A consequence of the internal structure of the lithophysal rock mass is the size effect on its strength. Many laboratory studies (BSC 2004, Figure E-22) have shown that the ultimate strength of rocks decreases as sample size is increased, but the rate of decrease slows with size, until it reaches an asymptotic level. The strength decrease is attributable to the inclusion of more and bigger aspects of the internal structure in the particular rock type. The minimum (asymptotic level of) strength is considered to be the inherent strength of the intact rock *in situ*, and varies with the type of rock being tested. This mechanical property is observed in the tuffs of Yucca Mountain (BSC 2004, Figure E-22). As a result of this effect, as smaller samples are considered, the blocks being analyzed are between fractures and lithophysae (see Figure 1), and are essentially nonlithophysal tuff and much stronger than the aggregate rock mass strength. The unconfined compressive strength (UCS) of the intact nonlithophysal rock 20 cm in size is roughly 90 MPa (BSC 2004, Figure E-22), which is much greater than the 30 MPa UCS of both the lithophysal Category 5 (BSC 2004, Table E-11) and the maximum thermally induced stress in the crown of the emplacement drift in lithophysal Category 5 (BSC 2004, Figure 6-144). Thus, these blocks will be elastic during the thermal cycle, as is assumed in the Voronoi block model. The failure of the lithophysal rock mass will not result in its disintegration into pieces that are of the centimeter size. Therefore, modeling of the drift stability using a smaller block size than 10 cm would be inconsistent with the internal structure and mechanical behavior of the lithophysal tuff. However, even the analysis using blocks as small as 4 cm (Section 1.4) does not significantly change the rockfall prediction.

The estimate of the 17-cm-thick overstressed region (see response to RAI 3.2.2.1.2.1-003) is made with an implicit assumption that rock mass strength is size-independent, or that the lithophysal rock mass strength is the same down to the centimeter scale. That assumption assigns a lower strength to the rock mass than would be predicted at the scale of the 17-cm failure zone for the lithophysal rock. If the proper scale effect on the lithophysal strength is taken into consideration in this particular case (showing a 17-cm-thick overstressed region), the lithophysal rock is actually not overstressed because its strength on the centimeter-size scale is greater than 30 MPa. Furthermore, because of the size of the internal structure (as shown in Figure 1) compared to the size of the overstressed region (i.e., 17 cm), even if the stresses are large enough to cause fracturing, the fracturing will not be coherent but a function of the internal geometry of the lithophysal rock (i.e., follow pre-existing fractures or pathways between lithophysal cavities).

1.3 OBSERVATIONS OF DAMAGE IN LITHOPHYSAL ROCK

The ESF and ECRB Cross-Drift walls are overstressed in poor quality (high porosity) lithophysal rock. The UCS of Categories 1 and 2 are 10 MPa and 15 MPa (BSC 2004, Table E-10), respectively, compared to estimated stress concentrations of 17.5 MPa (see response to RAI 3.2.2.1.2.1-003) in the drift wall under *in situ* stress conditions. In fact, the depth of the overstressed region under *in situ* conditions in the drift wall of Category 1 (BSC 2004, Figure 6-141) is not significantly greater than 17 cm, the depth of the overstressed region in the drift crown during the thermal cycle in Category 5 lithophysal rock mass (BSC 2004, Figure 6-144). Otherwise, the effect of thermally induced stresses on the drift stability is mechanically equivalent to the effect of *in situ* stresses. Furthermore, the walls of the ESF and the ECRB Cross Drift are currently unsupported and observed to have remained stable after more than a decade.

The response of the lithophysal rock mass to overstressing can be observed in a few boreholes drilled in the walls of existing drifts in poor quality lithophysal rock mass, as illustrated in Figure 2. The fractures have developed parallel to the drift wall to a depth of approximately 50 cm. Overstressing of the lithophysal rock mass in the drift walls did not result in the formation of broken rock with a block size on the order of several centimeters or more. The spacing of stress-induced fractures inside the borehole is on the order of 10 cm or greater (considering that the borehole diameter is 12 inches). Also the stress-induced fractures are associated with pre-existing fractures and/or lithophysae. The UDEC Voronoi block model, its representation of the block size, and the size effect on the lithophysal rock mass strength are consistent with the observations of fracturing around the existing excavations in the lithophysal rock mass (BSC 2004, Section 7.6.5.3).

Source: BSC (2004), Figure 7-25, top photo

NOTE: The photo shows sidewall fracturing/opening of preexisting wall-parallel fractures in a 12-inch-diameter horizontal borehole drilled in the springline of the ESF in low quality Tptpll (approximately Category 1). Overburden depth is approximately 325 m. Depth of fracturing is approximately 1.5 to 2 ft (0.46 to 0.61 m).

Figure 2. Observed Rock Mass Conditions at the Tunnel Springline in Lithophysal Rock in the ESF

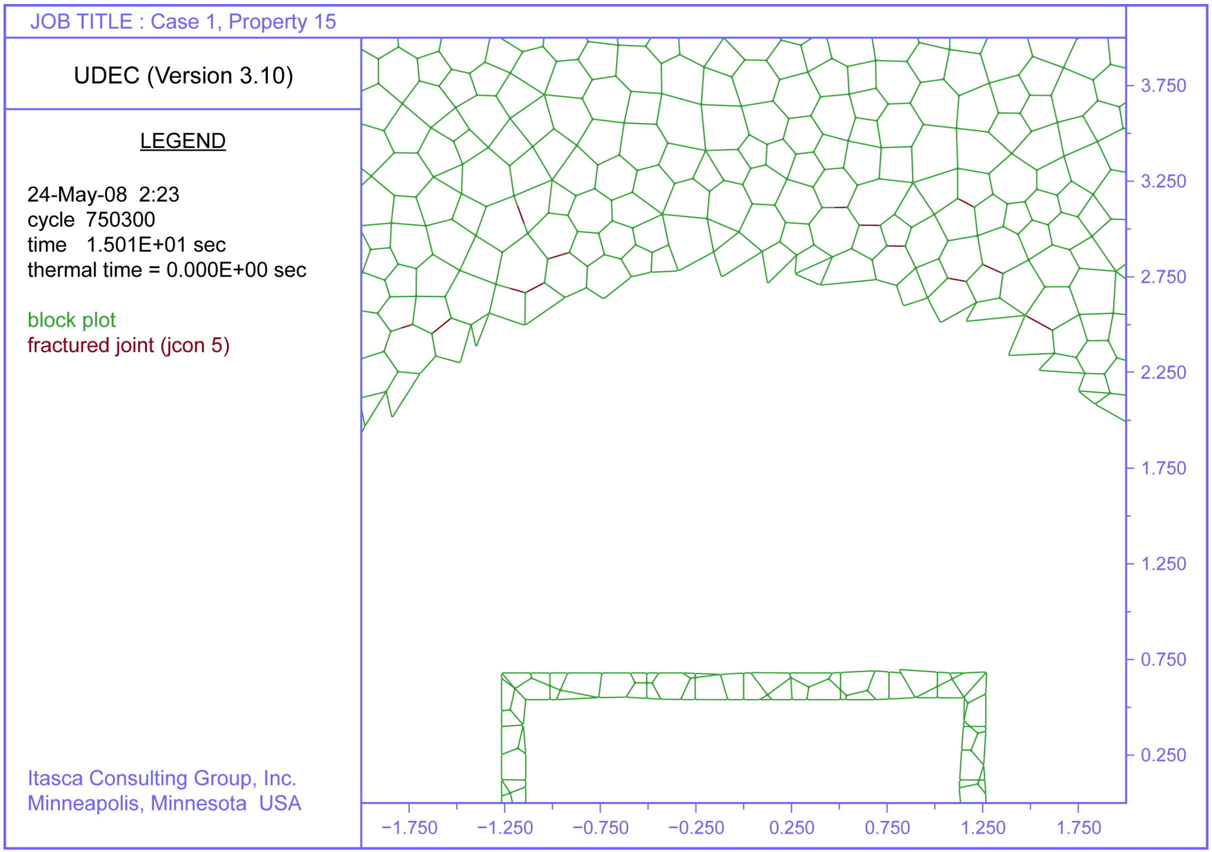
In the laboratory testing of lithophysal tuffs (Price et al. 1985), the fractures created as the sample approached its peak strength are observed to form as short discontinuous cracks that predominantly propagate from one lithophysal cavity to another. The number of fractures increases with stress until the sample fails. Failure occurs because enough cracks interconnect and produce an overall decreased strength. The result of this damage is that blocks of rock are formed, some of which are completely bounded by open fractures, and some have both fractured and intact boundaries. The sizes of these blocks are observed to be directly related to the size and spacing of the lithophysal cavities. Since the lithophysae in the upper lithophysal tuff zone in the Topopah Spring Tuff generally tend to be relatively small (a few millimeters to several centimeters but closely spaced), at the conclusion of a mechanical property experiment, the sizes of the remaining blocks of undamaged tuff are on the order of centimeters. However, the lower lithophysal tuff has larger lithophysae (up to a meter in diameter) than the upper lithophysal tuff.

These lithophysae are spaced farther apart, but even in the laboratory samples, which typically have smaller lithophysal cavities, the undamaged block sizes are on the order of tens of centimeters. Similarly, field observations show that most of the lithophysal zones (both the upper and the lower zones) have a greater average lithophysal spacing, which results in block sizes that are typically tens of centimeters or more.

1.4 EFFECT OF VORONOI BLOCK SIZE ON DEPTH OF DAMAGE

The effect of Voronoi block size on fracturing and the depth of failure, when the models with different block sizes are calibrated (BSC 2004, Section 7.6.4) to the same UCS, is illustrated in Figures 3, 4, and 5 for block sizes of 20 cm, 10 cm, and 4 cm, respectively. The figures show fracturing in the drift crown in the lithophysal rock Category 5 after 80 years of heating. (The maximum temperature, the maximum stresses, and the maximum thickness of the overstressed region of 17 cm in the crown are reached at approximately 80 years.) The results for 4-cm block size are included to corroborate the general trends of rock mass mechanical behavior. The 4-cm block size is inconsistent with the observed rock-mass fabric and size effect on the strength of the lithophysal rock mass. Although the models are calibrated to the same UCS, they are representations of three different materials, with different internal structure, with 20-cm, 10-cm, and 4-cm internal block sizes.

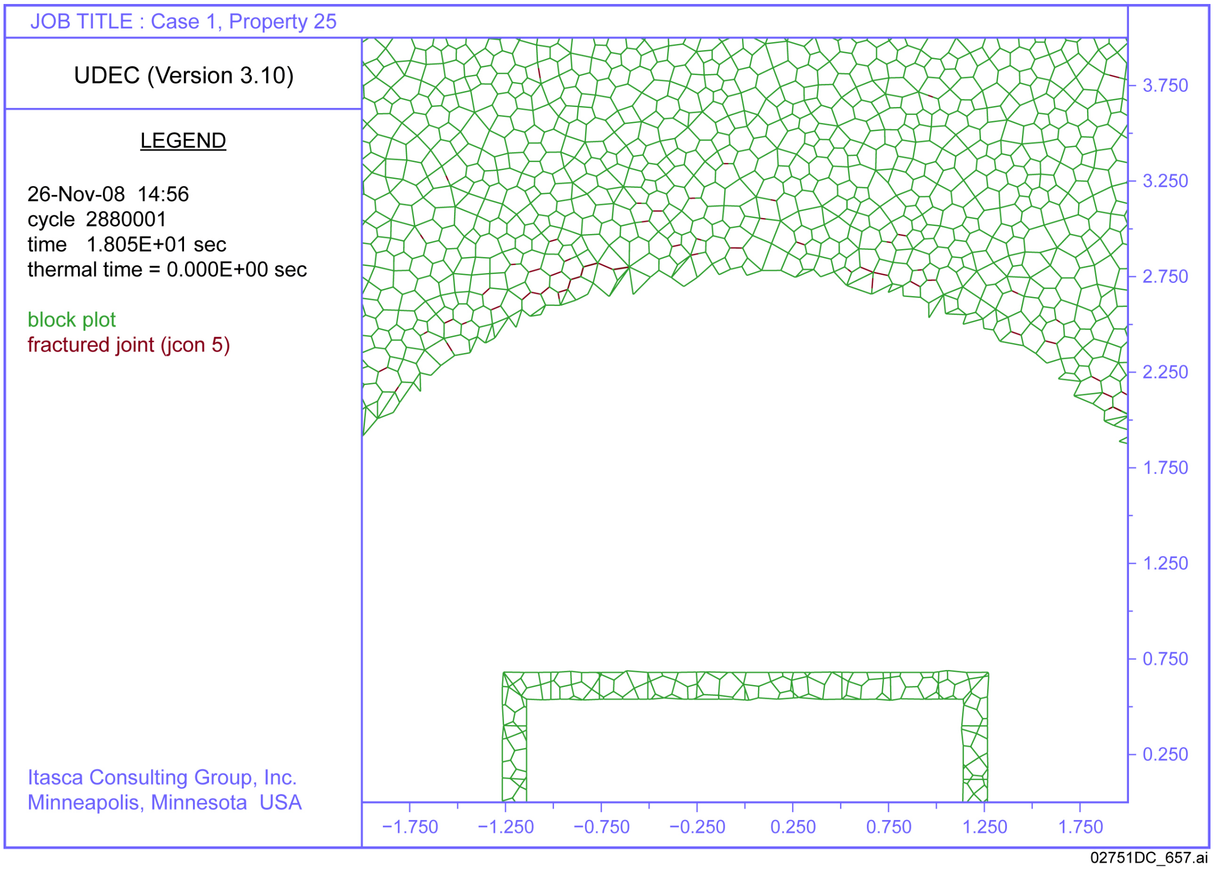
In the case of the 4-cm block size, there are four to five blocks across the thickness of the overstressed region, compared to one or two blocks in the cases of the models with larger blocks. Nonetheless, the responses of the models to particular loading conditions are similar. In all cases, the thermal stresses induce fracturing that extends 20 to 30 cm into the rock. No major rockfall is predicted. Figure 4 for the 10-cm block size illustrates fractures coalescing with the formation of potentially loose blocks in the crown, although the block size is 10 cm compared to the approximately 17-cm-thick overstressed region. Figure 5 for 4-cm block size shows more small-scale fractures, resulting in minor rockfall, but results in the same depth of fracturing as the models with larger block sizes.



02751DC_656.ai

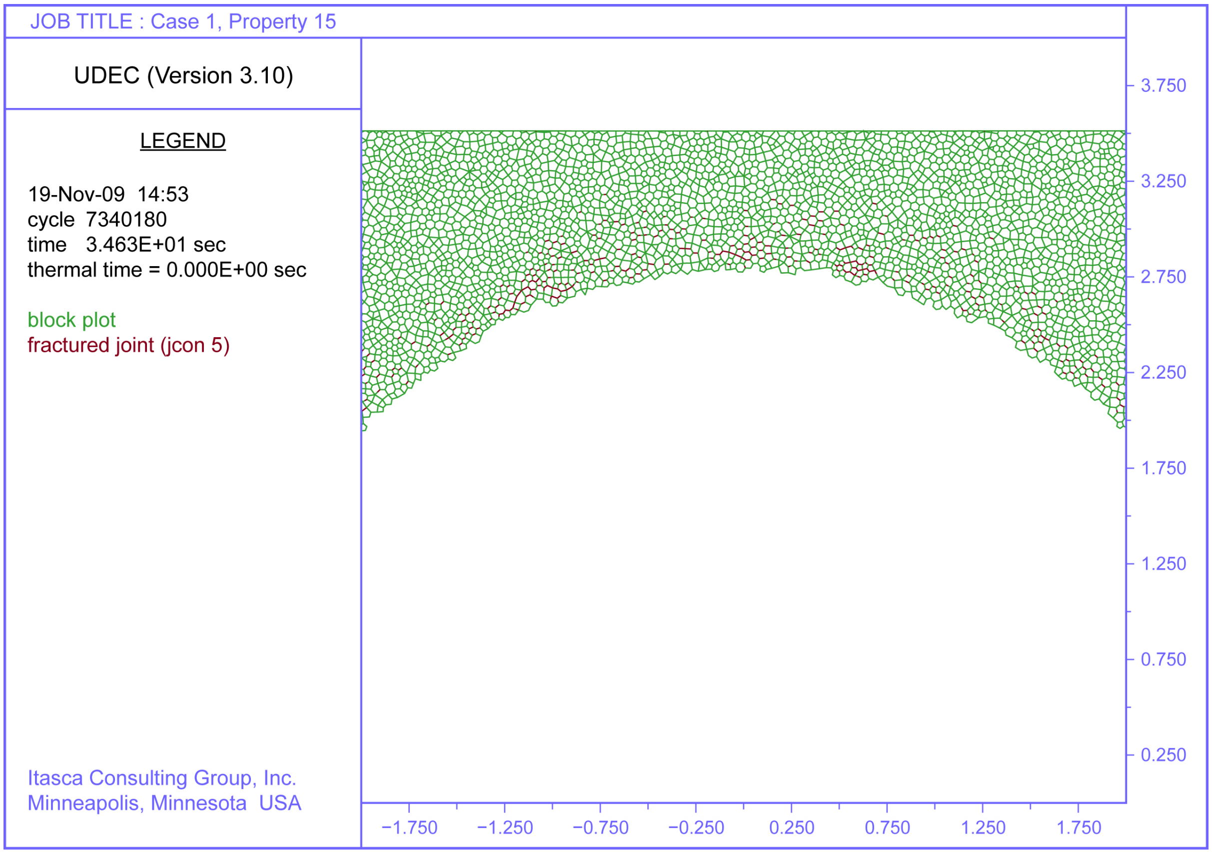
NOTE: Red lines are broken contacts that represent open fractures. Scale is meters.

Figure 3. Damage around the Emplacement Drift in Lithophysal Category 5 after 80 Years of Heating Predicted with Model with 20-cm Block Size



NOTE: Red lines are broken contacts that represent open fractures. Scale in meters

Figure 4. Damage around the Emplacement Drift in Lithophysal Category 5 after 80 Years of Heating Predicted with Model with 10-cm Block Size



02751DC_658.ai

NOTE: Red lines are broken contacts that represent open fractures. Scale in meters

Figure 5. Damage around the Emplacement Drift in Lithophysal Category 5 after 80 Years of Heating Predicted with Model with 4-cm Block Size

1.5 CONCLUSION

The Voronoi block model with a block size in the range of 10 to 30 cm realistically represents deformation and damage of the lithophysal rock mass when it is subjected to high (thermally induced) stresses that exceed the rock mass strength in a 17-cm-thick region along the drift wall and/or crown. In this case, the ratio between the thickness of the overstressed region and the average size of a block created by fractures and lithophysal holes is relatively small (less than ten). Consequently, the response of the rock is a function of the intact block size, which is adequately represented in the model. Furthermore, because of the effect of block size on rock mass strength, a 17-cm-thick overstressed region in the lithophysal rock mass will not result in coherent yielding (fracturing) even if the stresses are sufficiently large to cause fracturing.

A representation of the lithophysal rock mass that would result in block-size-independent damage and rockfall in a 17-cm-thick overstressed region would require a Voronoi block size of less than 2 cm. However, this block size would practically imply that the lithophysal strength of the intact pieces 20 cm in size or less (i.e., the nonlithophysal rock) is the same as the rock mass strength (on a meter scale). That representation of the strength of the lithophysal rock mass would be unrealistically low, particularly on the scale of 10 cm. As a result of a strong size effect, the intact lithophysal rock between the fractures and the lithophysae has much greater strength than the lithophysal rock mass.

The numerical analyses illustrate that the reduction of block size to 4 cm (compared to 10 cm or 20 cm block size) does not have a significant effect on the depth of fracturing or volume of rockfall when the thickness of the overstressed region is 17 cm.

2. COMMITMENTS TO NRC

None.

3. DESCRIPTION OF PROPOSED LA CHANGE

None.

4. REFERENCES

ASTM D 7012. 2007. *Standard Test Method for Compressive Strength and Elastic Moduli of Intact Rock Core Specimens under Varying States of Stress and Temperatures*. ASTM International, West Conshohocken, PA.

BSC (Bechtel SAIC Company) 2004. *Drift Degradation Analysis.* ANL-EBS-MD-000027 REV 03. Las Vegas, Nevada: Bechtel SAIC Company. ACC: DOC.20040915.0010; DOC.20050419.0001; DOC.20051130.0002; DOC.20060731.0005; LLR.20080311.0066.

BSC (Bechtel SAIC Company) 2005. *Peak Ground Velocities for Seismic Events at Yucca Mountain, Nevada.* ANL-MGR-GS-000004 REV 00. Las Vegas, Nevada: Bechtel SAIC Company. ACC: DOC.20050223.0002.

Hoek, E. and Marinos, P.G. 2009. Keynote address at EUROCK2009, Dubrovnik, Croatia. In *Rock Engineering in Difficult Ground Conditions – Soft Rocks and Karst*. Ivan Vrkljan, ed. New York, New York: CRC Press.

Otto, S.J. and Buesch, D.C. 2003. "Porosity, Bulk Density, and Rock-Particle Density of Lithostratigraphic Components in Lithophysal Rocks of the Topopah Spring Tuff at Yucca Mountain, Nevada." *Abstracts with Programs - Geological Society of America*, *35*, (6), 434-435. Boulder, Colorado: Geological Society of America.