ENCLOSURE 8

Supplemental Rockfall Analyses for RAI 3.2.2.1.2.1-001 and RAI 3.2.2.1.2.1-006

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Supplemental Rockfall Analyses for RAI 3.2.2.1.2.1-001 and RAI 3.2.2.1.2.1-006

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Dwayne Kicker is the checker of the Product output DTN: MO0901ROCKFALL.000

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FIGURES

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ACRONYMS AND ABBREVIATIONS

BSC	Bechtel SAIC Company
CRWMS	Civilian Radioactive Waste Management System
DOE	U.S. Department of Energy
DSHT	Drift Scale Heater Test
DTN	data tracking number
M&O	Management and Operating (Contractor)
NRC	U.S. Nuclear Regulatory Commission
RAI	request for additional information
SAR	safety analysis report
SNL	Sandia National Laboratories

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1. INTRODUCTION

The long-term stability of emplacement drifts at the proposed high-level nuclear waste repository at Yucca Mountain, Nevada, was analyzed to support development of the nominal and seismic scenario classes for the License Application. These analyses are described in Section 2.3.4.4 of the *Safety Analysis Report* (SAR) (DOE 2008 [DIRS 185301]) and in the *Drift Degradation Analysis* report, ANL-EBS-MD-000027 (BSC 2004 [DIRS 166107]). These analyses considered a wide variety of loading conditions on the host rock, including *in situ* stress, thermal loading (from heat released by nuclear waste), seismic loading, and the effects of time-dependent strength degradation of the rock mass. These analyses are generally referred to as drift degradation analyses or rockfall analyses in this report.

Since the SAR was submitted to the U.S. Nuclear Regulatory Commission (NRC), the NRC has identified several technical questions related to the drift degradation analyses that are not explicitly evaluated as part of the technical baseline for the SAR. In response to these questions, supplemental analyses have been performed to assist in answering these questions and the analyses are documented in this report. These questions include assessing the impact of the assumed block size and block type (elastic versus inelastic) on the numerical analyses of drift degradation in lithophysal rock types and the comparison of final data for tunnel spalling from the Drift Scale Heater Test (DSHT) with the validation of the UDEC numerical model.

These questions are formally documented in the NRC's requests for additional information (RAIs). Two RAIs specifically relate to the uncertainties in block size/type and model validation mentioned above:

- RAI 3.2.2.1.2.1-001. "*Provide a technical basis for the key assumptions used in the numerical model for estimating the extent and timing of drift degradation due to thermal loading or time-dependent rock weakening. This basis should evaluate how the following assumptions could affect the model results with respect to rock spalling: (i) the simulated rock mass can only fail along randomly oriented surfaces; (ii) blocks behave elastically and therefore a potential fracture cannot propagate through a block; and (iii) the selection of block sizes and size distributions does not bias results against spalling. The technical basis should demonstrate that the assumptions do not lead to results that underestimate the quantity of potential rubble accumulation on and around the engineered barriers. Also, the justification should explain how uncertainties in important parameters are evaluated in the model. This information is needed to verify compliance with 10 CFR 63.114 (e), (f), (g).*"

- RAI 3.2.2.1.2.1-006. "*Provide a technical basis to demonstrate how the results of the drift-scale heater test are reconciled with the results of the numerical model simulation of the test. The reconciliation should address differences between rubble accumulation from the field test and the numerical model. Also, explain the implications of* *not modeling the field-test ground support (rock bolt and wire mesh) and three-dimensional geometry. If the drift-scale heater test is not deemed an appropriate analog for model support, then provide additional support for the model from empirical observations of heated tunnels. This information is needed to verify compliance with 10 CFR 63.114 (e), (f), (g).”*

Background information for these two issues/uncertainties is provided in the following paragraphs.

Previous analyses of lithophysal drift degradation represented the rock mass as an assembly of polygonal (Voronoi) blocks with an average size of 0.3 meters (BSC 2004 [DIRS 166107] Section 6.4.2.1). The block size was selected to be relatively small compared to the drift diameter ($\ell_b / r_d = 0.3 / 5.5 = 0.054$) and to be approximately the same as the average block size in the lithophysal rock mass created by *in situ* jointing and lithophysal cavities. The blocks were assumed to be elastic. When elastic blocks are used to simulate the response of the rock mass, failure of the rock mass occurs on the pre-existing and randomly oriented boundaries between elastic blocks, rather than by forming a new fracture within a block (an elastic block cannot fracture). To further demonstrate that the model predictions are not sensitive to the block size/type assumptions, supplemental rockfall analyses were carried out using smaller average block sizes of 0.2 m and 0.1 m. Predicted lithophysal rockfall volumes are compared for the 0.3 m, 0.2 m, and 0.1 m average block sizes to demonstrate that predicted volumes are independent of block size/type.

One of the methods used to validate the drift degradation model is comparison with observation of drift response, specifically the volume of failed rock during the Drift Scale Heater Test (BSC 2004 [DIRS 166107] Section 7.6.5.3). Although the heated drift was supported by rock bolts and wire mesh, the ground support was not included in the original model validation (BSC 2004 [DIRS 166107] Figure 7-31). Supplemental model validation calculations have been performed for a supported and an unsupported drift to evaluate the effect of the ground support, and are documented in this report. The supplemental analyses also have a more accurate representation of the DSHT configuration than was used for the original validation in the *Drift Degradation Analysis* report (BSC 2004 [DIRS 166107] Section 7.6.5.3). The more accurate representation has a circular drift and a concrete-filled invert, and incorporates the temperature dependence of the coefficient of thermal expansion for tuff. After the heated drift had cooled sufficiently, the spatial extent of spalling was delineated with paint, photographed, and recorded in a scientific notebook (Kelly 2007 [DIRS 185958]). Predicted rockfall volume is compared with the volume of loose rock observed in the drift survey after cooling of the DSHT, confirming the results of the original validation of the UDEC model.

The supplemental rockfall analyses were performed and documented in accordance with SCI-PRO-009, *Postclosure Analysis Reports* and are considered Diagnostic Analyses, as defined in SCI-PRO-009, because the results of these analyses do not change the postclosure technical baseline for the License Application.

2. INPUT AND SOFTWARE

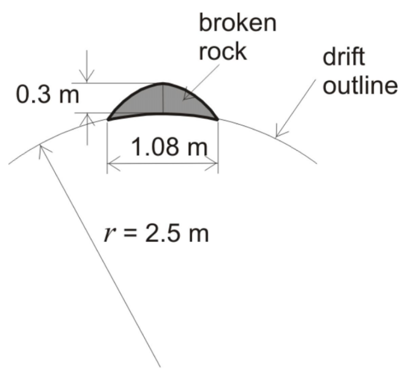
2.1 ASSUMPTIONS

The supplemental rockfall analyses use Assumptions 5.1.1, Simultaneous Emplacement, 5.1.2 Ventilation Heat Removal Ratio, 5.1.3, Thermal Expansion, and 5.2.2, Block Size Distribution for Potential Rockfall in Lithophysal Units, as documented in *Drift Degradation Analysis* (BSC 2004 [DIRS 166107] Sections 5.1 and 5.2). Assumption 5.2.1 in (BSC 2004 [DIRS 166107]), Joint Position Parameter in DRKBA, is not required because the DRKBA fracture geometry is not used for these rockfall analyses. These assumptions are used in Sections 4.1 and 4.2 of this report.

Two additional assumptions for the UDEC model validation with the results of the DSHT are described below. No further assumptions are required for the supplemental rockfall analyses.

2.1.1 Maximum Depth of Spalled Region in the DSHT

Assumption: The shape of the breakout is assumed to be as in Figure 2-1 and the maximum depth of the spalled region in the DSHT, if it were not held by ground support, is estimated to be 0.3 m.



Source: For illustrative purposes only.

Figure 2-1. Geometric Configuration for Defining Maximum Depth of the Region of Spalled Rock in the DSHT

Basis: The nonlithophysal rock where the DSHT was carried out is more massive than lithophysal rock. Because of relatively large spacing of pre-existing joints, and relatively large induced stresses compared to the intact rock strength, the thermally induced stresses caused spalling damage in the crown of the heated drift. Rock spalling occurs as a result of unstable fractures that are very close to and almost parallel with the free surface of the drift. Typically, when the equilibrium configuration is reached and unstable rock falls, spalling results in a "dog-ear" shaped breakout (e.g., Figure 2.13, Kaiser et al. 2000). The maximum depth of the "dog-ear" shaped breakout, d_f, formed due to overstress in massive and brittle rocks can be estimated from the empirical relation based on stress-to-strength ratio (Equation 3.3, Kaiser et al. 2000):

$$\frac{d_f}{a} = 1.25\frac{\sigma_{max}}{\sigma_c} - 0.51(\pm 0.1) \qquad \text{(Eq. 2-1)}$$

where $\sigma_{\max}$ is the maximum tangential elastic stress, σ_c is the intact rock unconfined compressive strength (determined on 54-mm diameter samples) and a is the tunnel radius. The illustration of the breakout shape, the relevant dimensions and the empirical data used to derive the linear fit are shown in Figure 2-2. This empirical relation is valid irrespective of the ground support. For example, Kaiser, et. al. (2000, Section 3.2.2) state that "*It is of practical importance to realize that in hard rock σ_{max} and therefore the depth of failure is insensitive to the support pressure applied at the excavation wall (for an extreme support pressure of 2 MPa the depth of failure is only reduced by 2 to 3%*)".

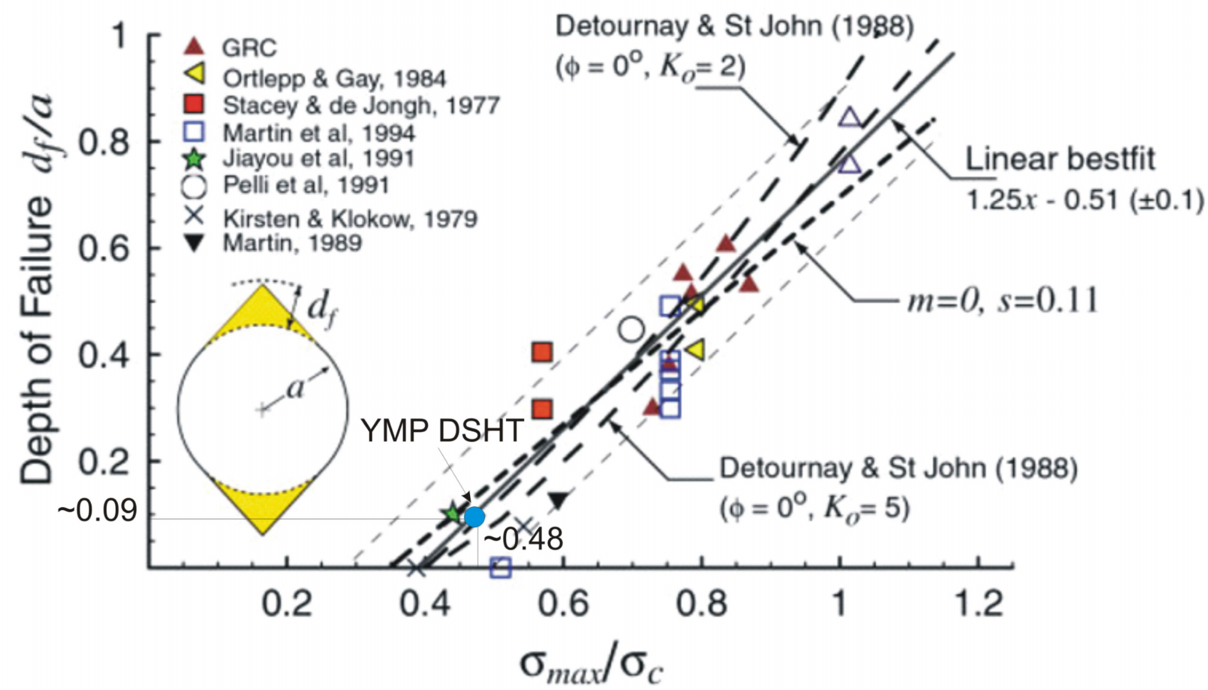
The unconfined compressive strength, σ_c, of intact nonlithophysal rock is 189 MPa (Table E-14, BSC 2004 [DIRS 166107]). The maximum tangential elastic stress is estimated from UDEC simulations of the lithophysal rock (e.g., Figure 7-36, BSC 2004 [DIRS 166107]) to be 90 MPa. Thus, the stress-to-strength ratio is $\sigma_{\max} / \sigma_c = 0.48$, and the nondimensional depth of failure is calculated from Equation (2-1) as: d_f/a = 1.25×0.48 – 0.51 = 0.09. This point is shown as the blue dot in Figure 2-2. The depth of breakout is then estimated to be $d_f = 0.09 \times 2.5 = 0.225\,\text{m}$.

The value of 0.09 for d_f/a is based on the linear best fit to the data, as shown in Figure 2-2. The grey dashed lines in Figure 2-2 also show the upper and lower bounds for Equation (2-1). The upper bound is reasonable for σ_{max}/σ_c greater than or equal to 0.6, based on the data in Figure 2-2, but appears to overestimate the upward variability at lower values of σ_{max}/σ_c, where the available data and various fits in Figure 2-2 cluster below or just slightly above the linear best fit. For example, the depths of breakout from the curves of Detournay and St. John (1988) are less than 0.225 m at σ_{max}/σ_c = 0.48. The curve labeled "m=0, s=0.11" in Figure 2-2 has a value for d_f/a of approximately 0.125 at σ_{max}/σ_c = 0.48 (estimated from Figure 2-2), resulting in a depth of breakout of 0.125×2.5 = 0.313 m.

Thus, for this failure mode, a 0.3 m depth is expected to define the upper depth of the broken rock relative to the nominal diameter of the tunnel, 5 m (CRWMS M&O 1997 [DIRS 185960], p.12), and the width of the spalled region, 1.08 m. The width of the spalled region is calculated as the total area of damaged rock, 37.1 m^2, divided by the distance between the endpoint of the painted area and the bulkhead, 34.5 m (output DTN: MO0901ROCKFALL.000, file: *DST rubble zone estimation4.xls*). That is, the width is calculated as: (37.1 m^2/34.5 m) = 1.08 m . These The use of a depth of 0.3 meters provides a substantial depth for the spalled rock, which is expected to lie very close to and almost parallel with the drift wall, as illustrated in Figures 2-1 and 2-2.

Confirmation Status: This assumption is confirmed above.

Use in Model: This assumption is used in Section 3.3.



Source: Kaiser et al. 2000, Figure 3.12

Figure 2-2. Relation of the Depth of Failure as a Function of the Maximum Boundary Stress to Uniaxial Compressive Strength Ratio for Tunnels in Hard Rock

2.1.2 Height of Concrete Invert in the DSHT

Assumption: The height of the concrete invert in the DSHT is assumed to be 1.2 m.

Basis: A DSHT concrete invert analysis was prepared in 1997, which identifies that the height of the concrete invert is 1.2 m for the unlined 5.0-m diameter circular heated drift (CRWMS M&O 1997 [DIRS 185960], p.12). The concrete invert analysis was developed as a non-Q design document. The invert height dimension is consistent with field observations.

Confirmation Status: This assumption does not require confirmation because it is a realistic assumption, consistent with field observations.

Use in Model: This assumption is used in Section 4.2.

2.2 DIRECT INPUT DATA

The direct input data for the rockfall analyses with UDEC are generally a subset of the direct input data for the rockfall analyses documented in *Drift Degradation Analysis* (BSC 2004 [DIRS 166107], Section 4.1 and Table 4-1). For example, the data for the temperature dependence of the coefficient of thermal expansion are defined in (BSC 2004 [DIRS 166107], Table 4-1 and Table E-20). Table 2-1 identifies the sources of any additional direct input data for the supplemental rockfall analyses.

2.3 SOFTWARE

The UDEC program is the controlled and baselined software that has been used for the supplemental rockfall analyses. Table 2-2 identifies the software tracking number, version, operating environment and range of use for UDEC. UDEC was obtained from Software Configuration Management in accordance with IM-PRO-003, *Software Management*. UDEC was used only within the range of its validation, as specified in the software qualification documentation, in accordance with IM-PRO-003.

Table 2-1. Additional Direct Input Information

Input Data or Information	Value	Source
Nominal diameter of emplacement drifts	5.5 m	SNL 2007 [DIRS 179466], Table 4-1 Parameter Number 01-10
Identification of DSHT damage zone	see photographs identified in the source document	Kelly 2007 [DIRS 185958], pp. 157 to 160 (Note: A list of photographs is provided in Kelly 2007 [DIRS 185958]. A complete set of photographs is provided in supplemental record, ACC: LLR.20070601.0201.)
Distance of endpoint station of the painted area from the bulkhead	34.5 m	Kelly 2007 [DIRS 185958], pp. 157 to 160 (Note: see photograph frame number 0355 provided in supplemental record, ACC: LLR.20070601.0201.)
DSHT invert concrete strength	see Table 4-1	Kelly 2007 [DIRS 185958], pp. 127 to 130
DSHT invert concrete Young's modulus	see Table 4-1	Kelly 2007 [DIRS 185958], pp. 127 to 130
DSHT invert concrete Poisson's ratio	see Table 4-1	Kelly 2007 [DIRS 185958], pp. 127 to 130
DSHT wire mesh size	75-mm (3-in) square	Williams 2001 [DIRS 159516], page 6 of enclosure
DSHT rockbolt length	3 m	Williams 2001 [DIRS 159516], page 6 of enclosure
DSHT rockbolt spacing	1 m x 1 m square pattern	Williams 2001 [DIRS 159516], page 6 of enclosure
DSHT rockbolt area	$\pi\frac{d_o^2 - d_i^2}{4} =$ $\pi\frac{0.054^2 - (0.054 - 2\times 0.003)^2}{4} =$ $4.807\times 10^{-4}\ \text{m}^2$	Bolt diameter 0.054 m and bolt wall thickness 0.003 m, taken from Table 6-5 (BSC 2007 [DIRS 183406])
DSHT rockbolt density	8000 kg/m3	Table 6-5 (BSC 2007 [DIRS 183406])
DSHT rockbolt steel Young's modulus	193 GPa	Table 6-5 (BSC 2007 [DIRS 183406])
DSHT rockbolt steel tensile strength	620 MPa	Table 6-5 (BSC 2007 [DIRS 183406])
DSHT rockbolt coefficient of thermal expansion	15.9×10^{-6} 1/°C	Table 6-5 (BSC 2007 [DIRS 183406])
DSHT rockbolt bond strength	2.75×10^{5} N/m	Table 6-5 (BSC 2007 [DIRS 183406])
DSHT rockbolt bond stiffness	3×10^{8} N/m/m	Table 6-5 (BSC 2007 [DIRS 183406])

Table 2-2. List of Qualified Software for Rockfall Analyses

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 mechanical and thermal effects on block movement in the host rock surrounding a drift (Sections 4.1 and 4.2). UDEC was selected for its capability of modeling block slip and block separation in plane strain condition. It is also capable of thermal and dynamic simulation. There are no known limitations on outputs.

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3. EVALUATION

3.1 ANALYSIS METHOD

The UDEC software has been used for the supplemental rockfall analyses. UDEC is appropriate for these analyses because the analyses are consistent with the intended use of the UDEC software. Table 2-2 also includes an explanation of why UDEC was selected and describes any limitations on outputs from UDEC.

3.2 EFFECT OF BLOCK SIZE ON THERMALLY INDUCED ROCKFALL

The technical approach for predictions of thermally induced rockfall (i.e., drift degradation) in the lithophysal zones of the repository is described in detail in *Drift Degradation Analysis* (BSC 2004 [DIRS 166107], Sections 6.4.2.1 and 6.4.2.3). Key aspects of the technical approach are summarized here.

The lithophysal rock mass was discretized by polygonal (Voronoi) blocks with a characteristic size of 0.3 m for the original rockfall analyses, consistent with the pattern of the randomly-oriented incipient fracture network which characterizes the lithophysal rock mass (BSC 2004 [DIRS 166107], Section 6.1.4.1). Consistent with the rock mass characterization, the block size was selected from the conditions that: (1) the average block size (0.3 m) should be a small fraction of the drift diameter (5.5 meters) (SNL 2007 [DIRS 179466], Table 4-1 Parameter Number 01-10), and (2) the block size is consistent with the spacing between the intense *in situ* jointing in the rock (BSC 2004 [DIRS 166107], Section 6.1.4.1). In a highly fractured rock mass, such as the lithophysal formations at Yucca Mountain, the mechanism of rock mass failure is primarily slipping along pre-existing fractures because it takes much less energy to propagate a pre-existing fracture than to propagate a new fracture through intact rock. If fractures do form in intact rock, they will generally connect adjacent lithophysae because high stresses will occur in and around the larger voids in the rock mass. Thus, the block size created by failure of the lithophysal rock mass will be controlled primarily by the size of the blocks created by the *in-situ* jointing and secondarily by the spacing of the larger lithophysae. The spacing of the *in-situ* jointing is generally on the order of 0.3 meters for the lithophysal rock, which provides the basis for the characteristic size of the Voronoi blocks in the UDEC model.

The Voronoi blocks are assumed to be elastic and cannot fail, so the numerical model represents failure of the rock mass by breaking the randomly oriented joints between blocks. The assumption of elastic response is reasonable because smaller rock blocks generally do not have the pre-existing fractures or large lithophysae of the overall rock mass. However, the numerical results may be sensitive to the size and joint orientation of the Voronoi blocks if the block size is too large. To investigate this possibility, two sets of supplemental drift degradation calculations under thermal loading were performed for 0.2-m and 0.1-m block sizes. The analyses were carried out for lithophysal rock mass Categories 2 and 5 in order to consider a range of unconfined compressive strength for the rock mass. Rock mass Category 2 represents weaker lithophysal rock and rock mass Category 5 represents the strongest lighophysal rock.

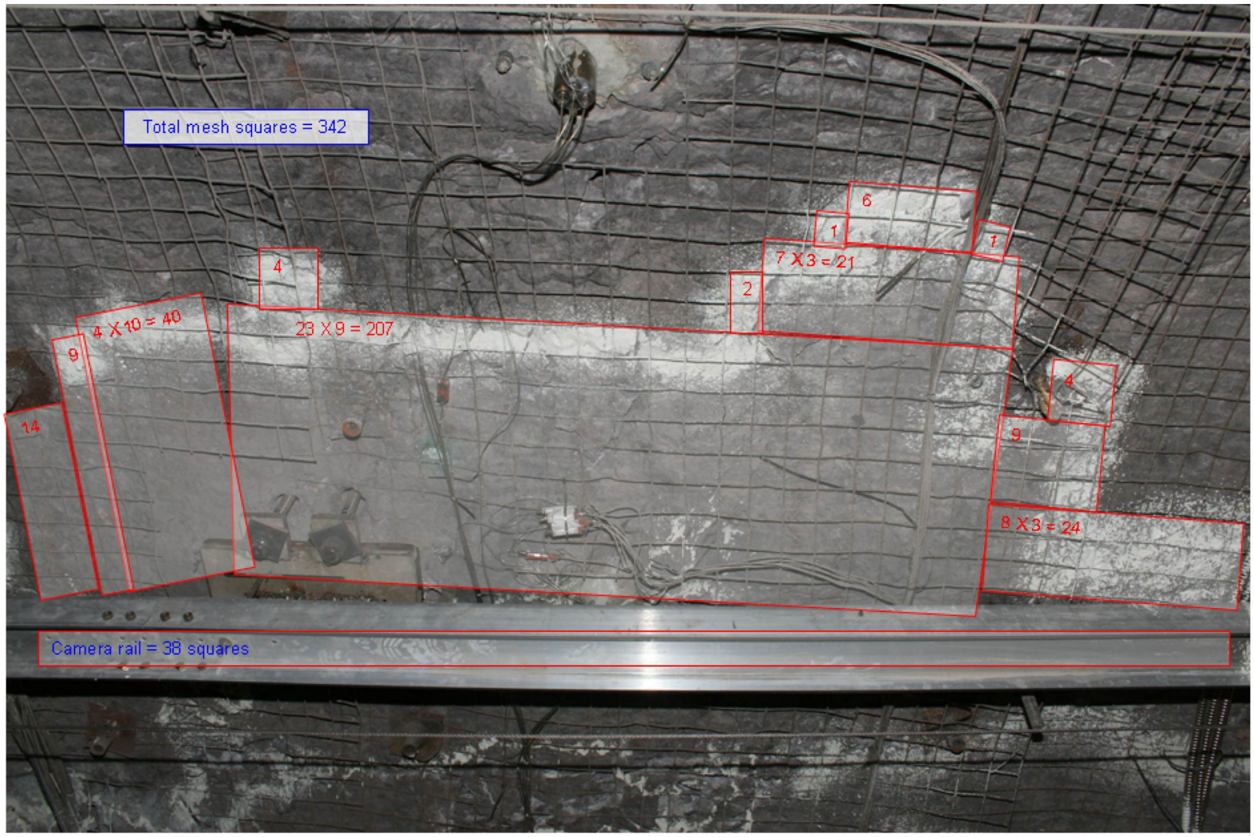
3.3 ADDITIONAL VALIDATION OF DRIFT STABILITY

Observations of rock spalling inside the DSHT, first made in late 1999, were used to validate the drift degradation model (BSC 2004 [DIRS 166107], Section 7.6.5.3). Small chips of rock were observed on the tunnel invert; and larger pieces of loose rock accumulated in the wire mesh installed in the drift crown. The DSHT was still ongoing at the time of the original validation calculations, and the areas where loose rocks accumulated were not accessible. Observations of broken rock and an estimate of the extent of fracturing were made remotely using a rail-mounted camera (Williams 2001 [DIRS 159516]).

When the DSHT was completed in 2006, the drift walls were carefully surveyed. All damaged areas were marked by white paint and the entire damaged drift surface was photographed. The process of marking and photographing the loose rock is described in scientific notebook, *Drift Scale Test Post-Test Activities* (Kelly 2007 [DIRS 185958], pp. 157 to 160).

The log of photographs is also documented in the scientific notebook (Kelly 2007 [DIRS 185958]), with a complete set of photographs provided in a supplemental record, ACC: LLR.20070601.0201. For example, frame number 0303, taken on the left rib, 21 m from the bulkhead, is shown in Figure 3-1. The wire mesh, which holds the loose rock for safety reasons, is built to 3-in squares (Williams 2001 [DIRS 159516], p. 6 of enclosure). Mesh squares within the painted rubble zone were counted and used to estimate the area of the fractured zone. The total area of the damaged drift surface was estimated to be 37.1 m^2 (output DTN: MO0901ROCKFALL.000, file: *DST rubble zone estimation4.xls*). Because the endpoint station of the painted area is 34.5 m from the bulkhead (frame number 0355), the average width of the damaged area in the plane of the drift cross-section is 37.1 m^2/34.5 m = 1.08 m.

Most of the loose rock is held by the wire mesh, which is supported on the rock bolts. To estimate the volume of rockfall that would occur in the DSHT if the rubble were not held by the ground support, it is assumed that the maximum depth of spalling is 0.3 m (see Assumption 2.1.1). This assumption is based on geometrical considerations: rock spalling occurs as a result of unstable fractures that lie very close to and almost parallel with the free surface of the drift, and 0.3 m most likely overestimates the depth of these fractures relative to the width of the damaged region. With this assumption, the estimated rockfall volume is (0.5 ×1.08 m×0.3 m) = 0.16 m^3 per meter of drift (output DTN: MO0901ROCKFALL.000, file: *DST rubble zone estimation4.xls*).



0303 left rib, 21 m from bulkhead, 180°, center

Source: Output DTN: MO0901ROCKFALL.000, file: *DST rubble zone estimation4.xls*, worksheet “left-rib photos”, frame 0303

Figure 3-1. Approximation of Loose-Rock Area (Indicated in White Paint) by Mesh Squares in Frame Number 0303 Taken on the Left Rib, 21 m from the Bulkhead

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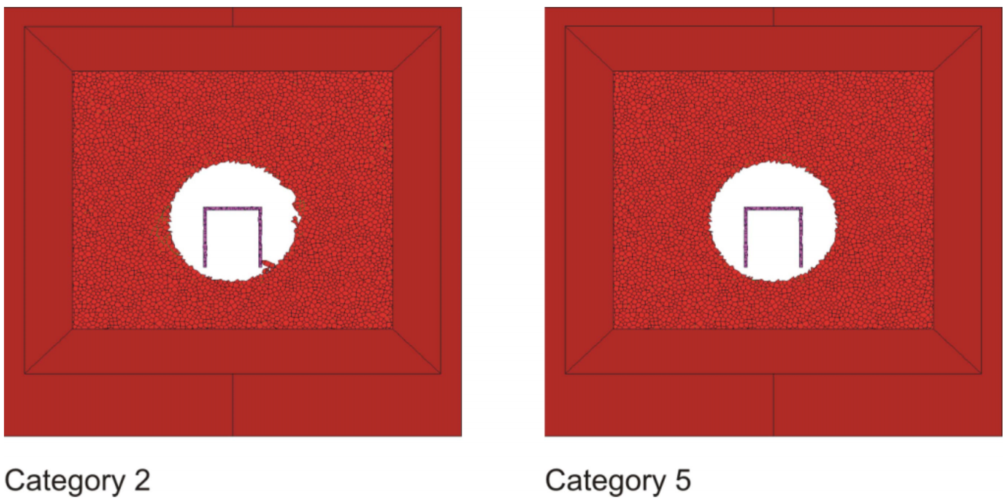
4. ANALYSIS RESULTS AND CONCLUSIONS

4.1 EFFECT OF BLOCK SIZE ON THERMALLY INDUCED ROCKFALL

The results of the new UDEC analyses for thermally induced rockfall with 0.2-m and 0.1-m Voronoi block sizes are shown in Figures 4-1 and 4-2, respectively. Figures 4-1 and 4-2 demonstrate that there is no significant rockfall induced by heating for rock mass Categories 2 or 5 with 0.2-m or 0.1-m block sizes. This conclusion is identical with the result from the previous UDEC analyses with 0.3-m block sizes, which demonstrated no significant rockfall or damage induced by heating for rock mass Categories 1 through 5 (BSC 2004 [DIRS 166107], Section 6.4.2.3.1; Figure 6-140 for rock mass Category 1). These results confirm that the UDEC analyses of lithophysal rockfall are not sensitive to the choice of a 0.1 m to 0.3-m characteristic size for the Voronoi blocks or to the assumption that the blocks are elastic (i.e., a model with small block size is equivalent with respect to predicting the volume of rubble that accumulates with time to a model with large block size in which the blocks are allowed to fracture internally).

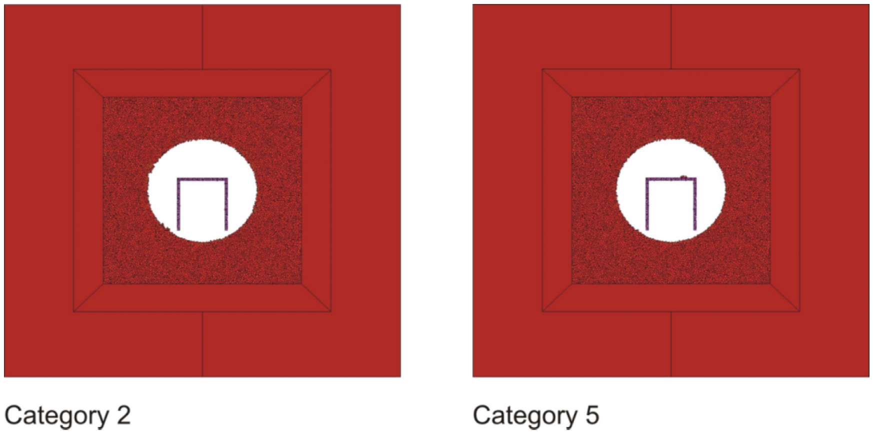


Source: Output DTN: MO0901ROCKFALL.000, thermal analysis block size effect submittal\0.2 m block size\category 2*plot10000.jpg*; thermal analysis block size effect submittal\0.2 m block size\category 5*plot10000.jpg*)

NOTE: Legends provided by the source files are not included.

Figure 4-1. Predicted Drift Profiles with 0.2-m Voronoi Block Size due to Thermal Load 10,000 years after Waste Emplacement

Figure 4-3 shows the detail of stresses and damage in the drift crown after 100 years of heating predicted in the model with 0.1 m block size. The stresses have initiated fractures sub-parallel to the drift crown, which did not eventually result in rockfall. Instead, the regions along the drift wall are practically distressed, while large stress concentrations are pushed deeper in the rock. Because those stress concentrations are associated with increase in confining stress too, they do not result in further fracturing.



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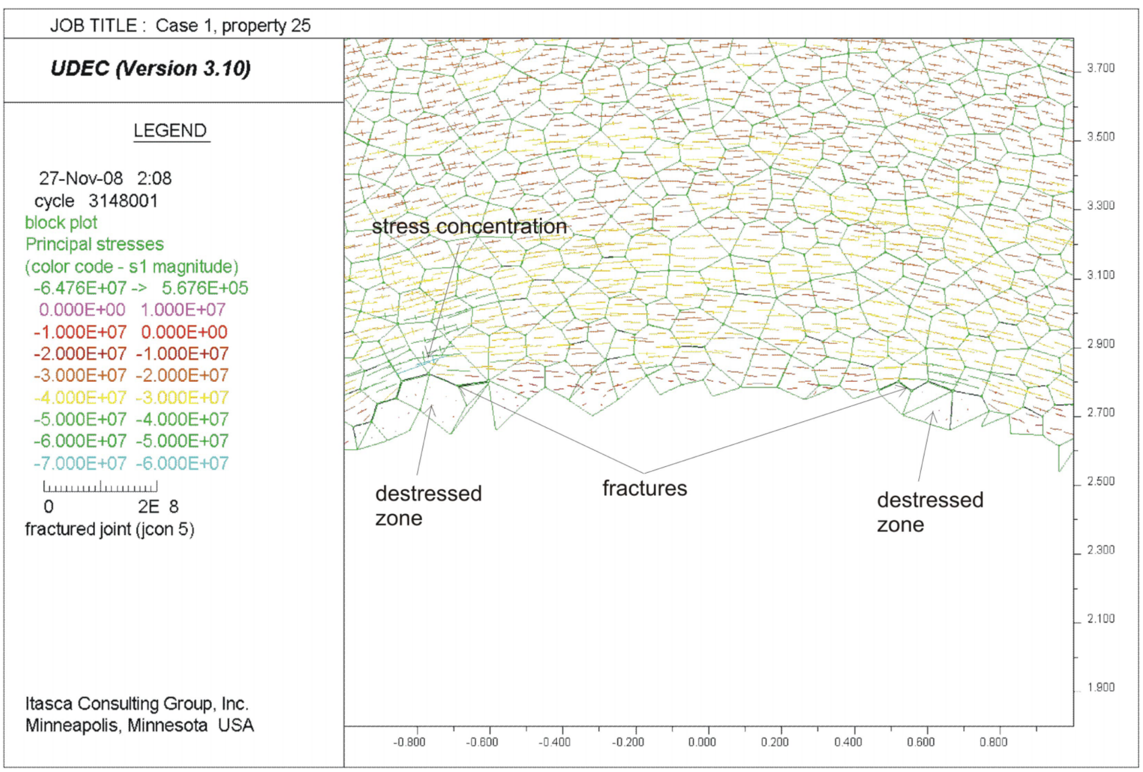
NOTE: Legends provided by the source files are not included.

Figure 4-2. Predicted Drift Profiles with 0.1-m Voronoi Block Size Due to Thermal Load 10,000 years after Waste Emplacement



Source: Output DTN: MO0901ROCKFALL.000, thermal analysis block size effect submittal*stress detail.pcx*)

NOTE: Locations of micro-cracks, or locations where contacts between the blocks have failed, are indicated by black lines.

Figure 4-3. Detail of Drift Crown, with Stress Tensor Field (Pa) Colored by Magnitude of the Major Principal Stress, After 100 Years of Heating as Predicted by the Model with 0.1-m Voronoi Block Size

4.2 ADDITIONAL VALIDATION OF DRIFT STABILITY MODEL

The original UDEC validation calculation using the DSHT data assumed that the drift was unsupported (BSC 2004 [DIRS 166107], Section 7.6.5.3). In fact, the walls above the springline and the crown of the drift were supported by 3-m long Super Swellex rockbolts on a one-meter-square pattern and a 3 inch by 3 inch welded wire mesh (Williams 2001 [DIRS 159516], p. 6 of enclosure). The purpose of the ground support was to eliminate a safety hazard by preventing loose rock from falling on workers.

The ground support was not included in the original UDEC validation, as illustrated by (BSC 2004 [DIRS 166107], Figure 7-31). The DSHT has now been reanalyzed using two numerical representations: one without ground support and the other with rock bolts as a ground support. Two additional changes were also made for the reanalysis of the DSHT:

1. The DSHT is represented as a circular tunnel of 2.5-m radius with a 1.2-m high concrete invert, consistent with the physical configuration of the DSHT. The original analysis of the DSHT assumed a horseshoe-shaped drift cross-section (BSC 2004 [DIRS 166107], Figure 7-31), which is not consistent with the actual configuration of the DSHT. Average values for concrete properties were calculated based on laboratory test data from scientific notebook, *Drift Scale Test Post-Test Activities* (Kelly 2007 [DIRS 185958], pp. 127 to 130), as documented in Table 4-1.

2. The linear coefficient of thermal expansion is temperature-dependent (data for TSw2 in Table E-20, BSC 2004 [DIRS 166107]). The original analysis of the DSHT assumed a constant value for the linear coefficient of thermal expansion, which underestimates thermally induced stresses.

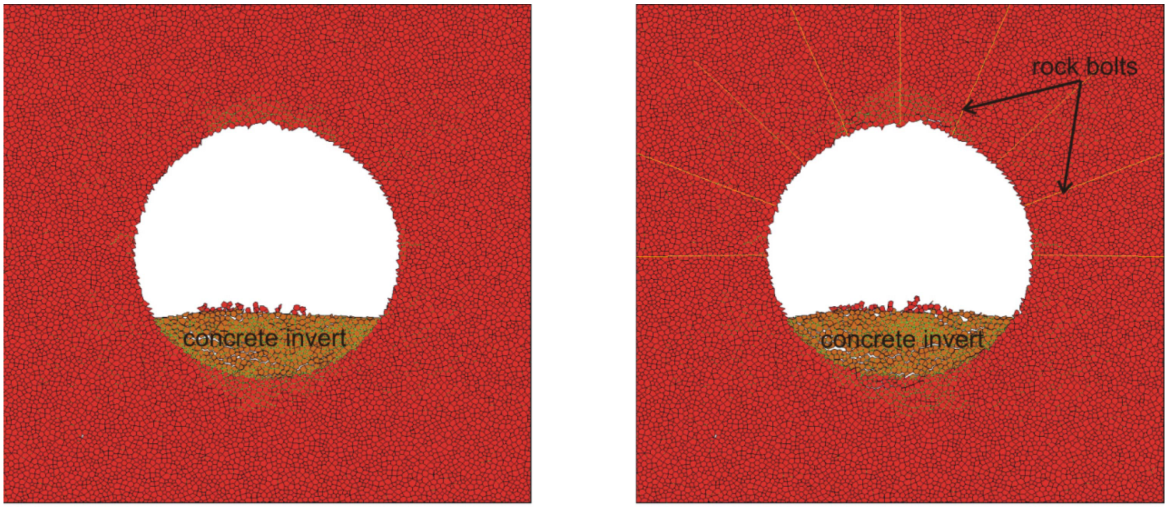
Figure 4-4 compares the drift configurations in 2002 for supported and unsupported drifts. Rockfall has caused a small amount of loose rock to accumulate on the invert for either drift configuration (supported or unsupported). Figure 4-4 demonstrates that the amount of rockfall and the new drift profiles formed by the rockfall are not affected by the rockbolts. A simulation of the DSHT through 2006, during the cool-down phase, did not predict any additional rockfall (output DTN: MO0901ROCKFALL.000, DST submittal\unsupported\ *Case1jointing10age2006.sav*).

Figure 4-4 indicates some damage and heave of the concrete floor, which has subsequently disappeared since the drift cooled down. The model overestimates the stresses and the damage in the concrete invert, which is not observed during the experiment, because of its representation of high strength in the interface between the concrete and rock. The high strength of the interface is a consequence of the exaggerated roughness in the drift outline in the model. In reality, slip along the interface between concrete and the rock resulted in reduced stresses in the invert and no observable damage. The inconsistency of the model with this observation from the experiment does not have significant effect on the main objective of the model, which is prediction of the damage and rockfall from the crown.

Table 4-1. Calculation of Average Concrete Properties from Laboratory Data

Compressive Strength		Modulus of Elasticity		Poisson's Ratio
psi	MPa	psi	GPa	
7477	51.6	2.80E+06	19.3	0.12
		2.60E+06	17.9	0.11
7453	51.4	2.60E+06	17.9	0.11
		2.60E+06	17.9	0.12
7487	51.6	2.95E+06	20.3	0.14
		2.55E+06	17.6	0.11
7370	50.8	2.80E+06	19.3	0.13
		2.70E+06	18.6	0.11
7610	52.5	2.90E+06	20.0	0.13
		2.80E+06	19.3	0.12
7573	52.2	2.85E+06	19.7	0.13
		2.90E+06	20.0	0.14
7417	51.2	2.85E+06	19.7	0.14
		2.75E+06	19.0	0.12
7913	54.6	2.90E+06	20.0	0.14
		3.00E+06	20.7	0.12
7577	52.3	2.90E+06	20.0	0.13
		2.55E+06	17.6	0.11
7793	53.7	3.85E+06	26.6	0.17
		3.85E+06	26.6	0.21
7763	53.5	2.60E+06	17.9	0.13
		2.75E+06	19.0	0.13
7550	52.1	2.65E+06	18.3	0.11
		2.85E+06	19.7	0.14
7247	50.0	2.65E+06	18.3	0.11
		2.70E+06	18.6	0.12
7450	51.4	2.70E+06	18.6	0.12
		2.75E+06	19.0	0.11
7933	54.7	4.65E+06	32.1	0.22
		5.55E+06	38.3	0.29
7403	51.1	3.60E+06	24.8	0.2
		4.35E+06	30.0	0.2
7803	53.8	4.45E+06	30.7	0.21
		5.25E+06	36.2	0.26
8010	55.2	4.95E+06	34.1	0.26
		4.20E+06	29.0	0.21
7407	51.1	4.60E+06	31.7	0.28
		4.45E+06	30.7	0.24
7803	53.8	4.50E+06	31.0	0.22
		5.00E+06	34.5	0.24
Average	***52.4***	**—**	***23.3***	***0.16***

Source: Kelly 2007 [DIRS 185958], pp. 127 to 130, for the data in columns 1, 3, and 5. The unit conversions in columns 2 and 4 and the average values in the last row are calculated values.



a) no support   b) supported with rock bolts

Source: Output DTN: MO0901ROCKFALL.000, DST submittal\unsupported*plot2002.jpg*; DST submittal \supported*plot2002.jpg*)

NOTE: Legends provided by the source files are not included.

Figure 4-4. Comparison of the DSHT Configurations in 2002 Back Analyzed Assuming Unsupported and Supported Drifts

The total volume of rock accumulated on the invert at the end of the experiment in 2006, as predicted by the numerical analysis, is 0.155 m^3 per meter of drift (determined by the sum of the area of failed rock blocks from output DTN: MO0901ROCKFALL.000, DST submittal\unsupported\ *Case1jointing10age2006.sav*), which is in very good agreement with the rockfall volume of 0.16 m^3 per meter of drift estimated from mapping the areas of loose rock (see Section 3.3).

4.3 CONCLUSIONS

Supplemental UDEC analyses have been performed to evaluate: (1) the sensitivity of UDEC model results to Voronoi block size, and (2) the validation of UDEC using the actual configuration for the DSHT, with and without ground support for the drift. The results from the supplemental analyses are as follows:

- **RAI 3.2.2.1.2.1-001.** Figures 4-1 and 4-2 demonstrate that there is no significant rockfall induced by heating for rock mass Categories 2 or 5 with 0.2-m or 0.1-m block sizes. This conclusion is identical with the result from the previous UDEC analyses with a characteristic block size of 0.3-m, which demonstrated no significant rockfall or damage induced by heating for rock mass Categories 1 through 5 (BSC 2004 [DIRS 166107], Section 6.4.2.3.1; Figure 6-140 for rock mass Category 1). These results confirm that the UDEC analyses of lithophysal rockfall are not sensitive to the choice of a 0.1 m to 0.3-m characteristic size for the Voronoi blocks or to the assumption that the blocks are elastic.

These results are directly relevant to RAI 3.2.2.1.2.1-001 because they demonstrate that the numerical results with UDEC model do not bias the results against spalling. The numerical results with UDEC are independent of a characteristic block size between 0.1 m and 0.3 m, and the UDEC results are not affected by the assumption that blocks behave elastically, restricting failure to randomly oriented surfaces between blocks.

- **RAI 3.2.2.1.2.1-006.** An analysis was performed to provide additional validation of the drift degradation model in UDEC, based on the final data from the Drift Scale Heater Test. The DSHT has been reanalyzed using two numerical representations: one without ground support and the other with rock bolts as a ground support. These numerical representations are based on a circular tunnel of 2.5-m radius with a 1.2-m high concrete invert, consistent with the physical configuration of the DST, and incorporate temperature dependence for the coefficient of thermal expansion.

  Figure 4-4 demonstrates that rockbolts do not affect amount of loose rock. Continuing the simulations to 2006, during the cool-down phase, did not result in any additional rockfall. The UDEC prediction for the volume of rock accumulated on the invert at the end of the experiment in 2006 is 0.155 m^3 per meter of drift, which is in very good agreement with the observed rockfall volume of 0.16 m^3 per meter of drift, estimated by mapping the areas of loose rock at the end of the DST.

  These results satisfy RAI 3.2.2.1.2.1-006 by reconciling the numerical UDEC results for the DST with the observed rockfall volume of the DST.

5. IMPACT TO LA OR POSTCLOSURE TECHNICAL BASELINE

The results reported in Section 4 corroborate the postclosure technical baseline for drift degradation as a function of ambient and thermal stress loadings over time. The postclosure technical baseline for nominal or seismic response, as documented in Section 2.3.4 of the SAR, is based on the rockfall calculations documented in *Drift Degradation Analysis* (BSC 2004 [DIRS 166107]). The postclosure technical baseline is unchanged by the supplemental rockfall analyses documented in Section 4 because (1) smaller (Voronoi) block sizes and the assumption of elasticity (i.e., the assumption that the blocks do no fracture) do not significantly change rockfall volumes, and (2) the predicted rockfall volume for the DST is very close to the observed rockfall volume after completion of the DST.

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