5})$$

Because

$$u(t) = u_s(t) + d(t) \quad (\text{Eq. VIII-6})$$

the total displacement of the SDOF can be written as

$$u(t) = \left[1 - \beta \left(\frac{\bar{\omega}}{\omega} \right)^2 \right] u_s(t) \quad (\text{Eq. VIII-7})$$

Similar relations exist between the velocity and acceleration. Consequently, because $\beta \approx 1$ and $(\bar{\omega}/\omega)^2 \approx 0$, the single degree of freedom is moving synchronously with the base, i.e.:

$$\begin{aligned} u(t) &\approx u_s(t) \\ \dot{u}(t) &\approx \dot{u}_s(t) \\ \ddot{u}(t) &\approx \ddot{u}_s(t) \end{aligned} \quad (\text{Eq. VIII-8})$$

Very similar reasoning can be applied to the vertical motion leading to the same conclusion.

Based on this simple consideration, in which the crushed tuff in the drift invert behaves elastically, the ground motions will be transferred through it without any practical modification. The other simplification inherent in this analysis is that the waste packages and other objects resting on the invert do not affect the motion of the invert. This is justified because of weak coupling between the objects resting on the invert and the crushed tuff in the invert. The objects can freely separate from the invert and only frictional forces prevent the sliding of objects relative to the tuff in the invert.

The non-linear effects of crushed tuff deformation on wave propagation were investigated in detail using numerical methods and the results of the analysis are presented in Sections VIII-3 and VIII-4. However, it is possible, again using a simple analytical approach, to conservatively estimate the level of ground motion when the crushed tuff in the invert detaches or slides relative to the rigid base (i.e., starts deforming inelastically). The factor of safety to sliding relative to the rigid base can be approximated with the following relation

$$FS_h = \frac{\tan \phi \left(1 + \frac{P_{conf}}{mg} \right)}{\frac{\ddot{u}_{sh,max}}{g}} \quad (\text{Eq. VIII-9})$$

where ϕ is the friction angle between the crushed tuff and the rigid base; p_{conf} is the effective confinement pressure on the top of the invert due to the weight of the free standing objects (the waste package, the emplacement pallet, the drip shield and the caved rock resulted from the emplacement drift collapse); $\ddot{u}_{sh,max}$ is the maximum horizontal ground acceleration; and g is the gravity acceleration. The similar relation can be written for the vertical direction

$$FS_v = \frac{1 + \frac{p_{conf}}{mg}}{\frac{\ddot{u}_{sv,max}}{g}} \quad (\text{Eq. VIII-10})$$

Simple calculations were carried out using the peak ground accelerations (PGA) for each ground motion from the 2.44-m/s and 5.35-m/s PGV levels. Two confining pressures, 50 kPa and 100 kPa, on the top of the crushed tuff in the invert were considered in the calculations. These confining pressures are consistent with the weight of the waste package, the drip shield, the emplacement pallet, and the caved rock mass accumulated on the sides and the top of the drip shield. The pressure of the caved rock mass on the top of the drip shield (and on the portion of the invert between the drip shield and the drift walls) is in excess of 100 kPa (BSC 2004 [DIRS 166107]). Most of the strong ground motions from the 2.44-m/s and 5.35-m/s PGV levels cause drift collapse within seconds after the onset of strong ground shaking (see Attachment V, Section V-4). The weight of the 21-PWR waste package averaged over the area of the horizontal outline of the emplacement pallet results in a confining pressure of approximately 50 kPa. The resulting calculated factors of safety (using Equations VIII-9 and VIII-10) against sliding or vertical separation of the crushed tuff from the drift bottom for case of two vertical confining pressures are listed in Tables VIII-1 and VIII-2. If the factors of safety are larger than 1, the shaking clearly does not cause sliding or separation of the crushed tuff in the invert from the rigid base and, consequently, the ground motion is not affected by the deformation of the invert. However, considering conservatism in this simplified analysis, the inelastic deformation of the invert will not occur for all cases when the factors of safety are less than 1.

For example, the results for the ground motions from the 2.44-m/s PGV level and confinement of 50 kPa indicate that some magnification could be expected for ground motions 1, 2, 3, 4, 8 and 9. If the confinement is increased to 100 kPa, it is likely none of the 2.44-m/s PGV level ground motions will cause inelastic deformation of the crushed tuff in the invert or be amplified in the invert. The simple analysis indicates that larger numbers of ground motions from the 5.35-m/s PGV level, in particular for confinement of 50 kPa, will cause the crushed tuff in the invert to slide and separate. (Inelastic deformation of the crushed tuff does not necessarily mean amplified ground motion.)

In order to correctly account for the important complexities of the problem (i.e., details of geometry and constitutive behavior, and full history of the ground motion) the problem is analyzed using the finite difference code FLAC in the next Section.

Table VIII-1. Factors of Safety with Respect to Sliding and Separation for Ground Motions from the 2.44-m/s PGV Level for Two Levels of Vertical Confining Pressure to the Invert

Ground Motion	PGA _{H2} (g)	PGA _V (g)	$p_{\text{conf}} = 50 \text{ kPa}$		$p_{\text{conf}} = 100 \text{ kPa}$	
			FS _h	FS _v	FS _h	FS _v
1	6.74	4.90	0.41	0.80	0.71	1.39
2	7.01	7.30	0.39	0.54	0.68	0.93
3	8.49	6.53	0.32	0.60	0.56	1.04
4	5.95	4.49	0.46	0.87	0.80	1.52
5	3.49	3.09	0.78	1.26	1.37	2.21
6	3.73	3.18	0.73	1.23	1.28	2.14
7	2.67	7.81	1.02	0.50	1.79	0.87
8	8.65	3.76	0.32	1.04	0.55	1.81
9	6.23	12.87	0.44	0.30	0.77	0.53
10	1.66	3.55	1.65	1.10	2.87	1.92
11	2.60	3.00	1.05	1.30	1.84	2.27
12	2.67	1.46	1.02	2.68	1.79	4.67
13	3.88	3.15	0.71	1.24	1.23	2.16
14	2.68	3.38	1.02	1.16	1.78	2.02
15	0.95	0.86	2.88	4.54	5.02	7.92
16	1.47	2.57	1.86	1.52	3.25	2.65
17	0.99	1.51	2.76	2.59	4.82	4.51

NOTE: FS_h = Factor of Safety Against Horizontal Sliding, FS_v = Factor of Safety Against Vertical Separation.

Table VIII-2. Factors of Safety with Respect to Sliding and Separation for Ground Motions from the 5.35-m/s PGV Level for Two Levels of Vertical Confining Pressure to the Invert

Ground motion	PGA _{H2} (g)	PGA _V (g)	$p_{\text{conf}} = 50 \text{ kPa}$		$p_{\text{conf}} = 100 \text{ kPa}$	
			FS _h	FS _v	FS _h	FS _v
1	14.79	13.15	0.18	0.30	0.32	0.52
2	15.37	19.56	0.18	0.20	0.31	0.35
3	18.61	17.50	0.15	0.22	0.26	0.39
4	13.04	12.04	0.21	0.32	0.37	0.57
5	7.65	8.28	0.36	0.47	0.62	0.82
6	8.17	8.53	0.33	0.46	0.58	0.80
7	5.85	20.94	0.47	0.19	0.82	0.33
8	18.95	10.08	0.14	0.39	0.25	0.68
9	13.66	34.52	0.20	0.11	0.35	0.20
10	3.63	9.53	0.75	0.41	1.31	0.72
11	5.70	8.05	0.48	0.49	0.84	0.85
12	5.85	3.92	0.47	1.00	0.82	1.74
13	8.50	8.43	0.32	0.46	0.56	0.81
14	5.87	9.08	0.47	0.43	0.81	0.75
15	2.09	2.30	1.31	1.70	2.28	2.96
16	3.21	6.89	0.85	0.57	1.49	0.99
17	2.18	4.00	1.25	0.98	2.19	1.70

NOTE: FS_h = Factor of Safety Against Horizontal Sliding, FS_v = Factor of Safety Against Vertical Separation.

Figure VIII-1. Power Spectral Densities for Ground Motion #1 from 2.44-m/s PGV Level Set

Figure VIII-2. Power Spectral Densities for Ground Motion #7 from 2.44-m/s PGV Level Set

Figure VIII-3. Power Spectral Densities for Ground Motion #1 from 5.35-m/s PGV Level Set

Figure VIII-4. Power Spectral Densities for Ground Motion #7 from 5.35-m/s PGV Level Set

VIII-3. CONTINUUM ANALYSIS

VIII-3.1. DESCRIPTION OF CONTINUUM NUMERICAL SIMULATIONS

Deformation of the crushed tuff in the invert of the emplacement drifts during strong seismic ground motion was analyzed numerically using FLAC V4.0 (BSC 2002 [DIRS 161953], STN: 10167-4.0-00). In the analysis the wave propagation was simulated through the crushed tuff in the invert only. It was assumed that the drift invert and walls were rigid boundaries moving synchronously with the free field (Assumption 3.2.2). The problem was analyzed as two-dimensional, thus only two components of the ground motions were used in the calculation: one horizontal, H2, and the vertical, V. The geometry of the numerical representation of the analyzed problem is shown in Figure VIII-5. The objects resting on the crushed tuff in the invert were not included in the calculations. Instead, their effect was accounted for by providing two different levels of confinement, 50 kPa (the approximate confinement afforded by the weight of the waste package) and 100 kPa (the approximate confinement afforded by rock rubble from a collapsed drift), as a vertical load on the top of the invert (Assumption 3.2.24).

Although the crushed tuff in the invert of the emplacement drift is a granular material, it is represented in these calculations as an elasto-plastic Mohr-Coulomb continuum. The inelastic volumetric deformation can occur as a result of tensile failure only. Possible irreversible volume change (i.e., compaction or bulking) of the granular material during cyclic shearing strain is not accounted for in this calculation. This effect (irreversible volume change during cycling shearing) is not expected to significantly impact the intensity of ground motion. Also because the crushed tuff will be well compacted, additional compaction cannot be significant. Although the Mohr-Coulomb constitutive model dissipates energy when a material yields, the energy

dissipation during small amplitude oscillations, which takes place in any geomaterial, is not accounted for. (The geomaterials exhibit non-linear, inelastic behavior at any level of strain.) Therefore, there is an additional 2 percent of energy dissipation specified in the numerical calculation as a Raleigh damping (see Assumption 3.2.25). The material properties used in the calculations are listed in Table VIII-3 (Assumption 3.2.18).

Table VIII-3. Material Properties of the Crushed Tuff in the Invert of the Emplacement Drift Used in the Numerical Calculation

Property	Value
Young's modulus	50 MPa
Poisson's ratio	0.25
Density	2,000 kg/m ³
Friction angle	45.
Friction angle between tuff and drift walls	35.

NOTE: The basis for property values provided in Assumption 3.2.18.

The calculations were carried out for all 17 ground motions from 2.44-m/s and 5.35-m/s PGV levels.

Figure VIII-5. Invert Model Geometry Representation at the End of the Simulation of Ground Motion #2 from 2.44-m/s PGV Level

VIII-3.2 RESULTS OF CONTINUUM NUMERICAL SIMULATIONS

The results of the numerical calculations for the ground motions from the 2.44-m/s PGV level are summarized in Tables VIII-4 (confinement of 50 kPa) and VIII-5 (confinement of 100 kPa); the results of the numerical calculations for ground motions from the 5.35-m/s PGV level are

summarized in Tables VIII-6 (confinement of 50 kPa) and VIII-7 (confinement of 100 kPa). The tables include only PGVs of the free field compared with PGVs on the top of the crushed tuff in the invert of the emplacement drift. Comparison of complete ground motions (of the free field and at the top of the crushed tuff) is shown for some selected ground motions in Figures VIII-6 through VIII-33. The results for the ground motions from the 2.44-m/s PGV level and confinement of 50 kPa are shown in Figures VIII-6 through VIII-11; the results for the ground motions from the 2.44-m/s PGV level and confinement of 100 kPa are shown in Figures VIII-12 through VIII-17; the results for the ground motions from the 5.35-m/s PGV level and confinement of 50 kPa are shown in Figures VIII-18 through VIII-27; the results for the ground motions from 5.35-m/s PGV level and confinement of 100 kPa are shown in Figures VIII-28 through VIII-33.

The effect of the crushed tuff in the invert of the emplacement drift on the ground motions from the 2.44-m/s PGV level is negligible—within 5 percent for most of the ground motions. The larger effect is observed (Table VIII-4) for ground motions 1 (horizontal component), 2 (vertical component), 3 (both components), 7 (vertical component) and 9 (vertical component). The complete velocity histories for ground motions 1, 2 and 3 are shown in Figures VIII-6 through VIII-11. The increased velocities are the result of large acceleration amplitudes and last for very short periods of time. The increases in vertical velocity occur when the crushed rock in the invert is thrown in free flight, when the objects originally resting on the invert will also be thrown in free flight. Thus, the increased vertical velocity will not affect the motion of those objects. If the vertical confining pressure on the crushed invert is 100 kPa, there is practically no increase in the velocities passing through the crushed tuff (Table VIII-5). (The vertical pressure on the invert will be more than 100 kPa when the drift collapses.) Comparison of the results obtained using a simple analytic approach (Table VIII-1) with numerical results for the 2.44-m/s PGV level indicate that a simple SDOF analysis is conservative. A large number of cases with a factor of safety (to sliding and separation from the invert) smaller than 1 clearly do not slide or separate from the invert. However, with few exceptions, the cases that show increased velocity from the numerical analysis are the cases which have the smallest factors of safety.

Table VIII-4. Comparison of the PGVs of the Far Field and the Top Surface of the Invert for 2.44-m/s PGV Level Set of Ground Motions in the Case of 50 kPa Confinement

Ground Motion	Horizontal PGV (m/s)		Vertical PGV (m/s)		Horizontal Amplification	Vertical Amplification
	Far Field	Top of Invert	Far Field	Top of Invert	%	%
1	1.95	2.06	1.11	1.12	5.64	0.90
2	2.69	2.71	2.33	3.31	0.74	42.06
3	6.41	6.85	6.09	6.6	6.86	8.37
4	2.59	2.64	2.97	2.98	1.93	0.34
5	2.57	2.59	1.14	1.14	0.78	0.00
6	1.32	1.34	2.71	2.72	1.52	0.37
7	2.42	2.45	6.37	6.79	1.24	6.59
8	4.02	4.04	1.54	1.54	0.50	0.00
9	8.17	8.19	4.57	5.37	0.24	17.51

Table VIII-4. Comparison of the PGVs of the Far Field and the Top Surface of the Invert for 2.44-m/s PGV Level Set of Ground Motions in the Case of 50 kPa Confinement (Continued)

Ground Motion	Horizontal PGV (m/s)		Vertical PGV (m/s)		Horizontal Amplification	Vertical Amplification
	Far Field	Top of Invert	Far Field	Top of Invert	%	%
10	0.78	0.79	0.84	0.87	1.28	3.57
11	2.56	2.57	1.28	1.28	0.39	0.00
12	2.71	2.75	1.95	1.95	1.48	0.00
13	3.03	3.04	3.37	3.38	0.33	0.30
14	1.25	1.27	2.46	2.47	1.60	0.41
15	1.53	1.54	4.53	4.54	0.65	0.22
16	1.58	1.59	2.12	2.12	0.63	0.00
17	1.6	1.6	1.58	1.58	0.00	0.00

Figure VIII-6. Horizontal Velocity Histories of the Far Field and Top of the Invert, Ground Motion #1 from the 2.44-m/s PGV Level Set, Confinement of 50 kPa

Figure VIII-7. Vertical Velocity Histories of the Far Field and Top of the Invert, Ground Motion #1 from the 2.44-m/s PGV Level Set, Confinement of 50 kPa

Figure VIII-8. Horizontal Velocity Histories of the Far Field and Top of the Invert, Ground Motion #2 from the 2.44-m/s PGV Level Set, Confinement of 50 kPa

Figure VIII-9. Vertical Velocity Histories of the Far Field and Top of the Invert, Ground Motion #2 from the 2.44-m/s PGV Level Set, Confinement of 50 kPa

Figure VIII-10. Horizontal Velocity Histories of the Far Field and Top of the Invert, Ground Motion #3 from the 2.44-m/s PGV Level Set, Confinement of 50 kPa

Figure VIII-11. Vertical Velocity Histories of the Far Field and Top of the Invert, Ground Motion #3 from the 2.44-m/s PGV Level Set, Confinement of 50 kPa

Table VIII-5. Comparison of the PGVs of the Far Field and the Top Surface of the Invert for the 2.44-m/s PGV Level Set of Ground Motions in the Case of 100 kPa Confinement

Ground motion	Horizontal PGV (m/s)		Vertical PGV (m/s)		Horizontal amplification	Vertical amplification
	Far field	Top of invert	Far field	Top of invert	%	%
1	1.95	2.02	1.11	1.13	3.59	1.80
2	2.68	2.71	2.33	2.37	1.12	1.72
3	6.42	6.62	6.09	6.10	3.12	0.16
4	2.59	2.64	2.97	2.98	1.93	0.34
5	2.57	2.59	1.14	1.14	0.78	0.00
6	1.32	1.34	2.71	2.72	1.52	0.37
7	2.42	2.45	6.37	6.47	1.24	1.57
8	4.02	4.04	1.54	1.54	0.50	0.00
9	8.17	8.19	4.57	4.59	0.24	0.44
10	0.78	0.79	0.84	0.87	1.28	3.57
11	2.56	2.57	1.28	1.28	0.39	0.00
12	2.71	2.75	1.94	1.95	1.48	0.52
13	3.03	3.04	3.37	3.38	0.33	0.30
14	1.26	1.27	2.46	2.47	0.79	0.41
15	1.53	1.54	4.54	4.54	0.65	0.00
16	1.58	1.58	2.12	2.12	0.00	0.00
17	1.60	1.60	1.73	1.74	0.00	0.58

Figure VIII-12. Horizontal Velocity Histories of the Far Field and Top of the Invert, Ground Motion #1 from the 2.44-m/s PGV Level Set, Confinement of 100 kPa

Figure VIII-13. Vertical Velocity Histories of the Far Field and Top of the Invert, Ground Motion #1 from the 2.44-m/s PGV Level Set, Confinement of 100 kPa

Figure VIII-14. Horizontal Velocity Histories of the Far Field and Top of the Invert, Ground Motion #2 from the 2.44-m/s PGV Level Set, Confinement of 100 kPa

Figure VIII-15. Vertical Velocity Histories of the Far Field and Top of the Invert, Ground Motion #2 from the 2.44-m/s PGV Level Set, Confinement of 100 kPa

Figure VIII-16. Horizontal Velocity Histories of the Far Field and Top of the Invert, Ground Motion #3 from the 2.44-m/s PGV Level Set, Confinement of 100 kPa

Figure VIII-17. Vertical Velocity Histories of the Far Field and Top of the Invert, Ground Motion #3 from the 2.44-m/s PGV Level Set, Confinement of 100 kPa

Although the ground motions from the 5.35-m/s PGV level are much stronger (i.e., larger PGVs and PGAs) than the ground motions from the 2.44-m/s PGV level, their effect on the motion of the crushed tuff in the invert is not much different. For a confinement of 50 kPa (Table VIII-6)

the following ground motions show significant magnification (more than 5 percent) of the PGV: 1 (vertical component), 2 (both components), 6 (both components), 7 (both components), 8 (vertical component) and 10 (vertical components). The analysis for ground motion number 9 did not complete because of numerical instability. The velocity histories (of the free field and top of the crushed tuff) for ground motion numbers 1, 2, 3, 4 and 6 are shown in Figures VIII-18 through VIII-27. The magnification of the ground motion, when it occurs, is associated with the high frequency portion of the motion, and usually for a short duration of time. The horizontal PGV is amplified for only 3 ground motions. If confinement is increased to 100 kPa (Table VIII-7), the horizontal PGV is amplified for only 2 ground motions.

Although some correlation between the result of the simple analytic calculation (Table VIII-2) and numerical results still exists for the 5.35-m/s PGV level ground motions, it is not as good as for the 2.44-m/s PGV level ground motions.

Table VIII-6. Comparison of the PGVs of the Far Field and the Top Surface of the Invert for the 5.35-m/s PGV Level Set of Ground Motions in the Case of 50 kPa Confinement

Ground motion	Horizontal PGV (m/s)		Vertical PGV (m/s)		Horizontal amplification	Vertical amplification
	Far field	Top of invert	Far field	Top of invert	%	%
1	4.28	4.04	2.98	6.05	-5.61	103.02
2	5.89	8.07	6.25	7.00	37.01	12.00
3	14.00	9.38	16.10	16.60	-33.00	3.11
4	5.69	5.83	7.98	7.98	2.46	0.00
5	5.63	5.69	3.05	3.06	1.07	0.33
6	2.90	3.84	7.26	8.90	32.41	22.59
7	5.31	6.12	17.10	18.90	15.25	10.53
8	8.81	8.88	4.12	4.33	0.79	5.10
9	numerical instability					
10	1.71	1.74	2.24	2.46	1.75	9.82
11	5.61	5.68	3.43	3.44	1.25	0.29
12	5.95	6.04	5.22	5.23	1.51	0.19
13	6.65	6.78	9.04	9.33	1.95	3.21
14	2.75	2.82	6.59	6.62	2.55	0.46
15	3.36	3.37	12.20	12.20	0.30	0.00
16	3.47	3.48	5.68	5.68	0.29	0.00
17	3.50	3.50	4.58	4.62	0.00	0.87

Figure VIII-18. Horizontal Velocity Histories of the Far Field and Top of the Invert, Ground Motion #1 from the 5.35-m/s PGV Level Set, Confinement of 50 kPa

Figure VIII-19. Vertical Velocity Histories of the Far Field and Top of the Invert, Ground Motion #1 from the 5.35-m/s PGV Level Set, Confinement of 50 kPa

Figure VIII-20. Horizontal Velocity Histories of the Far Field and Top of the Invert, Ground Motion #2 from the 5.35-m/s PGV Level Set, Confinement of 50 kPa

Figure VIII-21. Vertical Velocity Histories of the Far Field and Top of the Invert, Ground Motion #2 from the 5.35-m/s PGV Level Set, Confinement of 50 kPa

Figure VIII-22. Horizontal Velocity Histories of the Far Field and Top of the Invert, Ground Motion #3 from the 5.35-m/s PGV Level Set, Confinement of 50 kPa

Figure VIII-23. Vertical Velocity Histories of the Far Field and Top of the Invert, Ground Motion #3 from the 5.35-m/s PGV Level Set, Confinement of 50 kPa

Figure VIII-24. Horizontal Velocity Histories of the Far Field and Top of the Invert, Ground Motion #4 from the 5.35-m/s PGV Level Set, Confinement of 50 kPa

Figure VIII-25. Vertical Velocity Histories of the Far Field and Top of the Invert, Ground Motion #4 from the 5.35-m/s PGV Level Set, Confinement of 50 kPa

Figure VIII-26. Horizontal Velocity Histories of the Far Field and Top of the Invert, Ground Motion #6 from the 5.35-m/s PGV Level Set, Confinement of 50 kPa

Figure VIII-27. Vertical Velocity Histories of the Far Field and Top of the Invert, Ground Motion #6 from the 5.35-m/s PGV Level Set, Confinement of 50 kPa

Table VIII-7. Comparison of the PGVs of the Far Field and the Top Surface of the Invert for the 5.35-m/s PGV Level Set of Ground Motions in the Case of 100 kPa Confinement

Ground motion	Horizontal PGV (m/s)		Vertical PGV (m/s)		Horizontal amplification	Vertical amplification
	Far field	Top of invert	Far field	Top of invert	%	%
1	4.27	4.32	2.98	4.60	1.17	54.36
2	5.89	6.55	6.23	8.05	11.21	29.21
3	14.10	10.20	16.30	18.10	-27.66	11.04
4	5.69	5.80	7.97	7.98	1.93	0.13
5	5.63	5.69	3.05	3.06	1.07	0.33
6	2.90	2.93	7.26	7.28	1.03	0.28
7	5.31	5.62	17.10	18.40	5.84	7.60
8	8.81	8.88	4.12	4.48	0.79	8.74
9	17.90	18.60	12.30	13.50	3.91	9.76
10	1.70	1.74	2.25	2.35	2.35	4.44
11	5.61	5.64	3.43	3.43	0.53	0.00
12	5.95	6.04	5.22	5.23	1.51	0.19
13	6.65	6.67	9.04	9.05	0.30	0.11
14	2.75	2.78	6.59	6.61	1.09	0.30
15	3.36	3.37	12.20	12.20	0.30	0.00
16	3.47	3.48	5.68	5.68	0.29	0.00
17	3.50	3.50	4.58	4.62	0.00	0.87

Figure VIII-28. Horizontal Velocity Histories of the Far Field and Top of the Invert, Ground Motion #1 from the 5.35-m/s PGV Level Set, Confinement of 100 kPa

Figure VIII-29. Vertical Velocity Histories of the Far Field and Top of the Invert, Ground Motion #1 from the 5.35-m/s PGV Level Set, Confinement of 100 kPa

Figure VIII-30. Horizontal Velocity Histories of the Far Field and Top of the Invert, Ground Motion #2 from the 5.35-m/s PGV Level Set, Confinement of 100 kPa

Figure VIII-31. Vertical Velocity Histories of the Far Field and Top of the Invert, Ground Motion #2 from the 5.35-m/s PGV Level Set, Confinement of 100 kPa

Figure VIII-32. Horizontal Velocity Histories of the Far Field and Top of the Invert, Ground Motion #3 from the 5.35-m/s PGV Level Set, Confinement of 100 kPa

Figure VIII-33. Vertical Velocity Histories of the Far Field and Top of the Invert, Ground Motion #3 from the 5.35-m/s PGV Level Set, Confinement of 100 kPa

VIII-4. UDEC ANALYSIS

The continuum analysis discussed in Section VIII-3 uses two approximations that can potentially affect the calculation results and conclusions drawn from the results.

- The crushed tuff in the invert of the emplacement drift is represented as a continuum, Mohr-Coulomb material. At certain levels of ground motion the granular materials could become loose (deforming as an assembly of discrete particles, not as a continuum) and/or undergo permanent volumetric deformation (either compaction or bulking). These effects cannot be accurately modeled within the framework of continuum mechanics, and particularly not with Mohr-Coulomb material approximation.
- The effect of the objects inside the emplacement drift was taken into account by applying the vertical confining pressure on the crushed tuff. Potentially, the interaction between the objects inside the emplacement drift and the invert can be more complex, considering the similarity of the masses of the objects (e.g., the waste package) and the crushed tuff in the invert.

Additional calculations were carried out with the numerical code UDEC V3.1 (BSC 2002 [DIRS 161949], STN 10173-3.1-00) to address these two issues.

VIII-4.1 DESCRIPTION OF UDEC SIMULATIONS

Stability of the emplacement drifts during the strong seismic ground motions was analyzed using a two-dimensional UDEC analysis in which the lithophysal rock mass was represented as an assembly of the randomly-defined, bonded polygonal blocks. The calculations and the results are described in detail in *Drift Degradation Analysis* (BSC 2004 [DIRS 166107], Section 6.4). Different assumptions were used regarding the motion of the objects inside the emplacement drift, but in all of the calculations the invert was modeled as rigid body and moving synchronously with free field rock mass. (For example, the geometry of the UDEC analysis using a rigid invert is shown on the left side of Figure VIII-34.) The problem was reanalyzed, representing the invert also as an assembly of randomly-defined polygonal blocks, as shown on the right side of Figure VIII-34. Unlike the representation of the rock mass in which the blocks were bonded together (i.e., the contacts between the blocks have both cohesive and tensile strength), there is only the frictional resistance (a friction angle of 35 degrees) between the polygonal blocks in the invert. The new calculations were conducted for a rock mass composed of Category 3 (approximately average strength condition) lithophysal rock mass using an average block size of 0.2 m. The reduced block size (compared to 0.3 m block size used in the original calculations for rigid invert) was selected as it better represented the average size of the crushed tuff grains in the emplacement drift invert. The average size of the crushed tuff grains will be less than 0.2 m, but using a smaller block size in the numerical calculations would result in very long calculation times. The block size of 0.2 m is a reasonable compromise, providing sufficient discretization to represent mechanical response of the invert as a granular material. The crushed tuff in the invert will be compacted to 31 percent porosity (BSC 2004 [DIRS 168138], Table 5). In the numerical representation the crushed tuff is represented by perfectly matching blocks, resulting in no porosity (Assumption 3.2.26).

The two-dimensional calculations were conducted for two components of the ground motion only: one horizontal component (H2), and vertical component (V). Because these calculations are time consuming, they were carried out for the duration of the seismic signal between times corresponding to 5 percent and 95 percent of the seismic energy. Four cases were simulated: ground motion numbers 1 and 10 from the 2.44-m/s and 5.35-m/s PGV levels. Based on the previous calculations (both analytical and numerical continuum), ground motion number 10 should not be affected by the invert, while ground motion number 1 resulted in changes of the PGVs on top of the crushed rock in the drift invert. The effect of the crushed tuff in the invert was assessed by comparing the results obtained with two calculations, representing the invert as: a) rigid and b) deformable. Two criteria were used for comparison. The configurations inside the emplacement drift at the end of the simulations (Figures VIII-34 through VIII-37) were qualitatively compared. For example, it was of interest if the ground shaking caused complete disintegration of the invert, resulting in the waste package and the drip shield not resting on the crushed tuff in the invert at the end of simulation. The other criterion was the effect of the deformable invert on the interaction between the waste package and the emplacement pallet and the drip shield. A number of impacts and maximum impact velocities are compared (between the cases with rigid and deformable invert) in Table VIII-8.

VIII-4.2 RESULTS OF UDEC NUMERICAL SIMULATIONS

Figures VIII-34 and VIII-35 illustrate that the two ground motions analyzed for the 2.44-m/s PGV level do not have an effect on the invert. Configurations of the objects inside the emplacement drifts are almost identical for two assumptions of invert deformability (contact frictions are different due to random selection). A difference in the extent of collapse in the rock mass above the emplacement drift for ground motion number 1, shown in Figure VIII-35, is a consequence of truncating the dynamic simulation at the time corresponding to 95 percent energy level, when analyses are not in equilibrium yet. Different block sizes considered in the calculations effect somewhat the transient evolution of the problems. A limited extent of rockfall predicted by the analyses for ground motion number 10 from the 2.44-m/s PGV level is a consequence of relatively small PGVs (less than 1 m/s) of the components H2 and V. In none of the considered cases for the 2.44-m/s PGV level does the configuration of the invert change noticeably. Throughout the simulations, the crushed tuff in the invert moves as a rigid body together with the emplacement drift. The maximum impact velocities between the waste package, the emplacement pallet and the drip shield are not significantly affected by the representation of the invert. In fact, the number of impacts is smaller in both cases analyzed when the invert was modeled as deformable. This result is somewhat surprising because the other results indicate that the invert moves as a rigid body inside the emplacement drift. However, the motions of the waste package and the other objects inside the emplacement drift during the strong seismic ground motion are chaotic processes, sensitive to even small perturbations, which can alter the final outcome of the motion. The important result is that the number of impacts are of the same order of magnitude and show similar trends between the ground motion numbers 1 and 10.

As illustrated in Figures VIII-36 and VIII-37, the ground motions from the 5.35-m/s PGV level cause permanent deformation of the crushed tuff in the invert and change in the configuration of the invert. The deformation is smaller for the ground motion of smaller intensity (i.e., ground motion number 10 shown in Figure VIII-36). However, the crushed tuff in the invert does not lose integrity and the objects inside the emplacement drift rest on the invert at the end of the simulation. The main reason for deformation of the invert observed in the numerical simulations is bulking of the granular material as a result of shaking. The blocks representing the invert were perfectly packed in the UDEC analysis in the original configuration (i.e., no initial porosity). It is usually observed that granular materials with porosity in the range between 20 and 30 percent undergo additional irreversible compaction after shaking. (The irreversible volumetric strain of granular materials due to shaking is the reason for liquefaction of saturated granular materials during earthquakes.) However, the ground motions considered here have a relatively strong vertical component that tends to cause loosening and bulking of the material, as opposed to compaction caused by horizontal shaking during construction. The crushed tuff will be compacted in the invert to approximately 31 percent porosity. It is not clear what kind of irreversible volumetric deformation (compaction or bulking) this material would undergo as a result of strong ground shaking. The numerical analysis, due to the idealization of no porosity in the initial configuration, certainly overestimates the bulking of the invert. If the bulking component of deformation is less pronounced, the deformation of the invert for the 5.35-m/s PGV level would be similar to the deformation for the 2.44-m/s PGV level. However, it does not seem that excessive bulking in the numerical representation has a significant effect on the important aspect of this analysis. The number of impacts between the waste package, the

emplacement pallet and the drip shield, and the maximum impact velocity is less if the invert is considered to be deformable, compared to the case when the invert is assumed to be rigid (Table VIII-8).

Table VIII-8. Comparison of Number of Impacts and Impact Velocities from the Calculations Using Different Representations of the Invert

Realization	Ground Motion	2.44-m/s PGV level				5.35-m/s PGV level			
		Number of Impacts		Maximum Velocity (m/s)		Number of Impacts		Maximum Velocity (m/s)	
		Deformable	Rigid	Deformable	Rigid	Deformable	Rigid	Deformable	Rigid
13	10	9(1)*	14(1)	1.06	1.01	19(9)	31(13)	1.56	3.39
14	1	17(4)	24(9)	1.46	1.86	29(13)	33(18)	3.21	4.73

*The number of impacts larger than 1 m/s is listed in parenthesis.

Figure VIII-34. Configurations Inside the Emplacement Drift after Simulation of Ground Motion Number 10 (Realization 13) from the 2.44-m/s PGV Level; Left: Rigid Invert, Right: Deformable Invert

Figure VIII-35. Configurations Inside the Emplacement Drift after Simulation of Ground Motion Number 1 (Realization 14) from the 2.44-m/s PGV Level; Left: Rigid Invert, Right: Deformable Invert

Figure VIII-36. Configurations Inside the Emplacement Drift after Simulation of Ground Motion Number 10 (Realization 13) from the 5.35-m/s PGV Level; Left: Rigid Invert, Right: Deformable Invert

Figure VIII-37. Configurations Inside the Emplacement Drift after Simulation of Ground Motion Number 1 (Realization 14) from the 5.35-m/s PGV Level; Left: Rigid Invert, Right: Deformable Invert

VIII-5. CONCLUSIONS

It is of interest in the analysis of the effects of vibratory motions on the waste package and the drip shield, which are designed to rest on the crushed tuff in the drift invert, to assess how the strong ground motions are modified by the drift invert. The potential for magnification of seismic ground motion passing through the crushed tuff in the invert of the emplacement drift is investigated analytically and numerically. A SDOF analysis shows that the natural frequency of the crushed tuff in the invert is much larger than the largest dominant frequency of the seismic ground motions. Consequently, if the deformation of the invert is elastic during the ground motion, the crushed tuff in the invert would move synchronously with the free field ground motion. Inelastic deformation of the crushed tuff, which is a material of relatively small strength in shear and tension, is expected during strong ground motion, particularly those from the 5.35-m/s PGV level. Numerical calculations, in which crushed tuff is represented as a cohesionless continuum material, were carried out for all ground motions from the 2.44-m/s and 5.35-m/s PGV levels. Vertical confinement of 50 kPa and 100 kPa was assumed in the analyses. This confinement is applied to the top of the crushed tuff and represents the average weight of the waste package and the emplacement pallet resting on the invert or the pressure due to potentially caved rock rubble. The numerical simulations indicate that in most cases the strong ground motions will induce PGV at the surface of the crushed tuff at the same or insignificantly larger value (within 5 percent) than the PGV of the free field. The increase in PGV and the number of cases with increased PGV is smaller for larger confinement and for less intense ground motions (i.e., the 2.44-m/s PGV level). The amplification, when it occurs, is associated with the high frequency portion of a motion and occurs over a relatively short duration of time.

The numerical calculations, which represent the invert as a granular material, include explicit representation of the waste package, the emplacement pallet and the drip shield, and simulate collapse of the drift, show that the invert: (a) deforms practically as a rigid body during ground

motions from the 2.44-m/s PGV level, and (b) undergoes irreversible deformation during ground motions from the 5.35-m/s PGV level. The irreversible deformation of the invert is probably overestimated in the numerical analysis, which represents the crushed tuff in the invert as a material with no porosity in the initial configuration. For the cases analyzed (both PGV levels) the maximum impact velocity (between the waste package and the emplacement pallet and the invert) and number of impacts decrease or remain the same if a deformable invert is assumed in the calculations, compared to the cases when the invert is represented as a rigid body.

The approach of representing the invert as a rigid body has an effect on the ground motions to which the objects inside the emplacement drift are subjected, but this effect is relatively small. With relatively small effect, the representation of the invert as a rigid body is considered as justified and reasonable.

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ATTACHMENT IX

**DEFORMABILITY OF THE CAVED LITHOPHYSAL
ROCK IN THE EMPLACEMENT DRIFTS**

IX-1. INTRODUCTION

The emplacement drifts in the lithophysal rock mass are expected to collapse for strong seismic ground motions with PGV larger than approximately 2 m/s. The numerical analyses predict that the drift collapse takes place within a few seconds after onset of the strong ground motion (BSC 2004 [DIRS 166107], Section 6.4.2.2.2). A possible configuration inside the emplacement drift after the collapse, as predicted by a two-dimensional simulation, is shown in Figure IX-1. The drip shield is represented crudely in this approximation as a rigid body of rectangular outline. Motion of the drip shield and interaction between the waste package, the drip shield and the emplacement pallet will be affected by the caved rubble filling the space between the drip shield and stable rock. (The waste package and the emplacement pallet inside the drip shield are not shown in Figure IX-1.) An estimate of deformability of the caved rock mass covering the drip shield is required for the analysis of the interaction between the waste package, the drip shield and the surrounding rock mass (Attachment VI). The estimate is done based on empirical results from the literature and by performing numerical compression testing experiments on "samples" taken from the analysis shown in Figure IX-1.

The computer files developed for this attachment can be accessed through the TDMS. DTN: MO0508SPAMECHA.000 includes the inputs and outputs for this attachment (files are located in *Attachment IX* folder).

Figure IX-1. Two-Dimensional Analysis of the Collapsed Drift with Indication of the Sampled and Numerical Compression-Tested Portions of the Caved Rock Mass

IX-2. EMPIRICAL ESTIMATE OF ROCK RUBBLE MECHANICAL RESPONSE

Duncan et al. (1980, [DIRS 161776]) proposed the following relation as an estimate of the tangent modulus for soils, including rockfill material:

$$E_t = \left[1 - \frac{R_f(1 - \sin \phi)(\sigma_1 - \sigma_3)}{2(c \cos \phi + \sigma_3 \sin \phi)} \right]^2 k p_a \left(\frac{\sigma_3}{p_a} \right)^n \quad (\text{Eq. IX-1})$$

where σ_1 and σ_3 are the major and minor principal stresses, respectively (i.e., the loading and confining pressures, respectively), $p_a = 101.325 \text{ kPa}$ is atmospheric pressure, and k, n, c, ϕ and R are the parameters determined by curve fitting to test results for the particular material. For the initial tangent stiffness (i.e., $\sigma_1 = \sigma_3$), Equation IX-1 simplifies to:

$$E_i = k p_a \left(\frac{\sigma_3}{p_a} \right)^n \quad (\text{Eq. IX-2})$$

The proposed equations for stiffness of granular soils (or crushed rock) have been fitted to a number of geotechnical materials. Values of the fitting parameters (i.e., k and n) used to calculate the initial tangent stiffness are listed in Table IX-1. The resulting curves for the range of confining stress between 0 and 1 MPa are shown in Figure IX-2. All curves converge to zero when there is no confinement. For confinement in the range between 0.2 MPa and 1 MPa, the initial tangent moduli are in the range between 50 MPa and 175 MPa, depending on the type of crushed rock and the magnitude of confining stress.

Table IX-1. Fitted Parameters for Different Types of Crushed Rock

Soil description	k	n	Source
Basalt rockfill	450	0.37	Duncan et al. (1980 [DIRS 161776])
Crushed basalt rock	1110	0.12	Marachi et al. (1972 [DIRS 157883])
Crushed Olivine Basalt	1000	0.22	Duncan et al. (1980 [DIRS 161776])
Quartzite Rockfill (Furnas Dam Shell)	560	0.48	Duncan et al. (1980 [DIRS 161776])

Figure IX-2. Initial Tangent Moduli for Some Crushed Rock Materials Fitted by the Empirical Relation

IX-3. NUMERICAL DISCONTINUUM ANALYSIS

A two-dimensional numerical code UDEC (BSC 2002 [DIRS 161949], STN: 10173-3.14-00) was used for all calculations presented in this Attachment. Numerical compression experiments were carried out on 3 “samples” of collapsed rock rubble extracted from the UDEC analysis of the collapsed emplacement drift (shown as Windows 1, 2 and 3 in Figure IX-1). Samples are selected to be 4 m × 4 m in size in order to avoid potential size effect in the results. The average block size in these simulations is 0.2 m, which is 20 times less than the edge length of the sample dimension. This ratio is sufficient to avoid a size effect in the numerical analysis. The drift collapse case shown in Figure IX-1 is for lithophysal rock-mass category 1—the lowest strength quality rock estimated for the Lower Lithophysal unit of the repository host horizon. There are 5 categories of rock mass quality in the lithophysal rock mass, 1 being the poorest quality and 5 being the highest quality (BSC 2004 [DIRS 166107], Appendix E). Category 3 is considered the median quality lithophysal rock mass in the Lower Lithophysal unit. The UDEC analysis was calibrated (i.e., mechanical properties of the blocks (elastic properties) and contacts adjusted) against large-core laboratory testing data for lithophysal rock. The calibrated UDEC properties are listed in the *Drift Degradation Analysis* (BSC 2004 [DIRS 166107], Appendix E and Section 7). Although the UDEC analysis shown in Figure IX-1 is for the highest porosity, lowest rock strength lithophysal rock mass (Category 1), one case also was analyzed using lithophysal rock mass mechanical properties calibrated to Category 4, a higher strength, lower porosity rock. The objective was to investigate the effect of the original rock-mass quality on the mechanical properties of the rubble. Essentially, the difference is in the elastic moduli of the rubble blocks. Two types of numerical compression tests were conducted on the rubble “samples” extracted from the UDEC analysis: a) biaxial stress test with constant stress (confinement) on the vertical boundaries; and b) uniaxial strain test which does not allow lateral strains, controlled by rigid vertical boundaries. The configurations of the tests and velocity fields

at the final stages of the tests are shown in Figures IX-3 and IX-4 for constant confinement and uniaxial strain loading conditions, respectively. The biaxial stress tests were conducted for different magnitudes of confinement, including 0.05 MPa, 0.1 MPa, 0.5 MPa and 1.0 MPa. (Unconfined compression experiments were not conducted because granular materials theoretically have zero strength under unconfined conditions.) The geometry of the samples taken from sample extraction windows 1, 2 and 3, indicated in Figure IX-1, and sets of stress-strain curves (in each set, 4 curves are presented for different biaxial confining stresses and 1 curve is for uniaxial strain loading conditions) for each sample are shown in Figures IX-5 through IX-10. The average porosities of the samples from sample extraction windows 1, 2 and 3 are 11.2 percent, 11.9 percent and 6.9 percent, respectively. The directional dependence of the deformability was investigated by loading the sample from extraction window 1 in the vertical and horizontal directions. In fact, in the second case, the loading was still in the vertical direction, but the sample was rotated by 90 degrees. The sample geometry for this case and the stress-strain curves obtained are shown in Figures IX-11 and IX-12. Finally, the effect of the initial rock mass-quality was investigated by testing the sample from extraction window 1 using the mechanical properties of the UDEC analysis that correspond to a category 4 lithophysal rock mass. The calculated stress-strain curves are shown in Figure IX-13.

The numerical results qualitatively show expected trends. The strength and stiffness of the samples increase as confinement increases. For very low confinement the strength and the stiffness converge to zero. This demonstrates that the sample size is sufficient; otherwise, were there a size effect, the samples would have finite strength for unconfined conditions. The curves for a uniaxial strain condition have a typical, hyperbolic, continuously hardening, concave upward shape.

An unexpected result is that sample taken from extraction window 3, with smallest porosity of 6.9 percent, exhibits the softest response. One possible explanation for this is that extraction window 3 lies on the vertical axis of symmetry of the drift, resulting in a particular distribution of voids between the blocks; when these blocks are loaded vertically, a relatively soft response results. One test of directional dependence of stiffness indicates that there is an anisotropy of the deformability of the rubble. Although the locations and size of the samples were selected such that porosity inside the sample is relatively uniform, it does vary. This variability might be affecting the results, but a more probable explanation of the anisotropy is the predominantly unidirectional (vertical) movement of the blocks during the collapse.

Figure IX-3. Velocity Vectors at the End of Simulation for the Biaxial Stress Case with Confinement of 1 MPa

Figure IX-4. Velocity Vectors at the End of Simulation for the Uniaxial Strain Case

Figure IX-5. Initial Configuration of the Sample Taken from Window 1 (Shown in Figure IX-1)

Figure IX-6. Stress-Strain Curves Obtained from Window 1

Figure IX-7. Initial Configuration of the Sample Taken from Window 2 (Shown in Figure IX-1)

Figure IX-8. Stress-Strain Curves Obtained from Window 2

Figure IX-9. Initial Configuration of the Sample Taken from Window 3 (Shown in Figure IX-1)

Figure IX-10. Stress-Strain Curves Obtained from Window 3

Figure IX-11. Initial Configuration of the Sample Taken from Window 1 (Shown in Figure IX-1) Rotated by 90 Degrees

Figure IX-12. Stress-Strain Curves Obtained from Window 1 Rotated by 90 Degrees

It seems that the original rock-mass quality has no significant effect on cases with constant confinement. Strength and stiffness practically did not change. However, the effect of the original rock-mass quality on the stress-strain curve from the test for uniaxial strain loading conditions is significant. The rubble in the better quality rock mass has a much stiffer response

(Figure IX-13). In the case of loading with constant confinement, the deformation of the sample is controlled predominantly by the relative movement of the blocks. For uniaxial strain conditions (with rigid vertical boundaries), the deformability of the blocks becomes the important factor in the overall deformability of the sample, and stiffer blocks result in a stiffer sample response.

The empirical curves and the numerical results are compared in Figure IX-14. With the exception of one set of UDEC results, the agreement in the range of confinement between 0.5 MPa and 1 MPa is excellent. For smaller confinement (0.1 MPa), the UDEC results are on the lower boundary of the set of the presented empirical curves.

Figure IX-13. Stress-Strain Curves Obtained from Window 1 Using material Properties for the Category 4 Lithophysal Rock Mass

Figure IX-14. Initial Tangent Moduli for Some Crushed Rock Materials Fitted by the Empirical Relation Compared with UDEC Results

IX-4. RESPONSE AT LARGE STRAINS

In cases of high-velocity impacts of the waste package into the drip shield, the strains and stresses generated in the caved rock mass covering the drip shield can significantly exceed the strain and stress ranges considered in the previous sections. The stress-strain response of some of the extracted samples of the rock rubble, discussed in the previous sections, was analyzed for uniaxial strain conditions for loading stresses exceeding 20 MPa. Uniaxial strain (i.e., fixed lateral strain under uniaxial compression) testing is reasonable since impact of the waste package to the drip shield will cause localized deformation of the rubble via the drip shield plates. It is considered that such a deformation will be confined—i.e., the rubble will strain almost uniaxially in the localized region of impact. In addition, at the end of the loading cycle the extracted samples were quasi-statically unloaded, not completely, but to a certain stress level below the maximum stress reached during the simulation. Rubble deformation during high-velocity impact will be highly nonlinear (e.g., Figure IX-6) and inelastic. The unloading deformation, which is expected to be stiffer than the loading deformation, could affect interaction between the drip shield and the rubble.

The mean stress as functions of volumetric strain for four analyzed cases are shown in Figure IX-15. All cases show a typical continuously hardening response with an increasing load resulting from confinement provided by the lateral restraint. With the exception of the curve for extracted window 1 rotated by 90 degrees, the three other curves show expected stiffer unloading than the loading stress-strain response. In the case of extracted window 1 rotated by 90 degrees, the unloading curve basically follows the loading curve. Such a response is a consequence of the linearly elastic blocks in the numerical representation. In reality, at average stresses of 20-30 MPa, the corners and edges of rock blocks will crush and fail, resulting in a larger

difference between the loading and unloading stiffnesses. The mechanical response predicted by the numerical approximation is conservative because it will overestimate the load that the broken rock mass will impose on the drip shield after impact due to likely overprediction of dilation in the rubble (due to lack of ability of sharp block corners to crush). The overall response of the rubble in the better quality (and stiffer) rock mass is much stiffer (i.e., the blue curve for extracted window 1—Category 4 in Figure IX-15) than the response of the rubble formed in poor quality (i.e., Category 1) rock mass. The three curves for Category 1 rock mass are similar. Category 1 lithophysal rock mass provides the softest response (compared to other categories and nonlithophysal rock mass) of the broken rubble. A softer rubble results in more deformation and greater stresses in the drip shield. The analysis of interaction between the drip shield and rubble was carried out for rubble in Category 1—i.e., for most unfavorable conditions. Any other category (including Category 4) would result in less deformation, stresses and damage in the drip shield.

Figure IX-15. Mean Stress versus Volumetric Strain Curves for Maximum Mean Stress Greater than 20 MPa

The mean stress versus volumetric strain curves shown in Figure IX-15 define only the volumetric (or hydrostatic) part of the material's stress-strain response. Although the shear resistance of the rubble is small relative to the shear resistance of the rock mass, it cannot be neglected, particularly at high confining stresses. The plot of the stresses in the vertical, loading direction (i.e., stresses on the top and bottom of the numerical test samples) and in the horizontal, lateral direction (i.e., stresses on the left and right walls) shown in Figure IX-16, illustrates the existence of the macro shear stresses in the rubble samples loaded in uniaxial strain; the principal stresses, which are vertical and horizontal in this case, are not equal.

Double yield models are constitutive models that represent both the volumetric and shear yield of a material. The volumetric response of a double yield material is completely defined by the

loading part of the mean stress versus the volumetric strain curve (shown in Figure IX-15) and unloading bulk modulus, which is the slope of the unloading part of the curve.

Figure IX-16. Different Stress Measures versus Strain Obtained from Window 1

A relatively general form of deviatoric (or shear) yield function can be expressed as follows (Hallquist 1998 [DIRS 155373], Section *MAT_SOIL_AND_FOAM):

$$\phi = J_2 - (a_0 + a_1 p + a_2 p^2) \quad (\text{Eq. IX-3})$$

where p is the mean stress or pressure; and J_2 is the second stress invariant defined in terms of principal stresses as follows:

$$J_2 = \frac{1}{6} [(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2] \quad (\text{Eq. IX-4})$$

For the uniaxial strain test two horizontal principal stresses are equal (i.e., $\sigma_2 = \sigma_3$), resulting in a simplification of the expression for the second stress invariant:

$$J_2 = \frac{1}{3} (\sigma_1 - \sigma_2)^2 \quad (\text{Eq. IX-5})$$

A yield condition, i.e., $\phi(\sigma_i) = 0$, can be expressed using Equations IX-3 and IX-5 as follows:

$$\frac{1}{3} (\sigma_1 - \sigma_2)^2 = a_0 + a_1 p + a_2 p^2 \quad (\text{Eq. IX-6})$$

Because the mean stress is

$$p = \frac{\sigma_1 + 2\sigma_2}{3} \quad (\text{Eq. IX-7})$$

it is clear that $a_0 = a_1 = 0$ in Equation IX-6, which simplifies to

$$\sigma_1 - \sigma_2 = \sqrt{3a_2} p \quad (\text{Eq. IX-8})$$

It can be shown, using Equation IX-8 and carrying out algebraic manipulations, that there is a linear relation between the vertical stress, σ_1 , and the mean stress, p , of the following form:

$$\sigma_1 = \left(1 + 2\sqrt{\frac{a_2}{3}}\right) p \quad (\text{Eq. IX-9})$$

This linear relation between the applied vertical and mean stress is confirmed by the numerical results. The vertical stress as a function of the mean stress for extracted window 1 as calculated from the numerical experiment results and the linear fit to the numerical data are shown in Figure IX-17. The coefficient a_2 used in the yield conditions can be expressed as a function of the slope of the linear fit, m , as follows

$$a_2 = \frac{3}{4}(m-1)^2 \quad (\text{Eq. IX-10})$$

Figure IX-17. Vertical Stress versus Mean Stress Obtained from Results of Numerical Compression Testing of Rubble from Extracted Window 1

The unloading bulk modulus and coefficient a_2 , as calculated from the results of the numerical experiments, are listed in Table IX-2.

Table IX-2. Equivalent Mechanical Properties for the Simulated Cases

Case	K (MPa)	a_2
Window 1	335	0.305
Window 3	482	0.267
Window 1 rotated	219	0.587
Window 1 category 4	1380	0.310

The density of the rubble (ρ_r) is a function of the density of the rock mass before it collapses (ρ_i) and its increase in volume (i.e. bulking) as a result of collapse. It can be calculated based on the following formula:

$$\rho_r = \frac{\rho_i}{1 + B} \quad (\text{Eq. IX-11})$$

The bulking factor (B) is most likely to be in the range of 0.2 to 0.4 (BSC 2004 [DIRS 166107], Section 6.4.2.5.2). The average dry bulk density for the Tptpl unit is reported as 1979 kg/m³ (BSC 2004 [DIRS 166107], Table E-1). The rubble density is therefore conservatively estimated to be around 1500 kg/m³.

The Poisson's ratio for the rubble is not readily available. The range of Poisson's ratio for the crushed tuff, 0.17 to 0.29, reported in *Estimation of Mechanical Properties of Crushed Tuff for Use as Ballast Material in Emplacement Drifts* (BSC 2004 Table 5 [DIRS 168138]) is used as the data source. The shear modulus of 201 MPa is estimated for the extracted window 1 case with bulk modulus of 335 MPa and Poisson's ratio of 0.25 (Table 5-1).

IX-5. CONCLUSIONS

The deformability of the caved rubble that potentially can cover the drip shield inside the emplacement drift is estimated based on empirical results obtained on similar granular materials and numerical experiments. The numerical experiments were carried out on "samples" taken from the existing drift degradation analyses that were developed as part of the investigation into mechanisms of potential collapse of the emplacement drift. Three samples were taken from different locations in the analysis and tested for different loading conditions.

The empirical and numerical results are in good agreement. With the exception of one set of UDEC results, which indicate an initial tangent stiffness in the range between 10 MPa and 40 MPa for confinement between 0.1 MPa and 1 MPa, all other results (both empirical and numerical) suggest that (for the same range of confinement) the initial tangent modulus is between 50 MPa and 200 MPa.

Uniaxial strain (confined) compression numerical experiments were carried to applied stress levels in excess of 20 MPa. Both the loading and unloading responses of the rubble were

investigated. As expected, the numerical experiment shows a stiffer unloading than the loading response. However, in reality the unloading response will be even stiffer than the response predicted in the numerical simulation. This idealization is conservative from the perspective of the interaction between the drip shield and the rubble. The stiffer unloading response will result in a smaller load of the rubble on the drip shield in the equilibrium state after impact of the waste package into the drip shield. Parameters of the double-yield constitutive model are calculated to match the mechanical response of the tested synthetic material.

ATTACHMENT X

**SAMPLING OF STOCHASTIC INPUT PARAMETERS FOR
WASTE PACKAGE KINEMATIC ANALYSES**

X-1. INTRODUCTION

The purpose of this calculation is to define the sampled values of stochastic (random) input parameters for waste package kinematic analyses with up to 21 waste packages. This appendix identifies the uncertain parameters and documents the sampled values for these parameters. The sampled values are determined by calculations with GoldSim V8.01 SP4 (BSC 2005 [DIRS 169695], STN: 10344-8.01SP4-00), using appropriate distribution types and parameter ranges. The results from the GoldSim calculation provide input data for the waste package kinematic analyses discussed in the main body of this report. No software development or model development was required for the GoldSim calculation.

The qualified code GoldSim was used for these calculations. The GoldSim calculation of the sampled values allows parameter uncertainty to be incorporated into the kinematic analyses that support development of the seismic scenario for the Total System Performance Assessment for the License Application (TSPA-LA). The results from the GoldSim calculation also address project requirements related to parameter uncertainty, as specified in the acceptance criteria in *Yucca Mountain Review Plan, Final Report* (NRC 2003 [DIRS 163274], Section 2.2.1.3.2.3).

The computer files developed for this attachment can be accessed through the TDMS. DTN: MO0508SPAMECHA.000 includes the inputs and outputs for this attachment (files are located in *Attachment X* folder).

X-2. INPUTS

Direct input data to this analysis is the input values for the number of ground motion time histories (17) that describe the potential variability of frequency content and amplitude in vibratory ground motions. The technical basis for this input is given below.

The number of ground motion time histories (17) for postclosure performance assessment is derived from the *Development of Earthquake Ground Motion Input for Preclosure Seismic Design and Postclosure Performance Assessment of a Geologic Repository at Yucca Mountain, NV* (BSC 2004 [DIRS 170027], Section 6.3.2.3). In that document, 17 sets of three-component time histories were developed for each annual probability of exceedance considered for postclosure analyses. The time histories selected were based on strong motion records chosen to represent the range of earthquake magnitudes and distances indicated by the PGV hazard analysis (BSC 2004 [DIRS 170027], Section 6.3.1.4). As explained in that document, 15 sets of input ground motions are recommended by NUREG/CR-6728 (McGuire et al. 2001 [DIRS 157510], p. 3-3) when using a suite of time histories to perform soil-structure interaction analysis that is consistent with a probabilistically-defined seismic hazard. Two extra sets were developed to allow for substitutions if any of the 15 sets were found to be inappropriate. For the present GoldSim calculation, the full suite of 17 three component ground motions is retained to provide the broadest range of variability in the kinematic response.

X-3. ANALYSIS AND RESULTS

This section presents the results of the GoldSim calculation that defines sampled values of stochastic (random) input parameters for the waste package kinematic analyses. GoldSim is a qualified code that is appropriate for sampling stochastic parameters. No changes to the

GoldSim software are required for these calculations because parameter sampling is a basic capability of the GoldSim software. These calculations only require definition of the distribution types and ranges for the stochastic parameters; no model is necessary for these calculations.

The GoldSim file *WP_Seis_Stoch_Input_GS8.01.400.gsm* (DTN: MO0508SPAMECHA.000, Attachment X folder) produced the sampling of stochastic input parameters for the kinematic analyses. The stochastic input parameters used as input to GoldSim are ground motion time history number, metal-to-metal friction coefficient, and metal-to-rock friction coefficient. Seventeen realizations are performed. The results from the GoldSim calculation are summarized in Tables X-1 and X-2.

X-3-1 IDENTIFICATION OF UNCERTAIN PARAMETERS

The major uncertain parameters for the kinematic analyses are the ground motion, the metal-to-metal friction coefficient, and the metal-to-rock friction coefficient. The ground motion time histories (accelerograms) are the major source of damage to the drip shield and waste package in the seismic scenario. The metal-to-metal and metal-to-rock friction coefficients determine the ease of sliding between EBS components during an earthquake, and have the potential to affect the coupling of energy from the ground motions to the drip shield and waste package. The identification of these parameters is based on engineering judgment presented in the *Structural Calculations of Drip Shield Exposed to Vibratory Ground Motion* (BSC 2004 [DIRS 172448], Section 3) and *Structural Calculations of Waste Package Exposed to Vibratory Ground Motion* (BSC 2004 [DIRS 167083], Section 3).

The uncertainty in the ground motion is represented by 17 time histories. The use of 17 ground motion time histories follows the recommendation in NUREG/CR-6728 (McGuire et. al. 2001 [DIRS 157510], p.3-3) for performing soil-structure interaction analyses that are consistent with a probabilistically defined seismic hazard, as discussed in Section 4.1. The rationale for the range of values for the rock-to-metal friction coefficient and for the metal-to-metal friction coefficient, defined as 0.2 to 0.8, is provided in Assumption 3.2.4.

X-3-2 COMPUTATIONAL RESULTS

This calculation generated a sampling of stochastic input parameters for kinematic analyses with up to 21 waste packages. There are 17 realizations for this GoldSim analysis, using a Monte Carlo approach with Latin Hypercube sampling. The three stochastic parameters for this analysis are:

Ground Motion Time History Number	Discrete distribution with the values 1, 2, 3, ..., 16 and 17; each value is equally probable.
Friction Coefficient - Metal-to-Metal n	Uniform distribution from 0.2 to 0.8 for $n = 1, 2, \dots, 20$, and 21
Friction Coefficient - Metal-to-Rock n	Uniform distribution from 0.2 to 0.8 for $n = 1, 2, \dots, 20$, and 21

Table X-1 presents the results for the sampling of ground motion time history number and metal-to-metal friction coefficient. Table X-2 presents the results for the sampling of ground motion time history number and metal-to-rock friction coefficient. Note that the information for ground motion time history number does not change between Tables X-1 and X-2, and is only repeated for the reader's convenience.

Table X-1. Input Values for Metal-to-Metal Friction Coefficients, Based on GoldSim Sampling Calculation

Realization Number	Ground Motion Time History Number	Friction Coefficient – Metal-to-Metal 1	Friction Coefficient - Metal-to-Metal 2	Friction Coefficient - Metal-to-Metal 3	Friction Coefficient - Metal-to-Metal 4	Friction Coefficient - Metal-to-Metal 5	Friction Coefficient - Metal-to-Metal 6	Friction Coefficient - Metal-to-Metal 7
1	17	0.23174	0.65366	0.32093	0.41049	0.59397	0.62892	0.60661
2	16	0.73774	0.29918	0.57656	0.22729	0.29634	0.37167	0.42698
3	3	0.51485	0.2101	0.2978	0.4157	0.42111	0.21613	0.39713
4	2	0.54161	0.24688	0.76289	0.77047	0.72159	0.46025	0.73011
5	11	0.66975	0.75363	0.40389	0.70558	0.5344	0.26819	0.37264
6	4	0.63488	0.71345	0.76851	0.54769	0.46224	0.27656	0.54725
7	12	0.79933	0.4989	0.5181	0.24096	0.58065	0.30793	0.50815
8	5	0.24163	0.5422	0.34158	0.29694	0.67685	0.55815	0.33421
9	15	0.56892	0.3427	0.43203	0.68965	0.77302	0.59291	0.64669
10	9	0.35504	0.55884	0.47415	0.44808	0.21811	0.4267	0.22592
11	8	0.28072	0.39109	0.61478	0.73592	0.31189	0.48914	0.71904
12	6	0.33509	0.77613	0.70504	0.32481	0.24897	0.74443	0.77381
13	10	0.59877	0.41564	0.21201	0.51689	0.36124	0.67096	0.67343
14	1	0.44514	0.66831	0.67482	0.61252	0.76417	0.38496	0.29131
15	7	0.47788	0.46891	0.64929	0.3414	0.65683	0.71042	0.58101
16	14	0.69783	0.32215	0.25919	0.57013	0.40938	0.54539	0.25453
17	13	0.403	0.61847	0.48698	0.65764	0.50213	0.7805	0.4677

Table X-1. Input Values for Metal-to-Metal Friction Coefficients, Based on GoldSim Sampling Calculation (Continued)

Realization Number	Ground Motion Time History Number	Friction Coefficient – Metal-to-Metal 8	Friction Coefficient – Metal-to-Metal 9	Friction Coefficient - Metal-to-Metal 10	Friction Coefficient - Metal-to-Metal 11	Friction Coefficient - Metal-to-Metal 12	Friction Coefficient - Metal-to-Metal 13	Friction Coefficient - Metal-to-Metal 14
1	17	0.75327	0.57638	0.76666	0.51524	0.75102	0.5157	0.35643
2	16	0.58001	0.74702	0.71202	0.45004	0.6042	0.54777	0.79724
3	3	0.64045	0.68395	0.38015	0.74051	0.30566	0.39408	0.72101
4	2	0.6898	0.77928	0.59089	0.69082	0.50778	0.63458	0.58404
5	11	0.25901	0.59054	0.5031	0.25947	0.25645	0.24232	0.2559
6	4	0.35055	0.21888	0.63054	0.61473	0.22337	0.67929	0.53094
7	12	0.39718	0.26039	0.46047	0.39442	0.47226	0.34823	0.20738
8	5	0.54781	0.35253	0.3539	0.56025	0.42133	0.33122	0.68088
9	15	0.22696	0.63342	0.25203	0.62505	0.56144	0.46093	0.44477
10	9	0.61641	0.38865	0.67503	0.70393	0.31181	0.77204	0.76396
11	8	0.27611	0.27828	0.5235	0.30831	0.64231	0.30564	0.51383
12	6	0.44932	0.50972	0.28727	0.44546	0.53103	0.43039	0.29137
13	10	0.7712	0.33653	0.75305	0.28574	0.39125	0.55866	0.63641
14	1	0.32614	0.53427	0.21966	0.37392	0.69048	0.21786	0.6201
15	7	0.48249	0.69819	0.43675	0.77906	0.37143	0.59041	0.33604
16	14	0.44579	0.46026	0.57408	0.2031	0.79285	0.73881	0.38888
17	13	0.72451	0.44673	0.31337	0.52999	0.72249	0.70122	0.45875

Table X-1. Input Values for Metal-to-Metal Friction Coefficients, Based on GoldSim Sampling Calculation (Continued)

Realization Number	Ground Motion Time History Number	Friction Coefficient – Metal-to-Metal 15	Friction Coefficient – Metal-to-Metal 16	Friction Coefficient - Metal-to-Metal 17	Friction Coefficient - Metal-to-Metal 18	Friction Coefficient - Metal-to-Metal 19	Friction Coefficient - Metal-to-Metal 20	Friction Coefficient - Metal-to-Metal 21
1	17	0.69366	0.73239	0.32978	0.45509	0.47652	0.33038	0.33917
2	16	0.4289	0.60267	0.66686	0.5569	0.53298	0.58714	0.22224
3	3	0.47896	0.62874	0.49866	0.39225	0.3118	0.76816	0.79222
4	2	0.56918	0.48607	0.75819	0.35277	0.41628	0.61648	0.46223
5	11	0.77613	0.7796	0.47424	0.7833	0.40907	0.2673	0.29155
6	4	0.33738	0.38909	0.63465	0.66789	0.36621	0.36401	0.34759
7	12	0.50467	0.20838	0.25892	0.28686	0.2363	0.29154	0.26157
8	5	0.20348	0.46616	0.54976	0.74678	0.51548	0.44214	0.64134
9	15	0.521	0.26916	0.41464	0.52274	0.76424	0.76228	0.51945
10	9	0.30025	0.36628	0.21822	0.2544	0.21257	0.52024	0.59787
11	8	0.26906	0.28635	0.77079	0.30623	0.64481	0.47137	0.71414
12	6	0.70908	0.71439	0.71873	0.6035	0.77892	0.68733	0.69367
13	10	0.38089	0.30884	0.59673	0.50447	0.58825	0.50157	0.3965
14	1	0.74224	0.44618	0.34999	0.44056	0.27381	0.6299	0.58273
15	7	0.63661	0.56526	0.55725	0.63521	0.71355	0.2114	0.51003
16	14	0.34412	0.68342	0.28076	0.20709	0.66586	0.6973	0.42339
17	13	0.61745	0.53808	0.38202	0.70639	0.58018	0.38288	0.74217

Table X-2. Input Values for Metal-to-Rock Friction Coefficients, Based on GoldSim Sampling Calculation

Realization Number	Ground Motion Time History Number	Friction Coefficient – Metal-to-Rock 1	Friction Coefficient – Metal-to-Rock 2	Friction Coefficient - Metal-to-Rock 3	Friction Coefficient - Metal-to-Rock 4	Friction Coefficient - Metal-to-Rock 5	Friction Coefficient - Metal-to-Rock 6	Friction Coefficient - Metal-to-Rock 7
1	17	0.7179	0.42599	0.75925	0.49458	0.53287	0.31878	0.35173
2	16	0.5599	0.30763	0.21838	0.26419	0.25372	0.21881	0.47556
3	3	0.2151	0.70431	0.32817	0.52106	0.71835	0.46306	0.23268
4	2	0.33054	0.29588	0.53062	0.7556	0.60512	0.70412	0.26512
5	11	0.651	0.25515	0.71205	0.67405	0.63946	0.51949	0.31998
6	4	0.59781	0.60713	0.39082	0.21636	0.51602	0.59847	0.65986
7	12	0.47336	0.46305	0.42466	0.30311	0.55353	0.36894	0.48884
8	5	0.35308	0.49958	0.2369	0.63152	0.37594	0.68582	0.76938
9	15	0.26153	0.76426	0.49614	0.57289	0.28445	0.40191	0.76276
10	9	0.41118	0.66982	0.29126	0.72884	0.7718	0.64684	0.57507
11	8	0.68768	0.53046	0.59736	0.44766	0.75096	0.73761	0.61313
12	6	0.28722	0.23096	0.69271	0.6006	0.45188	0.27697	0.54717
13	10	0.55162	0.6353	0.78792	0.3432	0.30981	0.2418	0.6487
14	1	0.73481	0.39148	0.36413	0.76763	0.66907	0.5721	0.41082
15	7	0.41511	0.36656	0.62453	0.39484	0.41988	0.42366	0.4285
16	14	0.49147	0.77983	0.46813	0.44287	0.39528	0.50229	0.30264
17	13	0.77779	0.55932	0.57103	0.31062	0.21597	0.7717	0.70299

Table X-2. Input Values for Metal-to-Rock Friction Coefficients, Based on GoldSim Sampling Calculation (Continued)

Realization Number	Ground Motion Time History Number	Friction Coefficient – Metal-to-Rock 8	Friction Coefficient – Metal-to-Rock 9	Friction Coefficient – Metal-to-Rock 10	Friction Coefficient – Metal-to-Rock 11	Friction Coefficient – Metal-to-Rock 12	Friction Coefficient – Metal-to-Rock 13	Friction Coefficient – Metal-to-Rock 14
1	17	0.74103	0.45704	0.69753	0.54255	0.38877	0.57453	0.79893
2	16	0.62115	0.30541	0.78146	0.72809	0.75214	0.32463	0.20062
3	3	0.54727	0.66563	0.47206	0.28081	0.60163	0.61272	0.25471
4	2	0.50095	0.75224	0.31661	0.51729	0.35038	0.43717	0.46407
5	11	0.21052	0.4118	0.54475	0.25932	0.69165	0.54699	0.35103
6	4	0.58546	0.78554	0.63455	0.77163	0.31924	0.72421	0.61791
7	12	0.37835	0.69816	0.57661	0.38194	0.48086	0.22705	0.73956
8	5	0.64869	0.6382	0.24013	0.42889	0.72895	0.6255	0.28395
9	15	0.34456	0.37726	0.30423	0.67262	0.64526	0.23701	0.38195
10	9	0.33072	0.3751	0.60203	0.61763	0.27976	0.73971	0.72279
11	8	0.2599	0.22524	0.74656	0.73279	0.76485	0.39674	0.6633
12	6	0.69196	0.50715	0.40301	0.45438	0.41936	0.27781	0.52803
13	10	0.79918	0.56208	0.49327	0.58555	0.55591	0.7672	0.42402
14	1	0.72599	0.60736	0.22821	0.32038	0.53052	0.46441	0.64702
15	7	0.4673	0.54813	0.35977	0.36674	0.24573	0.51169	0.49723
16	14	0.4403	0.2652	0.44273	0.65572	0.21804	0.66316	0.31832
17	13	0.29046	0.3228	0.66081	0.21857	0.4937	0.37117	0.56647

Table X-2. Input Values for Metal-to-Rock Friction Coefficients, Based on GoldSim Sampling Calculation (Continued)

Realization Number	Ground Motion Time History Number	Friction Coefficient – Metal-to-Rock 15	Friction Coefficient – Metal-to-Rock 16	Friction Coefficient - Metal-to-Rock 17	Friction Coefficient - Metal-to-Rock 18	Friction Coefficient - Metal-to-Rock 19	Friction Coefficient - Metal-to-Rock 20	Friction Coefficient - Metal-to-Rock 21
1	17	0.56298	0.34316	0.54326	0.52918	0.20182	0.51192	0.46437
2	16	0.60189	0.27448	0.6097	0.72886	0.76432	0.68681	0.51312
3	3	0.64311	0.72375	0.27107	0.78317	0.29239	0.78193	0.37888
4	2	0.26659	0.77564	0.34663	0.73924	0.36955	0.7167	0.22874
5	11	0.67948	0.50768	0.46019	0.24674	0.77885	0.21525	0.33299
6	4	0.79615	0.45665	0.41425	0.36236	0.60087	0.37303	0.25612
7	12	0.34598	0.3188	0.586	0.44123	0.72705	0.2458	0.74939
8	5	0.2151	0.57393	0.22714	0.60287	0.32736	0.43934	0.70549
9	15	0.44947	0.3943	0.26013	0.33219	0.66914	0.59323	0.27669
10	9	0.33801	0.68688	0.64201	0.48012	0.56923	0.28825	0.55645
11	8	0.51543	0.25447	0.72468	0.22319	0.43012	0.56685	0.76967
12	6	0.27384	0.21461	0.7963	0.50208	0.46139	0.32037	0.66281
13	10	0.53312	0.64854	0.68441	0.57084	0.54066	0.53606	0.64098
14	1	0.44138	0.6173	0.38265	0.68507	0.39297	0.63893	0.3599
15	7	0.72925	0.73842	0.50685	0.64582	0.51668	0.40874	0.52078
16	14	0.38214	0.52296	0.31738	0.39991	0.64781	0.75924	0.59896
17	13	0.73483	0.41704	0.75098	0.2781	0.24537	0.46195	0.44139

X-4. CONCLUSION

This calculation defines the sampled values of stochastic (random) input parameters for kinematic analyses with multiple waste packages. The ranges of the stochastic parameters are specifically designed to represent the uncertainty in input variables for the kinematic analyses that support the seismic scenario. The sampled values are determined by GoldSim calculations using a Monte Carlo approach with Latin Hypercube sampling of the appropriate distribution types and parameter ranges.

Tables X-1 and X-2 present the sampled values of the stochastic parameters for the kinematic analyses that support the seismic scenario for TSPA-LA.

The major uncertainty in this work relates to the identification of the sampled parameters. For example, the calculations include the ground motion time history as an uncertain (stochastic) parameter and the variability in the ground motion is represented through 17 time histories. Uncertainty in the range of friction parameters for metal-to-metal and metal-to-rock contact is addressed by sampling a broad range of friction coefficients that reasonably cover the expected values of these parameters. The stochastic samplings of the parameters presented in this attachment are specifically developed for the kinematic analyses discussed in the Sections 5.4.1, 5.4.2, Attachments I, and II.

ATTACHMENT XI

**ASSESSMENT OF THE PERFORMANCE OF THE
EMPLACEMENT PALLET TUBES DURING SEISMIC EVENTS**

XI-1. INTRODUCTION

The purpose of this attachment is to assess emplacement pallet tubes survivability during the course of low probability seismic events. Understanding the kinematics of the EBS components (i.e. waste package, drip shield, and emplacement pallet) during vibratory ground motion is essential for insight into tube survivability. The analysis presented herein is not intended to be an in depth analysis of the emplacement pallet and tubes, rather, this analysis is used to support engineering judgment as to whether or not the emplacement pallet tubes will continue to perform their intended function: to keep the waste package supports upright and spaced apart.

One severe ground motion is used for this assessment. Ground motion 6 with a PGV of 5.25 m/s (DTN: M0403AVTMH107.003 [DIRS 168892], *MAT06H1.VTS*, *MAT06H2.VTS*, *MAT06V.VTS* in *VTS.ZIP*) causes violent movement of waste packages relative to adjacent waste packages, the drip shield, and emplacement pallets. In this analysis, the drift is assumed to collapse with low probability seismic events (Assumption 3.2.1), pinning the drip shield to the invert. All EBS components are represented in 3-dimensions, with all three components (h1, h2, and v DTN: M0403AVTMH107.003 [DIRS 168892], *MAT06H1.VTS*, *MAT06H2.VTS*, *MAT06V.VTS* in *VTS.ZIP*) of the ground motion acceleration time history applied to the invert. Seven waste packages are incorporated in the analysis: two 5-DHLW/DOE-Long waste packages and five 21-PWR waste packages (Assumption 3.2.17). The dimensions and mass of the waste packages are taken from BSC 2005 [DIRS 173501].

The information provided by the current design configuration (BSC 2005 [DIRS 173303], BSC 2005 [DIRS 173501]) are that of the potential designs of the emplacement pallet, drip shield, and waste packages considered in this attachment and provides the potential dimensions and materials for those designs. All obtained results are valid for these designs only.

The computer files developed for this attachment can be accessed through the TDMS. DTN: MO0508SPAMECHA.000 includes the inputs and outputs for this attachment (files are located in *Attachment XI* folder).

XI-2. ANALYSIS DESCRIPTION

Modeling long duration ground motions in a three dimensional space is inherently complex and computationally intensive. Ground motion acceleration time histories are applied to the invert; momentum is transferred to and among the unanchored structures (drip shield, waste packages, and emplacement pallets) solely by the way of friction and impact. The computational time step in the explicit analysis required to capture the phenomenon is necessarily small (on the order of 1 μ s). Simplifications must be made to achieve results in a reasonable amount of time.

There are several loading conditions adverse to the survivability of the emplacement pallet SS tubes. One potential failure mechanism of the emplacement pallet tubes is being crushed by direct contact of a falling waste package. This scenario is only possible when enough room along the drift is present for the waste package to shift off of the waste package support. A simplification used in this analysis reduces the amount of waste packages represented along the drift to seven (Assumption 3.2.17). As seen in Figures XI-1 and XI-2, the number and order of the waste packages is similar to the kinematic analysis in Attachment I (Figure I-1). For

purposes of emplacement pallet tube survivability, having seven waste packages with free end conditions (longitudinally) provides realistic boundary conditions for the center waste package without being over conservative (i.e., providing no adjacent waste packages would allow unrealistic longitudinal motion relative to the emplacement pallet). Waste packages are spaced at 0.1 m intervals (BSC 2004 [DIRS 168489]; Table 1).

Figure XI-1. Side View of the Waste Package Line-Up

Figure XI-2. Isometric View of the Waste Package Line-Up

The termination time of the analysis covers the range from 5 percent to 90 percent of the externally applied energy of the ground motion. All three components of ground motion are taken into account when determining the 5 and 90 percent times. The reasoning for the ground motion energy cutoff is two-fold: computational time is significantly reduced and accelerations causing relative motion between EBS components primarily exist in this energy window. The effect of time-history cutoff is examined in Attachment VII of BSC 2004 [DIRS 167083].

XI-2.1 WASTE PACKAGE

The numerical representation of the waste package is identical between the 21-PWR and 5-DHLW/DOE-Long except for the dimensions and mass. In other words, the same amounts of elements are used for the two types of waste packages; the dimensions and mass are unique to the waste package type they represent.

There are two main components to the waste package (Figure XI-3): the OCB and IV. In the FE representation, the OCB is modeled with fully integrated shell elements and three integration

points through the thickness. Lids are included on the ends of the OCB. A “skirt” of elements extends past the lid on one side representing the bottom trunion sleeve. A bilinear elastic-plastic material model (Livermore Software Technology Company (LSTC) 2003 [DIRS 166841]; Section 20.30) is used for the OCB with properties found in Table 5-1. The IV is represented as an open cylinder using solid elements. The outer diameter is that of the current design configuration (BSC 2005 [DIRS 173501]); the inner diameter is adjusted to calibrate the total waste package mass. This representation allows contribution of the IV to the kinematics of the system while remaining mindful of computational efficiency. A linear elastic material model is used for the IV (LSTC 2003 [DIRS 166841] Section 20.21), with properties found in Section XI-2.5.

Figure XI-3. Waste Package Outer Corrosion Barrier (Blue) and Inner Vessel (Red)

XI-2.2 DRIP SHIELD AND INVERT

The drip shield is modeled using shell elements with a rigid material model (LSTC 2003 [DIRS 166841]; Section 20.81) (Assumptions 3.2.1 and 3.2.2). The surface of the shell elements profiles the innermost surfaces of the drip shield creating vertical and cross-drift boundary constraints (y and x axes in Figure XI-4). Although both Ti-7 and Ti-24 are used in the drip shield, only Ti-7 is used to simplify the analysis. Because the drip shield is rigid in this analysis, the effect of only using Ti-7 for the drip shield representation is negligible. Interlocking components of the drip shield are not included, making the surface continuous the entire length of the FE representation (Assumption 3.2.21). A list of documents containing the dimensions of the drip shield is found in BSC 2005 [DIRS 173303].

Vibratory ground motion is applied to the FE representation through the invert. The acceleration time histories for all three directions are applied to the nodes of the invert (files *acc6h1.dat*, *acc6h2.dat*, and *acc6v.dat* in DTN: MO0508SPAMECHA.000, *Attachment XI* folder contains the acceleration time histories for the z, x, and y directions in Figure XI-4, respectively). This applied boundary condition forces the nodes to move synchronously throughout the ground

motion. Although an elastic material model is used for the invert, the applied motion of its nodes prevents relative movement between them, essentially making them rigid (Assumption 3.2.20).

The length of the drip shield and invert in this analysis is sufficient to remain around the waste packages despite longitudinal motion of the waste packages. That is, during the course of the simulation, the waste packages are free to move in the longitudinal direction (z-axis in Figures XI-1, XI-2, and XI-4), without leaving the confines of the drip shield and invert.

Figure XI-4. Finite-Element Representation of the Drip Shield and Invert

XI-2.3 EMPLACEMENT PALLET

The emplacement pallets are represented using fully integrated shell elements with three integration points through the thickness (Figure XI-5). A bilinear elastic-plastic material model (LSTC 2003 [DIRS 166841]; Section 20.30) is paired with the material properties in Table 5-1. The density of the SS tubes is adjusted (Assumption 3.2.31) to increase the mass of the emplacement pallet to 1970 kg (BSC 2005 [DIRS 173303], Table 7). Corrosion is taken into account for the SS tubes, thinning them by 2.1 mm (Assumption 3.2.30).

Figure XI-5. Finite-Element Representation of the Emplacement Pallet

XI-2.4 CONTACTS AND FRICTION

In this analysis, the drift is collapsed, pinning the drip shield to the invert (Assumption 3.2.1). A tied contact is defined between the drip shield and invert synchronizing their movements. Automatic surface to surface contact (LSTC 2003 [DIRS 166841], Section *CONTACT) is defined for all EBS components that may contact each other.

The friction coefficients for metal-to-metal contact and metal-to-rock contact are considered random parameters in this calculation (Assumption 3.2.4). The range of values for both of these friction coefficients is 0.2 to 0.8 (Table XI-1). Each position in the analysis is randomly assigned a friction value for metal-to-metal and metal-to-rock contacts. The values listed in Table XI-1 correspond to those for Realization 12 of Tables X-1 and X-2 for the metal-to-metal and metal-to-rock contacts respectively. Position 4 in the analysis herein correlates to position 11 of the aforementioned tables. The correlation between the tables continues position 3 herein correlates to position 10 in Tables X-1 and X-2, position 5 herein correlates to position 12 in Tables X-1 and X-2, and so forth. Friction for contacts between adjacent positions is averaged between the positions.

Table XI-1. Friction Values for Specified Position and Contact Types

Contact Type	Position						
	1	2	3	4	5	6	7
Metal-to-Metal	0.45	0.51	0.29	0.45	0.53	0.43	0.29
Metal-to-Metal Average		0.48	0.40	0.37	0.49	0.48	0.36
Metal-to-Rock	0.69	0.51	0.40	0.45	0.42	0.28	0.53

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 this analysis. Therefore, the effect of relative velocity of the surfaces in contact is not considered in these calculations by assuming that the functional friction coefficient and static friction coefficient are both equal to the dynamic friction coefficient (Assumption 3.2.11).

XI-2.5 MATERIAL PROPERTIES

Material properties used in these analyses are described in Section 5.2. The material properties are evaluated for 150°C (Assumption 3.2.12). Some of the temperature-dependent material properties are not available for Alloy 22, 316 SS, Ti-7, and TSw2 rock. Therefore, RT density and RT Poisson's ratio are used for Alloy 22, 316 SS, and Ti-7 (see Assumption 3.2.6). The RT material properties are used for TSw2 rock. Note that the tangent (hardening) modulus, listed in this section, is a parameter of the bilinear elastoplastic constitutive representation used for the drip shield materials in this calculation.

The LS-DYNA FE code requires input in terms of true stress and strain definitions (for the true stress and strain definitions see Dieter 1976 [DIRS 118647]; Chapter 9). Also, the results of this simulation are required to include elastic and plastic deformations of the OCB and emplacement pallet materials. When the materials are driven into the plastic range, the slope of the stress-strain curve continuously changes. Thus, a simplification for the stress-strain curve is needed to incorporate plasticity into the FE analysis. A simple approximation often used in engineering is to use a straight line that connects the yield strength point and the ultimate strength point of the material (bilinear elastoplastic constitutive representation, Figure 5-2). The tangent (hardening) modulus represents the slope of the stress-strain curve in the plastic region.

XI-3. RESULTS

The position of the EBS components at the end of the simulation can be seen in Figure XI-6. The simulation shows no indication that all four tubes of any of the emplacement pallets will fail. By examining the time-maximum Von-Mises stress histories of the emplacement pallet tubes (Figure XI-7), periods of high stresses are easily detected; these spikes in the stress plot indicate when an emplacement pallet tube is undergoing severe events. Using the plot as a guide, stress spikes above 400 MPa are closely investigated¹. Table XI-1 lists the times, part number involved, and a description of the event causing the high stresses. For purposes of the FE representation, all four tubes of each emplacement pallet are represented with one part. The part number indicates the location of the part; as the number increases so does the part's location along the z-axis (Figure XI-6). Parts 201 and 261 are the first and last set of tubes in Figure XI-6, respectively (from left to right).

¹ Stresses within 1/3 of the true ultimate strength are investigated to account for uncertainty in the stress values from mesh sensitivity. Considering the mesh density compared to those of mesh objectivity studies (i.e., Attachment IX of BSC 2004 [DIRS 167083]), maximum Von-Mises stress values are not expected to change more than 1/3 of their current values with mesh refinement. 400 MPa is chosen as 2/3 the true ultimate strength of the material rounded downward. Mesh objectivity was not performed for this study.

Figure XI-6. Initial (a) and Final (b) Positions of the EBS Components

NOTE: The mesh of the emplacement pallet is not tested for objectivity (stress values may be mesh sensitive). The spikes in this graph are used as bookmarks indicating severe events. The tubes are examined at these times to gain insight to damaging events.

Figure XI-7. Time Maximum Von-Mises Stress (Pa) for the Emplacement Pallet SS Tubes

Table XI-2. Events Causing Peak Stresses in Figure XI-7

Time	Part #	Event Description
0.85	241	Upper Tube Pinioned Between Waste Package and Drip Shield
1.47	201	Direct Impact to Upper Tube
1.65	221	Upper Tube Pinioned Between Waste Package and Drip Shield
3.86	241	Upper Tube Pinioned Between Waste Package and Drip Shield
3.89	231	Hard Landing on Emplacement Pallet Near Upper Tube
4.65	201	Direct Impact to Upper Tube
6.23	201	Direct Impact to Upper Tube
6.5	201	Direct Impact to Upper Tube

Emplacement pallet tube survivability is well supported considering the events listed in Table XI-2. Static loads on the waste package supports, bending or twisting of the tubes from opposing motion of the waste package supports, and impacts between the emplacement pallet and invert do not cause high stresses in the tubes. All of the stresses above 400 MPa in Figure XI-7 are from impacts by the waste package. It needs to be emphasized that the ground motion used for this analysis, has a PGV outside the range considered for the regulatory period. If a more benign ground motion is considered, the frequency and magnitude of impacts between waste packages and emplacement pallets will be reduced.

Comparing the event description to the location of the part in Table XI-2 reveals sensitivity to the boundary conditions. The FE representation allows the end waste packages to “walk” freely away from the center of the model. Because of this feature, the outside waste packages are able to translate more in the longitudinal direction than the center waste packages. Part number 201, which is an end tube set, is the only set of emplacement pallet tubes to receive a direct impact from the waste package; the center waste package remains within the range of support of its emplacement pallet. Most of the waste packages in the drift will have adjacent waste packages limiting the longitudinal travel.

The high stress experienced by part number 241 at 3.86 seconds is caused by the waste package impacting the top of waste package support (where the SS tube connects to the waste package support), which pinions the tube between the waste package and rigid drip shield (Figure XI-8). This stress is exaggerated by the rigid boundary condition: physically, the drip shield and surrounding rubble would give way to the impact, absorbing some of the impact energy. A deformable boundary condition would reduce the stresses seen in three of the eight events in Table XI-2.

Figure XI-8. Pinioning Impact Sequence Causing Peak Stress in Part 241

The number of tubes that keep the waste package supports aligned provides the most supporting argument for emplacement pallet tube survivability. Of all the events causing high stresses in the emplacement pallet tubes, none are to the lower tubes. The waste package is geometrically limited to the positions it may come in contact with the lower tubes; the range of motion is limited within the free space under the drip shield and between adjacent waste packages. Even

considering failure of one of the upper tubes and subsequent contact with a lower tube, the other side of the emplacement pallet will likely remain intact. Similarly for the upper tubes, if both upper tubes fail, the chances of the remaining ground motion to induce impact between the waste package and lower tubes is highly unlikely. The redundancy of four SS tubes in the emplacement pallet makes alignment of the waste package supports possible throughout the regulatory period.

XI-4. SUMMARY

Three-dimensional analysis of seven waste packages subjected to vibratory ground motion was performed to understand the kinematics of EBS components during a seismic event. Results from the analysis are used to support engineering judgment regarding the survivability of the emplacement pallet SS tubes. Limited ability for the waste package to make contact with the emplacement pallet tubes, non-rigid boundary conditions, and redundancy in the number of longitudinal tubes indicates that the emplacement pallet SS tubes will perform their intended function throughout the regulatory period.

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