Expansion Analyses of Strategic Petroleum Reserve in Bayou Choctaw – Revised Locations

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Expansion Analyses of Strategic Petroleum Reserve in Bayou Choctaw – Revised Locations

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Abstract

This report summarizes a series of three-dimensional simulations for the Bayou Choctaw Strategic Petroleum Reserve. The U.S. Department of Energy plans to leach two new caverns and convert one of the existing caverns within the Bayou Choctaw salt dome to expand its petroleum reserve storage capacity. An existing finite element mesh from previous analyses is modified by changing the locations of two caverns. The structural integrity of the three expansion caverns and the interaction between all the caverns in the dome are investigated. The impacts of the expansion on underground creep closure, surface subsidence, infrastructure, and well integrity are quantified. Two scenarios were used for the duration and timing of workover conditions where wellhead pressures are temporarily reduced to atmospheric pressure. The three expansion caverns are predicted to be structurally stable against tensile failure for both scenarios. Dilatant failure is not expected within the vicinity of the expansion caverns. Damage to surface structures is not predicted and there is not a marked increase in surface strains due to the presence of the three expansion caverns. The wells into the caverns should not undergo yield. The results show that from a structural viewpoint, the locations of the two newly proposed expansion caverns are acceptable, and all three expansion caverns can be safely constructed and operated.
ACKNOWLEDGMENTS

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<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>BC</td>
<td>Bayou Choctaw</td>
</tr>
<tr>
<td>BH</td>
<td>Big Hill</td>
</tr>
<tr>
<td>BMSL</td>
<td>Below Mean Sea Level</td>
</tr>
<tr>
<td>DOE</td>
<td>U.S. Department of Energy</td>
</tr>
<tr>
<td>DILFAC</td>
<td>DILatant damage FACtor</td>
</tr>
<tr>
<td>FEM</td>
<td>Finite Element Method</td>
</tr>
<tr>
<td>MCS</td>
<td>Minimum Compressive Stress</td>
</tr>
<tr>
<td>MMB</td>
<td>Million Barrels</td>
</tr>
<tr>
<td>RF</td>
<td>elastic modulus Reduction Factor</td>
</tr>
<tr>
<td>SMF</td>
<td>Structural Multiplication Factor</td>
</tr>
<tr>
<td>SNL</td>
<td>Sandia National Laboratories</td>
</tr>
<tr>
<td>SPR</td>
<td>Strategic Petroleum Reserve</td>
</tr>
<tr>
<td>UTP</td>
<td>Union Texas Petroleum</td>
</tr>
<tr>
<td>WIPP</td>
<td>Waste Isolation Pilot Plant</td>
</tr>
<tr>
<td>UTM</td>
<td>Universal Transverse Mercator</td>
</tr>
<tr>
<td>WH</td>
<td>West Hackberry</td>
</tr>
</tbody>
</table>
1. INTRODUCTION

1.1. Background

The Strategic Petroleum Reserve (SPR) currently stores 727 million barrels (MMB) of crude oil at four sites located along the Gulf Coast. The existing 62 caverns are currently at full capacity. The U.S. Department of Energy (DOE) may increase the size of the reserve. The Bayou Choctaw (BC) site is the smallest SPR site with only six existing caverns and a storage capacity of 73 MMB. The site is limited in its expansion capability due to the small size of the salt dome and other commercial storage operations on the dome. The SPR may expand the site’s capacity through the development of two new caverns on existing SPR property and the acquisition of one existing cavern, for an increase of 33 MMB. This will provide increased capacity on the Capline Distribution System. Details of the expansion plan can be found at the DOE web site (http://www.fossil.energy.gov/programs/reserves/spr/expansion-eis.html) and in the DOE Draft Environmental Impact Statement [2006] and Expansion Plan [2007].

1.2. Previous Work

This report summarizes a series of three-dimensional structural simulations of the BC SPR salt dome. In a previous report, Park et al. [2006] developed a three-dimensional finite element method (FEM) analysis to model the caverns in the dome. The simulation was used to evaluate the structural integrity of the caverns located at the BC site which is considered a candidate for expansion. Fifteen active and nine abandoned caverns exist currently at BC, with a total cavern volume of 164 MMB. The DOE has a plan to leach two additional caverns and convert one extant cavern within the BC salt dome for SPR use [URS, 2006].

Ehgartner and Lord [2006] suggested the location for two new caverns at BC (A and M1 in Figure 1) from their previous work [Lord and Ehgartner, 2005] that detailed the criteria behind cavern placement. Cavern 102, a former Union Texas Petroleum (UTP) cavern, is potentially available for conversion to a SPR cavern. The DOE would like to acquire it as part of the expansion. Park and Ehgartner [2008] investigated the structural integrity of the three expansion caverns and their interaction with other caverns in the dome. The impacts of the expansion by three caverns on underground creep closure, surface subsidence, infrastructure, and well integrity were quantified. Essentially, the three modeled SPR caverns and the other caverns in the dome were predicted to be structurally stable (no tensile or dilatants failure) through five drawdowns2. The addition of two new caverns (A and M) did not make the structural stability of the existing caverns worse. The results show that from a structural viewpoint, the locations of the two newly proposed expansion caverns are acceptable, and all three expansion caverns can be safely constructed and operated.

Lord et al. [2009] suggested alternative locations for two new caverns. Figure 1 displays a plan view of the BC salt dome at -3000 ft, which is at a depth within the dome where new caverns will be placed. The proposed expansion caverns are colored brown. The green shading depicts

---

1 Caverns A and M have been renamed by DOE to Caverns 103 and 104, respectively.
2 “Drawdown” is when the crude oil is withdrawn from the cavern. Fresh water is used to withdraw the crude oil. Because the cavern enlarges due to salt dissolving from the cavern walls, it is called a “drawdown leach”.


11
the 300 ft standoff from edge of salt. The blue lines represent edge of salt and the subsequent 300 ft standoff at -3000 ft. The green lines represent the property boundary and the subsequent 100 ft standoff distance. Note that some of the proposed cavern locations are outside of the DOE property line, specifically Caverns 1, 3, and 4. Within the DOE property, cavern locations 5 and A3, which will be renamed Caverns 103 and 104, were selected as a viable options. The locations are outside the known zone of cavern pressure communication and no surface infrastructure is present.

1.3. Objectives

This report investigates the structural integrity of the three expansion caverns and their interaction with other caverns in the dome in a manner similar to the previous analyses [Park and Ehgartner, 2008]. The impacts of the expansion by three caverns on underground creep closure, surface subsidence, infrastructure, and well integrity are quantified. For these, the existing three dimensional FEM mesh [Park and Ehgartner, 2008] is modified by changing the locations of two new caverns (Caverns A3 and 5 instead of Caverns A and M).

Figure 1: Proposed locations of expansion caverns at Bayou Choctaw. Also shown are the required standoff distances from dome edge (green shading), the proposed expansion caverns (brown), the edge of salt and the subsequent 300 ft standoff at -3000 ft (blue lines) and DOE property boundaries (green lines) [Lord et al., 2009].
1.4. Report Organization

The remainder of this report describes the analyses details. Section 2 presents an overview of the geomechanical model including salt dome geometry, cavern geometries and layout, model history, thermal conditions, and so forth. The constitutive models and material properties are also described. Section 3 provides the discretized finite element mesh for six existing SPR, three expansion SPR, two inactive, seven abandoned, and eight UTP caverns within the salt dome considering five drawdown leaches in the SPR caverns. Section 4 provides the criteria for checking the structural stability of caverns, wells, and surface structures. Section 5 lists the computer codes used in this analyses and the file naming convention for the calculations. Section 6 describes the cavern deformation due to salt creep, storage loss with time, subsidence on the surface, integrity of cavern wells, and cavern stability using criteria for dilatant damage and tensile failure. The stress distributions around the expansion SPR caverns are illustrated in this section. Section 7 provides some additional perspective on these calculations and concluding remarks. References are listed in Section 8. Every computational scripts such as input files for JAS3D, user-supplied subroutine to provide an internal pressure state in the caverns, FORTRAN script for calculating the temperature at each node, journal file for mesh generation, and ALGEBRA scripts are provided in the appendices.
2. ANALYSIS MODEL

2.1. Geomechanical Model

2.1.1. Salt dome geometry

The stratigraphy near the BC salt dome is shown in Figure 2. The top layer is overburden, which consists of sand, silts and clays. It has a thickness of approximately 500 ft. Below the overburden is the caprock, which consists of gypsum, anhydrite, and sand. The caprock is about 150 ft thick. The bottom boundary of the analyses is set at 8,000 ft below the surface. All SPR caverns are located below 2,000 ft from the surface.

Figure 2: Stratigraphy near the Bayou Choctaw salt dome [Neal et al., 1993] and the thickness of each layer used for modeling. Blue line box approximates the converted maximum size of Cavern 102.
Figure 3: Plan view of the Bayou Choctaw site [Neal et al., 1993] at 4000 ft below mean sea level. Red lines indicate the extents used to determine major and minor diameters of salt dome for modeling. The blue circles with red fonts show the proposed two new cavern locations (103 and 104) and one converted cavern (102).

Figure 3 shows the plan view of the BC site. The horizontal shape of the dome is approximately elliptical. The major and minor radii are measured as 4882 ft and 4265 ft, respectively. The caverns planned for expansion (Caverns 102, 103, and 104) are also shown in Figure 3. The geometric parameters of the dome estimated from Figure 2 and Figure 3 are listed in Table 1.
Table 1: Geometric parameters of the salt dome at Bayou Choctaw.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>UTM Coordinate of West Edge at 4000 ft BMSL</td>
<td>E 2,005,738 ft</td>
</tr>
<tr>
<td>UTM Coordinate of East Edge at 4000 ft BMSL</td>
<td>E 2,010,000 ft</td>
</tr>
<tr>
<td>UTM Coordinate of South Edge at 4000 ft BMSL</td>
<td>N 597,000 ft</td>
</tr>
<tr>
<td>UTM Coordinate of North Edge at 4000 ft BMSL</td>
<td>N 601,881 ft</td>
</tr>
<tr>
<td>UTM Coordinate of Center at 4000 ft BMSL</td>
<td>E 2,007,869 ft</td>
</tr>
<tr>
<td>UTM Coordinate of Center at 4000 ft BMSL</td>
<td>N 599,440 ft</td>
</tr>
<tr>
<td>Major Diameter at 4000 ft BMSL</td>
<td>4,881 ft</td>
</tr>
<tr>
<td>Minor Diameter at 4000 ft BMSL</td>
<td>4,262 ft</td>
</tr>
<tr>
<td>Avg. Elevation Top Salt</td>
<td>-650 ft</td>
</tr>
<tr>
<td>Avg. Elevation Top Caprock</td>
<td>-500 ft</td>
</tr>
</tbody>
</table>

Note: BMSL – Below Mean Sea Level
UTM – Universal Transverse Mercator

2.1.2. Salt constitutive model and parameters

A power-law creep model, which considers only secondary or steady-state creep, is used for the salt creep constitutive model. The secondary creep strain rate is given by:

\[
\dot{\varepsilon} = A \left( \frac{\sigma}{\mu} \right)^n \exp \left( -\frac{Q}{RT} \right)
\]  

(1)

where, \( \dot{\varepsilon} \) = creep strain rate,
\( \sigma \) = von Mises equivalent stress,
\( \mu \) = shear modulus = \( E / (1+\nu) \), where \( E \) is Young’s modulus and \( \nu \) is Poisson’s ratio
\( T \) = absolute temperature,
\( A \) = power law creep constant determined from back-fitting the model to creep data
\( n \) = stress exponent,
\( Q \) = effective activation energy,
\( R \) = universal gas constant.

The geomechanical properties of BC salt are not entirely known for modeling. The field data for the creep constants, the stress exponent, and the thermal constant have not been determined. The values of the stress exponent and the thermal constant are assumed to be the same as the values obtained from Waste Isolation Pilot Plant (WIPP) rock salt. Through a number of back-fitting analyses [Park et al., 2006], the calibrated power law creep constant was determined. The values used as input data in the present analyses are listed in Table 2.
Table 2: Material parameters of Bayou Choctaw salt used in the analyses.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young’s modulus (E)</td>
<td>psi</td>
<td>4.496×10⁶</td>
<td>Krieg, 1984</td>
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<tr>
<td>Density (ρ)</td>
<td>lb/ft³</td>
<td>143.6</td>
<td>Krieg, 1984</td>
</tr>
<tr>
<td>Poisson’s ratio (ν)</td>
<td>-</td>
<td>0.25</td>
<td>Krieg, 1984</td>
</tr>
<tr>
<td>Elastic modulus reduction factor (RF)</td>
<td>-</td>
<td>12.5</td>
<td>Morgan and Krieg, 1988</td>
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<tr>
<td>Bulk modulus (K)</td>
<td>psi</td>
<td>2.397×10⁵</td>
<td></td>
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<tr>
<td>Two μ (2μ)</td>
<td>psi</td>
<td>2.878×10⁵</td>
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<tr>
<td>Power law creep constant (A)</td>
<td>Pa·s⁻¹</td>
<td>5.79×10⁻³⁶</td>
<td>Krieg, 1984</td>
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<td>Structure multiplication factor (SMF)</td>
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<td>0.12</td>
<td>Park et al., 2006</td>
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<tr>
<td>Calibrated power law creep constant (Ac)</td>
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<td>Park et al., 2006</td>
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<td>Stress exponent (n)</td>
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<td>Thermal constant (Q)</td>
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<tr>
<td>Input thermal constant (Q/R)</td>
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2.1.3. Material model and parameters for lithologies around the salt dome

An elastic model is assumed for the lithologies encompassing the salt dome. The surface overburden layer, which is mostly comprised of sand, is assumed to exhibit elastic material behavior. The sand layer is considered isotropic, and has no assumed failure criteria. The values of the required model parameters for the overburden are not available for BC, so the McCormick Ranch Sand properties used in the West Hackberry (WH) analysis [Ehgartner and Sobolik, 2002] were used. The caprock layer, consisting of gypsum, anhydrite and sand, is also assumed to behave elastically. Samples of caprock from core holes at BC were tested by Dames and Moore [1978] to determine physical properties. The tested samples were from massive gypsum-anhydrite units at depths of 602 ft and 645 ~ 648 ft in Core Hole 1 and 558 ~ 642 ft in Core Hole 2 [Hogan, 1980]. The rock surrounding the salt dome is sedimentary rock that consists mostly of sandstone and shale, which is assumed isotropic, homogeneous elastic rock. The values of the required model parameters of the surrounding rocks are also not available. Typical values for the Young’s moduli of sandstones and shales range from 6×10⁴ to 1×10⁷ psi [Carmichael, 1984]. For simplifying the analysis, a median value of the Young’s modulus of sandstone, 5×10⁶ psi, is assumed. The mechanical properties used in the present analysis are listed in Table 3.

Table 3: Material model parameters of the lithologies around salt dome used in the analyses [Park et al., 2006]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Overburden</th>
<th>Caprock</th>
<th>Surrounding Rock</th>
</tr>
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<tbody>
<tr>
<td>Young’s modulus</td>
<td>psi</td>
<td>1.450×10⁴</td>
<td>2.277×10⁶</td>
<td>5×10⁶</td>
</tr>
<tr>
<td>Density</td>
<td>lb/ft³</td>
<td>117.0</td>
<td>144.8</td>
<td>156.1</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>-</td>
<td>0.33</td>
<td>0.29</td>
<td>0.33</td>
</tr>
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</table>
2.2. Cavern Model

2.2.1. Cavern geometry and layout

Existing Caverns

The cavern shapes and locations vary widely as shown in Figure 2 and Figure 3. Since the three caverns planned for the expansion, the six existing SPR caverns and eighteen other caverns may have structural interactions, a model including all caverns in the dome was used to investigate the SPR structural behavior.

Table 4 lists the geotechnical parameters for the existing twenty-four caverns [Neal et al., 1993; Stein, 2005]. The X- and Y-coordinates of the center of each cavern were calculated by subtracting Universal Transverse Mercator (UTM) coordinates of the center of the dome listed in Table 1 from UTM coordinates of each cavern. That is, the origin of the coordinates system used in the modeling is the center of the dome.

Expansion Caverns

Table 5 lists the geotechnical parameters for the three caverns planned for the expansion [Lord et al., 2009]. Caverns 103 and 104 have the same size and will be leached at the same elevation. Their height will be 2000 ft with the roof elevation of -2500 ft. The initial diameter will be 215 ft which will be increased to 305 ft after five drawdowns. In practice, SPR caverns are designed to have a shaped roof, even though they are classified as cylindrical after 5 drawdowns. While modeled as flat horizontal roofs and floors in this study, the caverns will be leached with a tapered roof area that results in a domed or conical roof to enhance stability. Design criteria for DOE caverns are governed by a requirements document [DOE, 2001].

Cavern 102, the converted UTP cavern, will have a height of 2700 ft from its original elevation and an initial diameter of 250 ft. The diameter will be enlarged to 355 ft after five drawdowns. DOE plans on leaching the existing cavern to create enough volume to accommodate 10 MMB more storage. The lower portion of the cavern may not be enlarged as modeled. Therefore, the simulated geometry of Cavern 102 is conservative.
Table 4: Geometric parameters for the existing 24 caverns [Neal et al., 1993; Stein, 2005].

<table>
<thead>
<tr>
<th>Cavern Number</th>
<th>X coordinate of center</th>
<th>Y coordinate of center</th>
<th>Initial gross volume</th>
<th>Gross volume after 5 drawdowns</th>
<th>Elevation of cavern top</th>
<th>Elevation of cavern bottom</th>
<th>Cavern height</th>
<th>Initial diameter</th>
<th>Diameter after 5 drawdowns</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ft</td>
<td>ft</td>
<td>MMB</td>
<td>MMB</td>
<td>ft</td>
<td>ft</td>
<td>ft</td>
<td>ft</td>
<td>ft</td>
</tr>
<tr>
<td>Cavern 1</td>
<td>-1002</td>
<td>-27</td>
<td>8.4</td>
<td>N/A</td>
<td>-950</td>
<td>-1810</td>
<td>860</td>
<td>250</td>
<td>N/A</td>
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<tr>
<td>Cavern 2</td>
<td>-817</td>
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<td>-715</td>
<td>-1590</td>
<td>875</td>
<td>260</td>
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<tr>
<td>Cavern 3</td>
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<td>N/A</td>
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<td>-1875</td>
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<td>200</td>
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<tr>
<td>Cavern 4</td>
<td>-212</td>
<td>12</td>
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<td>-620</td>
<td>-1710</td>
<td>1090</td>
<td>280</td>
<td>N/A</td>
</tr>
<tr>
<td>Allied 6</td>
<td>-192</td>
<td>1353</td>
<td>0.8</td>
<td>N/A</td>
<td>-1195</td>
<td>-1562</td>
<td>367</td>
<td>126</td>
<td>N/A</td>
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<tr>
<td>Cavern 7</td>
<td>-786</td>
<td>1679</td>
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<td>N/A</td>
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<tr>
<td>Cavern 8</td>
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<td>N/A</td>
</tr>
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<td>912</td>
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<td>N/A</td>
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<tr>
<td>Cavern 11</td>
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<td>521</td>
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<td>N/A</td>
<td>-1030</td>
<td>-1800</td>
<td>770</td>
<td>280</td>
<td>N/A</td>
</tr>
<tr>
<td>Cavern 13</td>
<td>-1241</td>
<td>969</td>
<td>4.3</td>
<td>N/A</td>
<td>-1103</td>
<td>-1880</td>
<td>777</td>
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<td>N/A</td>
</tr>
<tr>
<td>Cavern 15</td>
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<td>669</td>
<td>16.5</td>
<td>33.1</td>
<td>-2605</td>
<td>-3296</td>
<td>691</td>
<td>412</td>
<td>585</td>
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<tr>
<td>Cavern 16</td>
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<td>-675</td>
<td>10.5</td>
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<td>-3228</td>
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<td>N/A</td>
</tr>
<tr>
<td>Cavern 17</td>
<td>573</td>
<td>736</td>
<td>12.2</td>
<td>24.5</td>
<td>-2600</td>
<td>-4023</td>
<td>1423</td>
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<td>350</td>
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<td>2094</td>
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<td>346</td>
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<tr>
<td>Cavern 19</td>
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<td>12.7</td>
<td>25.5</td>
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<td>-4228</td>
<td>1293</td>
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<td>375</td>
</tr>
<tr>
<td>Cavern 20</td>
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<td>9.2</td>
<td>18.5</td>
<td>-3830</td>
<td>-4225</td>
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<td>514</td>
<td>578</td>
</tr>
<tr>
<td>Allied 24</td>
<td>664</td>
<td>-798</td>
<td>5.6</td>
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<td>-4373</td>
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<tr>
<td>Allied 25</td>
<td>451</td>
<td>-1167</td>
<td>7.1</td>
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<td>N/A</td>
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<tr>
<td>Cavern 26</td>
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<td>0.7</td>
<td>N/A</td>
<td>-3076</td>
<td>-3470</td>
<td>394</td>
<td>113</td>
<td>N/A</td>
</tr>
<tr>
<td>Cavern 101</td>
<td>-951</td>
<td>-325</td>
<td>13.1</td>
<td>26.3</td>
<td>-2550</td>
<td>-4830</td>
<td>2280</td>
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<td>287</td>
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<tr>
<td>Cavern 102</td>
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<td>270</td>
<td>4.2</td>
<td>N/A</td>
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<td>-5340</td>
<td>2700</td>
<td>105.5</td>
<td>N/A</td>
</tr>
<tr>
<td>Allied 11</td>
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<td>1682</td>
<td>0.8</td>
<td>N/A</td>
<td>-2854</td>
<td>-3945</td>
<td>1091</td>
<td>70</td>
<td>N/A</td>
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<tr>
<td>Allied N1</td>
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<td>1686</td>
<td>0.5</td>
<td>N/A</td>
<td>-2670</td>
<td>-3590</td>
<td>920</td>
<td>62</td>
<td>N/A</td>
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<tr>
<td>UTP 1</td>
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<td>1.4</td>
<td>N/A</td>
<td>-2360</td>
<td>-3502</td>
<td>1142</td>
<td>94</td>
<td>N/A</td>
</tr>
</tbody>
</table>

†: Elevation from the surface.

Table 5: Geometric parameters for three caverns planned for the expansion [Lord et al., 2009].

<table>
<thead>
<tr>
<th>Cavern Number</th>
<th>X coordinate of center</th>
<th>Y coordinate of center</th>
<th>Initial gross volume</th>
<th>Gross volume after 5 drawdowns</th>
<th>Elevation of cavern top</th>
<th>Elevation of cavern bottom</th>
<th>Cavern height</th>
<th>Initial diameter</th>
<th>Diameter after 5 drawdowns</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ft</td>
<td>ft</td>
<td>MMB</td>
<td>MMB</td>
<td>ft</td>
<td>ft</td>
<td>ft</td>
<td>ft</td>
<td>ft</td>
</tr>
<tr>
<td>Cavern 102</td>
<td>-1169</td>
<td>270</td>
<td>23.6</td>
<td>47.5</td>
<td>-2640</td>
<td>-5340</td>
<td>2700</td>
<td>250</td>
<td>355</td>
</tr>
<tr>
<td>Cavern 103</td>
<td>-1469</td>
<td>290</td>
<td>12.9</td>
<td>26.0</td>
<td>-2500</td>
<td>-4500</td>
<td>2000</td>
<td>215</td>
<td>305</td>
</tr>
<tr>
<td>Cavern 104</td>
<td>-937</td>
<td>-1010</td>
<td>12.9</td>
<td>26.0</td>
<td>-2500</td>
<td>-4500</td>
<td>2000</td>
<td>215</td>
<td>305</td>
</tr>
</tbody>
</table>
2.2.2. Model history (Scenarios 1 and 2)

The drill dates of the existing caverns varied from 1934 to 1990. The last sonar measurements to
determine the cavern shapes were taken between 1977 and 1993 [Hogan, 1980; Neal et al., 1993].
To simplify the model history for the purposes of the present simulation, it is assumed that all
existing caverns were initially leached in 1987. This is considered time $t = 0$ years. After that,
leaching to expand Cavern 102 will start at 21 years and will be completed one year later at 22
years. The initial leaching of Caverns 104 and 103 will start at 22 years and 23 years,
respectively. The leaching process will require one year to complete. Figure 4 shows the time
sequence of the initial cavern leaches, the expansion leaches, and the five times drawdown
leaches used in the simulation.

![Figure 4: The time sequence for the simulation.](image)

The analysis simulates caverns that were leached to full size over a one year period by means of
gradually switching from salt to fresh water in the caverns. It was assumed that the SPR caverns
were filled with petroleum and non-SPR caverns were filled with brine at year one after their
initial leaches start. The existing caverns are simulated as creeping for thirty years. Cavern 102 is
permitted to creep for nine years after completion of leaching in year 22. Caverns 104 and 103
are allowed to creep for eight and seven years, respectively, after their initial leaching cycles are
completed in years 23 and 24, respectively. The simulation will then perform oil drawdowns in
the SPR caverns.

Every five years after the 31st year from the beginning of the simulation, every SPR cavern is
modeled as being instantaneously leached. Modeling of the drawdown process of the caverns is
performed by deleting elements along the walls of the caverns so that the volume is increased by
15% over the current volume after creep closure has occurred with each leach. Leaching is
assumed to occur uniformly along the entire height of the cavern. However, leaching is not
permitted in the floor or roof of the caverns. The 5-year period between each drawdown allows
the stress state in the salt to return to a steady-state condition, as will be evidenced in the
predicted closure rates. The simulation will continue until the 5th drawdown is completed to
investigate the structural behavior of the dome for a total of 56 years. Creep closure will be
allowed to occur in all caverns during the simulation period.

The pressure conditions applied to the caverns are based on average wellhead pressures listed in
Table 6. Using Cavern 15 as an example, the cavern is operated over a range of pressures from
815 to 990 psi under normal conditions. The pressure starts at 815 psi, then, due to creep closure
and thermal expansion of fluids, the pressure gradually rises to 990 psi. At that time the brine is
removed from the cavern to reduce the pressure down to 815 psi again. Thus, on average, a
pressure of 903 psi is used for Cavern 15 as the operating wellhead pressure under normal
In the same manner, the pressures of 903, 715, 925, 850, and 913 psi are used for the normal operating wellhead pressures of Caverns 17, 18, 19, 20, and 101, respectively [Park et al., 2006]. It is assumed that the normal operating wellhead pressures of expansion caverns 102, 103, and 104 are the same as that of Cavern 101 because the casing seat depths of the new caverns will be approximately the same.

Table 6: Range of operating pressures measured at the wellhead for SPR caverns at Bayou Choctaw.

<table>
<thead>
<tr>
<th>Cavern</th>
<th>Operating Pressure Range (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low</td>
</tr>
<tr>
<td>Cavern 15</td>
<td>815</td>
</tr>
<tr>
<td>Cavern 17</td>
<td>815</td>
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<tr>
<td>Cavern 18</td>
<td>690</td>
</tr>
<tr>
<td>Cavern 19</td>
<td>900</td>
</tr>
<tr>
<td>Cavern 20</td>
<td>825</td>
</tr>
<tr>
<td>Cavern 101</td>
<td>825</td>
</tr>
<tr>
<td>Cavern 102</td>
<td>-</td>
</tr>
<tr>
<td>Cavern 103</td>
<td>-</td>
</tr>
<tr>
<td>Cavern 104</td>
<td>-</td>
</tr>
</tbody>
</table>

In general, the SPR caverns are most susceptible to structural instability when a workover is in progress. In this analysis, the workover is simulated by means of an internal pressure change in the SPR caverns. Modeling of the workover processes is used to investigate the structural stability of the caverns. As mention in our previous report [Park et al., 2006], workover durations for the existing five SPR caverns are approximately 1 month. This is referred to as Scenario 1, as described in more detail below. Workover durations of three months were used for the West Hackberry (WH) and Big Hill (BH) analyses [Ehgartner and Sobolik, 2002; Park et. al, 2005]. A longer duration was used to capture creep during the times not modeled when cavern pressures are intermediate to normal operating conditions and workover pressures. To investigate the effect of the workover duration, an alternative model history is considered as Scenario 2.

Caverns 15 and 17 are currently operated as a gallery, maintaining equal pressures at all times, including during the workover periods. Rather than complicating the analyses, the following assumptions were made for Scenarios 1 and 2. Figure 5 and Figure 6 show the wellhead histories of each SPR cavern for Scenarios 1 and 2 respectively.

**Scenario 1:**

- A constant pressure is applied for the majority of the time, with pressure drops periodically included.
- For workover conditions, zero wellhead pressure is used.

---

3 “Workover” is when the wellhead pressure in the cavern is dropped to zero for maintenance.
Caverns 15 and 17 are worked over together one year after switching from brine to petroleum. After that, workovers are performed on Caverns 102, 19, and 18 in order. Then, after 2.2 more years, Caverns 20, 101, 104, and 103, respectively, are worked over one by one. As shown in Figure 4, Caverns 102, 104, and 103 are worked over after the expansion is completed.

Workover durations are 1 month for all caverns.

This workover cycle is repeated every 5 years.

For both normal and workover conditions, the caverns are assumed to be full of oil having a pressure gradient of 0.37 psi/ft of depth.

The pressure due to the oil head plus the wellhead is applied on the cavern boundary during the normal operation.

Scenario 2:

Scenario 2 is the same as Scenario 1 except for the following:

- After Caverns 15 and 17 have been worked over together, workovers are performed on Caverns 102, 19, 18, 20, 101, 104, and 103 in turn.

- Workovers are performed three months after the workover of the prior cavern.

- Workover durations are 3 months for all caverns.

For the non-SPR caverns, except Cavern 7, a pressure due to brine head and pressure gradient of 0.52 psi/ft is applied on the cavern boundaries. In case of Cavern 7, a pressure gradient of 0.4 psi/ft is applied on the wall and 0.812 psi/ft is applied on the floor and roof to represent the collapsed state of the cavern [Park et al., 2006].
Figure 5: Wellhead histories of each SPR cavern for Scenario 1.

Figure 6: Wellhead histories of each SPR cavern for Scenario 2.
2.3. Thermal Conditions

The finite element model includes a depth-dependent temperature gradient which starts at 84.0°F (28.9°C) at the surface and increases at the rate of 1.38°F/100ft (2.51°C/100m). The temperature profile is based on the average temperature data recorded in well logs from BC prior to leaching [Ballard and Ehgartner, 2000]. The temperature distribution is important because the creep response of the salt is temperature dependent. Radial temperature gradients due to cavern cooling effects from the cavern contents are not considered in these calculations. Previous 2D cavern studies have shown the predicted cavern deformation to be insensitive to the developed radial thermal gradients [Hoffman, 1992]. The FORTRAN script for calculating the temperature at each node is provided in Appendix C.
3. MESH GENERATION

The coordinates of two new caverns, 103 and 104 were changed in the mesh used for our previous analyses [Park and Ehgartner, 2008]. Figure 7 shows an overview of the finite element meshes of the stratigraphy and cavern field at BC. The meshes have been separated to show the individual material blocks. The X-axis of model is in the EW direction, Y-axis is in the NS direction, and Z-axis is the vertical direction. Four material blocks are used in the model for the overburden, caprock, salt dome, and surrounding rocks. The six existing SPR, three expansion SPR, two inactive, seven abandoned, and eight UTP caverns are modeled within the salt dome mesh. The numbers of the two new caverns and one converted cavern are written in blue.

Figure 8 shows the cavern layout within the salt dome and the relative elevation of the caverns. Each SPR cavern is modeled as having five cylindrical layers to be removed to account for the drawdown activities. The shapes of all existing caverns also are simplified as cylindrical shapes using the geometric parameters in Table 4.

Figure 9 shows the idealized mesh for the salt dome and the caprock in the surrounding rock block. An elliptical shape was used as an approximation for the actual shape of the dome. Figure 10 shows the assembled mesh and the boundary conditions. The salt dome is modeled as having fixed far-field boundary conditions. The lengths of the confining boundaries are 24,410 ft in the NS direction and 21,325 ft in the EW direction. These lengths are about five times the major or minor diameter of the salt dome, respectively. This ratio (5) is far better than the generally accepted ratio (3 to 4) between the maximum dimensions/minimum excavation sizes. The model consists of 508,028 nodes and 495,564 elements. The model consists of 13 element blocks, 73 side sets, and 6 node sets. The meshes were created using CUBIT Version 12.0 which is mesh generation software copyrighted by Sandia Corporation. The journal files for the meshes are provided in Appendix C.
Figure 7: Overview of the finite element mesh of the stratigraphy and cavern field at Bayou Choctaw and the cavern geometry within the salt dome. For comparison purposes to show how large the caverns are, a silhouette of the Willis Tower is shown.

Figure 8: Plan view of cavern layout and side view of cavern geometry. Hands are pointing to the two new caverns, 103 and 104, and the expanded Cavern 102.
Figure 9: Mesh for salt dome and caprock (left). The three dimensional representation of the salt dome (right) is from Rautman and Stein [2004].

Figure 10: Finite mesh discretization and boundary conditions at Bayou Choctaw.
4. FAILURE CRITERIA

4.1. Structural Stability of Salt Dome

Potential damage to or around the new and converted SPR caverns was evaluated based on two failure criteria: dilatant damage and tensile failure.

To check for dilatant damage, the dilatancy criterion discussed in our previous analyses [Park et al., 2006] is used;

\[
D = \frac{0.257 \cdot I_1}{\sqrt{J_2}}
\]

where, \( D \) = damage factor

\( I_1 = \sigma_1 + \sigma_2 + \sigma_3 = 3\sigma_m \) : the first invariant of the stress tensor.

\[
\sqrt{J_2} = \sqrt{\frac{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2}{6}}
\]

: the square root of the second invariant of the deviatoric stress tensor

\( \sigma_1, \sigma_2, \sigma_3 \) are the maximum, intermediate, and minimum principal stresses, respectively.

\( \sigma_m \) is the mean stress.

When \( D \leq 1 \), the shear stresses in the salt \( (J_2) \) are large compared to the mean stress \( (I_1) \) and dilatant behavior is expected. When \( D > 1 \), the shear stresses are small compared to the mean stress and dilatancy is not expected. The stability of the caverns may be controlled by weaker dirty salts and the variability in the measured strength and dilatancy values, so a 20% uncertainty in the safety factor is used with this criterion. Therefore an allowable safety factor against dilatancy is assumed to be 1.2 in this study. The web of salt between Caverns 15 and 17 is predicted to have a historical safety factor of 1.2 in this study and the caverns are presently stable.

In addition, in order to check the tensile failure, the tensile strength of the salt is conservatively assumed to be zero. Tensile cracking in rock salt initiates perpendicular to the largest tensile stress direction.

4.2. Allowable Strains for Well and Surface Structures

The physical presence of wells and surface structures are not included in the finite element model, but the potential for ground deformation producing damage in these structures can be conservatively estimated by assuming that they will deform according to the predicted ground deformation.

Subsidence will primarily induce elongation of the axis of the well. Under these conditions, the cemented annulus of the wells may crack, forming a horizontal tensile fracture that may extend around the wellbore. Vertical fluid migration is not expected under these conditions, however
horizontal flow could occur. The allowable axial strain for purposes of this study is assumed to be 2 millistrain in compression and 0.2 millistrain in tension [Thorton and Lew, 1983]. The benefit of the steel casings in reinforcing the strength of the cement, especially under elongation, is not accounted for in this evaluation. The 2 millistrain limit is also representative of the typical yield point for steel casings in the SPR.

Structural damage on the surface is typically caused by the accumulation of large surface strains due to subsidence. These strains can cause distortion, damage, and failure of infrastructure such as buildings, pipelines, roads, and bridges. Surface strains will accumulate in structures over time, which increases the possibility of damage in older facilities. For purposes of this study, the allowable strain is taken to be 1 millistrain for both compression and tension.
5. COMPUTER CODES AND FILE NAMING CONVENTION

5.1. Computer Codes

The finite element code JAS3D [Blanford, 2001] is used in the present calculations. Two material models were chosen for use in the analyses: an elastic model for the overburden material (sand), caprock, and sandstone; and a power law creep model for the salt. Related preprocessing, mesh generation, and post processing codes were used in conjunction with JAS3D. Sandia Corporation copyrights the mesh generation software CUBIT Version 12.0. Applicable software and version numbers used in this analysis are listed in Table 7. A number of commercial off-the-shelf software programs, including MathCAD®, Excel®, Visio®, CorelDRAW®, or Corel Paint Shop Pro X® running on MS Windows XP®-based PC workstations, were also utilized.

Table 7: Applicable software and version number

<table>
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<tr>
<th>Code Name</th>
<th>Version</th>
<th>Use</th>
</tr>
</thead>
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<td>2.07</td>
<td>Preprocessor</td>
</tr>
<tr>
<td>CUBIT</td>
<td>12.0</td>
<td>Mesh generation</td>
</tr>
<tr>
<td>EMERGE</td>
<td>1.50</td>
<td>Adds temperature to the mesh</td>
</tr>
<tr>
<td>JAS3D</td>
<td>2.4C</td>
<td>FEM solver</td>
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<td>ALGEBRA2</td>
<td>1.30</td>
<td>Postprocessor</td>
</tr>
<tr>
<td>BLOT II-2</td>
<td>1.66</td>
<td>Postprocessor</td>
</tr>
</tbody>
</table>

5.2. File Naming Convention

These calculations were performed on Sandia National Laboratories (SNL) HP PROLIANT DL360 G5 workstation (SEALS), using the operating system Redhat kernel version 2.6. All files are move to ‘Red Sky’ which is a scientific, engineering and high performance computing platform in SNL. The general path for any of these subdirectories is ‘Red Sky: //home/bypark/bc_exp/’. The files related to the mesh generation, the FEM solver, and the volume calculations reside in the subdirectories `~/bc_exp/mesh/`, `~/bc_exp/solv/`, and `~/bc_exp/volc/`. The files related to Scenario 1 and Scenario 2 are located in the subdirectories of `~/bc_exp/solv/scn1/` and `~/bc_exp/solv/scn2/`. All the files that remain within each subdirectory are listed and described in Table 8. Input Files are files that should be obtained from SEALS in order to run the programs; Intermediate Files are created during the execution; Output files are created as a result of execution and which are stored in SEALS. Intermediate files are typically output files created by one program and used as input to another program. Table 8 also lists the names of the user-defined subroutines, and the names of any executables needed to run the entire analysis from grid generation through post processing. JAS3D input files; user-supplied subroutines to provide an internal pressure state in the caverns; FORTRAN scripts for calculating the temperature at each node; CUBIT journal files for mesh generation; user-supplied subroutines to calculate the volume change of each caverns; and ALGEBRA scripts for
computing the subsidence, principal stresses, and safety factor against dilatant damage are provided in Appendices A, B, C, D, E, and F, respectively.

**Table 8: File naming convention for expansion calculations of strategic petroleum reserve caverns in the Bayou Choctaw salt dome (* means wild card)**

<table>
<thead>
<tr>
<th>File Names</th>
<th>Description</th>
<th>Appendix provided in</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Input Files</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BC_26cav5l_*.jou</td>
<td>CUBIT journal file for mesh generation</td>
<td>Appendix D</td>
</tr>
<tr>
<td>bc_26cav5l.g0</td>
<td>3D GENESIS mesh generated using CUBIT</td>
<td></td>
</tr>
<tr>
<td>bc_26cav5l.g</td>
<td>3D GENESIS mesh contains the temperature data at each node and used for the execution of JAS3D</td>
<td></td>
</tr>
<tr>
<td>bc_26cav5l.nod</td>
<td>ASCII node data of coordinates</td>
<td></td>
</tr>
<tr>
<td>emerge.inp</td>
<td>Emerge input file for merging the temperature data onto the mesh</td>
<td></td>
</tr>
<tr>
<td>spr_bc*.alg</td>
<td>ALGEBRA script for computing the subsidence, principal stresses, safety factor against dilatant damage, safety factor for shear failure</td>
<td>Appendix F</td>
</tr>
<tr>
<td>bc_26cav5*.i</td>
<td>JAS3D input files</td>
<td>Appendix A</td>
</tr>
<tr>
<td><strong>Intermediate Files</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>bc_26cav5l.th</td>
<td>Binary temperature data of each node</td>
<td></td>
</tr>
<tr>
<td>tempz_bc_26cav5l.f</td>
<td>FORTRAN file for calculating the temperature at each node</td>
<td>Appendix C</td>
</tr>
<tr>
<td>*.blk</td>
<td>BLK file for compiling FORTRAN files</td>
<td></td>
</tr>
<tr>
<td>usrpbc_26cav5l.o</td>
<td>Objective file from compiling FORTRAN file</td>
<td></td>
</tr>
<tr>
<td><strong>User Defined Subroutines</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>usrpbc_26cav5*.f</td>
<td>User-supplied subroutine to provide an internal pressure state in the caverns</td>
<td>Appendix B</td>
</tr>
<tr>
<td>volcav.f</td>
<td>User-supplied subroutine to calculate the volume change of each cavern as a function of time</td>
<td>Appendix E</td>
</tr>
<tr>
<td><strong>Output files</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>temp_check.dat</td>
<td>ASCII data for checking the temperature at each node</td>
<td></td>
</tr>
<tr>
<td>*.ps</td>
<td>Post script file</td>
<td></td>
</tr>
<tr>
<td>26cav5l_bc_smax_mindil_*.dat</td>
<td>ASCII data of the principal stresses, safety factor against dilatant damage</td>
<td></td>
</tr>
<tr>
<td>bc_26cav5*.e</td>
<td>EXODUS output files</td>
<td></td>
</tr>
<tr>
<td>bc_26cav5*.ea</td>
<td>EXODUS output files manipulated using ALGEBRA script</td>
<td></td>
</tr>
<tr>
<td>volcav.csv</td>
<td>Excel output from the volume calculation of caverns with time</td>
<td></td>
</tr>
<tr>
<td>bc_26cav5*.o</td>
<td>ASCII output file</td>
<td></td>
</tr>
<tr>
<td>*.log</td>
<td>Log file during execution</td>
<td></td>
</tr>
<tr>
<td><strong>Executables</strong></td>
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<td></td>
</tr>
<tr>
<td>a.out</td>
<td>Calculates the temperature at each node</td>
<td></td>
</tr>
<tr>
<td>jas3d</td>
<td>Baseline</td>
<td></td>
</tr>
<tr>
<td>Makefile</td>
<td>Commands to compile volcav.f</td>
<td></td>
</tr>
<tr>
<td>volcav</td>
<td>Calculates the volume change of each cavern with time</td>
<td></td>
</tr>
<tr>
<td>volcav.run</td>
<td>Commands to run volcav</td>
<td></td>
</tr>
</tbody>
</table>
6. ANALYSES RESULTS

6.1. Cavern Deformation

Creep closure decreases cavern volume over time and is more pronounced near the bottom of the caverns. The flow of salt can be illustrated by displacement vectors at each node. Figure 11 shows the deformed cavern shapes and displacement vectors around the expansion SPR caverns at 31 years. The salt flows are primarily downward near the roofs of the caverns, upward near the floors, and lateral in the pillar. The largest displacements occur in the floors of the caverns. The predicted displacements in the center of the floor are more than twice those predicted near the edge of the floor. This produces an upward curvature in the floor. Lateral salt deformation causes the cavern walls to move inward over time.

Figure 11: Displacement vectors around Caverns 102, 103, and 104 at 31 years for Scenario 1.
Figure 12 shows the quantified vertical displacements contours around the new and converted SPR caverns at 31 years. Positive displacements are directed upward.

Note that the numerous black vertical lines in the Figure 11 and Figure 12 are the element edges which are visible because of the cross-sectional cut. The element sides are not necessarily parallel to the cross-sectional cut, which is not flat.

6.2. Storage Loss

Figure 13 and Figure 14 show the predicted total volumetric closure normalized to overall storage volume for the current six SPR caverns before expansion starts at 21 years, then for the six SPR caverns and the three expansion SPR caverns after expansion is completed at 24 years for Scenario 1 and Scenario 2, respectively. Because the current caverns are initially leached at the beginning of the analysis and then the expansion cavern leaches are complete at 24 years,
then again at 31 years and every 5 years thereafter, the percentage of closure is normalized by the volume immediately following each leach.

The rates of decrease for Scenarios 1 and 2 are about 1.5% and 2.0%, respectively for 21 years. These rates are the same as the results from the previous analyses [Park et al., 2006] because the expansion does not start in the present model until 21 years. We also observed the predicted normalized volume closure using Scenario 2 is larger than the one using Scenario 1. The increased normalized volume closure is due to the increased workover duration from one to three months. The impact of workover pressure is also evident in Figure 13 and Figure 14 by the abrupt change in normalized volumetric closures that occur each month (Scenario 1) or every three months (Scenario 2) following leach.

![Graph 13](image1.png)

**Figure 13: Predicted total volumetric closure normalized to overall storage volume for Scenario 1.**

![Graph 14](image2.png)

**Figure 14: Predicted total volumetric closure normalized to overall storage volume for Scenario 2.**
Figure 15 and Figure 16 show the volumetric closure of each cavern normalized by the cavern volume immediately following each leach for Scenario 1 and 2, respectively.

Leaching of Cavern 102 starts at 21 years. Prior to expansion, Cavern 102 is filled with ethane and its wellhead pressure is zero, while the current six SPR caverns contain petroleum with the wellhead pressures as mentioned in Section 2.2.2 in the same period. In addition, the elevation of the bottom of Cavern 102 is deeper than other SPR caverns. Thus the closure rate of Cavern 102 is calculated to be larger than that of the other SPR caverns.

The peaks appear in the graphs of Figures 13 through 16 for each cavern at every 5 years when the wellhead pressures drop down to zero psi during the workovers. The width of peaks depends on the workover duration. The width for Scenario 1 is narrower than for Scenario 2 because the durations are one month and three months for Scenarios 1 and 2, respectively.

In this study, attention will be focused on the two new caverns and the one converted cavern. Even though the initial volumes of Caverns 103 and 104 are exactly the same, the volumetric closure rate of Cavern 103 is less than that of Cavern 104 perhaps due to its closer proximity to the dome edge.

Figure 15: Normalized volumetric closure of each cavern with time for Scenario 1.

Figure 16: Normalized volumetric closure of each cavern with time for Scenario 2.
6.3. Subsidence

The subsidence above the central axis of each SPR cavern is plotted as a function of time in Figure 17. The magnitude of subsidence slowly increases with time as a result of creep and increasing cavern size. The subsidence above Caverns 15 and 18 is larger than that above the other caverns. The locations of these caverns are near the center of the dome (Figure 8). This suggests that the amount of subsidence depends on the location at which the subsidence is calculated, and subsidence contributed by other caverns is compounded. The subsidence rate increases after expansion is completed at 24 years. The additional creep closure in Caverns 102, 104, and 103 increases the subsidence on the surface. The subsidence for Scenario 2 is larger than for Scenario 1 because the closure duration due to the workover for Scenario 2 (3 months) is longer than for Scenario 1 (1 month).

Figure 18 shows the calculated surface strains at 21 years and 56 years for Scenario 1. The accumulated strain is below the limiting value of 1 millistrain and thus structural damage should not occur. There is no marked increase in surface strains due to the expansion at 21 years.

![Figure 17: Predicted subsidence on the surface near the center of SPR caverns.](image1)

![Figure 18: Predicted radial surface strains at 21 years and 56 years for Scenario 1.](image2)
6.4. Cavern Wells

The calculated vertical ground strains around the roofs of Caverns 102 and 103 during workover of Cavern 102 after the initial leach (left) and the 5th drawdown leach (right) for Scenario 1 are shown in Figure 19. Figure 20 also shows the calculated vertical ground strains around the roofs of Caverns 103 and 104 during workovers of Caverns 104 (left) and 103 (right) after the initial leach (top) and the 5th drawdown leach (bottom) for Scenario 1.

Of interest are the strain magnitudes in the proximity of the cavern wells from the surface to near the cavern roofs. In this report, the steel and cement well components are not modeled, but are assumed to bear the predicted ground strains in the vertical direction. Well casings typically extend from the surface to about 100 ft above the cavern roof. The collapse strength of the steel component of a well is reduced as the casing stretches. In general, steel will not yield until about 2 millistrain. Also, fracturing in the cement surrounding the steel is thought to occur for tensile strains greater than 0.2 millistrain. Therefore, predicted strains near the cavern wells larger than 0.2 millistrain in tension are predicted to cause failure in the cement. Only the lower sections of the cemented casing are affected, and failure does not extend to the top of salt.

The salt strains in the well sections more than 100 ft above the cavern roofs of Caverns 104, 103, and 102 during their workovers after both the initial leach and 5th drawdown leach are predicted to be larger than 2 millistrain. However, it is not necessarily proven that the steel in the casing will actually undergo yield since that was not modeled. Factors that may influence whether yield occurs include being right at the yield point; the steel and cement resisting salt creep; a loss of adhesion between the casing, cement, and/or the salt; and the variation in salt properties. Therefore, even though the strains above the roofs are larger than the yield limit, the steel casing may not experience large deformations. In reality, slippage may occur along the cement interfaces and strains may localize at casing joints. Under such conditions, thread jump or collar breakage could occur at lower ground strains than assumed in this report. Therefore, we need to keep an eye on the field situation. If possible, we need to monitor the casing deformation above the SPR caverns with time and compare with the analysis result.

The ground strain contours derived from the previous analyses for the candidate caverns A and M [Park and Ehgartner, 2008] predicted a similar phenomenon as shown Figure 21 and Figure 22. Therefore, we may not say the locations of Caverns A and M are better than the location of Caverns 103 and 104 from a cavern well view point. Again, the vertical lines in the plots are the edges of the model elements, as mentioned in Section 6.1. Note that the positive value of strain indicates tensile strain.
Figure 19: Vertical strain contours around Caverns 102 and 103 during workover of Cavern 102 after the initial leach (left) and the 5th drawdown leach (right) for Scenario 1.

Figure 20: Vertical strain contours around Caverns 103 and 104 during workovers of Caverns 104 (left) and 103 (right) after the initial leach (top) and the 5th drawdown leach (bottom) for Scenario 1.
Figure 21: Vertical strain contours around Caverns M and 102 during workovers of Caverns M (left) and 102 (right) after the initial leach (top) and the 5th drawdown leach (bottom) for Scenario 1 derived from the previous analyses by Park and Ehgartner [2008].

Figure 22: Vertical strain contours around Cavern A and 19 during workover of Cavern A after the initial leach (left) and the 5th drawdown leach (right) for Scenario 1 derived from the previous analyses by Park and Ehgartner [2008].
6.5. Cavern Stability

As mentioned in Section 4.1, the stability of the caverns is evaluated by examination for any tensile stresses and by calculation of the safety factors against dilatant damage.

6.5.1. Minimum compressive stress

Figure 23 and Figure 24 show the minimum compressive stress\(^4\) (MCS) histories for Scenarios 1 and 2, respectively. The MCS in the entire salt dome is calculated to be -207 psi at 1 year when the brine in the SPR caverns was switched to oil. The negative sign (-) indicates a compressive stress. The most critical location is always found to be in the top of the salt dome because of earth pressure. The MCS in the upper part of the dome are not problematic. All SPR caverns are located below 2000 ft. In Figure 23 and Figure 24, ‘Below 2000 ft’ means that the data above 2000 ft is screened out to show the detailed change of MCS below that elevation near SPR caverns.

Figure 25 and Figure 26 show the MCS histories in the elements within 130 ft of Caverns 15, 17, 18, 102, 104, and 103 for Scenario 1 or 2, respectively. The web between Caverns 15 and 17 is the weakest spot as shown in Figure 27. However, the MCS is still less than 0, thus tensile failure is not predicted to occur in the web until the 5\(^{th}\) leach is complete. This analysis assumes Caverns 15 and 17 are operated as a gallery, therefore large differential pressures do not exist across the web of salt separating the caverns.

Figure 28 shows the MCS around Caverns 102 and 103 when the smallest compressive stress is predicted, i.e. during workover of the caverns. The MCS in the roof of caverns is larger than that at other locations. Figure 29 shows the MCS around Caverns 103 and 104 at 49.83 years that is during workover of Cavern 103 after the 4\(^{th}\) leach. The MCS around the caverns appears to be low enough to be structurally safe.

All stresses were found to be compressive. Thus, all caverns are predicted to be structurally stable against tensile failure throughout the entire simulation time. From a compressive stress stability viewpoint, based on this analysis, the roofs of the caverns appear to be the areas of greater concern than the webs between the caverns except the web between Caverns 15 and 17.

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\(^4\) The compressive stresses are calculated in every element in the salt dome at each time step. The minimum compressive stress means the minimum value among the stresses in every element in a specific volume at a specific time.
Figure 23: Minimum compressive stress history for Scenario 1.

Figure 24: Minimum compressive stress history for Scenario 2.
Figure 25: Minimum compressive stress history in the elements within 130 ft of cylindrical Caverns 15, 17, 18, 102, 103 and 104 (Scenario 1).

Figure 26: Minimum compressive stress history in the elements within 130 ft of cylindrical Caverns 15, 17, 18, 102, 103 and 104 (Scenario 2).
Figure 27: Compressive stress contours during workover of Caverns 15 & 17 after 5 leaches for Scenario 2, vertical cross-section through the centers of caverns (left) and horizontal cross-section at the elevation where the minimum compressive stress occurs (right). The blue lines show where the mesh was cut.

Figure 28: Compressive stress contours around Caverns 102 and 103 during workover of each cavern at 47.17 years and 49.83 years for Scenario 1.
6.5.2. Safety factor against dilatant damage

The minimum safety factor\(^5\) histories against dilatancy damage are plotted in Figure 30 and Figure 31 for Scenarios 1 and 2, respectively. For Scenario 1, the dilatant damage factor (DILFAC) is predicted to be 1.20 at 47.08 years. The potential dilatant failure occurs when the DILFAC is 1.2 or less as discussed in Section 4.1.

To examine the location where the failure may occur in the salt dome, DILFAC histories in the elements within 130 ft of Caverns 15, 17, 102, 103 and 104 for Scenario 1 are plotted in Figure 32. A DILFAC of 1.20 is predicted around Caverns 15 and 17 at 47.08 years when the workover on the Caverns 15 and 17 is performed after the 4\(^{th}\) leach (Figure 32 (a)). The DILFAC distribution in the elements within 130 ft of Caverns 15 and 17 during workover of the caverns after the 4\(^{th}\) and 5\(^{th}\) leach for Scenario 1 is provided in Figure 33. Similar to the prediction in our previous analyses [Park et al., 2006], the web between Caverns 15 and 17 is expected to fail during the first workover after the 4\(^{th}\) leach for Scenario 1. The weakest spot in the web of salt appears at approximately three quarters-height of Cavern 17. In the same manner, the web between Caverns 15 and 17 is expected to fail during the first workover after the 5\(^{th}\) leach for Scenario 2 as shown Figure 34.

The DILFACs at 2.03 years, 22.17 years, 24.75 years and 24.83 years are predicted to be closer to 1.2 than at other times for Scenario 1 as shown in Figure 30. These are the times of the first workovers after the initial leach (Figure 5). The first workover after the expansion leach of Cavern 102 is performed at 22.17 years. The lowest safety factor for Cavern 102 is predicted at the time of the first workover after the expansion leach (Figure 32 (b)). The weakest spot against dilatant damage appears around Cavern 102, but not in the vicinity of Caverns 15 and 17 at this

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\(^5\) The safety factors are calculated in every element in the salt dome at each time step. The minimum safety factor means the minimum value among the safety factors in every element at a specific time.
The location of the minimum DILFAC is predicted at the upper wall near the roof of the cavern (Figure 35 (a)). This suggests that the first workover after the expansion of Cavern 102 needs to be performed more carefully than other workovers. In the same manner, the lowest safety factors for Caverns 103 and 104 are predicted at the first workovers after the initial leach as shown in Figure 32 (c) and (d), respectively. Figure 35 (b) and Figure 36 show the DILFAC contours around Caverns 103 and 104, respectively. Again, the weakest spot appears in the upper wall near the roof. The DILFACs at the weakest spot of Caverns 102, 104, and 103 are larger than 1.2, i.e. Cavern 102, 104, and 103 are considered structurally safe for the expansion from the dilatancy point of view.

The web of salt between Caverns 15 and 17 has the lowest predicted safety factor of the caverns in the dome as predicted in our previous analysis [Park et al., 2006]. The minimum safety factor values for dilatant damage for Scenario 2 are larger than that for Scenario 1 (Figure 31 and Figure 34), i.e. a duration of three months for the workover is safer than a duration of one month. All safety factors in the elements within 130 ft of Caverns 103, 102, and 104 were found to be larger than 1.2. Thus, Caverns 104, 103, and 102 appear to be structurally stable against dilatant damage throughout the entire simulation time. This suggests that Caverns 103 and 104 can be safely leached and Cavern 102 can be safely converted in the BC salt dome. The planned locations of Caverns 103 and 104 are found to have no problem from a structural stability viewpoint according to this analysis.

![Figure 30: Minimum safety factor history against dilatant damage for Scenario 1.](image-url)
Figure 31: Minimum safety factor history against dilatant damage for Scenario 2.

Figure 32: Minimum safety factor history against dilatant damage in the elements within 130 ft of Caverns 15, 17, 102, 103 and 104 for Scenario 1.
Figure 33: Safety factor contours against dilatant damage during workover of Caverns 15 and 17 after 4th (left) and 5th (right) leach, respectively, for Scenario 1 on the horizontal cross-section at the elevation where the minimum compressive stress occurs.

Figure 34: Minimum safety factor history against dilatant damage in the elements within 130 ft of Caverns 15, 17, 102, 103 and 104 for Scenario 2.
Figure 35: Safety factor contours against dilatant damage around Caverns 102 and 103 during workover of each cavern at 22.17 years and 24.83 years for Scenario 1.

Figure 36: Safety factor contours against dilatant damage during first workover of Cavern 103 after the initial leach for Scenario 1. Vertical cross-section through the centers of Caverns 103 and 104 (left) and horizontal cross-section at the elevation where the minimum safety factor occurs (right). The blue lines show where the mesh was cut.
7. SUMMARY AND CONCLUDING REMARKS

An existing three dimensional FEM mesh from our previous analyses [Park and Ehgartner, 2008] was modified to change the locations of two new caverns. The structural stability for the BC dome was evaluated based on the failure criteria for dilatant damage and tensile failure. Two scenarios were used for the duration and timing of workover conditions. The impacts of the expansion of three caverns on underground creep closure, surface subsidence, infrastructure, and well integrity were investigated.

Overall

The additional three SPR caverns considered for expansion along with the extant caverns in the dome are predicted to be structurally stable against tensile failure for both Scenarios 1 and 2. Dilatant failure is not expected to occur within the vicinity of the three expansion caverns. However, the web between Cavern 15 and 17 is predicted to fail when the workover on the caverns is performed after the 4th drawdown for Scenario 1 and the 5th drawdown for Scenario 2. This is the same prediction as in our previous analysis before the expansion. Damage to surface structures was not predicted because there was not a predicted marked increase in surface strains due to the addition of the three caverns. The predicted strains near the cavern wells larger than 0.2 millistrain in tension are predicted to cause failure in positions of the cement above the casings seat. The predicted strains over 100 ft above the cavern roofs of Caverns 104, 103, and 102 at 31 and 56 years are larger than 2 millistrain. However, it is not necessarily proven that the steel in the casing will actually undergo yield since that was not modeled. Factors that may influence whether yield occurs include being right at the yield point; the steel and cement resisting salt creep; a loss of adhesion between the casing, cement, and/or the salt; and the variation in salt properties. Therefore, even though the strains above the roofs are larger than the yield limit, the steel casing may not experience large deformations. The expansion does not make the structural stability of the existing caverns worse. Finally, the simulations show that from a structural viewpoint, the proposed locations of the two new caverns are acceptable, and the three expansion caverns can be safely constructed and operated. However, because salt strength is known to vary, mechanical testing should be performed on core extracted from the new cavern well locations.

Workover duration and timing effect

The minimum safety factor values against dilatant damage for workover Scenario 2 are predicted to be larger than that for Scenario 1. This suggests that the workover sequence simulating three month durations would be better than the scenario where the duration was one month, which is counter-intuitive. While the workover sequence was the same for the caverns, the timing of the workover and the duration of the workovers had an influence on the safety factors computed in this study. These two scenarios were examined because actual cavern pressure histories were not simulated, but future operational pressures and conditions can only be estimated.

Others

The results show that the first workover after the initial or expansion caverns are leached needs to be performed more carefully than other subsequent workovers because the lowest safety factor against the dilatancy for Cavern 103 and 104 are predicted at the first workovers after leaching.
Also, the lowest safety factor for Cavern 102 is predicted during the first workover after conversion to an expansion cavern.

In comparison to previous expansion cavern locations considered, the minimum safety factor against dilations are virtually the same [Park and Ehgartner, 2008].
8. REFERENCES


Stein, J.S., 2005, *RE: Data of Bayou Choctaw*, E-mail to B.Y. Park dated July 11, 2005, Sandia National Laboratories, Carlsbad, NM.


APPENDIX A: INPUT FOR JAS3D

Scenario 1

title
SPR Bayou Choctaw Exp. A3 and S, 26cavS1_scn1 (BC salt, SMF=(SMF=0.12), E4=(E4=35e9), WHP=each)

$Material Properties$
$Salt (Material 1):
$ Young's Modulus={E1=31.0E9}(Krieg, 1984)$
$ Density={rho1=2300.}, Poisson's Ratio={nu1=0.25}(Krieg, 1984)$
$ Bulk Modulus={K1=E1/(3.*(1.-2.*nu1))}, Shear Modulus={mu1=E1/(2.*(1.+nu1))}$
$ Creep Constant={A=5.79e-36}, Stress Exponent={n=4.9}$
$ Thermal Constant={Q=12.0E3}(Krieg, 1984), Universal gas constant={R=1.987}$
$ Salt Reduction Factor={RF=12.5} (Morgan and Krieg, 1988)$
$ Structure Factor Multiplication Factor={SMF}(Adjusted through back analysis)$

$Caprock (Material 2):$
$ Young's Modulus={E2=1.572E10}(Hogan, R. G., SAND80-7140)$
$ Density={rho2=2319.}, Poisson's Ratio={nu2=0.288}(Hogan, R. G., SAND80-7140)$

$Overburden (Material 3):$
$ Young's Modulus={E3=0.1E9}(Hoffman and Ehgartner, 1993)$
$ Density={rho3=1874.}, Poisson's Ratio={nu3=0.33}(Hoffman and Ehgartner, 1993)$

$Surrounding Rock (Material 4):$
$ Young's Modulus={E4}(Carmichael, 1984)$
$ Density={rho4=2500.}, Poisson's Ratio={nu4=0.33}(Lama and Vutukuri, 1978)$

$SECDAY = {SECDAY=86400.} s$
$DAYMON = {(DAYMON=30.416666666666666667)} days
$DAYYR = {(DAYYR=365.)} days$
$SECMON = {(SECMON=SECDAY*DAYMON)} s
$SECYR = {(SECYR=SECDAY*DAYYR)} s$
$SECCEN = {(SECCEN=SECDAY*SECDAY)} s
$SECMIL = {(SECMIL=SECDAY*SECDAY*SECDAY)} s

Initial leaches start
$SECST = {SECST=0.} s$ (SECST/SECYR) years

Time at the expansion leach for Cavern 102 starts
$SECL102 = {(SECL102=SECST+21.*SECDAY)} s$ (SECL102/SECDAY) years

Time at the initial leach for Caverns A and M start
$SECI A = {(SECI A=SECL102+1.*SECST)} s$ (SECI A/SECDAY) years

Time at the leaches for all SPR caverns start
$SECST = {(SECST=SECST+31.*SECDAY)} s$ (SECST/SECDAY) years
$SECST2 = {(SECST2=SECST+5.*SECDAY)} s$ (SECST2/SECDAY) years
$SECST3 = {(SECST3=SECST2+5.*SECDAY)} s$ (SECST3/SECDAY) years
$SECST4 = {(SECST4=SECST3+5.*SECDAY)} s$ (SECST4/SECDAY) years
$SECST5 = {(SECST5=SECST4+5.*SECDAY)} s$ (SECST5/SECDAY) years

Time at the simulation completes
$SECEND = {(SECEND=SECST5+5.*SECDAY)} s$ (SECEND/SECDAY) years

start time 0.0
ITERATI ON P R I NT, 20
MAXI M U M I T E R ATI ON, 40000
TARGET TOLERANCE, 0.00005
ACCEPTABLE TOLERANCE, 0.0001
predictor scale factor, 0.0,0.0
Time steps, 1 $1 step=({SECDAY-0.0})/1/SECDAY$ days
PLOT every, 1
print every, 1
write restart frequency, 0
next time (1.*SECDAY) $1 days$
time steps, 9 $1 step=({10.*SECDAY-1.*SECDAY})/9/SECDAY$ days
PLOT every, 9
print every, 9
write restart frequency, 0
next time (10.*SECDAY) $10 days$
time steps, 4 $1 step=({SECMON-10.*SECDAY})/4/SECDAY$ days
PLOT every, 4
print every, 1
write restart frequency, 0
next time (SECMON) $1 month$
time steps, (ITS=12) $1 step=(SECDAY-SECMON)/ITS/SECDAY$ days
PLOT every, (ITS)
print every, (ITS)
write restart frequency, 0
next time (3.*SECMON) $ 3 months
time steps, 9 $ 1 step=((SECST+SECYR-3.*SECMON)/9/SECMON) month
PLOT every, 9
print every, 9
write restart frequency, 0
next time (SECST+SECYR) $ Change to oil/brine/liquid in caverns: ((SECST+SECYR)/SECYR) years
time steps (ITS) $ 1 step=((SECST+2.*SECYR)-(SECST+SECYR))/ITS/SECMON) months
PLOT every, 3 $ every 3.*((SECST+2.*SECYR)-(SECST+SECYR))/ITS/SECMON) months = 1.25, 1.5, 1.75 years
print every, (ITS)
write restart frequency, 0
$ Half years = (HYR=6) months
next time (DDS1=SECST+2.*SECYR) $ {DDS1/SECYR} years - Cav.15,17,102,19,18 drawdown starts
time steps, (HYR*3) $ 1 step=(0.5*SECYR/(HYR*3)/SECDAY) days
PLOT every, 1 $ every (0.5*SECYR/(HYR*3)/SECDAY) days
print every, (HYR*3)
write restart frequency, 0
next time (DDS2=DDS1+0.5*SECYR) $ {DDS2/SECYR} years - drawdown ends
time steps, (2*ITS) $ 1 step=(2.*SECYR/(2*ITS)/SECMON) months
PLOT every, 3 $ every (2.*SECYR/(2*ITS)/SECMON) months
print every, (2*ITS)
write restart frequency, 0
$ (TRM=5.*SECYR) s = 5 years
next time (DDS1+TRM) $ (DDS1+TRM)/SECYR) years - Cav.15,17,102,19,18 drawdown starts
time steps, (HYR*3) $ 1 step=(0.5*SECYR/(HYR*3)/SECDAY) days
PLOTevery, 1 $ every (0.5*SECYR/(HYR*3)/SECDAY) days
print every, (HYR*3)
write restart frequency, 0
next time (DD2+TRM) $ (DD2+TRM)/SECYR) years - drawdown ends
time steps, (2*ITS) $ 1 step=(2.*SECYR/(2*ITS)/SECMON) months
PLOT every, 3 $ every (2.*SECYR/(2*ITS)/SECMON) months
print every, (2*ITS)
write restart frequency, 0
$ (2.*TRM/SECYR) years = 10 years
next time (DDS1+2.*TRM) $ (DDS1+2.*TRM)/SECYR) years - Cav.15,17,102,19,18 drawdown starts
time steps, (HYR*3) $ 1 step=(0.5*SECYR/(HYR*3)/SECDAY) days
PLOT every, 1 $ every (0.5*SECYR/(HYR*3)/SECDAY) days
print every, (HYR*3)
write restart frequency, 0
next time (DDS2+2.*TRM) $ (DDS2+2.*TRM)/SECYR) years - drawdown ends
time steps, (2*ITS) $ 1 step=(2.*SECYR/(2*ITS)/SECMON) months
PLOT every, 3 $ every (2.*SECYR/(2*ITS)/SECMON) months
print every, (2*ITS)
write restart frequency, 0
$ (3.*TRM/SECYR) years = 15 years
next time (DDS1+3.*TRM) $ (DDS1+3.*TRM)/SECYR) years - Cav.15,17,102,19,18 drawdown starts
time steps, (HYR) $ 1 step=(0.5*SECYR/(HYR)/SECDAY) months
PLOT every, 1 $ every (0.5*SECYR/(HYR)/SECDAY) months
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print every, {HYR}  
write restart frequency, 0  
next time (DDE1+3.*TRM) $ ((DDE1+3.*TRM/SECYR) years - drawdown ends  
time steps, {2*ITS} $ 1 step=(2.*SECYR/ITS)/SECMON mths  
PLOT every, 3 $ every (3.*SECYR/2*ITS)/SECMON mths  
print every, {2*ITS}  
write restart frequency, 0  
next time (DDS2+3.*TRM) $ ((DDS2+3.*TRM/SECYR) years - Cav. 20, 101 drawdown starts  
time steps, {HYR} $ 1 step=(0.5*SECYR/HYR)/SECMON mths  
PLOT every, 1 $ every (0.5*SECYR/HYR)/SECMON mths  
print every, {HYR}  
write restart frequency, 0  
next time (DDE2+3.*TRM) $ ((DDE2+3.*TRM/SECYR) years - drawdown ends  
time steps, {1*TS} $ 1 step=(2.*SECYR/2*ITS)/SECMON mths  
p rint every, {1*TS} $ every (3.*SECYR/2*ITS)/SECMON mths  
write restart frequency, 0  
$ (4*TRM/SECYR) years = 20 years  
next time (SEC102) $ Expansion leak of 102 starts: (SEC102/SECYR) years  
time steps, {ITS} $ 1 step=(SEC LA/SEC102)/ITS/SECMON mths  
PLOT every, 1 $ every (SEC LA/SEC102)/ITS/SECMON mths  
write restart every, 0  
PLOT every, 1  
print every, {ITS}  
next time (SEC LA) $ 102 done, initial leak for A starts: (SEC LA/SECYR) years  
time steps, {ITS} $ 1 step=(SEC LM SEC LA)/ITS/SECMON mths  
PLOT every, 0 $ every (SEC LM SEC LA)/ITS/SECMON mths  
print every, {ITS}  
extime (SEC LM) $ A done, initial leak for M starts: (SEC LM SECYR) years  
time steps, {ITS} $ 1 step=(SEC LM SECYR).SEC LM)/ITS/SECMON mths  
PLOT every, 1 $ every (SEC LM SECYR).SEC LM)/ITS/SECMON mths  
print every, {ITS}  
nextime (SEC LM SECYR) $ M done: (SEC LM SECYR SECYR) years  
time steps, {3*ITS} $ 1 step=((DD1+5.*TRM - (SEC LM SECYR))/3*ITS)/SECMON mths  
PLOT every, 1 $ every (DD1+5.*TRM - (SEC LM SECYR))/3*ITS)/SECMON mths  
print every, {3*ITS}  
$ (5*TRM/SECYR) years = 25 years  
nextime (DDE1+5.*TRM) $ ((DDE1+5.*TRM/SECYR) years - Cav. 15, 17, 102, 19, 18 drawdown starts  
time steps, {HYR} $ 1 step=(0.5*SECYR/HYR)/SECMON mths  
PLOT every, 1 $ every (0.5*SECYR/HYR)/SECMON mths  
write restart frequency, 0  
nextime (DDE2+5.*TRM) $ ((DDE2+5.*TRM/SECYR) years - drawdown ends  
time steps, {2*ITS} $ 1 step=(2.*SECYR/2*ITS)/SECMON mths  
PLOT every, 3 $ every (3.*SECYR/2*ITS)/SECMON mths  
write restart frequency, 0  
nextime (DDS2+5.*TRM) $ ((DDS2+5.*TRM/SECYR) years - Cav. 20, 101, 106(A), 107(SPR 5) drawdown starts  
time steps, {HYR} $ 1 step=(0.5*SECYR/HYR)/SECMON mths  
PLOT every, 1 $ every (0.5*SECYR/HYR)/SECMON mths  
write restart frequency, 0  
nextime (DDE1+6.*TRM) $ ((DDE1+6.*TRM/SECYR) years - Cav. 15, 17, 102, 19, 18 drawdown starts  
time steps, {HYR} $ 1 step=(0.5*SECYR/HYR)/SECMON mths  
PLOT every, 1 $ every (0.5*SECYR/HYR)/SECMON mths  
write restart frequency, 0  
nextime (DDE2+6.*TRM) $ ((DDE2+6.*TRM/SECYR) years - drawdown ends  
time steps, {2*ITS} $ 1 step=(2.*SECYR/2*ITS)/SECMON mths  
PLOT every, 3 $ every (3.*SECYR/2*ITS)/SECMON mths  
write restart frequency, 0  
nextime (DDS2+6.*TRM) $ ((DDS2+6.*TRM/SECYR) years - Cav. 20, 101, 106(A), 107(SPR 5) drawdown starts  
time steps, {HYR} $ 1 step=(0.5*SECYR/HYR)/SECMON mths  
PLOT every, 1 $ every (0.5*SECYR/HYR)/SECMON mths  
write restart frequency, 0  
nextime (DDE1+6.*TRM) $ ((DDE1+6.*TRM/SECYR) years - Cav. 15, 17, 102, 19, 18 drawdown starts  
time steps, {HYR} $ 1 step=(0.5*SECYR/HYR)/SECMON mths  
PLOT every, 1 $ every (0.5*SECYR/HYR)/SECMON mths  
write restart frequency, 0  
nextime (DDE2+6.*TRM) $ ((DDE2+6.*TRM/SECYR) years - drawdown ends  
time steps, {2*ITS} $ 1 step=(2.*SECYR/2*ITS)/SECMON mths  
PLOT every, 3 $ every (3.*SECYR/2*ITS)/SECMON mths  
write restart frequency, 0  
nextime (DDS2+6.*TRM) $ ((DDS2+6.*TRM/SECYR) years - Cav. 20, 101, 106(A), 107(SPR 5) drawdown starts  
time steps, {HYR} $ 1 step=(0.5*SECYR/HYR)/SECMON mths  
PLOT every, 1 $ every (0.5*SECYR/HYR)/SECMON mths  
write restart frequency, 0
write restart frequency, 0
$ (7 * TRM/SECRY) years = 35 years
next time (DDS1+7.*TRM) $ (DDS1+7.*TRM/SECRY) years - Cav. 15, 17, 102, 19, 18 drawdown starts
time steps, (HYR) $ 1 step=(0.5*SECRY/(HYR)/SECMON) mthns
PLOT every, 1 $ every (0.5*SECRY/(HYR)/SECMON) mthns
print every, (HYR)
write restart frequency, 0
next time (DDE1+7.*TRM) $ (DDE1+7.*TRM/SECRY) years - drawdown ends
time steps, (2*ITS) $ 1 step=(2.*SECRY/(2*ITS)/SECMON) mthns
PLOT every, 3 $ every (3.*2.*SECRY/(2*ITS)/SECMON) mthns
print every, (2*ITS)
write restart frequency, 0
next time (DDS2+7.*TRM) $ (DDS2+7.*TRM/SECRY) years - Cav. 20, 101, 106(A), 107(SPR 5) drawdown starts
time steps, (HYR) $ 1 step=(0.5*SECRY/(HYR)/SECMON) mthns
PLOT every, 1 $ every (0.5*SECRY/(HYR)/SECMON) mthns
print every, (HYR)
write restart frequency, 0
next time (DDE2+7.*TRM) $ (DDE2+7.*TRM/SECRY) years - drawdown ends
time steps, (2*ITS) $ 1 step=(2.*SECRY/(2*ITS)/SECMON) mthns
PLOT every, 3 $ every (3.*2.*SECRY/(2*ITS)/SECMON) mthns
print every, (2*ITS)
write restart frequency, 0
$ (8 * TRM/SECRY) years = 40 years
next time (DDS1+8.*TRM) $ (DDS1+8.*TRM/SECRY) years - Cav. 15, 17, 102, 19, 18 drawdown starts
time steps, (HYR) $ 1 step=(0.5*SECRY/(HYR)/SECMON) mthns
PLOT every, 1 $ every (0.5*SECRY/(HYR)/SECMON) mthns
print every, (HYR)
write restart frequency, 0
next time (DDE1+8.*TRM) $ (DDE1+8.*TRM/SECRY) years - drawdown ends
time steps, (2*ITS) $ 1 step=(2.*SECRY/(2*ITS)/SECMON) mthns
PLOT every, 3 $ every (3.*2.*SECRY/(2*ITS)/SECMON) mthns
print every, (2*ITS)
write restart frequency, 0
next time (DDS2+8.*TRM) $ (DDS2+8.*TRM/SECRY) years - Cav. 20, 101, 106(A), 107(SPR 5) drawdown starts
time steps, (HYR) $ 1 step=(0.5*SECRY/(HYR)/SECMON) mthns
PLOT every, 1 $ every (0.5*SECRY/(HYR)/SECMON) mthns
print every, (HYR)
write restart frequency, 0
next time (DDE2+8.*TRM) $ (DDE2+8.*TRM/SECRY) years - drawdown ends
time steps, (2*ITS) $ 1 step=(2.*SECRY/(2*ITS)/SECMON) mthns
PLOT every, 3 $ every (3.*2.*SECRY/(2*ITS)/SECMON) mthns
print every, (2*ITS)
write restart frequency, 0
$ (9 * TRM/SECRY) years = 45 years
next time (DDS1+9.*TRM) $ (DDS1+9.*TRM/SECRY) years - Cav. 15, 17, 102, 19, 18 drawdown starts
time steps, (HYR) $ 1 step=(0.5*SECRY/(HYR)/SECMON) mthns
PLOT every, 1 $ every (0.5*SECRY/(HYR)/SECMON) mthns
print every, (HYR)
write restart frequency, 0
next time (DDE1+9.*TRM) $ (DDE1+9.*TRM/SECRY) years - drawdown ends
time steps, (2*ITS) $ 1 step=(2.*SECRY/(2*ITS)/SECMON) mthns
PLOT every, 3 $ every (3.*2.*SECRY/(2*ITS)/SECMON) mthns
print every, (2*ITS)
write restart frequency, 0
next time (DDS2+9.*TRM) $ (DDS2+9.*TRM/SECRY) years - Cav. 20, 101, 106(A), 107(SPR 5) drawdown starts
time steps, (HYR) $ 1 step=(0.5*SECRY/(HYR)/SECMON) mthns
PLOT every, 1 $ every (0.5*SECRY/(HYR)/SECMON) mthns
print every, (HYR)
write restart frequency, 0
next time (DDE2+9.*TRM) $ (DDE2+9.*TRM/SECRY) years - drawdown ends
time steps, (2*ITS) $ 1 step=(2.*SECRY/(2*ITS)/SECMON) mthns
PLOT every, 3 $ every (3.*2.*SECRY/(2*ITS)/SECMON) mthns
print every, (2*ITS)
write restart frequency, 0
$ (10 * TRM/SECRY) years = 50 years
next time (DDS1+10.*TRM) $ (DDS1+10.*TRM/SECRY) years - Cav. 15, 17, 102, 19, 18 drawdown starts
time steps, (HYR) $ 1 step=(0.5*SECRY/(HYR)/SECMON) mthns
PLOT every, 1 $ every (0.5*SECRY/(HYR)/SECMON) mthns
print every, (HYR)
write restart frequency, 0
next time (DDE1+10.*TRM) $ (DDE1+10.*TRM/SECRY) years - drawdown ends
time steps, (2*ITS) $ 1 step=(2.*SECRY/(2*ITS)/SECMON) mthns
PLOT every, 3 $ every (3.*2.*SECRY/(2*ITS)/SECMON) mthns
print every, (2*ITS)
write restart frequency, 0
next time (DDS2+10.*TRM) $ (DDS2+10.*TRM/SECRY) years - Cav. 20, 101, 106(A), 107(SPR 5) drawdown starts
time steps, (HYR) $ 1 step=(0.5*SECRY/(HYR)/SECMON) mthns

PLOT every, 1          $ every \{0.5*SECYR/(HYR)/SECMON\} months
print every, (HYR)
write restart frequency, 0
next time \{(DDE2+10.*TRM)/SECYR\} years - drawdown ends
time steps, \{(ITS)\}    $ 1 step=\{(SECEND-(DDE2+10.*TRM))/ITS/SECMON\} months
PLOT every, 3          $ every \{(3.*(SECEND-(DDE2+10.*TRM))/ITS/SECMON)\} months
print every, \{(ITS)\}
write restart frequency, 0
end time  \{(SECEND)\}    $ \{(SECEND-SECST)/SECYR\} years since initial leach

$ Output
thermal stress external, tmpnod
plot state, EqCS, temp
plot nodal, displacement, tmpnod
plot element, sig, vonmis, eps, pressure

$ Node boundary
no displacements Z 2 $ Bottom of mesh	no displacements x 3 $ West side
no displacements x 4 $ East side
no displacements y 5 $ South side
no displacements y 6 $ North side

$ Pressures on side set are the initial cavern pressure
pressure 10 user 1. $ 15 pressure in cavern 1
pressure 20 user 1. $ 25 pressure in cavern 2
pressure 30 user 1. $ 35 pressure in cavern 3
pressure 40 user 1. $ 45 pressure in cavern 4
pressure 60 user 1. $ 55 pressure in cavern 6
pressure 70 user 1. $ 65 pressure in cavern 7
pressure 71 user 1. $ 75 pressure in cavern 7
pressure 80 user 1. $ 85 pressure in cavern 8
pressure 100 user 1. $ 95 pressure in cavern 10
pressure 110 user 1. $ 105 pressure in cavern 11
pressure 130 user 1. $ 115 pressure in cavern 13
pressure 150 user 1. $ 125 pressure in cavern 15
pressure 160 user 1. $ 135 pressure in cavern 16
pressure 170 user 1. $ 145 pressure in cavern 17
pressure 180 user 1. $ 155 pressure in cavern 18
pressure 190 user 1. $ 165 pressure in cavern 19
pressure 200 user 1. $ 175 pressure in cavern 20
pressure 240 user 1. $ 185 pressure in cavern 24
pressure 250 user 1. $ 195 pressure in cavern 25
pressure 260 user 1. $ 205 pressure in cavern 26
pressure 1010 user 1. $ 215 pressure in cavern 101
pressure 1020 user 1. $ 225 pressure in cavern 102 before expansion
pressure 1026 user 1. $ 235 pressure in cavern 102 after expansion
pressure 1030 user 1. $ 245 pressure in cavern 103(J1)
pressure 1040 user 1. $ 255 pressure in cavern 104(N1)
pressure 1050 user 1. $ 265 pressure in cavern 105(UTP1)
pressure 1060 user 1. $ 275 pressure in cavern 106(A3)
pressure 1070 user 1. $ 285 pressure in cavern 107(SPR 5)

$ Pressures on side set are the pressures after the 1st leach
pressure 151 user 1. $ pressure in cavern 15
pressure 171 user 1. $ pressure in cavern 17
pressure 181 user 1. $ pressure in cavern 18
pressure 191 user 1. $ pressure in cavern 19
pressure 201 user 1. $ pressure in cavern 20
pressure 1011 user 1. $ pressure in cavern 101
pressure 1021 user 1. $ pressure in cavern 102
pressure 1061 user 1. $ pressure in cavern 106(A3)
pressure 1071 user 1. $ pressure in cavern 107(SPR 5)

$ Pressures on side set are the pressures after the 2nd leach
pressure 152 user 1. $ pressure in cavern 15
pressure 172 user 1. $ pressure in cavern 17
pressure 182 user 1. $ pressure in cavern 18
pressure 192 user 1. $ pressure in cavern 19
pressure 202 user 1. $ pressure in cavern 20
pressure 1012 user 1. $ pressure in cavern 101
pressure 1022 user 1. $ pressure in cavern 102
pressure 1062 user 1. $ pressure in cavern 106(A3)
pressure 1072 user 1. $ pressure in cavern 107(SPR 5)

$ Pressures on side set are the pressures after the 3rd leach
pressure 153 user 1. $ pressure in cavern 15
pressure 173 user 1. $ pressure in cavern 17
$ Pressures on side set are the pressures after the 4th leach
pressure 154 user 1. $ pressure in cavern 15
pressure 174 user 1. $ pressure in cavern 17
pressure 184 user 1. $ pressure in cavern 18
pressure 194 user 1. $ pressure in cavern 19
pressure 204 user 1. $ pressure in cavern 20
pressure 1014 user 1. $ pressure in cavern 101
pressure 1024 user 1. $ pressure in cavern 102
pressure 1064 user 1. $ pressure in cavern 106(A3)
pressure 1074 user 1. $ pressure in cavern 107(SPR 5)

$ Pressures on side set are the pressures after the 5th leach
pressure 155 user 1. $ pressure in cavern 15
pressure 175 user 1. $ pressure in cavern 17
pressure 185 user 1. $ pressure in cavern 18
pressure 195 user 1. $ pressure in cavern 19
pressure 205 user 1. $ pressure in cavern 20
pressure 1015 user 1. $ pressure in cavern 101
pressure 1025 user 1. $ pressure in cavern 102
pressure 1065 user 1. $ pressure in cavern 106(A3)
pressure 1075 user 1. $ pressure in cavern 107(SPR 5)

gravity
  gravitational constant = 9.81
  direction 0.0 -1.0
  magnitude 1.0
  use function 3
end gravity

material 1, power law creep, \( \{ \rho_1 \} \) $ Salt
  bulk modulus = \( \{ K_1 \} \)
  two mu = \( \{ 2 \mu_1 \} \)
  creep constant = \( \{ SMF \} \)
  stress exponent = \( \{ n \} \)
  thermal constant = \( \{ Q \} \)
end material

$active limits, 10, 0.0, \{ \text{SECST-1*SECYR/ITS} \} $ \{ \text{SECST-1*SECYR/ITS/ITS} \} years $ Initial leaching of caverns
active limits, 10, 0.0, \{ EXST=0.01 \} $ \{ SECST-1*SECYR/ITS \} $ Initial leaching of caverns
material 10, power law creep, \( \{ \rho_1 \} \) $ Salt
  bulk modulus = \( \{ K_1 \} \)
  two mu = \( \{ 2 \mu_1 \} \)
  creep constant = \( \{ SMF \} \)
  stress exponent = \( \{ n \} \)
  thermal constant = \( \{ Q \} \)
end material

active limits, 102, 0.0, \{ SECL102 \} $ Expansion leach for 102 at \{ SECL102/SECYR \} years
material 102, power law creep, \( \{ \rho_1 \} \) $ Salt
  bulk modulus = \( \{ K_1 \} \)
  two mu = \( \{ 2 \mu_1 \} \)
  creep constant = \( \{ SMF \} \)
  stress exponent = \( \{ n \} \)
  thermal constant = \( \{ Q \} \)
end material

active limits, 106, 0.0, \{ SECIL0 \} $ Initial leach for A at \{ SECIL0/SECYR \} years
material 106, power law creep, \( \{ \rho_1 \} \) $ Salt
  bulk modulus = \( \{ K_1 \} \)
  two mu = \( \{ 2 \mu_1 \} \)
  creep constant = \( \{ SMF \} \)
  stress exponent = \( \{ n \} \)
  thermal constant = \( \{ Q \} \)
end material

active limits, 107, 0.0, \{ SECILM \} $ Initial leach for M at \{ SECILM/SECYR \} years
material 107, power law creep, \( \{ \rho_1 \} \) $ Salt
  bulk modulus = \( \{ K_1 \} \)
two mu = \left(\frac{2\mu_1}{RF}\right)
creep constant = \{SMF*A\}
stress exponent = \{n\}
thermal constant = \{Q/R\}

END

active limits, 11, 0.0, \{SEC1ST\} $ 1st leach at \{SEC1ST/SECYR\} years
material 11, power law creep, \{rho1\} $ Salt
bulk modulus = \{K1/RF\}
two mu = \left(\frac{2\mu_1}{RF}\right)
creep constant = \{SMF*A\}
stress exponent = \{n\}
thermal constant = \{Q/R\}
END

active limits, 12, 0.0, \{SEC2ND\} $ 2nd leach at \{SEC2ND/SECYR\} years
material 12, power law creep, \{rho1\} $ Salt
bulk modulus = \{K1/RF\}
two mu = \left(\frac{2\mu_1}{RF}\right)
creep constant = \{SMF*A\}
stress exponent = \{n\}
thermal constant = \{Q/R\}
END

active limits, 13, 0.0, \{SEC3RD\} $ 3rd leach at \{SEC3RD/SECYR\} years
material 13, power law creep, \{rho1\} $ Salt
bulk modulus = \{K1/RF\}
two mu = \left(\frac{2\mu_1}{RF}\right)
creep constant = \{SMF*A\}
stress exponent = \{n\}
thermal constant = \{Q/R\}
END

active limits, 14, 0.0, \{SEC4TH\} $ 4th leach at \{SEC4TH/SECYR\} years
material 14, power law creep, \{rho1\} $ Salt
bulk modulus = \{K1/RF\}
two mu = \left(\frac{2\mu_1}{RF}\right)
creep constant = \{SMF*A\}
stress exponent = \{n\}
thermal constant = \{Q/R\}
END

active limits, 15, 0.0, \{SEC5TH\} $ 5th leach at \{SEC5TH/SECYR\} years
material 15, power law creep, \{rho1\} $ Salt
bulk modulus = \{K1/RF\}
two mu = \left(\frac{2\mu_1}{RF}\right)
creep constant = \{SMF*A\}
stress exponent = \{n\}
thermal constant = \{Q/R\}
END

material 2, elastic, \{rho2\} $ Caprock (Gypsum and Limestone)
youngs modulus = \{E2\}
poissons ratio = \{nu2\}
end
$ \{thick2=45.72\}

material 3, elastic, \{rho3\} $ Overburden (sand)
youngs modulus = \{E3\}
poissons ratio = \{nu3\}
end
$ \{thick3=152.4\}

material 4, elastic, \{rho4\} $ Rock surrounding salt dome (sandstone)
youngs modulus = \{E4\}
poissons ratio = \{nu4\}
end
$ \{thick4=2286.\}

initial value USIGZZ=Function Z 1, 1., material 3
initial value USIGXX=Function Z 1, \{nu3/(1.-nu3)\}, material 3
initial value USIGYY=Function Z 1, \{nu3/(1.-nu3)\}, material 3
initial value USIGZZ=Function Z 1, 1., material 2
initial value USIGXX=Function Z 1, \{nu2/(1.-nu2)\}, material 2
initial value USIGYY=Function Z 1, \{nu2/(1.-nu2)\}, material 2
initial value USIGZZ=Function Z 2, 1., material 4
initial value USIGXX=Function Z 2, \{nu4/(1.-nu4)\}, material 4
initial value USIGYY=Function Z 2, \{nu4/(1.-nu4)\}, material 4
Scenario 2:

#include("units.txt")
#include("thickness.txt")

title
SPR Bayou Choctaw Exp. A3 & 5, 26cav5d_scn2, BC salt, SMF={SMF=0.12}, E4={E4=35e9}, WHP=each

$Material Properties$

$Salt (Material 1):

$Young's Modulus={E1=31.0E9} (Krieg, 1984)$
$Density={rho1=2300.}, Poisson's Ratio={nu1=0.25} (Krieg, 1984)$
$Bulk Modulus={K1=E1/(3.*(1.-2.*nu1))}, Shear Modulus={mu1=E1/(2.*(1.+nu1))}$
$Creep Constant={A=5.79e-36}, Stress Exponent={n=4.9}$
$Thermal Constant={Q=12.0E3}(Krieg, 1984), Universal gas constant={R=1.987}$
$Salt Reduction Factor={RF=12.5} (Morgan and Krieg, 1988)$
$Structure Factor Multiplication Factor={SMF}(Adjusted through back analysis)$

$Caprock (Material 2):
$\text{Young's Modulus} = E_2 = 1.572 \times 10^{10} (\text{Hogan, R.G., SAND80-7140})$

$\text{Density} = \rho_2 = 2319., \text{Poisson's Ratio} = \nu_2 = 0.288 (\text{Hogan, R.G., SAND80-7140})$

$\text{Overburden (Material 3)}$:
$\text{Young's Modulus} = E_3 = 0.1 \times 10^9 (\text{Hoffman and Ehgartner, 1992})$

$\text{Density} = \rho_3 = 1874., \text{Poisson's Ratio} = \nu_3 = 0.33 (\text{Hoffman and Ehgartner, 1992})$

$\text{Surrounding Rock (Material 4)}$:
$\text{Young's Modulus} = E_4 (\text{Carmichael, 1984})$

$\text{Density} = \rho_4 = 2500., \text{Poisson's Ratio} = \nu_4 = 0.33 (\text{Lama and Vutukuri, 1978})$

$\text{Time at the initial leaches begin}$
$\text{bgn_s} = 0.$ s

$\text{Time at the expansion leach for Cavern 102 starts}$
$\text{EL102_s} = \text{bgn_s} + 21 \times \text{yr_s}$ s $\text{EL102_s/yr_s}$ years

$\text{Times at the initial leachs for Caverns A and M start}$
$\text{ILA_s} = \text{bgn_s} + 1 \times \text{yr_s}$ s $\text{ILA_s/yr_s}$ years

$\text{Time at the leaches for all SPR caverns start}$
$\text{Dist_s} = \text{bgn_s} + 31 \times \text{yr_s}$ s $\text{Dist_s/yr_s}$ years

$\text{Time at the simulation completes}$
$\text{end_s} = \text{bgn_s} + 5 \times \text{yr_s}$ s

$\text{Number of nodes} = \text{nnod} = 603216.$

$\text{start time} 0.0$
$\text{ITERATION PRINT, 20}$
$\text{MAX M.M. ITERAT IONS, (nnod) \text{ number of nodes}}$
$\text{TARGET TOLERANCE, 5.e-5 \text{ was 5.e-5}}$
$\text{ACCEPTABLE TOLERANCE, 1.e-5 \text{ was 1.e-5}}$
$\text{predictor scale factor, 0.0, 0.0}$
$\text{time steps, 1 \text{ step=(d_s/1/d_s) day}}$

$\text{write restart frequency, 0}$
$\text{next time (1.*d_s) 1 day}$
$\text{time steps, 9 \text{ step=(10.*d_s-1.*d_s)/9/d_s) day}}$

$\text{write restart frequency, 0}$
$\text{next time (10.*d_s) 10 days}$
$\text{time steps, 4 \text{ step=(mn_s-10.*d_s)/4/d_s) days}}$

$\text{write restart frequency, 0}$
$\text{next time (mn_s) 1 month}$
$\text{time steps, (ITS=12) \text{ step=(3.*mn_s-mn_s)/12s/1/d_s) days}}$

$\text{write restart frequency, 0}$
$\text{next time (3.*mn_s) 3 months}$
$\text{time steps, 9 \text{ step=(bgn_s+yr_s-3.*mn_s)/9/d_s) days}}$

$\text{write restart frequency, 0}$
$\text{next time (bgn_s+yr_s) \text{ Change to oil/brine/liquid in caverns: (bgn_s+yr_s)/yr_s years}}$
$\text{time steps, (20*ITS) \text{ step=(EL102_s-(bgn_s+yr_s))/(20*ITS)/mn_s) months}}$

$\text{write restart every, 0}$
$\text{next time (EL102_s) \text{ Expansion leach of 102 starts: (EL102_s/yr_s) years}}$
$\text{time steps, (ITS) \text{ step=(ILA_s-EL102_s)/1/ITS/mn_s) months}}$

$\text{write restart every, 0}$
$\text{next time (ILA_s) \text{ 102 done, initial leach for A starts: (ILA_s/yr_s) years}}$
$\text{time steps, (ITS) \text{ step=(ILM_s-ILA_s)/1/ITS/mn_s) months}}$

$\text{write restart every, 0}$
$\text{next time (ILM_s) \text{ A done, initial leach for M starts: (ILM_s/yr_s) years}}$
$\text{time steps, (ITS) \text{ step=(ILM_s-yr_s-1*yr_s)/1/ITS/mn_s) months}}$

$\text{write restart every, 0}$
$\text{next time (ILM_s+yr_s) \text{ M done: (ILM_s+yr_s)/yr_s years}}$
$\text{time steps, (32*ITS) \text{ step=(end_s-(ILM_s+yr_s))/(32*ITS)/mn_s) months}}$
write restart every, 0
plot every, (TS)
print every, (TS)
end time $(end_s - bgn_s)/yr_s$ years since simulation starts

$=======
$ Output
thermal stress external, tmpnod
plot state, EqCS, temp
plot nodal, displacements, tmpnod
plot element, sig, vonmis, eps, pressure

$ Node boundary
no displacements Z 2 $ Bottom of mesh
no displacements x 3 $ West side
no displacements x 4 $ East side
no displacements y 5 $ South side
no displacements y 6 $ North side

$ Pressures on side set are the initial cavern pressure
pressure 10 user 1. $ pressure in cavern 1
pressure 20 user 1. $ pressure in cavern 2
pressure 30 user 1. $ pressure in cavern 3
pressure 40 user 1. $ pressure in cavern 4
pressure 60 user 1. $ pressure in cavern 6
pressure 70 user 1. $ pressure in cavern 7 $ Wall
pressure 80 user 1. $ pressure in cavern 8 $ Floor and Roof
pressure 100 user 1. $ pressure in cavern 10
pressure 110 user 1. $ pressure in cavern 11
pressure 130 user 1. $ pressure in cavern 13
pressure 150 user 1. $ pressure in cavern 15
pressure 160 user 1. $ pressure in cavern 16
pressure 170 user 1. $ pressure in cavern 17
pressure 180 user 1. $ pressure in cavern 18
pressure 190 user 1. $ pressure in cavern 19
pressure 200 user 1. $ pressure in cavern 20
pressure 240 user 1. $ pressure in cavern 24
pressure 250 user 1. $ pressure in cavern 25
pressure 260 user 1. $ pressure in cavern 26
pressure 1010 user 1. $ pressure in cavern 101
pressure 1020 user 1. $ pressure in cavern 102 before expansion
pressure 1026 user 1. $ pressure in cavern 102 after expansion
pressure 1030 user 1. $ pressure in cavern 103($1$)
presure 1040 user 1. $ pressure in cavern 104($2$)
presure 1050 user 1. $ pressure in cavern 105($UTP1$)
presure 1060 user 1. $ pressure in cavern 106($A$)
presure 1070 user 1. $ pressure in cavern 107($M$)

$ Pressures on side set are the pressures after the 1st leach
pressure 151 user 1. $ pressure in cavern 15
pressure 171 user 1. $ pressure in cavern 17
pressure 181 user 1. $ pressure in cavern 18
pressure 191 user 1. $ pressure in cavern 19
pressure 201 user 1. $ pressure in cavern 20
pressure 1011 user 1. $ pressure in cavern 101
pressure 1021 user 1. $ pressure in cavern 102
pressure 1061 user 1. $ pressure in cavern 106($A$)
presure 1071 user 1. $ pressure in cavern 107($M$)

$ Pressures on side set are the pressures after the 2nd leach
pressure 152 user 1. $ pressure in cavern 15
pressure 172 user 1. $ pressure in cavern 17
pressure 182 user 1. $ pressure in cavern 18
pressure 192 user 1. $ pressure in cavern 19
pressure 202 user 1. $ pressure in cavern 20
pressure 1012 user 1. $ pressure in cavern 101
pressure 1022 user 1. $ pressure in cavern 102
pressure 1062 user 1. $ pressure in cavern 106($A$)
presure 1072 user 1. $ pressure in cavern 107($M$)

$ Pressures on side set are the pressures after the 3rd leach
pressure 153 user 1. $ pressure in cavern 15
pressure 173 user 1. $ pressure in cavern 17
pressure 183 user 1. $ pressure in cavern 18
pressure 193 user 1. $ pressure in cavern 19
pressure 203 user 1. $ pressure in cavern 20
pressure 1013 user 1. $ pressure in cavern 101
pressure 1023 user 1. $ pressure in cavern 102
pressure 1063 user 1. $ pressure in cavern 106($A$)
presure 1073 user 1. $ pressure in cavern 107($M$)

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$ Pressures on side set are the pressures after the 4th leach
pressure 154 user 1. $ pressure in cavern 15
pressure 174 user 1. $ pressure in cavern 17
pressure 184 user 1. $ pressure in cavern 18
pressure 194 user 1. $ pressure in cavern 19
pressure 204 user 1. $ pressure in cavern 20
pressure 1014 user 1. $ pressure in cavern 101
pressure 1024 user 1. $ pressure in cavern 102
pressure 1064 user 1. $ pressure in cavern 106(A)
pressure 1074 user 1. $ pressure in cavern 107(M)

$ Pressures on side set are the pressures after the 5th leach
pressure 155 user 1. $ pressure in cavern 15
pressure 175 user 1. $ pressure in cavern 17
pressure 185 user 1. $ pressure in cavern 18
pressure 195 user 1. $ pressure in cavern 19
pressure 205 user 1. $ pressure in cavern 20
pressure 1015 user 1. $ pressure in cavern 101
pressure 1025 user 1. $ pressure in cavern 102
pressure 1065 user 1. $ pressure in cavern 106(A)
pressure 1075 user 1. $ pressure in cavern 107(M)

gravity
  gravitational constant = 9.81
  direction 0. 0. -1.
  magnitude 1.0
  use function 3
end gravity

material 1, power law creep, \{rho1\} $ Salt, Baseline
  bulk modulus = \{K1/RF\}
  two mu = \{2*mu1/RF\}
  creep constant = \{SMF*A\}
  stress exponent = \{n\}
  thermal constant = \{Q/R\}
END
$ Salt dome height, \{h_SD\} m

active limits, 10, 0.0,0.01 $ Initial leaching of caverns
material 10, power law creep, \{rho1\} $ Salt
  bulk modulus = \{K1/RF\}
  two mu = \{2*mu1/RF\}
  creep constant = \{SMF*A\}
  stress exponent = \{n\}
  thermal constant = \{Q/R\}
END

active limits, 102, 0.0, \{EL102_s\} $ Expansion leach for 102 at \{EL102_s/yr_s\} years
material 102, power law creep, \{rho1\} $ Salt
  bulk modulus = \{K1/RF\}
  two mu = \{2*mu1/RF\}
  creep constant = \{SMF*A\}
  stress exponent = \{n\}
  thermal constant = \{Q/R\}
END

active limits, 106, 0.0, \{ILA_s\} $ Initial leach for A at \{ILA_s/yr_s\} years
material 106, power law creep, \{rho1\} $ Salt
  bulk modulus = \{K1/RF\}
  two mu = \{2*mu1/RF\}
  creep constant = \{SMF*A\}
  stress exponent = \{n\}
  thermal constant = \{Q/R\}
END

active limits, 107, 0.0, \{ILM_s\} $ Initial leach for M at \{ILM_s/yr_s\} years
material 107, power law creep, \{rho1\} $ Salt
  bulk modulus = \{K1/RF\}
  two mu = \{2*mu1/RF\}
  creep constant = \{SMF*A\}
  stress exponent = \{n\}
  thermal constant = \{Q/R\}
END

active limits, 11, 0.0, \{D1st_s\} $ 1st leach at \{D1st_s/yr_s\} years
material 11, power law creep, \{rho1\} $ Salt
  bulk modulus = \{K1/RF\}
  two mu = \{2*mu1/RF\}
  creep constant = \{SMF*A\}
  stress exponent = \{n\}
  thermal constant = \{Q/R\}
active limits, 12, 0.0, {D2nd_s} $ 2nd leach at {D2nd_s/yr_s} years
material 12, power law creep, {rho1} $ Salt
  bulk moduli = {K1/RF}
  two mu = {2*mu1/RF}
  creep constant = {SMF*A}
  stress exponent = {n}
  thermal constant = {Q/R}
END

active limits, 13, 0.0, {D3rd_s} $ 3rd leach at {D3rd_s/yr_s} years
material 13, power law creep, {rho1} $ Salt
  bulk moduli = {K1/RF}
  two mu = {2*mu1/RF}
  creep constant = {SMF*A}
  stress exponent = {n}
  thermal constant = {Q/R}
END

active limits, 14, 0.0, {D4th_s} $ 4th leach at {D4th_s/yr_s} years
material 14, power law creep, {rho1} $ Salt
  bulk moduli = {K1/RF}
  two mu = {2*mu1/RF}
  creep constant = {SMF*A}
  stress exponent = {n}
  thermal constant = {Q/R}
END

active limits, 15, 0.0, {D5th_s} $ 5th leach at {D5th_s/yr_s} years
material 15, power law creep, {rho1} $ Salt
  bulk moduli = {K1/RF}
  two mu = {2*mu1/RF}
  creep constant = {SMF*A}
  stress exponent = {n}
  thermal constant = {Q/R}
END

material 2, elastic, {rho2} $ Caprock (Gypsum and Limestone)
  youngs moduli = {E2}
  poissons ratio = {nu2}
end
$ Caprock thickness, {t_CR} m

material 3, elastic, {rho3} $ Overburden (sand)
  youngs moduli = {E3}
  poissons ratio = {nu3}
end
$ Overburden thickness, {t_OB} m

material 4, elastic, {rho4} $ Farfield (sandstone)
  youngs moduli = {E4}
  poissons ratio = {nu4}
end
$ Surrounding rock thickness, {t_SR} m

initial value USIGZZ=Function Z 1, 1., material 3
initial value USIGXX=Function Z 1, {nu3/(1.-nu3)}, material 3
initial value USIGYY=Function Z 1, {nu3/(1.-nu3)}, material 3
initial value USIGZZ=Function Z 1, 1., material 2
initial value USIGXX=Function Z 1, {nu2/(1.-nu2)}, material 2
initial value USIGYY=Function Z 1, {nu2/(1.-nu2)}, material 2
initial value USIGZZ=Function Z 2, 1., material 4
initial value USIGXX=Function Z 2, {nu4/(1.-nu4)}, material 4
initial value USIGYY=Function Z 2, {nu4/(1.-nu4)}, material 4
initial value USIGZZ=Function Z 1, 1., material 1
initial value USIGXX=Function Z 1, 1., material 1
initial value USIGYY=Function Z 1, 1., material 1
initial value USIGZZ=Function Z 1, 1., material 10
initial value USIGXX=Function Z 1, 1., material 10
initial value USIGYY=Function Z 1, 1., material 10
initial value USIGZZ=Function Z 1, 1., material 11
initial value USIGXX=Function Z 1, 1., material 11
initial value USIGYY=Function Z 1, 1., material 11
initial value USIGZZ=Function Z 1, 1., material 12
initial value USIGXX=Function Z 1, 1., material 12
initial value USIGYY=Function Z 1, 1., material 12
initial value USIGZZ=Function Z 1, 1., material 13
initial value USIGXX=Function Z 1, 1., material 13
initial value USIGYY=Function Z 1, 1., material 13
initial value USIGZZ=Function Z 1, 1., material 14
initial value USIGXX=Function Z 1, 1., material 14
initial value USIGXX=Function Z 1, 1., material 14
initial value USIGGY=Function Z 1, 1., material 14
initial value USIGZZ=Function Z 1, 1., material 15
initial value USIGXX=Function Z 1, 1., material 15
initial value USIGGY=Function Z 1, 1., material 15
initial value USIGZZ=Function Z 1, 1., material 102
initial value USIGXX=Function Z 1, 1., material 102
initial value USIGGY=Function Z 1, 1., material 102
initial value USIGZZ=Function Z 1, 1., material 106
initial value USIGXX=Function Z 1, 1., material 106
initial value USIGGY=Function Z 1, 1., material 106
initial value USIGZZ=Function Z 1, 1., material 107
initial value USIGXX=Function Z 1, 1., material 107

$ \{ \text{sig}_v_{\text{OB}} = -\rho_3*9.81*t_{\text{OB}} \} \text{ Pa} $ $\text{Vertical stress at bottom of overburden or top of caprock}$
$ \{ \text{sig}_v_{\text{CR}} = \text{sig}_v_{\text{OB}} - \rho_2*9.81*t_{\text{CR}} \} \text{ Pa} $ $\text{Vertical stress at bottom of caprock or top of salt}$
$ \{ \text{sig}_v_{\text{SD}} = \text{sig}_v_{\text{CR}} - \rho_1*9.81*h_{\text{SD}} \} \text{ Pa} $ $\text{Vertical stress at bottom of salt}$
$ \{ \text{sig}_v_{\text{SR}} = \text{sig}_v_{\text{OB}} - \rho_4*9.81*t_{\text{SR}} \} \text{ Pa} $ $\text{Vertical stress at bottom of surrounding rock}$

$ \text{ASCENDING ORDER IS REQUIRED FOR DEFINING FUNCTION} \$

function 1 linear $\text{initial stress function for overburden (mat.3), caprock (mat.2), and salt}$
(mat.1)
\[
\begin{align*}
{\text{h}}_{\text{SD}} - t_{\text{CR}} - t_{\text{OB}} & \{ \text{sig}_v_{\text{SD}} \} \text{ $\text{Bottom of salt}$} \\
{t_{\text{CR}} - t_{\text{OB}}} & \{ \text{sig}_v_{\text{CR}} \} \text{ $\text{Bottom of caprock or top of salt}$} \\
0.0 & \{ \text{sig}_v_{\text{OB}} \} \text{ $\text{Bottom of overburden or top of caprock}$} \\
0.0 & \text{ Top of overburden}
\end{align*}
\]
end function 1

function 2 linear $\text{initial stress function for surrounding rock (mat.4)}$
\[
\begin{align*}
{t_{\text{CR}} - t_{\text{OB}}} & \{ \text{sig}_v_{\text{SR}} \} \text{ $\text{Bottom of surrounding rock}$} \\
0.0 & \{ \text{sig}_v_{\text{OB}} \} \text{ $\text{Bottom of overburden or top of surrounding rock}$} \\
0.0 & \text{ Top of overburden}
\end{align*}
\]
end function 2

function 3 $\text{Gravity and normal displacement function}$
\[
\begin{align*}
0. & 1.0 \\
\{ \text{end_s} \} & 1.0
\end{align*}
\]
end function 3

exit

[units.txt]

Jennifer conversion:

$\text{Length:}$
\[
\begin{align*}
\text{ft} & = \{ \text{ft_m} = 0.3048 \} \text{ m} \\
\text{m} & = \{ \text{m_ft} = 1/\text{ft_m} \} \text{ ft}
\end{align*}
\]

$\text{Pressure:}$
\[
\begin{align*}
\text{MPa} & = \{ \text{MPa_Pa} = 1E6 \} \text{ Pa} \\
\text{Pa} & = \{ \text{Pa_MPa} = 1/\text{MPa_Pa} \} \text{ MPa}
\end{align*}
\]

$\text{Time:}$
\[
\begin{align*}
\text{min} & = \{ \text{min_s} = 60 \} \text{ s} \\
\text{h} & = \{ \text{h_min} = 60 \} \text{ min} \\
\text{d} & = \{ \text{d_h} = 24 \} \text{ h} \\
\text{mon} & = \{ \text{mon_d} = 30.4166666667 \} \text{ d} \\
\text{yr} & = \{ \text{yr_d} = 365 \} \text{ d} \\
\text{dec} & = \{ \text{dec_yr} = 10 \} \text{ yr} \\
\text{cen} & = \{ \text{cen_dec} = 10 \} \text{ dec} \\
\text{mil} & = \{ \text{mil_cen} = 10 \} \text{ cen} \\
\text{h} & = \{ \text{h_s} = \text{h_min}*\text{min_s} \} \text{ s} \\
\text{d} & = \{ \text{d_s} = \text{d_h}*\text{h_s} \} \text{ s} \\
\text{mon} & = \{ \text{mon_s} = \text{mon_d}*\text{d_s} \} \text{ s} \\
\text{yr} & = \{ \text{yr_s} = \text{yr_d}*\text{d_s} \} \text{ s} \\
\text{dec} & = \{ \text{dec_s} = \text{dec_yr}*\text{yr_s} \} \text{ s} \\
\text{cen} & = \{ \text{cen_s} = \text{cen_dec}*\text{dec_s} \} \text{ s} \\
\text{mil} & = \{ \text{mil_s} = \text{mil_cen}*\text{cen_s} \} \text{ s}
\end{align*}
\]

[thickness.txt]

Jennifer thicknesses of each layer

Jennifer thickness of overburden: $ t_{\text{OB}} = \{ t_{\text{OB}} = 500*\text{ft_m} \} \text{ m}$
Jennifer thickness of caprock: $ t_{\text{CR}} = \{ t_{\text{CR}} = 150*\text{ft_m} \} \text{ m}$
Jennifer height of salt dome: $ h_{\text{SD}} = \{ h_{\text{SD}} = 7350*\text{ft_m} \} \text{ m}$
Jennifer thickness of surrounding rock: $ t_{\text{SR}} = \{ t_{\text{SR}} = \text{t_CR} + h_{\text{SD}} \} \text{ m}$
[References]


APPENDIX B: USER-SUPPLIED SUBROUTINE

Scenario 1:

C $Id: usrpbc.f,v 5.0 1998/08/07 21:42:02 mbelanf Exp $
C $Modified for Bayou Choctaw by B.Y.Park, 12/02/2007
C Convert Cavern 102 to SPR and add Caverns A3 and 5 as SPR for Scenario 1
C The stabilizing process of lithologies does not conduct,
C The existing caverns are leached as soon as the stabilization completes
C Cavern 102 is expanded at 21 years after the stabilization
C A3 and 5 are leached at 22 and 23 years respectively after the stabilization
C
SUBROUTINE USRPBC( FAC, CORDES, KSFLG, SCALE, NE, TIME, NESNS, NEBLK,  
   * NSPC )
C**********************************************************************
C   DESCRIPTION:
C     This routine provides pressure boundary conditions to JAS3D
C**********************************************************************
C234567890123456789012345678901234567890123456789012345678901234567890
C
C INCLUDE 'precision.blk'
C INCLUDE 'rcdata.blk'
C INCLUDE 'numbers.blk'
C
C declare logical variables for drawdown flags
C
LOGICAL FINIO,FINIT,F1ST,F2ND,F3RD,F4TH,F5TH
C
DIMENSION FAC(NEBLK),CORDES(NESNS,NEBLK,NSPC)
C
C --- After stabilizing process of lithologies for this simulation,
C --- the caverns is formed from 0 to 1 year using freshwater,
C --- translating linearly in time from lithostatic pressure with salt to
C --- hydrostatic pressure with water.
C --- The oil/brine/liquid setup is held in place using the corresponding
C --- hydrostatic pressure
C
C TIME constants
SECDAY=86400.
DAYMON=30.416666666666666667
DAYYR=365.
SECYR=SECDAY*DAYYR
SECMON=SECDAY*DAYMON
SECDEC=10.*SECYR
SECCEN=10.*SECDEC
SECML=10.*SECCECN
C Define times at each event - BYP 7/30/2007
C --- Time at the initial leaches start (except expanded caverns)
SECST=0.
C --- Time at the expansion leach for Cavern 102 starts
SEC102 = SECST + 21.*SECYR
C --- Times at the initial leaches for Caverns A and M start
SEC1A = SEC102 + 1.*SECYR
SEC1M = SEC1A + 1.*SECYR
C --- Times at the leaches for all SPR caverns start
SEC1ST = SECST + 31.*SECYR
SEC2ND = SEC1ST + 5.*SECYR
SEC3RD = SEC2ND + 5.*SECYR
SEC4TH = SEC3RD + 5.*SECYR
SECSTH = SEC4TH + 5.*SECYR
C Skip for stabilizing process of lithologies BYP 9.20.2006
IF (TIME.LT.SECST) GO TO 1001
C Truncates Time
TIMEYR=(TIME-SECST)/SECYR
A1=A1NT(TIMEYR)
A2=A2NT(A1/5.)
A3=A2*5.+1.
A4=TIMEYR-A3
C Initialize the drawdown flags
FINIO = .FALSE.
FINIT = .FALSE.
F1ST  = .FALSE.
F2ND  = .FALSE.
F3RD  = .FALSE.
F4TH  = .FALSE.
F5TH  = .FALSE.
C rho-g factors for oil, fresh water, brine in Pa/m
C in psi/ft, brine=0.52, oil=0.37, fresh water=0.43
C convert with 1psi = 6894.757 Pa, 1 ft = 0.3048 m
C GRAVITY=9.81
OVRNU=0.33
C RGOVR=1874.*GRAVITY
RGCAP=2319.*GRAVITY
RGSALT=2300.*GRAVITY
C RGH2O=9726.86
RGOIL=8369.62
RGBRINE=11762.7
C RGPROP=514.35*GRAVITY
RGETHY=1253.0*GRAVITY
RGLNG =424.49*GRAVITY
RGETHA=570.26*GRAVITY
C z-locations for layer interfaces, m
ZSURF=0.
ZOVR=-152.
ZCAP=-198.
C Use a well head pressure of 903 psi for cavern 15,17;
C 715 psi for cavern 18; 925 psi for cavern 19;
C 850 psi for cavern 20; 913 psi for cavern 101,102,A,M
C IF(KSFLG.GE.150.AND.KSFLG.LE.155) THEN
PHEAD=903.0*6894.757
ELSEIF(KSFLG.GE.170.AND.KSFLG.LE.175) THEN
PHEAD=903.0*6894.757
ELSEIF(KSFLG.GE.180.AND.KSFLG.LE.185) THEN
PHEAD=715.0*6894.757
ELSEIF(KSFLG.GE.190.AND.KSFLG.LE.195) THEN
PHEAD=925.0*6894.757
ELSEIF(KSFLG.GE.200.AND.KSFLG.LE.205) THEN
PHEAD=850.0*6894.757
ELSEIF(KSFLG.GE.1010.AND.KSFLG.LE.1015) THEN
PHEAD=913.0*6894.757
ELSEIF(KSFLG.GE.1021.AND.KSFLG.LE.1026) THEN
PHEAD=913.0*6894.757
ELSEIF(KSFLG.GE.1060.AND.KSFLG.LE.1075) THEN
PHEAD=913.0*6894.757
ELSE
PHEAD=0.
ENDIF
C Dead Load
DEADLOAD=RGOVR*(ZSURF-ZOVR)+RGCAP*(ZOVR-ZCAP)
C Set zero on the face
DO 10 I = 1,NE
FAC(I)=0.
10 CONTINUE
DO 1000 I = 1, NE

C Coordinates of the center of the face

* XFAC = PFORTH*(CORDES(1,1,1) + CORDES(2,1,1) + 
     CORDES(3,1,1) + CORDES(4,1,1))
* YFAC = PFORTH*(CORDES(1,1,2) + CORDES(2,1,2) + 
     CORDES(3,1,2) + CORDES(4,1,2))
* ZFAC = PFORTH*(CORDES(1,1,3) + CORDES(2,1,3) + 
     CORDES(3,1,3) + CORDES(4,1,3))

PLITHO = DEADLOAD + RGSALT*(ZCAP-ZFAC)
PH2O = RGH2O*(ZSURF-ZFAC)
POIL = RGBRINE*(ZSURF-ZFAC)
PETHY = PETHY*(ZSURF-ZFAC)
PLNG = PLNG*(ZSURF-ZFAC)
POVRH = PHOVRH*(ZSURF-ZFAC)
POVRV = POVRV*(ZSURF-ZFAC)

PH2O = PH2O +PHEAD
POIL = POIL +PHEAD
PBRI = PBRI +PHEAD
PPROP = PPROP+PHEAD
PETHY = PETHY+PHEAD
PH2O = PH2O +PHEAD
POIL = POIL +PHEAD
PBRI = PBRI +PHEAD
PPROP = PPROP+PHEAD
PETHY = PETHY+PHEAD

C2345678912345678921234567893123456789412345678951234567896123456789712
C --- Cavern 102 is expanded 21 years after the stabilization.
C --- New cavern A and M are leached at 22 and 23 years respectively
C --- after the stabilization.
C --- Side set 1026 indicates Cavern 102 after the expansion.

IF (KSFLG.NE.1026) GO TO 50
IF (TIME.LE.(SECL102)) THEN
  PWELL=(PHH2O-PLITHO)*(TIME-SECL102)/SECYR + PLITHO
  FINIT = .TRUE.
  GO TO 69
ELSE
  PWELL=PHOIL
  FINIT = .TRUE.
  GO TO 54
ENDIF

50 IF (KSFLG.NE.1060) GO TO 51
IF (TIME.LE.(SECI102+SECYR+SECDAY)) THEN
  PWELL=(PHH2O-PLITHO)*(TIME-SECI102)/SECYR + PLITHO
  FINIT = .TRUE.
  GO TO 69
ELSE
  PWELL=PHOIL
  FINIT = .TRUE.
  GO TO 54
ENDIF

51 IF (KSFLG.NE.1070) GO TO 52
IF (TIME.LE.(SECILM+SECYR+SECDAY)) THEN
  PWELL=(PHH2O-PLITHO)*(TIME-SECILM)/SECYR + PLITHO
  FINIT = .TRUE.
  GO TO 69
ELSE
  PWELL=PHOIL
  FINIT = .TRUE.
  GO TO 54
ENDIF

C --- Revised pressure calculation of changing to other liquid 1 year
C --- after the stabilization.

52 IF (TIME.LE.(SECST+SECYR+SECDAY)) THEN
  PWELL=(PHH2O-PLITHO)*(TIME-SECST)/SECYR + PLITHO
C --- Set zero on 1020 after the expansion of cavern 102 starts.
ELSEIF ((KSFLG.EQ.1020).AND.(TIME.GE.SECL102)) THEN
  FAC(I)=0.0
  GO TO 1000
C
C --- Internal pressure of the caverns containing liquid gas is
C --- the same as that of the caverns containing brine because
C --- a brine pool exists at the bottom of each cavern.
C
ELSEIF ((KSFLG.EQ. 10).OR.(KSFLG.EQ. 20).OR.(KSFLG.EQ. 30)
  .OR.(KSFLG.EQ. 40).OR.(KSFLG.EQ. 60).OR.(KSFLG.EQ. 80)
  .OR.(KSFLG.EQ. 110).OR.(KSFLG.EQ. 130)
  .OR.(KSFLG.EQ. 140).OR.(KSFLG.EQ. 240).OR.(KSFLG.EQ. 250)
  .OR.(KSFLG.EQ. 260).OR.(KSFLG.EQ.1020).OR.(KSFLG.EQ.1030)
  .OR.(KSFLG.EQ.1040).OR.(KSFLG.EQ.1050)) THEN
  PWELL=PHBRI
  FINIO = .TRUE.
  GO TO 69
C
C --- Cavern 7 was collapsed in 1954 and was filled by overburden material.
C --- The pressure gradient of 0.4 psi/ft is applied on the wall and
C --- 0.812 psi/ft is applied on the floor and roof.
C
ELSEIF  (KSFLG.EQ.  70) THEN
  PWELL=PHOVRH
  FINIO = .TRUE.
  GO TO 69
ELSEIF  (KSFLG.EQ.  71) THEN
  PWELL=PHOVRV
  FINIO = .TRUE.
  GO TO 69
C
C --- Revised pressure calculation of changing to other liquid after 1 year.
C
ELSE
  PWELL=PHOIL
ENDIF
C
C --- Determine which drawdown the simulation is at
C
IF ((KSFLG.EQ.  10) .OR. (KSFLG.EQ.  20) .OR. (KSFLG.EQ.  30)
  .OR.(KSFLG.EQ.  40) .OR. (KSFLG.EQ.  60) .OR. (KSFLG.EQ.  70)
  .OR.(KSFLG.EQ.  110).OR.(KSFLG.EQ.  130)
  .OR.(KSFLG.EQ. 140).OR.(KSFLG.EQ. 240).OR.(KSFLG.EQ. 250)
  .OR.(KSFLG.EQ. 260).OR.(KSFLG.EQ.1010).OR.(KSFLG.EQ.1020)
  .OR.(KSFLG.EQ.1030).OR.(KSFLG.EQ.1040).OR.(KSFLG.EQ.1050)
  .OR.(KSFLG.EQ.  71)) THEN
  FINIT = .TRUE.
ELSEIF ((KSFLG.EQ. 151).OR.(KSFLG.EQ. 171).OR.(KSFLG.EQ. 181)
  .OR.(KSFLG.EQ. 191).OR. (KSFLG.EQ. 201).OR. (KSFLG.EQ. 1011)
  .OR.(KSFLG.EQ. 1021).OR.(KSFLG.EQ. 1061).OR.(KSFLG.EQ. 1071)
  . ) THEN
  F1ST = .TRUE.
ELSEIF ((KSFLG.EQ. 152).OR.(KSFLG.EQ. 172).OR.(KSFLG.EQ. 182)
  .OR.(KSFLG.EQ. 192).OR. (KSFLG.EQ. 202).OR. (KSFLG.EQ. 1012)
  .OR.(KSFLG.EQ. 1022).OR.(KSFLG.EQ. 1062).OR.(KSFLG.EQ. 1072)
  . ) THEN
  F2ND = .TRUE.
ELSEIF ((KSFLG.EQ. 153).OR.(KSFLG.EQ. 173).OR.(KSFLG.EQ. 183)
  .OR.(KSFLG.EQ. 193).OR. (KSFLG.EQ. 203).OR. (KSFLG.EQ. 1013)
  .OR.(KSFLG.EQ. 1023).OR.(KSFLG.EQ. 1063).OR.(KSFLG.EQ. 1073)
  . ) THEN
  F3RD = .TRUE.
ELSEIF ((KSFLG.EQ. 154).OR.(KSFLG.EQ. 174).OR.(KSFLG.EQ. 184)
  .OR.(KSFLG.EQ. 194).OR. (KSFLG.EQ. 204).OR. (KSFLG.EQ. 1014)
  .OR.(KSFLG.EQ. 1024).OR.(KSFLG.EQ. 1064).OR.(KSFLG.EQ. 1074)
  . ) THEN
  F4TH = .TRUE.
ELSEIF ((KSFLG.EQ. 155).OR.(KSFLG.EQ. 175).OR.(KSFLG.EQ. 185)
  .OR.(KSFLG.EQ. 195).OR. (KSFLG.EQ. 205).OR. (KSFLG.EQ. 1015)
  .OR.(KSFLG.EQ. 1025).OR.(KSFLG.EQ. 1065).OR.(KSFLG.EQ. 1075)
  . ) THEN
  F5TH = .TRUE.
ENDIF
C
C --- Determine if well is down for workover (zero pressure for 1 month)
C --- Caverns 15 and 17 currently maintain equal pressures at all time
C --- including the workover periods.
C
54 IF (TIME.GT.(SECST+SECYR+SECDAY)) THEN
C Cavern 15 is regarded as 1st group
 IF ((A4.GE.1.0001.AND.A4.LE.1.0834).AND. 
  1 (KSFLG.GE.150.AND.KSFLG.LE.175)) PWELL=PWEFL-PHEAD
C Cavern 17 is regarded as 1st group
 IF ((A4.GE.1.0834.AND.A4.LE.1.1667).AND. 
  1 (KSFLG.GE.170.AND.KSFLG.LE.175)) PWELL=PWEFL-PHEAD
C Cavern 102 is regarded as 2nd group
  1 (KSFLG.GE.1021.AND.KSFLG.LE.1026)) PWELL=PWEFL-PHEAD
C Cavern 19 is regarded as 3rd group
  1 (KSFLG.GE.1026.AND.KSFLG.LE.185)) PWELL=PWEFL-PHEAD
C C Cavern 20 is regarded as 5th group
  1 (KSFLG.GE.200.AND.KSFLG.LE.205)) PWELL=PWEFL-PHEAD
C Cavern 101 is regarded as 6th group
  1 (KSFLG.GE.1010.AND.KSFLG.LE.1015)) PWELL=PWEFL-PHEAD
C Cavern 106(A) is regarded as 7th group
  1 (KSFLG.GE.1060.AND.KSFLG.LE.1065)) PWELL=PWEFL-PHEAD
C Cavern 107(M) is regarded as 8th group
  1 (KSFLG.GE.1070.AND.KSFLG.LE.1075)) PWELL=PWEFL-PHEAD
ENDIF
C
69 IF ((TIME.LE.SEC1ST).and.FINIT) THEN
 FAC(I) = S1 * PWELL
ELSEIF ((TIME.GT.SEC1ST.AND.TIME.LE.SEC2ND).and.F1ST) THEN
 FAC(I) = S1 * PWELL
ELSEIF ((TIME.GT.SEC2ND.AND.TIME.LE.SEC3RD).and.F2ND) THEN
 FAC(I) = S1 * PWELL
ELSEIF ((TIME.GT.SEC3RD.AND.TIME.LE.SEC4TH).and.F3RD) THEN
 FAC(I) = S1 * PWELL
ELSEIF ((TIME.GT.SEC4TH.AND.TIME.LE.SEC5TH).and.F4TH) THEN
 FAC(I) = S1 * PWELL
ELSEIF (FINIO) THEN
 FAC(I) = S1 * PWELL
ELSEIF (FINIO) THEN
 FAC(I) = 0.0
ENDIF
C
1000 CONTINUE
C
C For checking
C
C2345678911234567891234567891323456789412345678951234567896123456789712
1001 CONTINUE
C
C if (TIME.LE. SECST).and. FINIT THEN
* FAC(I) = S1 * PWELL
ELSEIF (TIME.GE. SECST+ 2.0*SECYR).and. F1ST THEN
* FAC(I) = S1 * PWELL
ELSEIF (TIME.GE. SECST+ 4.9*SECYR).and. F3RD THEN
* FAC(I) = S1 * PWELL
ELSEIF (TIME.GE. SECST+ 9.9*SECYR).and. F4TH THEN
* FAC(I) = S1 * PWELL
ELSEIF (TIME.GE. SECST+14.9*SECYR).and. F5TH THEN
* FAC(I) = 0.0
ENDIF
C
1000 CONTINUE
C
C For checking
C
C23456789112345678921234567893123456789412345678951234567896123456789712
Scenario 2:

The existing caverns are leached as soon as the stabilization completes. Cavern 102 is expanded at 21 years after the stabilization. A3 and A5 are leached at 22 and 23 years respectively after the stabilization.

```
SUBROUTINE USRPBC( FAC, CORDES, KSFLG, SCALE, NE, TI ME, NESNS, NEBLK, 
* NSPC )
```

Description:
This routine provides pressure boundary conditions to JAS3D.

**Formal Parameters:**
- FAC      REAL       Array which must be returned with the required face pressure.
- CORDES   REAL       Nodal coordinate array.
- KSFLG    INTEGER     Side set ID for this pressure BC.
- SCALE    REAL       Pressure scale factor from input record.
- NE       INTEGER     Number of faces having this pressure BC.
- TIME     REAL       Problem time.
- NESNS    INTEGER     Number of Element Side Nodes.
- NEBLK    INTEGER     Number of Elements per Vector Block.
- NSPC     INTEGER     Number of Spatial Coordinate Components.

Called By: EXLOAD, called once per iteration for each user-defined pressure BC.

Include 'units_fortran.txt'

Define times at each event - BYP 7/30/2007

- Time at the initial leaches start (except expanded caverns)
  bgn_s = 0.
- Time at the expansion leach for Cavern 102 starts
  EL102_s = bgn_s + 21.*yr_s
- Times at the initial leaches for Caverns A and M start
  I LA_s = EL102_s + 1.*yr_s
  ILM_s = I LA_s + 1.*yr_s
- Times at the leaches for all SPR caverns start
  D1st_s = bgn_s + 31.*yr_s
  D2nd_s = D1st_s + 5.*yr_s
  D3rd_s = D2nd_s + 5.*yr_s
  D4th_s = D3rd_s + 5.*yr_s
  D5th_s = D4th_s + 5.*yr_s

Skip for stabilizing process of lithologies BYP 9.20.2006

Truncates Time:
```
TI MEYR=(TI ME-bgn_s)/yr_s
A1=A1 NT(TI MEYR)
```
A2 = A1/N (A1/5.)
A3 = A2*5. -1.
A4 = Ti MEYR A3

C initialize the drawdown flags

FINO = .FALSE.
FINT = .FALSE.
F1ST = .FALSE.
F2ND = .FALSE.
F3RD = .FALSE.
F4TH = .FALSE.
F5TH = .FALSE.

C rho-g factors for oil, fresh water, brine in Pa/m
C in psi/ft, brine=0.52, oil=0.37, fresh water=0.43
C convert with 1 psi = 6894.757 Pa, 1 ft = 3048 m

GRAVITY = 9.81
OVRNU = 0.33

RGOVR = 1874. * GRAVITY
RGCAP = 2319. * GRAVITY
RGSALT = 2300. * GRAVITY

RGOIL = 8369.62
RGBRINE = 11762.7

RGPROP = 514.35 * GRAVITY
RGETHY = 1253.0 * GRAVITY
RGLNG = 424.49 * GRAVITY
RGETHA = 570.26 * GRAVITY

HOROVR = RGOVR*(OVRNU/(1-OVRNU))
VEROVR = RGOVR

C z-locations for layer interfaces, m
ZSURF = 0.
ZOVR = -152.
ZCAP = -198.

C Use a well head pressure of 903 psi for cavern 15, 17;
715 psi for cavern 18; 925 psi for cavern 19;
850 psi for cavern 20; 913 psi for cavern 101, 102, A, M

IF (KSFLG.GE.150. AND. KSFLG.LE.155) THEN
PHEAD = 903.0*6894.757
ELSE IF (KSFLG.GE.170. AND. KSFLG.LE.175) THEN
PHEAD = 903.0*6894.757
ELSE IF (KSFLG.GE.180. AND. KSFLG.LE.185) THEN
PHEAD = 715.0*6894.757
ELSE IF (KSFLG.GE.190. AND. KSFLG.LE.195) THEN
PHEAD = 925.0*6894.757
ELSE IF (KSFLG.GE.200. AND. KSFLG.LE.205) THEN
PHEAD = 850.0*6894.757
ELSE IF (KSFLG.GE.1010. AND. KSFLG.LE.1015) THEN
PHEAD = 913.0*6894.757
ELSE IF (KSFLG.GE.1021. AND. KSFLG.LE.1026) THEN
PHEAD = 913.0*6894.757
ELSE IF (KSFLG.GE.1060. AND. KSFLG.LE.1065) THEN
PHEAD = 913.0*6894.757
ELSE IF (KSFLG.GE.1070. AND. KSFLG.LE.1075) THEN
PHEAD = 913.0*6894.757
ELSE
PHEAD = 0.
ENDIF

C Dead Load
DEADLOAD = RGOVR*(ZSURF-ZOVR) + RGCAP*(ZOVR-ZCAP)

C Set zero on the face
DO 10 I = 1, NE
FAC(I) = 0.0
10 CONTINUE
S1 = SCALE
DO 1000 I = 1, NE
C Coordinates of the center of the face

\[ \text{XFAC} = P \times (\text{CORDES}(1,1) + \text{CORDES}(2,1) + \text{CORDES}(3,1) + \text{CORDES}(4,1)) \]
\[ \text{YFAC} = P \times (\text{CORDES}(1,2) + \text{CORDES}(2,2) + \text{CORDES}(3,2) + \text{CORDES}(4,2)) \]
\[ \text{ZFAC} = P \times (\text{CORDES}(1,3) + \text{CORDES}(2,3) + \text{CORDES}(3,3) + \text{CORDES}(4,3)) \]

\[ \text{PLITHO} = \text{DEADLOAD} + R \times (Z_{\text{CAP}} - Z_{\text{FAC}}) \]
\[ \text{PH2O} = R \times (Z_{\text{SURF}} - Z_{\text{FAC}}) \]
\[ \text{POIL} = R \times (Z_{\text{SURF}} - Z_{\text{FAC}}) \]
\[ \text{PBRI} = R \times (Z_{\text{SURF}} - Z_{\text{FAC}}) \]
\[ \text{PPROP} = R \times (Z_{\text{SURF}} - Z_{\text{FAC}}) \]
\[ \text{PETHY} = R \times (Z_{\text{SURF}} - Z_{\text{FAC}}) \]
\[ \text{PLNG} = R \times (Z_{\text{SURF}} - Z_{\text{FAC}}) \]
\[ \text{PETHA} = R \times (Z_{\text{SURF}} - Z_{\text{FAC}}) \]
\[ \text{POVRH} = R \times (Z_{\text{SURF}} - Z_{\text{FAC}}) \]
\[ \text{POVRV} = R \times (Z_{\text{SURF}} - Z_{\text{FAC}}) \]

\[ \text{PHH2O} = \text{PH2O} + \text{PHEAD} \]
\[ \text{PHOIL} = \text{POIL} + \text{PHEAD} \]
\[ \text{PHBRI} = \text{PBRI} + \text{PHEAD} \]
\[ \text{PHPROP} = \text{PPROP} + \text{PHEAD} \]
\[ \text{PETHY} = \text{PETHY} + \text{PHEAD} \]
\[ \text{PHLNG} = \text{PLNG} + \text{PHEAD} \]
\[ \text{PETHA} = \text{PETHA} + \text{PHEAD} \]
\[ \text{PHOVRH} = \text{POVRH} + \text{PHEAD} \]
\[ \text{PHOVRV} = \text{POVRV} + \text{PHEAD} \]

--- Cavern 102 is expanded 21 years after the stabilization.
--- New cavern A and M are leached at 22 and 23 years respectively after the stabilization.
--- Side set 1026 indicates Cavern 102 after the expansion.

\[
\text{IF (KSFLG.NE.1026) GO TO 50}
\text{IF (TIME.LT.EL102_s) GO TO 1001}
\text{IF (TIME.LE.(EL102_s+yr_s+d_s)) THEN}
\text{PWELL}=(PHH2O-PLITHO)*(TIME-EL102_s)/yr_s + PLITHO
\text{FINIO} = .TRUE.
\text{GO TO 69}
\text{ELSE}
\text{PWELL}=PHOIL
\text{FINIT} = .TRUE.
\text{GO TO 54}
\text{ENDIF}
\text{50 IF (KSFLG.NE.1060) GO TO 51}
\text{IF (TIME.LT.ILA_s) GO TO 1001}
\text{IF (TIME.LE.(ILA_s+yr_s+d_s)) THEN}
\text{PWELL}=(PHH2O-PLITHO)*(TIME-ILA_s)/yr_s + PLITHO
\text{FINIO} = .TRUE.
\text{GO TO 69}
\text{ELSE}
\text{PWELL}=PHOIL
\text{FINIT} = .TRUE.
\text{GO TO 54}
\text{ENDIF}
\text{51 IF (KSFLG.NE.1070) GO TO 52}
\text{IF (TIME.LT.ILM_s) GO TO 1001}
\text{IF (TIME.LE.(ILM_s+yr_s+d_s)) THEN}
\text{PWELL}=(PHH2O-PLITHO)*(TIME-ILM_s)/yr_s + PLITHO
\text{FINIO} = .TRUE.
\text{GO TO 69}
\text{ELSE}
\text{PWELL}=PHOIL
\text{FINIT} = .TRUE.
\text{GO TO 54}
\text{ENDIF}
\text{--- Revised pressure calculation of changing to other liquid 1 year after the stabilization.}
\text{52 IF (TIME.LE.(bgn_s+yr_s+d_s)) THEN}
\text{PWELL}=(PHH2O-PLITHO)*(TIME-bgn_s)/yr_s + PLITHO
\text{--- Set zero on 1020 after the expansion of cavern 102 starts.}
\text{ELSEIF ((KSFLG.EQ.1020).AND.(TIME.GE.EL102_s)) THEN}
\text{FAC(I)=0.0}
\text{GO TO 1000}
\text{--- Internal pressure of the caverns containing liquid gas is}
--- the same as that of the caverns containing brine because
--- a brine pool exists at the bottom of each cavern.
ELSEIF ((KSFLG.EQ. 10).OR.(KSFLG.EQ. 20).OR.(KSFLG.EQ. 30)
1 .OR.(KSFLG.EQ. 40).OR.(KSFLG.EQ. 60).OR.(KSFLG.EQ. 80)
2 .OR.(KSFLG.EQ. 100).OR.(KSFLG.EQ. 110).OR.(KSFLG.EQ. 130)
3 .OR.(KSFLG.EQ. 160).OR.(KSFLG.EQ. 240).OR.(KSFLG.EQ. 250)
4 .OR.(KSFLG.EQ. 260).OR.(KSFLG.EQ. 1020).OR.(KSFLG.EQ. 1030)
5 .OR.(KSFLG.EQ. 1040).OR.(KSFLG.EQ. 1050)) THEN
PWELL=PHBRI
FINIO = .TRUE.
GO TO 69
ELSEIF (KSFLG.EQ. 70) THEN
PWELL=PHOVRH
FINIO = .TRUE.
GO TO 69
ELSEIF (KSFLG.EQ. 71) THEN
PWELL=PHOVRV
FINIO = .TRUE.
GO TO 69
ELSE
PWELL=PHOIL
ENDIF
--- Cavern 7 was collapsed in 1954 and was filled by overburden material.
--- The pressure gradient of 0.4 psi/ft is applied on the wall and
--- 0.812 psi/ft is applied on the floor and roof.
ELSEIF  (KSFLG.EQ. 70) THEN
PWELL=PHOVRH
FINIO = .TRUE.
GO TO 69
ELSEIF  (KSFLG.EQ. 71) THEN
PWELL=PHOVRV
FINIO = .TRUE.
GO TO 69
--- Revised pressure calculation of changing to other liquid after 1 year.
ELSE
PWELL=PHOIL
ENDIF
--- Determine which drawdown the simulation is at
IF ((KSFLG.EQ. 10) .OR. (KSFLG.EQ. 20) .OR. (KSFLG.EQ. 30)
1 .OR.(KSFLG.EQ. 40) .OR. (KSFLG.EQ. 60) .OR. (KSFLG.EQ. 80)
2 .OR.(KSFLG.EQ. 100) .OR. (KSFLG.EQ. 110) .OR. (KSFLG.EQ. 130)
3 .OR.(KSFLG.EQ. 160) .OR. (KSFLG.EQ. 170) .OR. (KSFLG.EQ. 180)
4 .OR.(KSFLG.EQ. 190) .OR. (KSFLG.EQ. 200) .OR. (KSFLG.EQ. 240)
5 .OR.(KSFLG.EQ. 250) .OR. (KSFLG.EQ. 1020) .OR. (KSFLG.EQ. 1030)
6 .OR.(KSFLG.EQ. 1040) .OR. (KSFLG.EQ. 1050) .OR. (KSFLG.EQ. 1040)
7 .OR.(KSFLG.EQ. 1050) .OR. (KSFLG.EQ. 1070)) THEN
FINIT = .TRUE.
ELSEIF ((KSFLG.EQ. 151).OR.(KSFLG.EQ. 171).OR.(KSFLG.EQ. 181)
* .OR.(KSFLG.EQ. 191).OR.(KSFLG.EQ. 201).OR.(KSFLG.EQ. 1011)
* .OR.(KSFLG.EQ. 1021).OR.(KSFLG.EQ. 1061).OR.(KSFLG.EQ. 1071)
* ) THEN
F1ST = .TRUE.
ELSEIF ((KSFLG.EQ. 152).OR.(KSFLG.EQ. 172).OR.(KSFLG.EQ. 182)
* .OR.(KSFLG.EQ. 192).OR.(KSFLG.EQ. 202).OR.(KSFLG.EQ. 1012)
* .OR.(KSFLG.EQ. 1022).OR.(KSFLG.EQ. 1062).OR.(KSFLG.EQ. 1072)
* ) THEN
F2ND = .TRUE.
ELSEIF ((KSFLG.EQ. 153).OR.(KSFLG.EQ. 173).OR.(KSFLG.EQ. 183)
* .OR.(KSFLG.EQ. 193).OR.(KSFLG.EQ. 203).OR.(KSFLG.EQ. 1013)
* .OR.(KSFLG.EQ. 1023).OR.(KSFLG.EQ. 1063).OR.(KSFLG.EQ. 1073)
* ) THEN
F3RD = .TRUE.
ELSEIF ((KSFLG.EQ. 154).OR.(KSFLG.EQ. 174).OR.(KSFLG.EQ. 184)
* .OR.(KSFLG.EQ. 194).OR.(KSFLG.EQ. 204).OR.(KSFLG.EQ. 1014)
* .OR.(KSFLG.EQ. 1024).OR.(KSFLG.EQ. 1064).OR.(KSFLG.EQ. 1074)
* ) THEN
F4TH = .TRUE.
ELSEIF ((KSFLG.EQ. 155).OR.(KSFLG.EQ. 175).OR.(KSFLG.EQ. 185)
* .OR.(KSFLG.EQ. 195).OR.(KSFLG.EQ. 205).OR.(KSFLG.EQ. 1015)
* .OR.(KSFLG.EQ. 1025).OR.(KSFLG.EQ. 1065).OR.(KSFLG.EQ. 1075)
* ) THEN
F5TH = .TRUE.
ENDIF
--- Determine if well is down for workover (zero pressure for 3 months)
--- Caverns 15 and 17 currently maintain equal pressures at all time
--- including the workover periods.
54 IF (TIME.GT.(bgn_s+yr_s+d_s)) THEN
C Cavern 15 is regarded as 1ST group
  IF ((A4.GE.1.0001. AND. A4.LE.1.2501). AND.
    1 (KSFLG.GE.150. AND. KSFLG.LE.155)) PWELL=PWELL-PHEAD
C Cavern 17 is regarded as 1st group
    IF ((A4. GE. 1.0001. AND. A4. LE. 1.2501). AND. 
        (KSFLG. GE. 170. AND. KSFLG. LE. 175))  PWELL=PWELL-PHEAD
C Cavern 102 is regarded as 2nd group
    IF ((A4. GE. 1.5001. AND. A4. LE. 1.7501). AND. 
        (KSFLG. GE. 1021. AND. KSFLG. LE. 1026))  PWELL=PWELL-PHEAD
C Cavern 19 is regarded as 3rd group
    IF ((A4. GE. 2.0001. AND. A4. LE. 2.2501). AND. 
        (KSFLG. GE. 190. AND. KSFLG. LE. 195))  PWELL=PWELL-PHEAD
C Cavern 18 is regarded as 4th group
        (KSFLG. GE. 180. AND. KSFLG. LE. 185))  PWELL=PWELL-PHEAD
C Cavern 20 is regarded as 5th group
        (KSFLG. GE. 200. AND. KSFLG. LE. 205))  PWELL=PWELL-PHEAD
C Cavern 101 is regarded as 6th group
        (KSFLG. GE. 1010. AND. KSFLG. LE. 1015))  PWELL=PWELL-PHEAD
C Cavern 106(A) is regarded as 7th group
        (KSFLG. GE. 1060. AND. KSFLG. LE. 1065))  PWELL=PWELL-PHEAD
C Cavern 107(M) is regarded as 8th group
        (KSFLG. GE. 1070. AND. KSFLG. LE. 1075))  PWELL=PWELL-PHEAD
ENDIF
C
69  IF ((TIME.LE.D1st_s).and.FINIT) THEN
    FAC(I) = S1 * PWELL
  ELSEIF ((TIME.GT.D1st_s.AND.TIME.LE.D2nd_s).and.F1ST) THEN
    FAC(I) = S1 * PWELL
  ELSEIF ((TIME.GT.D2nd_s.AND.TIME.LE.D3rd_s).and.F2ND) THEN
    FAC(I) = S1 * PWELL
  ELSEIF ((TIME.GT.D3rd_s.AND.TIME.LE.D4th_s).and.F3RD) THEN
    FAC(I) = S1 * PWELL
  ELSEIF ((TIME.GT.D4th_s.AND.TIME.LE.D5th_s).and.F4TH) THEN
    FAC(I) = S1 * PWELL
  ELSEIF ((TIME.GT.D5th_s).and.F5TH) THEN
    FAC(I) = S1 * PWELL
  ELSEIF (FINIO) THEN
    FAC(I) = S1 * PWELL
  ELSE
    FAC(I) = 0.0
  ENDIF
C
1000 CONTINUE
C
C For checking
C23456789112345678921234567893123456789412345678951234567896123456789712
1001 CONTINUE

if ((ti me_ ge_ (bgn_s-. 900. *yr_s). and. time_ le_ (. (bgn_s+. 2. 0*d_s))) 
* or. (ti me_ ge_ (bgn_s+. 4. 4*yr_s). and. time_ le_ (. (bgn_s+. 5. 4*yr_s))) 
* or. (ti me_ ge_ (bgn_s+. 0. 9*yr_s). and. time_ le_ (. (bgn_s+. 1. 0*yr_s))) 
* or. (ti me_ ge_ (bgn_s+. 1. 9*yr_s). and. time_ le_ (. (bgn_s+. 2. 1*yr_s))) 
* or. (ti me_ ge_ (bgn_s+. 4. 4*yr_s). and. time_ le_ (. (bgn_s+. 5. 0*yr_s))) 
* or. (ti me_ ge_ (bgn_s+. 40. 9*yr_s). and. time_ le_ (. (bgn_s+. 24. 5*yr_s))) 
* or. (ti me_ ge_ (bgn_s+. 30. 9*yr_s). and. time_ le_ (. (bgn_s+. 32. 5*yr_s))) 
* or. (ti me_ ge_ (bgn_s+. 35. 9*yr_s). and. time_ le_ (. (bgn_s+. 37. 5*yr_s))) 
* or. (ti me_ ge_ (bgn_s+. 40. 9*yr_s). and. time_ le_ (. (bgn_s+. 42. 5*yr_s))) 
* or. (ti me_ ge_ (bgn_s+. 45. 9*yr_s). and. time_ le_ (. (bgn_s+. 47. 5*yr_s))) 
* or. (ti me_ ge_ (bgn_s+. 50. 9*yr_s). and. time_ le_ (. (bgn_s+. 52. 5*yr_s))) 
* or. (ti me_ ge_ (bgn_s+. 55. 9*yr_s). and. time_ le_ (. (bgn_s+. 56. 5*yr_s))) 
) then
C
    * write("*","( Years ‘ 1x, ‘ A4 ‘ 1x, ‘ NE ‘ 1x, 
    * ‘ ZFAC ‘ 1x, ‘ KSFLG ‘ 1x, ‘ FAC (NE) ‘ 1x, 
    * ‘ PLTHO ‘ 1x, ‘ PHH2O ‘ 1x, ‘ PHBRI ‘ 1x, ‘ PHOVRH ‘ 1x, 
    * ‘ PHOVRV ‘ 1x, ‘ POIL ‘ 1x, ‘ PHEAD ‘ 1x")
    if ((NE. LT. 32) . AND. (KSFLG eq. 20)) 
    * write("*",'(" Years ‘ 1x, ‘ A4 ‘ 1x, ‘ NE ‘ 1x, 
    * ‘ ZFAC ‘ 1x, ‘ KSFLG ‘ 1x, ‘ FAC (NE) ‘ 1x, 
    * ‘ PLTHO ‘ 1x, ‘ PHH2O ‘ 1x, ‘ PHBRI ‘ 1x, ‘ PHOVRH ‘ 1x, ‘ PHOVRV ‘ 1x, 
    * ‘ POIL ‘ 1x, ‘ PHEAD ‘ 1x")
    if ((NE. LT. 32) . OR. ((KSFLG eq. 1026) . AND. (ZFAC . LT. 805))) 
    * write("*",’("F7. 4, 1x, F6. 3, 1x, 12, 1x, F7. 1, 1x, 15, 1x 
    * B(9. 3, 1x)")’ Ti MEYR, A4. NE, ZFAC, KSFLG 
    * FAC (NE), PLTHO, PHH2O, PHBRI, PHOVRH, PHOVRV, POIL, PHEAD 
end f
RETURN
END
APPENDIX C: FORTRAN SCRIPT FOR TEMPERATURE AT EACH NODE

```fortran
program load
parameter (ntimes=2, numnod=508028)
dimensions temp(numnod), tdays(ntimes),
1          z(numnod)
character*5 stuff
open(unit=7, file="bc_26cav5l.th", form="UNFORMATTED")
open(unit=9, file="temp_check.dat")
open(8, file="bc_26cav5l.nod", status="OLD")
C --- from 0 day to 2000 years
    data (tdays(i),i=1,ntimes) /0.,730000./
    numer=numnod
    do 10 i=1,numnod
        read(8,*,err=500) stuff,j,x,y,z(i)
        if (j.ne.i.or.j.gt.numnod) go to 500
        c --- Bayou Choctaw temperature profile (SAND2000-1751, App. A)
        C --- Temp. at Top of Surface=28.90dC, Absolute Temp=273.15dK,
        C --- Temp Slope with Depth=0.0138dF/ft=0.0251dC/m (7/27/05, B. Y. Park)
        temp(j)=273.15+28.90-z(i)*0.0251
        write(9,901) i, j, numer, z(i), temp(j)
    901 format(i6,2x,i6,2x,i6,2x,f10.3,2x,f10.3)
10 continue
i=0
3       continue
C --- make .th file at t=0 and 2000 years
    i=i+1
    time=tdays(i)*86400.
    write(*,*) time
    write(7) time, (temp(j), j=1,numer)
    if (i.ge.ntimes) go to 1
    go to 3
1 continue
C
    close(8)
stop
500 write(*,900) j,numer
900 format(*** Number of nodes in nodes file does not match ***,i6,1x,i6)
    stop 1
end

[References]
```
APPENDIX D: JOURNAL SCRIPT FOR MESH GENERATION

# Cubit 12.0 is used
# Journalized by B.Y. Park on November 12, 2009
# Consider 1st to 5th drawdown leach for SPR caverns.
# Mesh for 9 SPR, 8 UTP, 2 inactive, and 7 abandoned cavern in BC site.
# Convert Cavern 102 (UTP) to SPR.
# Add two SPR in the Bayou Choctaw salt dome.
# Cylindrical SPR caverns A3 and 5.
# Add the original cavern before the expansion in Cavern 102A (SPR)
#
reset
#
# Graphics Mode truehiddenline
Graphics Mode Perspective
Graphics Mode Wireframe
rot -20 about z
rot -120 about x
rot 180 about y
rot 180 about z
#
## increasing volume of cavern by 15% \( (IR=1.15) \)
#
# major radius (REW_D=649.51), minor radius (RNS_D=743.86) of salt dome
#
# create brick (Surrounding rock height \( (H_{SR}=2286) \), Overburden height \( (H_{OB}=152.4) \))
Brick x (EW_B=10*REW_D) y (NS_B=10*RNS_D) z \( \{(H_{SR}+H_{OB})\} \)
volume \( \{V_{BR}=1\} \) move x 0 y 0 z \( \{-\frac{(H_{SR}+H_{OB})}{2}\}\)
#
# create dome (Salt dome height \( (H_{SD}=2240.28) \), Caprock height \( (H_{CR}=45.72) \))
Cylinder height \( (H_{SD}+H_{CR}) \) major or radius (REW_D) minor or radius (RNS_D)
volume \( \{V_{DM}=V_{BR}+1\} \) move x 0 y 0 z \( \{-\frac{(H_{SD}+H_{CR})}{2}-H_{OB}\}\)
#
# create cavern 1 (Abandoned)
create cylinder height \( (H_{01}=262.13) \) radius \( (R_{01}=40.32) \)
volume \( \{V_{01}=V_{DM}+1\} \) move x \( \{X_{01}= -305.47\} \) y \( \{Y_{01}= -8.18\} \) z \( \{Z_{01}= 420.62\} \)
#
# create cavern 2 (Abandoned)
create cylinder height \( (H_{02}=266.70) \) radius \( (R_{02}=41.37) \)
volume \( \{V_{02}=V_{01}+1\} \) move x \( \{X_{02}= -249.04\} \) y \( \{Y_{02}= 112.38\} \) z \( \{Z_{02}= 351.28\} \)
#
# create cavern 3 (Abandoned)
create cylinder height \( (H_{03}=300.23) \) radius \( (R_{03}=40.32) \)
volume \( \{V_{03}=V_{02}+1\} \) move x \( \{X_{03}= -250.36\} \) y \( \{Y_{03}= 329.78\} \) z \( \{Z_{03}= 421.39\} \)
#
# create cavern 4 (Inactive)
create cylinder height \( (H_{04}=332.23) \) radius \( (R_{04}=40.32) \)
volume \( \{V_{04}+V_{03}+1\} \) move x \( \{X_{04}= -354.47\} \) y \( \{Y_{04}= -8.18\} \) z \( \{Z_{04}= 420.62\} \)
#
# create Allied 6 (UTP)
create cylinder height \( (H_{06}=111.86) \) radius \( (R_{06}=30.35) \)
volume \( \{V_{06}+V_{04}+1\} \) move x \( \{X_{06}= -58.54\} \) y \( \{Y_{06}= 412.25\} \) z \( \{Z_{06}= 420.17\} \)
#
# create Cavern 7 (Inactve)
create cylinder height \( (H_{07}=341.38) \) radius \( (R_{07}=30.35) \)
volume \( \{V_{07}+V_{06}+1\} \) move x \( \{X_{07}= -239.49\} \) y \( \{Y_{07}= 511.63\} \) z \( \{Z_{07}= H_{OB}+H_{CR}+H_{04}/2\} \)
#
# create cavern 8A (Abandoned)
create cylinder height \( (H_{08}=235.86) \) radius \( (R_{08}=30.35) \)
volume \( \{V_{08}+V_{07}+1\} \) move x \( \{X_{08}= -247.24\} \) y \( \{Y_{08}= 184.18\} \) z \( \{Z_{08}= 489.36\} \)
#
# create cavern 9 (Abandoned)
create cylinder height \( (H_{10}=277.98) \) radius \( (R_{10}=30.35) \)
volume \( \{V_{10}+V_{08}+1\} \) move x \( \{X_{10}= -519.85\} \) y \( \{Y_{10}= 36.08\} \) z \( \{Z_{10}= 440.74\} \)
#
# create cavern 11 (Abandoned)
create cylinder height \( (H_{11}=234.70) \) radius \( (R_{11}=30.35) \)
volume \( \{V_{11}+V_{10}+1\} \) move x \( \{X_{11}= -444.26\} \) y \( \{Y_{11}= 158.69\} \) z \( \{Z_{11}= 431.29\} \)
#
# create cavern 13 (Abandoned)
create cylinder height \( (H_{13}=236.83) \) radius \( (R_{13}=30.35) \)
volume \( \{V_{13}+V_{11}+1\} \) move x \( \{X_{13}= -378.27\} \) y \( \{Y_{13}= 295.42\} \) z \( \{Z_{13}= 454.61\} \)
#
# create cavern 15A (SPR)
### initial cavern
create cylinder height {H_15=210.62} radius {R0_15=62.86}
volume {V_15+1} move x {X_15=27.94} y {Y_15=203.83} z {Z_15=-899.31}

### 1st drawdown
create cylinder height {H_15} radius {R0_15}
create cylinder height {H_15} radius {R1_15=R0_15*sqrt(IR)}
subtract volume {V_15+1} from volume {V_15+2}

### 2nd drawdown
create cylinder height {H_15} radius {R1_15}
create cylinder height {H_15} radius {R2_15=R1_15*sqrt(IR)}
subtract volume {V_15+3} from volume {V_15+4}

### 3rd drawdown
create cylinder height {H_15} radius {R2_15}
create cylinder height {H_15} radius {R3_15=R2_15*sqrt(IR)}
subtract volume {V_15+5} from volume {V_15+6}

### 4th drawdown
create cylinder height {H_15} radius {R3_15}
create cylinder height {H_15} radius {R4_15=R3_15*sqrt(IR)}
subtract volume {V_15+7} from volume {V_15+8}

### 5th drawdown
create cylinder height {H_15} radius {R4_15}
create cylinder height {H_15} radius {R5_15=R4_15*sqrt(IR)}
subtract volume {V_15+9} from volume {V_15+10}

### move to exact location
volume {V_15+2} {V_15+4} {V_15+6} {V_15+8} {V_15+10} move x {X_15} y {Y_15} z {Z_15}

# create cavern 16 (UTP)
create cylinder height {H_16=187.76} radius {R0_16=53.17}
volume {V_16} move x {X_16=-20.68} y {Y_16=205.60} z {Z_16=890.02}

# create cavern 17 (SPR)
### initial cavern
create cylinder height {H_17=433.73} radius {R0_17=37.19}
volume {V_17} move x {X_17=174.77} y {Y_17=224.44} z {Z_17=1009.35}

### 1st drawdown
create cylinder height {H_17} radius {R0_17}
create cylinder height {H_17} radius {R1_17=R0_17*sqrt(IR)}
subtract volume {V_17+1} from volume {V_17+2}

### 2nd drawdown
create cylinder height {H_17} radius {R1_17}
create cylinder height {H_17} radius {R2_17=R1_17*sqrt(IR)}
subtract volume {V_17+3} from volume {V_17+4}

### 3rd drawdown
create cylinder height {H_17} radius {R2_17}
create cylinder height {H_17} radius {R3_17=R2_17*sqrt(IR)}
subtract volume {V_17+5} from volume {V_17+6}

### 4th drawdown
create cylinder height {H_17} radius {R3_17}
create cylinder height {H_17} radius {R4_17=R3_17*sqrt(IR)}
subtract volume {V_17+7} from volume {V_17+8}

### 5th drawdown
create cylinder height {H_17} radius {R4_17}
create cylinder height {H_17} radius {R5_17=R4_17*sqrt(IR)}
subtract volume {V_17+9} from volume {V_17+10}

### move to exact location
volume {V_17+2} {V_17+4} {V_17+6} {V_17+8} {V_17+10} move x {X_17} y {Y_17} z {Z_17}

# create cavern 18 (SPR)
### initial cavern
create cylinder height {H_18=638.25} radius {R0_18=37.19}
volume {V_18} move x {X_18=185.64} y {Y_18=13.17} z {Z_18=966.83}

### 1st drawdown
create cylinder height {H_18} radius {R0_18}
create cylinder height {H_18} radius {R1_18=R0_18*sqrt(IR)}
subtract volume {V_18+1} from volume {V_18+2}

### 2nd drawdown
create cylinder height {H_18} radius {R1_18}
create cylinder height {H_18} radius {R2_18=R1_18*sqrt(IR)}
subtract volume {V_18+3} from volume {V_18+4}

### 3rd drawdown
create cylinder height {H_18} radius {R2_18}
create cylinder height {H_18} radius {R3_18=R2_18*sqrt(IR)}
subtract volume {V_18+5} from volume {V_18+6}

### 4th drawdown
create cylinder height {H_18} radius {R3_18}
create cylinder height {H_18} radius {R4_18=R3_18*sqrt(IR)}
subtract volume {V_18+7} from volume {V_18+8}

### 5th drawdown
create cylinder height {H_18} radius {R4_18}
create cylinder height {H_18} radius {R5_18=R4_18*sqrt(IR)}
subtract volume \( V_{18}+9 \) from volume \( V_{18}+10 \)

### move to exact location
volume \( V_{18}+2 \), \( V_{18}+4 \), \( V_{18}+6 \), \( V_{18}+8 \), \( V_{18}+10 \)
move \( x \{X_{18}\} \) \( y \{Y_{18}\} \) \( z \{Z_{18}\} \)

# # create cavern 19A (SPR)
### initial cavern
create cylinder height \( H_{19}=394.11 \) radius \( R_{0,19}=40.33 \)
volume \( V_{19}=V_{18}+11 \) move \( x \{X_{19}=145.25\} \) \( y \{Y_{19}=415.07\} \) \( z \{Z_{19}=1091.64\} \)
### 1st drawdown
create cylinder height \( H_{19} \) radius \( R_{0,19} \)
calculate \( R_{1,19}=R_{0,19}\sqrt{IR} \)
subtract volume \( V_{19}+1 \) from volume \( V_{19}+2 \)
### 2nd drawdown
create cylinder height \( H_{19} \) radius \( R_{1,19} \)
calculate \( R_{2,19}=R_{1,19}\sqrt{IR} \)
subtract volume \( V_{19}+3 \) from volume \( V_{19}+4 \)
### 3rd drawdown
create cylinder height \( H_{19} \) radius \( R_{2,19} \)
calculate \( R_{3,19}=R_{2,19}\sqrt{IR} \)
subtract volume \( V_{19}+5 \) from volume \( V_{19}+6 \)
### 4th drawdown
create cylinder height \( H_{19} \) radius \( R_{3,19} \)
calculate \( R_{4,19}=R_{3,19}\sqrt{IR} \)
subtract volume \( V_{19}+7 \) from volume \( V_{19}+8 \)
### 5th drawdown
create cylinder height \( H_{19} \) radius \( R_{4,19} \)
calculate \( R_{5,19}=R_{4,19}\sqrt{IR} \)
subtract volume \( V_{19}+9 \) from volume \( V_{19}+10 \)
### move to exact location
volume \( V_{19}+2 \), \( V_{19}+4 \), \( V_{19}+6 \), \( V_{19}+8 \), \( V_{19}+10 \)
move \( x \{X_{19}\} \) \( y \{Y_{19}\} \) \( z \{Z_{19}\} \)

# # create cavern 20A (SPR)
### initial cavern
create cylinder height \( H_{20}=120.40 \) radius \( R_{0,20}=62.10 \)
volume \( V_{20}=V_{19}+11 \) move \( x \{X_{20}=145.25\} \) \( y \{Y_{20}=285.19\} \) \( z \{Z_{20}=1227.58\} \)
### 1st drawdown
create cylinder height \( H_{20} \) radius \( R_{0,20} \)
calculate \( R_{1,20}=R_{0,20}\sqrt{IR} \)
subtract volume \( V_{20}+1 \) from volume \( V_{20}+2 \)
### 2nd drawdown
create cylinder height \( H_{20} \) radius \( R_{1,20} \)
calculate \( R_{2,20}=R_{1,20}\sqrt{IR} \)
subtract volume \( V_{20}+3 \) from volume \( V_{20}+4 \)
### 3rd drawdown
create cylinder height \( H_{20} \) radius \( R_{2,20} \)
calculate \( R_{3,20}=R_{2,20}\sqrt{IR} \)
subtract volume \( V_{20}+5 \) from volume \( V_{20}+6 \)
### 4th drawdown
create cylinder height \( H_{20} \) radius \( R_{3,20} \)
calculate \( R_{4,20}=R_{3,20}\sqrt{IR} \)
subtract volume \( V_{20}+7 \) from volume \( V_{20}+8 \)
### 5th drawdown
create cylinder height \( H_{20} \) radius \( R_{4,20} \)
calculate \( R_{5,20}=R_{4,20}\sqrt{IR} \)
subtract volume \( V_{20}+9 \) from volume \( V_{20}+10 \)
### move to exact location
volume \( V_{20}+2 \), \( V_{20}+4 \), \( V_{20}+6 \), \( V_{20}+8 \), \( V_{20}+10 \)
move \( x \{X_{20}\} \) \( y \{Y_{20}\} \) \( z \{Z_{20}\} \)

# # create Allied 24 (UTP)
create cylinder height \( H_{24}=377.04 \) radius \( R_{0,24}=27.39 \)
volume \( V_{24}=V_{20}+11 \) move \( x \{X_{24}=202.37\} \) \( y \{Y_{24}=243.38\} \) \( z \{Z_{24}=1133.40\} \)

# # create Allied 25 (UTP) (Lowest Bottom)
create cylinder height \( H_{25}=675.13 \) radius \( R_{0,25}=23.04 \)
volume \( V_{25}=V_{24}+1 \) move \( x \{X_{25}=137.51\} \) \( y \{Y_{25}=355.82\} \) \( z \{Z_{25}=1427.23\} \)

# # create Allied 26 (UTP)
create cylinder height \( H_{26}=120.09 \) radius \( R_{0,26}=17.30 \)
volume \( V_{26}=V_{25}+1 \) move \( x \{X_{26}=227.67\} \) \( y \{Y_{26}=508.57\} \) \( z \{Z_{26}=-997.61\} \)

# # create cavern 101B (SPR)
### initial cavern
create cylinder height \( H_{101}=694.94 \) radius \( R_{0,101}=30.83 \)
volume \( V_{101}=V_{26}+1 \) move \( x \{X_{101}=289.91\} \) \( y \{Y_{101}=99.08\} \) \( z \{Z_{101}=1124.71\} \)
### 1st drawdown
create cylinder height \( H_{101} \) radius \( R_{0,101} \)
calculate \( R_{1,101}=R_{0,101}\sqrt{IR} \)
subtract volume \( V_{101}+1 \) from volume \( V_{101}+2 \)
### 2nd drawdown
create cylinder height \(H_{101}\) radius \(R_{101}\)
create cylinder height \(H_{101}\) radius \(R_{201} = R_{101} \times \sqrt{IR}\)
subtract volume \(V_{101+3}\) from volume \(V_{101+4}\)

### 3rd drawdown
create cylinder height \(H_{101}\) radius \(R_{101}\)
create cylinder height \(H_{101}\) radius \(R_{301} = R_{101} \times \sqrt{IR}\)
subtract volume \(V_{101+5}\) from volume \(V_{101+6}\)

### 4th drawdown
create cylinder height \(H_{101}\) radius \(R_{101}\)
create cylinder height \(H_{101}\) radius \(R_{401} = R_{101} \times \sqrt{IR}\)
subtract volume \(V_{101+7}\) from volume \(V_{101+8}\)

### 5th drawdown
create cylinder height \(H_{101}\) radius \(R_{101}\)
create cylinder height \(H_{101}\) radius \(R_{501} = R_{101} \times \sqrt{IR}\)
subtract volume \(V_{101+9}\) from volume \(V_{101+10}\)

### move to exact location
volume \(V_{101+2}\) \(V_{101+4}\) \(V_{101+6}\) \(V_{101+8}\) \(V_{101+10}\) move x \(X_{101}\) y \(Y_{101}\) z \(Z_{101}\)

---

### create Cavern 102A (UTP)

### initial cavern
create cylinder height \(H_{102}=822.66\) radius \(R_{010}=38.10\)
volume \(V_{102} = V_{101} + 11\) move x \(X_{102} = -356.33\) y \(Y_{102} = 82.15\) z \(Z_{102} = 1216.00\)

### 1st drawdown
create cylinder height \(H_{102}\) radius \(R_{010}\)
create cylinder height \(H_{102}\) radius \(R_{102} = R_{010} \times \sqrt{IR}\)
subtract volume \(V_{102+1}\) from volume \(V_{102+2}\)

### 2nd drawdown
create cylinder height \(H_{102}\) radius \(R_{102}\)
create cylinder height \(H_{102}\) radius \(R_{202} = R_{102} \times \sqrt{IR}\)
subtract volume \(V_{102+3}\) from volume \(V_{102+4}\)

### 3rd drawdown
create cylinder height \(H_{102}\) radius \(R_{202}\)
create cylinder height \(H_{102}\) radius \(R_{302} = R_{202} \times \sqrt{IR}\)
subtract volume \(V_{102+5}\) from volume \(V_{102+6}\)

### 4th drawdown
create cylinder height \(H_{102}\) radius \(R_{302}\)
create cylinder height \(H_{102}\) radius \(R_{402} = R_{302} \times \sqrt{IR}\)
subtract volume \(V_{102+7}\) from volume \(V_{102+8}\)

### 5th drawdown
create cylinder height \(H_{102}\) radius \(R_{402}\)
create cylinder height \(H_{102}\) radius \(R_{502} = R_{402} \times \sqrt{IR}\)
subtract volume \(V_{102+9}\) from volume \(V_{102+10}\)

### move to exact location
volume \(V_{102+2}\) \(V_{102+4}\) \(V_{102+6}\) \(V_{102+8}\) \(V_{102+10}\) move x \(X_{102}\) y \(Y_{102}\) z \(Z_{102}\)

---

### create Allied J1 (UTP)
create cylinder height \(H_{J1}=332.54\) radius \(R_{010}=10.68\)
volume \(V_{J1} = V_{102} + 11\) move x \(X_{J1} = -28.06\) y \(Y_{J1} = 512.53\) z \(Z_{J1} = 1036.17\)

---

### create Allied N1 (UTP)
create cylinder height \(H_{N1}=280.42\) radius \(R_{010}=9.40\)
volume \(V_{N1} = V_{J1} + 1\) move x \(X_{N1} = 109.10\) y \(Y_{N1} = 513.75\) z \(Z_{N1} = 954.02\)

---

### create Allied U1 (UTP)
create cylinder height \(H_{U1}=348.08\) radius \(R_{010}=14.32\)
volume \(V_{U1} = V_{N1} + 1\) move x \(X_{U1} = 112.46\) y \(Y_{U1} = 372.63\) z \(Z_{U1} = 892.76\)

---

### create cavern A (SPR A3)

### initial cavern
create cylinder height \(H_{A}=609.60\) radius \(R_{010}=32.77\)
volume \(V_{A} = V_{U1} + 1\) move x \(X_{A} = 285.61\) y \(Y_{A} = 307.99\) z \(Z_{A} = 1066.80\)

---

### create Allied J1 (UTP)
create cylinder height \(H_{J1}=332.54\) radius \(R_{010}=10.68\)
volume \(V_{J1} = V_{102} + 11\) move x \(X_{J1} = -28.06\) y \(Y_{J1} = 512.53\) z \(Z_{J1} = 1036.17\)

---

### create Allied N1 (UTP)
create cylinder height \(H_{N1}=280.42\) radius \(R_{010}=9.40\)
volume \(V_{N1} = V_{J1} + 1\) move x \(X_{N1} = 109.10\) y \(Y_{N1} = 513.75\) z \(Z_{N1} = 954.02\)

---

### create Allied U1 (UTP)
create cylinder height \(H_{U1}=348.08\) radius \(R_{010}=14.32\)
volume \(V_{U1} = V_{N1} + 1\) move x \(X_{U1} = 112.46\) y \(Y_{U1} = 372.63\) z \(Z_{U1} = 892.76\)

---

### create cavern A (SPR A3)

### initial cavern
create cylinder height \(H_{A}=609.60\) radius \(R_{010}=32.77\)
volume \(V_{A} = V_{U1} + 1\) move x \(X_{A} = 285.61\) y \(Y_{A} = 307.99\) z \(Z_{A} = 1066.80\)
create cylinder height \( H_A \) radius \{R4_A\}
create cylinder height \( H_A \) radius \{R5_A=R4_A*\sqrt{IR}\}
subtract volume \{V_A+9\} from volume \{V_A+10\}
### move to exact location
\[ \text{move } x \{X_A\} \ y \{Y_A\} \ z \{Z_A\} \]

# # create cavern M (SPR 5)
### initial cavern
create cylinder height \( H_M=H_A \) radius \{R0_M=R0_A\}
volume \{V_M+V_A+11\} move \ x \{X_M\} \ y \{Y_M\} \ z \{Z_M\}
### 1st drawdown
create cylinder height \( H_M \) radius \{R0_M\}
cylinder height \( H_M \) radius \{R1_M=R0_M*\sqrt{IR}\}
subtract volume \{V_M+2\} from volume \{V_M+3\}
### 2nd drawdown
create cylinder height \( H_M \) radius \{R1_M\}
cylinder height \( H_M \) radius \{R2_M=R1_M*\sqrt{IR}\}
subtract volume \{V_M+4\} from volume \{V_M+5\}
### 3rd drawdown
create cylinder height \( H_M \) radius \{R2_M\}
cylinder height \( H_M \) radius \{R3_M=R2_M*\sqrt{IR}\}
subtract volume \{V_M+6\} from volume \{V_M+7\}
### 4th drawdown
create cylinder height \( H_M \) radius \{R3_M\}
cylinder height \( H_M \) radius \{R4_M=R3_M*\sqrt{IR}\}
subtract volume \{V_M+8\} from volume \{V_M+9\}
### 5th drawdown
create cylinder height \( H_M \) radius \{R4_M\}
cylinder height \( H_M \) radius \{R5_M=R4_M*\sqrt{IR}\}
subtract volume \{V_M+10\} from volume \{V_M+11\}
### move to exact location
\[ \text{move } x \{X_M\} \ y \{Y_M\} \ z \{Z_M\} \]

# # 119-141=-22 (volume number of difference between prior (BC_26cav5l_frustum) and current model)
# webcut from highest surface of cylinders to lowest surface cylinders
webcut volume 1 with plane surface 9 # top of salt dome (volume 2)
webcut volume 2 119 with plane surface 21 # top of cavern 4 (volume 6)
webcut volume 120 121 with plane surface 287 # bottom of cavern 25 (volume 70)
### upper and lower of dome (volume 122)
webcut volume 123 119 121 with sheet extended from surface 520
### related to dome in overburden (volume 126)
### delete duplicated volumes (volume 2 120 122)
del volume 125 127 124
# then volumes of overburden are 126 (done) 1 (surrounding)
# volumes of caprock are 2 (done) 119 (surrounding)
# volumes of mid part are 122 (done) 123 (surrounding)
# volumes of lower part are 120 (done) 121 (surrounding)
zoom volume 122

# # the volumes in the upper and lower dome parts along the cavern cylinders
### upper and lower of caverns
#### cavern 1 (volume 3, 132)
webcut volume 126 2 122 120 with sheet extended from surface 10
webcut volume 130 with plane surface 12 # Upper
webcut volume 132 with plane surface 11 # Lower
delete volume 133
#### cavern 2 (volume 4, 138)
webcut volume 126 2 122 120 with sheet extended from surface 13
webcut volume 136 with plane surface 15
webcut volume 138 with plane surface 14
delete volume 139
#### cavern 3 (volume 5, 144)
webcut volume 126 2 122 120 with sheet extended from surface 16
webcut volume 142 with plane surface 18
webcut volume 144 with plane surface 17
delete volume 145
#### cavern 4 (volume 6, 148)
webcut volume 126 2 122 120 with sheet extended from surface 19
webcut volume 148 with plane surface 20
delete volume 150
#### allied 6 (volume 7, 155)
webcut volume 126 2 122 120 with sheet extended from surface 22
webcut volume 153 with plane surface 24
webcut volume 155 with plane surface 23
delete volume 156
#### cavern 7 (volume 158, 161, 159)
webcut volume 126 2 122 120 with sheet extended from surface 25
webcut volume 159 with plane surface 26
delete volume 8

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### then volume of cavern 7 is 158 in caprock, 161 in salt
### cavern 8 (volume 9, 166)
webcut volume 126 2 122 120 with plane surface 28
webcut volume 164 with plane surface 30
webcut volume 160 with plane surface 29
delete volume 167
### cavern 10 (volume 10, 172)
webcut volume 126 2 122 120 with plane surface 31
webcut volume 170 with plane surface 33
webcut volume 172 with plane surface 32
delete volume 173
### cavern 11 (volume 11, 178)
webcut volume 126 2 122 120 with plane surface 34
webcut volume 176 with plane surface 36
webcut volume 178 with plane surface 35
delete volume 179
### cavern 13 (volume 12, 184)
webcut volume 126 2 122 120 with plane surface 37
webcut volume 182 with plane surface 39
webcut volume 184 with plane surface 38
delete volume 185
##--- Hereafter refer to C:\Sandia.dat\SPR\BC_exp\Calculation\AM to A3_5.xls
### cavern 15A (volume 13 15 17 19 21 23 210 211 212 213 214 215
webcut volume 126 2 122 120 with plane surface 40
webcut volume 126 2 122 120 with plane surface 46
webcut volume 126 2 122 120 with plane surface 55
webcut volume 126 2 122 120 with plane surface 64
webcut volume 126 2 122 120 with plane surface 73
webcut volume 126 2 122 120 with plane surface 82
webcut volume 188 192 196 200 204 208 with plane surface 42
webcut volume 210 211 212 213 214 215 with plane surface 41
delete volume 216 217 218 219 220 221
### cavern 16 (volume 24 226
webcut volume 126 2 122 120 with plane surface 88
webcut volume 224 with plane surface 90
webcut volume 226 with plane surface 89
delete volume 227
### cavern 17 (volume 25 27 29 31 33 35 252 253 254 255 256 257
webcut volume 126 2 122 120 with plane surface 91
webcut volume 126 2 122 120 with plane surface 97
webcut volume 126 2 122 120 with plane surface 106
webcut volume 126 2 122 120 with plane surface 115
webcut volume 126 2 122 120 with plane surface 124
webcut volume 126 2 122 120 with plane surface 133
webcut volume 252 253 254 255 256 257 with plane surface 92
delete volume 258 259 260 261 262 263
### cavern 18 (volume 36 38 40 42 44 46 288 289 290 291 292 293
webcut volume 126 2 122 120 with plane surface 139
webcut volume 126 2 122 120 with plane surface 145
webcut volume 126 2 122 120 with plane surface 154
webcut volume 126 2 122 120 with plane surface 163
webcut volume 126 2 122 120 with plane surface 172
webcut volume 126 2 122 120 with plane surface 181
webcut volume 256 270 274 278 282 286 with plane surface 141
webcut volume 288 290 291 292 293 with plane surface 140
delete volume 294 295 296 297 298 299
### cavern 19A (volume 47 49 51 53 55 57 324 325 326 327 328 329
webcut volume 126 2 122 120 with plane surface 187
webcut volume 126 2 122 120 with plane surface 193
webcut volume 126 2 122 120 with plane surface 202
webcut volume 126 2 122 120 with plane surface 211
webcut volume 126 2 122 120 with plane surface 220
webcut volume 126 2 122 120 with plane surface 229
webcut volume 302 306 310 314 318 322 with plane surface 189
webcut volume 324 325 326 327 328 329 with plane surface 188
delete volume 330 331 332 333 334 335
### cavern 20A (volume 56 60 62 64 66 68 360 361 362 363 364 365
webcut volume 126 2 122 120 with plane surface 235
webcut volume 126 2 122 120 with plane surface 241
webcut volume 126 2 122 120 with plane surface 250
webcut volume 126 2 122 120 with plane surface 259
webcut volume 126 2 122 120 with plane surface 268
webcut volume 126 2 122 120 with plane surface 277
webcut volume 338 342 346 350 354 358 with plane surface 237
webcut volume 360 361 362 363 364 365 with plane surface 236
delete volume 366 367 368 369 370 371
### allied 24 (volume 69 376
webcut volume 126 2 122 120 with plane surface 283
webcut volume 374 with plane surface 285
webcut volume 376 with plane surface 284
delete volume 377

### allied 25 (volume 70 380
webcut volume 126 2 122 120 with sheet extended from surface 286
webcut volume 380 with plane surface 288
delete volume 382

### cavern 26 (volume 71 387
webcut volume 126 2 122 120 with sheet extended from surface 289
webcut volume 387 with plane surface 291
delete volume 388

### cavern 101B (volume 72 74 76 78 80 82 413 414 415 416 417 418
webcut volume 126 2 122 120 with sheet extended from surface 292
webcut volume 126 2 122 120 with sheet extended from surface 298
webcut volume 126 2 122 120 with sheet extended from surface 307
webcut volume 126 2 122 120 with sheet extended from surface 316
webcut volume 126 2 122 120 with sheet extended from surface 325
webcut volume 126 2 122 120 with sheet extended from surface 334
webcut volume 391 395 399 403 407 411 with plane surface 294
webcut volume 427 431 435 439 443 447 with plane surface 342
webcut volume 449 451 452 453 454 with plane surface 341
delete volume 455 456 457 458 459 460

### allied J1 (volume 94 465
webcut volume 126 2 122 120 with sheet extended from surface 388
webcut volume 465 with plane surface 390
delete volume 466

### cavern NL (volume 95 471
webcut volume 126 2 122 120 with sheet extended from surface 391
webcut volume 469 with plane surface 393
webcut volume 471 with plane surface 392
delete volume 472

### UTP1 (volume 96, 477
webcut volume 126 2 122 120 with sheet extended from surface 394
webcut volume 475 with plane surface 396
webcut volume 477 with plane surface 395
delete volume 478

### cavern A (volume 97 99 101 103 105 107 503 504 505 506 507 508
webcut volume 126 2 122 120 with sheet extended from surface 397
webcut volume 126 2 122 120 with sheet extended from surface 403
webcut volume 126 2 122 120 with sheet extended from surface 412
webcut volume 126 2 122 120 with sheet extended from surface 421
webcut volume 126 2 122 120 with sheet extended from surface 430
webcut volume 126 2 122 120 with sheet extended from surface 439
webcut volume 491 495 499 493 497 501 with plane surface 399
webcut volume 503 504 505 506 507 508 with plane surface 398
delete volume 509 510 511 512 513 514

### cavern M (volume 108 110 112 114 116 118 539 540 541 542 543 544
webcut volume 126 2 122 120 with sheet extended from surface 445
webcut volume 126 2 122 120 with sheet extended from surface 451
webcut volume 126 2 122 120 with sheet extended from surface 460
webcut volume 126 2 122 120 with sheet extended from surface 469
webcut volume 126 2 122 120 with sheet extended from surface 478
webcut volume 126 2 122 120 with sheet extended from surface 487
webcut volume 517 521 525 529 533 537 with plane surface 447
webcut volume 539 540 541 542 543 544 with plane surface 446
delete volume 545 546 547 548 549 550
#
# then volumes of mid part are 122 (dome) 123 (surrounding)
#
# zoom volume 122
# To produce a non-manifold geometry model from a manifold geometry,
# coincident surfaces must be merged together
#
# imprint all
# if there are not duplicated volumes, no warnings
# merge all

### until consolidated 0 pare of surface, curves, and vertices
# if there are not duplicated volumes, no warnings
#
# Create the original cavern before the expansion in Cavern 102
create cylinder height \{H_{102}\} radius \{R_{102}=16.07\}
volume (Vb_102=551) move x {X_102} y {Y_102} z {Z_102}
### original cavern after the expansion
create cylinder height {H_102} radius {RI_102}
volume (Va_102=Vb_102+1) move x {X_102} y {Y_102} z {Z_102}
subtract volume (Va_102) from volume (V_102)
webcut volume 425 426 427 428 449 with sheet extended from surface 3070
imprint all

# Mesh caverns manually first
# Use round off to get integer for interval of mesh
#
## Cavern 1 (volume 3)
surface 11 interval {RI_01=10}
merge all
mesh volume 3

## Cavern 2 (volume 4)
surface 14 interval 
{((fmod(R0_02*RI_01,R0_01)<0.5 ? int(R0_02/R0_01*RI_01) + 1) : int(R0_02/R0_01*RI_01))}
mesh surface 14
mesh volume 4

## Cavern 3 (volume 5)
surface 17 interval 
{((fmod(R0_03*RI_01,R0_01)<0.5 ? int(R0_03/R0_01*RI_01) + 1) - 1) - 1}

## Cavern 4 (volume 6)
surface 20 interval 
{((fmod(R0_04*RI_01,R0_01)<0.5 ? int(R0_04/R0_01*RI_01) + 1) + 1)}

## Allied 6 (volume 7)
surface 23 interval 
{((fmod(R0_06*RI_01,R0_01)<0.5 ? int(R0_06/R0_01*RI_01) + 1) + 1)}

## Cavern 7 (volume 158, 161)
surface 715 interval 
{((fmod((H_07-H_CR)*HI_01,H_01)<0.5 ? int((H_07-H_CR)/H_01*HI_01) + 1) + 1)}
surface 717 interval 
{((fmod(H_CR*HI_01,H_01)<0.5 ? int(H_CR/H_01*HI_01) + 1) + 1)}

## Cavern 8A (volume 9)
surface 29 interval 
{((fmod(R0_08*RI_01,R0_01)<0.5 ? int(R0_08/R0_01*RI_01) + 1) + 1)}

## Cavern 10 (volume 10)
surface 32 interval 
{((fmod(R0_10*RI_01,R0_01)<0.5 ? int(R0_10/R0_01*RI_01) + 1) + 1)}

mesh volume 10
#
## Cavern 11 (volume 11)
surface 35 interval 
\{(fmod(R_11/R_01,R_01)<0.5 ? int(R_11/R_01*RI_01) : int(R_11/R_01*RI_01)+1)\}
mesh surface 35
surface 34 interval 
\{(fmod(H_11/H_01,H_01)<0.5 ? int(H_11/H_01*HI_01) : int(H_11/H_01*HI_01)+1)\}
mesh volume 11
#
## Cavern 13 (volume 12)
surface 38 interval 
\{(fmod(R_13/R_01,R_01)<0.5 ? int(R_13/R_01*RI_01) : int(R_13/R_01*RI_01)+1)\}
mesh surface 38
surface 37 interval 
\{(fmod(H_13/H_01,H_01)<0.5 ? int(H_13/H_01*HI_01) : int(H_13/H_01*HI_01)+1)\}
mesh volume 12
#
## Cavern 15A (volume 13 15 17 19 21 23)
surface 41 50 59 68 77 86 interval 
\{(fmod(R_15/R_01,R_01)<0.5 ? int(R_15/R_01*RI_01) : int(R_15/R_01*RI_01)+1)\}
mesh surface 41 50 59 68 77 86
surface 40 46 55 64 73 82 interval 
\{(fmod(H_15/H_01,H_01)<0.5 ? int(H_15/H_01*HI_01) : int(H_15/H_01*HI_01)+1)\}
mesh volume 13 15 17 19 21 23
#
## Cavern 16 (volume 24)
surface 89 interval 
\{(fmod(R_16/R_01,R_01)<0.5 ? int(R_16/R_01*RI_01) : int(R_16/R_01*RI_01)+1)\}
mesh surface 89
surface 88 interval 
\{(fmod(H_16/H_01,H_01)<0.5 ? int(H_16/H_01*HI_01) : int(H_16/H_01*HI_01)+1)\}
mesh volume 24
#
## Cavern 17 (volume 25 27 29 31 33 35)
surface 92 101 110 128 137 137 interval 
\{(fmod(R_17/R_01,R_01)<0.5 ? int(R_17/R_01*RI_01) : int(R_17/R_01*RI_01)+1)\}
mesh surface 92 101 110 128 137
surface 91 97 106 115 124 133 interval 
\{(fmod(H_17/H_01,H_01)<0.5 ? int(H_17/H_01*HI_01) : int(H_17/H_01*HI_01)+1)\}
mesh volume 25 27 29 31 33 35
#
## Cavern 18 (volume 36 38 40 42 44 46)
surface 140 149 158 167 176 185 interval 
\{(fmod(R_18/R_01,R_01)<0.5 ? int(R_18/R_01*RI_01) : int(R_18/R_01*RI_01)+1)\}
mesh surface 140 149 158 167 176 185
surface 139 145 154 163 172 181 interval 
\{(fmod(H_18/H_01,H_01)<0.5 ? int(H_18/H_01*HI_01) : int(H_18/H_01*HI_01)+1)\}
mesh volume 36 38 40 42 44 46
#
## Cavern 19A (volume 47 49 51 53 55 57)
surface 188 197 206 215 224 233 interval 
\{(fmod(R_19/R_01,R_01)<0.5 ? int(R_19/R_01*RI_01) : int(R_19/R_01*RI_01)+1)\}
mesh surface 188 197 206 215 224 233
surface 187 192 201 210 219 228 interval 
\{(fmod(H_19/H_01,H_01)<0.5 ? int(H_19/H_01*HI_01) : int(H_19/H_01*HI_01)+1)\}
mesh volume 47 49 51 53 55 57
#
## Cavern 20A (volume 58 60 62 64 66 68)
surface 236 245 254 263 272 281 interval 
\{(fmod(R_20/R_01,R_01)<0.5 ? int(R_20/R_01*RI_01) : int(R_20/R_01*RI_01)+1)\}
mesh surface 236 245 254 263 272 281
surface 235 244 253 262 271 280 interval 
\{(fmod(H_20/H_01,H_01)<0.5 ? int(H_20/H_01*HI_01) : int(H_20/H_01*HI_01)+1)\}
mesh volume 58 60 62 64 66 68
#
## Allied 24 (volume 69)
surface 284 interval 
\{(fmod(R_24/R_01,R_01)<0.5 ? int(R_24/R_01*RI_01) : int(R_24/R_01*RI_01)+1)\}
mesh surface 284
surface 283 interval 
\{(fmod(H_24/H_01,H_01)<0.5 ? int(H_24/H_01*HI_01) : int(H_24/H_01*HI_01)+1)\}
mesh volume 69
#
## Allied 25 (volume 70, 380) # make the same interval as the cavern in volume 380
surface 287 interval 
\{(fmod(R_25/R_01,R_01)<0.5 ? int(R_25/R_01*RI_01) : int(R_25/R_01*RI_01)+1)\}
mesh surface 287
surface 286 2016 interval 
\{(fmod(H_25/H_01,H_01)<0.5 ? int(H_25/H_01*HI_01) : int(H_25/H_01*HI_01)+1)\}
mesh volume 70 380
vol all in above_caverns size 80
vol all in above_caverns scheme auto
mesh vol all in above_caverns
#
# Block set (Ctrl + Drag Right button on the screen for V.12.0)
# Toggle select Enclosed/Extended, Select XRay has to be on.
## Salt
### Salt around caverns
block 1 Volume 3 to 7, 9 to 13, 15, 17, 19, 21, 23 to 25, 27, \ 
  29, 31, 33, 35 to 36, 38, 40, 42, 44, 46 to 47, 49, 51, 53, \ 
  55, 57 to 59, 60, 62, 64, 66, 68 to 72, 74, 76, 78, 80, 82 to 83, \ 
  85, 87, 89, 91, 93 to 97, 99, 101, 103, 105, 107 to 108, 110, \ 
  112, 114, 116, 118, 120, 122, 130 to 132, 136 to 138, 142 to 144, \ 
  148 to 149, 153 to 155, 159 to 161, 164 to 166, 170 to 172, \ 
  176 to 178, 182 to 184, 188 to 189, 192 to 193, 196 to 197, \ 
  200 to 201, 204 to 205, 208 to 215, 224 to 226, 230 to 231, \ 
  234 to 235, 238 to 239, 242 to 243, 246 to 247, 250 to 257, \ 
  266 to 267, 270 to 271, 274 to 275, 278 to 279, 282 to 283, \ 
  286 to 287, 290 to 292, 296 to 297, 301 to 304, 306 to 307, \ 
  310 to 311, 314 to 315, 318 to 321, 322 to 329, 338 to 339, \ 
  342 to 343, 346 to 347, 350 to 351, 354 to 355, 358 to 365, \ 
  374 to 376, 380 to 381, 385 to 387, 391 to 392, 395 to 396, \ 
  399 to 400, 403 to 404, 407 to 408, 411 to 418, 427 to 428, \ 
  431 to 432, 435 to 436, 439 to 440, 443 to 444, 447 to 454, \ 
  457 to 458, 462 to 465, 469 to 471, 475 to 477, 481 to 482, \ 
  485 to 486, 489 to 490, 493 to 494, 497 to 498, 501 to 508, \ 
  517 to 518, 521 to 522, 525 to 526, 529 to 530, 533 to 534, \ 
  537 to 544, 551, 555 to 557
### refer to "Caverns" below
block 1 volume 3 4 5 6 7 161 9 10 11 12 13 24 25 36 47 58 69 70 71 \ 
  72 551 83 94 95 96 97 108 \ 
  15 27 38 49 60 74 85 99 110, 17 29 40 51 62 76 87 101 112 \ 
  19 31 42 53 64 78 89 103 114, 21 33 44 55 66 80 91 105 116 \ 
  23 35 46 57 68 82 93 107 118 remove
#
## Caprock
block 2 Volume 2, 129, 135, 141, 147, 152, 158, 163, 169, 175, \ 
  245, 249, 265, 269, 273, 277, 281, 285, 301, 305, 309, 313, \ 
  317, 321, 337, 341, 345, 349, 353, 357, 373, 379, 384, 390, \ 
  394, 398, 402, 406, 410, 426, 430, 434, 438, 442, 446, 462, \ 
  468, 474, 480, 484, 488, 492, 496, 500, 516, 520, 524, 528, \ 
  532, 536, 554
### refer to "Caverns" below
block 2 volume 158 remove
#
## Overburden
block 3 Volume 1, 126, 128, 134, 140, 146, 151, 157, 162, 168, \ 
  174, 180, 186, 190, 194, 198, 202, 206, 222, 226, 232, 236, \ 
  240, 244, 248, 264, 268, 272, 276, 280, 284, 300, 304, 308, \ 
  312, 316, 320, 336, 340, 344, 348, 352, 356, 372, 378, 383, \ 
  389, 393, 397, 401, 405, 409, 425, 429, 433, 437, 441, 445, \ 
  461, 467, 473, 479, 483, 487, 491, 495, 499, 515, 519, 523, \ 
  527, 531, 535, 553
#
## Surrounding rocks (Just click on the volume)
block 4 volume 119 121 123
#
### Caverns
### refer to "Cut column related to cavern" above

# APPENDIX
#
# 1# Cavern   1 (Volume  3)
# 2# Cavern   2 (Volume  4)
# 3# Cavern   3 (Volume  5)
# 4# Cavern   4 (Volume  6)
# 5# Allied   6 (Volume  7)
# 6# Cavern   7 (Volume 158 in caprock, 161 in salt)
# 7# Cavern   8A (Volume  9)
# 8# Cavern   10 (Volume 10)
# 9# Cavern   11 (Volume 11)
#10# Cavern   13 (Volume 12)
#11# Cavern   15A (Volume 13 15 17 19 21 23)
#12# Cavern   16 (Volume 24)
#13# Cavern   17 (Volume 25 27 29 31 33 35)

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sideset 130 surface 37 wrt volume 122 # wall at initial
sideset 130 surface 38 wrt volume 184 # floor at initial
sideset 130 surface 39 wrt volume 182 # roof at initial

## Cavern 15A (draw volume 13 15 17 19 21 23 210 211 212 213 214 215 188 192 196 200 204 208
# 210 211 212 213 214 215 \n # 188 192 196 200 204 208 )
sideset 150 surface 40 wrt volume 15 # wall at initial
sideset 150 surface 41 wrt volume 210 # floor at initial
sideset 150 surface 42 wrt volume 188 # roof at initial
sideset 151 surface 46 wrt volume 17 # wall after 1st leach
sideset 151 surface 41 wrt volume 210 # floor at initial
sideset 151 surface 42 wrt volume 188 # roof at initial
sideset 151 surface 50 wrt volume 211 # floor after 1st leach
sideset 151 surface 51 wrt volume 192 # roof after 1st leach
sideset 152 surface 55 wrt volume 19 # wall after 2nd leach
sideset 152 surface 41 wrt volume 210 # floor at initial
sideset 152 surface 42 wrt volume 188 # roof at initial
sideset 152 surface 51 wrt volume 192 # roof after 1st leach
sideset 152 surface 59 wrt volume 212 # floor after 2nd leach
sideset 152 surface 60 wrt volume 196 # roof after 2nd leach
sideset 153 surface 64 wrt volume 21 # wall after 3rd leach
sideset 153 surface 41 wrt volume 210 # floor at initial
sideset 153 surface 42 wrt volume 188 # roof at initial
sideset 153 surface 50 wrt volume 211 # floor after 1st leach
sideset 153 surface 51 wrt volume 192 # roof after 1st leach
sideset 153 surface 59 wrt volume 212 # floor after 2nd leach
sideset 153 surface 60 wrt volume 196 # roof after 2nd leach
sideset 153 surface 68 wrt volume 213 # floor after 3rd leach
sideset 153 surface 69 wrt volume 200 # roof after 3rd leach
sideset 153 surface 73 wrt volume 23 # wall after 4th leach
sideset 154 surface 41 wrt volume 210 # floor at initial
sideset 154 surface 42 wrt volume 188 # roof at initial
sideset 154 surface 50 wrt volume 211 # floor after 1st leach
sideset 154 surface 51 wrt volume 192 # roof after 1st leach
sideset 154 surface 60 wrt volume 196 # roof after 2nd leach
sideset 154 surface 68 wrt volume 213 # floor after 3rd leach
sideset 154 surface 69 wrt volume 200 # roof after 3rd leach
sideset 154 surface 73 wrt volume 204 # roof after 4th leach
sideset 155 surface 82 wrt volume 122 # wall after 5th leach
sideset 155 surface 41 wrt volume 210 # floor at initial
sideset 155 surface 42 wrt volume 188 # roof at initial
sideset 155 surface 50 wrt volume 211 # floor after 1st leach
sideset 155 surface 51 wrt volume 192 # roof after 1st leach
sideset 155 surface 59 wrt volume 212 # floor after 2nd leach
sideset 155 surface 60 wrt volume 196 # roof after 2nd leach
sideset 155 surface 68 wrt volume 213 # floor after 3rd leach
sideset 155 surface 69 wrt volume 200 # roof after 3rd leach
sideset 155 surface 77 wrt volume 214 # floor after 4th leach
sideset 155 surface 78 wrt volume 204 # roof after 4th leach

## Cavern 16 (draw Volume 24 226 224
sideset 160 surface 41 wrt volume 122 # wall at initial
sideset 160 surface 42 wrt volume 226 # floor at initial
sideset 160 surface 40 wrt volume 224 # roof at initial

## Cavern 17 (draw volume 25 27 29 31 33 35 252 253 254 255 256 257 230 234 238 242 246 250
# 252 253 254 255 256 257
# 230 234 238 242 246 250
sideset 170 surface 91 wrt volume 27 # wall at initial
sideset 170 surface 92 wrt volume 252 # floor at initial
sideset 170 surface 93 wrt volume 230 # roof at initial
sideset 171 surface 97 wrt volume 29 # wall after 1st leach
sideset 171 surface 92 wrt volume 252 # floor at initial
sideset 171 surface 93 wrt volume 230 # roof at initial
sideset 171 surface 101 wrt volume 253 # floor after 1st leach
sideset 171 surface 102 wrt volume 234 # roof after 1st leach
sideset 172 surface 106 wrt volume 31 # wall after 2nd leach
sideset 172 surface 92 wrt volume 252 # floor at initial
sideset 172 surface 93 wrt volume 230 # roof at initial
sideset 172 surface 101 wrt volume 253 # floor after 1st leach
sideset 172 surface 102 wrt volume 234 # roof after 1st leach
sideset 172 surface 110 wrt volume 254 # floor after 2nd leach
sideset 172 surface 111 wrt volume 238 # roof after 2nd leach
sideset 173 surface 115 wrt volume 33 # wall after 3rd leach
sideset 173 surface 92 wrt volume 252 # floor at initial
sideset 173 surface 93 wrt volume 230 # roof at initial
sideset 173 surface 101 wrt volume 253 # floor after 1st leach
sideset 173 surface 102 wrt volume 234 # roof after 1st leach
sideset 173 surface 110 wrt volume 254 # floor after 2nd leach
sideset 173 surface 111 wrt volume 238 # roof after 2nd leach
sideset 173 surface 119 wrt volume 255 # floor after 3rd leach
sideset 173 surface 120 wrt volume 242 # roof after 3rd leach
sideset 173 surface 111 wrt volume 252 # floor at initial
sideset 173 surface 112 wrt volume 230 # roof at initial
sideset 173 surface 112 wrt volume 253 # floor after 1st leach
sideset 173 surface 112 wrt volume 234 # roof after 1st leach
sideset 173 surface 111 wrt volume 254 # floor after 2nd leach
sideset 173 surface 111 wrt volume 238 # roof after 2nd leach
sideset 173 surface 119 wrt volume 255 # floor after 3rd leach
sideset 173 surface 120 wrt volume 242 # roof after 3rd leach
sideset 173 surface 119 wrt volume 255 # floor after 3rd leach
sideset 173 surface 120 wrt volume 242 # roof after 3rd leach
sideset 174 surface 124 wrt volume 35 # wall after 4th leach
sideset 174 surface 92 wrt volume 252 # floor at initial
sideset 174 surface 93 wrt volume 230 # roof at initial
sideset 174 surface 101 wrt volume 253 # floor after 1st leach
sideset 174 surface 102 wrt volume 234 # roof after 1st leach
sideset 174 surface 110 wrt volume 254 # floor after 2nd leach
sideset 174 surface 111 wrt volume 238 # roof after 2nd leach
sideset 174 surface 119 wrt volume 255 # floor after 3rd leach
sideset 174 surface 120 wrt volume 242 # roof after 3rd leach
sideset 174 surface 128 wrt volume 256 # floor after 4th leach
sideset 174 surface 129 wrt volume 246 # roof after 4th leach
sideset 175 surface 133 wrt volume 122 # wall after 5th leach
sideset 175 surface 92 wrt volume 252 # floor at initial
sideset 175 surface 93 wrt volume 230 # roof at initial
sideset 175 surface 101 wrt volume 253 # floor after 1st leach
sideset 175 surface 102 wrt volume 234 # roof after 1st leach
sideset 175 surface 110 wrt volume 254 # floor after 2nd leach
sideset 175 surface 111 wrt volume 238 # roof after 2nd leach
sideset 175 surface 119 wrt volume 255 # floor after 3rd leach
sideset 175 surface 120 wrt volume 242 # roof after 3rd leach
sideset 175 surface 128 wrt volume 256 # floor after 4th leach
sideset 175 surface 129 wrt volume 246 # roof after 4th leach
sideset 175 surface 137 wrt volume 257 # floor after 5th leach
sideset 175 surface 138 wrt volume 250 # roof after 5th leach

## Cavern 18 (draw volume 36 38 40 42 44 46 288 289 290 291 292 293 266 270 274 278 282 286
# 288 289 290 291 292 293
# 266 270 274 278 282 286
sideset 180 surface 139 wrt volume 38 # wall at initial
sideset 180 surface 140 wrt volume 288 # floor at initial
sideset 180 surface 141 wrt volume 266 # roof at initial
sideset 181 surface 145 wrt volume 40 # wall after 1st leach
sideset 181 surface 140 wrt volume 288 # floor at initial
sideset 181 surface 141 wrt volume 266 # roof at initial
sideset 181 surface 149 wrt volume 289 # floor after 1st leach
sideset 181 surface 150 wrt volume 270 # roof after 1st leach
sideset 182 surface 154 wrt volume 42 # wall after 2nd leach
sideset 182 surface 140 wrt volume 288 # floor at initial
sideset 182 surface 141 wrt volume 266 # roof at initial
sideset 182 surface 149 wrt volume 289 # floor after 1st leach
sideset 182 surface 150 wrt volume 270 # roof after 1st leach
sideset 182 surface 158 wrt volume 290 # floor after 2nd leach
sideset 182 surface 159 wrt volume 274 # roof after 2nd leach
sideset 183 surface 163 wrt volume 44 # wall after 3rd leach
sideset 183 surface 140 wrt volume 288 # floor at initial
sideset 183 surface 141 wrt volume 266 # roof at initial
sideset 183 surface 149 wrt volume 289 # floor after 1st leach
sideset 183 surface 150 wrt volume 270 # roof after 1st leach
sideset 183 surface 158 wrt volume 290 # floor after 2nd leach
sideset 183 surface 159 wrt volume 274 # roof after 2nd leach
sideset 183 surface 167 wrt volume 291 # floor after 3rd leach
sideset 183 surface 168 wrt volume 278 # roof after 3rd leach
sideset 184 surface 172 wrt volume 46 # wall after 4th leach
sideset 184 surface 140 wrt volume 288 # floor at initial
sideset 184 surface 141 wrt volume 266 # roof at initial
sideset 184 surface 149 wrt volume 289 # floor after 1st leach
sideset 184 surface 150 wrt volume 270 # roof after 1st leach
sideset 184 surface 158 wrt volume 290 # floor after 2nd leach
sideset 184 surface 159 wrt volume 274 # roof after 2nd leach
sideset 184 surface 167 wrt volume 291 # floor after 3rd leach
sideset 184 surface 168 wrt volume 278 # roof after 3rd leach
sideset 184 surface 176 wrt volume 292 # floor after 4th leach
sideset 184 surface 177 wrt volume 282 # roof after 4th leach

sideset 185 surface 181 wrt volume 122 # wall after 5th leach
sideset 185 surface 140 wrt volume 288 # floor at initial
sideset 185 surface 141 wrt volume 266 # roof at initial
sideset 185 surface 149 wrt volume 289 # floor after 1st leach
sideset 185 surface 150 wrt volume 270 # roof after 1st leach
sideset 185 surface 158 wrt volume 291 # floor after 3rd leach
sideset 185 surface 159 wrt volume 278 # roof after 3rd leach
sideset 185 surface 167 wrt volume 292 # floor after 4th leach
sideset 185 surface 176 wrt volume 292 # roof after 4th leach
sideset 185 surface 177 wrt volume 282 # roof after 4th leach

sideset 185 surface 185 wrt volume 293 # floor after 5th leach
sideset 185 surface 186 wrt volume 286 # roof after 5th leach

## Cavern 19A (draw volume 47 49 51 53 55 57 324 325 326 327 328 329 302 306 310 314 318 322
sideset 190 surface 187 wrt volume 49 # wall at initial
sideset 190 surface 188 wrt volume 324 # floor at initial
sideset 190 surface 189 wrt volume 302 # roof at initial

sideset 191 surface 193 wrt volume 51 # wall after 1st leach
sideset 191 surface 188 wrt volume 324 # floor at initial
sideset 191 surface 189 wrt volume 302 # roof at initial
sideset 191 surface 197 wrt volume 325 # floor after 1st leach
sideset 191 surface 198 wrt volume 306 # roof after 1st leach
sideset 192 surface 202 wrt volume 53 # wall after 2nd leach
sideset 192 surface 188 wrt volume 324 # floor at initial
sideset 192 surface 189 wrt volume 302 # roof at initial
sideset 192 surface 197 wrt volume 325 # floor after 1st leach
sideset 192 surface 198 wrt volume 306 # roof after 1st leach
sideset 192 surface 206 wrt volume 326 # floor after 2nd leach
sideset 192 surface 207 wrt volume 310 # roof after 2nd leach

sideset 193 surface 211 wrt volume 55 # wall after 3rd leach
sideset 193 surface 188 wrt volume 324 # floor at initial
sideset 193 surface 189 wrt volume 302 # roof at initial
sideset 193 surface 197 wrt volume 325 # floor after 1st leach
sideset 193 surface 198 wrt volume 306 # roof after 1st leach
sideset 193 surface 207 wrt volume 310 # roof after 2nd leach
sideset 193 surface 215 wrt volume 327 # floor after 3rd leach
sideset 193 surface 216 wrt volume 314 # roof after 3rd leach

sideset 194 surface 220 wrt volume 57 # wall after 4th leach
sideset 194 surface 188 wrt volume 324 # floor at initial
sideset 194 surface 189 wrt volume 302 # roof at initial
sideset 194 surface 197 wrt volume 325 # floor after 1st leach
sideset 194 surface 198 wrt volume 306 # roof after 1st leach
sideset 194 surface 206 wrt volume 326 # floor after 2nd leach
sideset 194 surface 207 wrt volume 310 # roof after 2nd leach
sideset 194 surface 215 wrt volume 327 # floor after 3rd leach
sideset 194 surface 216 wrt volume 314 # roof after 3rd leach
sideset 194 surface 224 wrt volume 328 # floor after 4th leach
sideset 194 surface 225 wrt volume 318 # roof after 4th leach

sideset 195 surface 229 wrt volume 122 # wall after 5th leach
sideset 195 surface 188 wrt volume 324 # floor at initial
sideset 195 surface 189 wrt volume 302 # roof at initial
sideset 195 surface 197 wrt volume 325 # floor after 1st leach
sideset 195 surface 198 wrt volume 306 # roof after 1st leach
sideset 195 surface 206 wrt volume 326 # floor after 2nd leach
sideset 195 surface 207 wrt volume 310 # roof after 2nd leach
sideset 195 surface 215 wrt volume 327 # floor after 3rd leach
sideset 195 surface 216 wrt volume 314 # roof after 3rd leach
sideset 195 surface 234 wrt volume 322 # roof after 5th leach

## Cavern 20A (draw volume 58 60 62 64 66 68 360 361 362 363 364 365 338 342 346 350 354 358
# 360 361 362 363 364 365
# 338 342 346 350 354 358
sideset 200 surface 235 wrt volume 60 # wall at initial
sideset 200 surface 236 wrt volume 360 # floor at initial
sideset 200 surface 237 wrt volume 338 # roof at initial
sideset 201 surface 241 wrt volume 62 # wall after 1st leach
sideset 201 surface 236 wrt volume 360 # floor at initial
sideset 201 surface 237 wrt volume 338 # roof at initial
sideset 201 surface 245 wrt volume 361 # floor after 1st leach
sideset 201 surface 246 wrt volume 342 # roof after 1st leach
sideset 202 surface 250 wrt volume 64 # wall after 2nd leach
sideset 202 surface 236 wrt volume 360 # floor at initial
sideset 202 surface 237 wrt volume 338 # roof at initial
sideset 202 surface 245 wrt volume 361 # floor after 1st leach
sideset 202 surface 246 wrt volume 342 # roof after 1st leach
sideset 202 surface 254 wrt volume 362 # floor after 2nd leach
sideset 202 surface 255 wrt volume 346 # roof after 2nd leach
sideset 203 surface 259 wrt volume 66 # wall after 3rd leach
sideset 203 surface 236 wrt volume 360 # floor at initial
sideset 203 surface 237 wrt volume 338 # roof at initial
sideset 203 surface 245 wrt volume 361 # floor after 1st leach
sideset 203 surface 246 wrt volume 342 # roof after 1st leach
sideset 203 surface 254 wrt volume 362 # floor after 2nd leach
sideset 203 surface 255 wrt volume 346 # roof after 2nd leach
sideset 203 surface 263 wrt volume 363 # floor after 3rd leach
sideset 203 surface 264 wrt volume 350 # roof after 3rd leach
sideset 204 surface 268 wrt volume 68 # wall after 4th leach
sideset 204 surface 236 wrt volume 360 # floor at initial
sideset 204 surface 237 wrt volume 338 # roof at initial
sideset 204 surface 245 wrt volume 361 # floor after 1st leach
sideset 204 surface 246 wrt volume 342 # roof after 1st leach
sideset 204 surface 254 wrt volume 362 # floor after 2nd leach
sideset 204 surface 255 wrt volume 346 # roof after 2nd leach
sideset 204 surface 263 wrt volume 363 # floor after 3rd leach
sideset 204 surface 264 wrt volume 350 # roof after 3rd leach
sideset 204 surface 272 wrt volume 364 # floor after 4th leach
sideset 204 surface 273 wrt volume 354 # roof after 4th leach
sideset 205 surface 277 wrt volume 122 # wall after 5th leach
sideset 205 surface 236 wrt volume 360 # floor at initial
sideset 205 surface 237 wrt volume 338 # roof at initial
sideset 205 surface 245 wrt volume 361 # floor after 1st leach
sideset 205 surface 246 wrt volume 342 # roof after 1st leach
sideset 205 surface 254 wrt volume 362 # floor after 2nd leach
sideset 205 surface 255 wrt volume 346 # roof after 2nd leach
sideset 205 surface 263 wrt volume 363 # floor after 3rd leach
sideset 205 surface 264 wrt volume 350 # roof after 3rd leach
sideset 205 surface 272 wrt volume 364 # floor after 4th leach
sideset 205 surface 273 wrt volume 354 # roof after 4th leach
sideset 205 surface 281 wrt volume 365 # floor after 5th leach
sideset 205 surface 282 wrt volume 358 # roof after 5th leach

## Allied 24 (draw volume 69 376 374
sideset 240 surface 283 wrt volume 122 # wall at initial
sideset 240 surface 284 wrt volume 376 # floor at initial
sideset 240 surface 285 wrt volume 374 # roof at initial

## Allied 25 (draw volume 70 381 380
sideset 250 surface 286 wrt volume 122 # wall at initial
sideset 250 surface 287 wrt volume 381 # floor at initial
sideset 250 surface 288 wrt volume 380 # roof at initial

## Cavern 26 (draw Volume 71 387 385 ## little bit move downward then can make coarse mesh
sideset 260 surface 289 wrt volume 122 # wall at initial
sideset 260 surface 290 wrt volume 387 # floor at initial
sideset 260 surface 291 wrt volume 385 # roof at initial

## Cavern 101B (draw volume 72 74 76 78 82 413 414 415 416 417 418 391 395 399 403 407 411
sideset 1010 surface 292 wrt volume 74 # wall at initial
sideset 1010 surface 293 wrt volume 413 # floor at initial
sideset 1010 surface 294 wrt volume 391 # roof at initial

## Allied 24 (draw volume 69 376 374
sideset 240 surface 283 wrt volume 122 # wall at initial
sideset 240 surface 284 wrt volume 376 # floor at initial
sideset 240 surface 285 wrt volume 374 # roof at initial

## Allied 25 (draw volume 70 381 380
sideset 250 surface 286 wrt volume 122 # wall at initial
sideset 250 surface 287 wrt volume 381 # floor at initial
sideset 250 surface 288 wrt volume 380 # roof at initial

## Cavern 26 (draw Volume 71 387 385 ## little bit move downward then can make coarse mesh
sideset 260 surface 289 wrt volume 122 # wall at initial
sideset 260 surface 290 wrt volume 387 # floor at initial
sideset 260 surface 291 wrt volume 385 # roof at initial

## Cavern 101B (draw volume 72 74 76 78 82 413 414 415 416 417 418 391 395 399 403 407 411
sideset 1010 surface 292 wrt volume 74 # wall at initial
sideset 1010 surface 293 wrt volume 413 # floor at initial
sideset 1010 surface 294 wrt volume 391 # roof at initial

sideset 1011 surface 298 wrt volume 76 # wall after 1st leach
sideset 1011 surface 293 wrt volume 413 # floor at initial
sideset 1011 surface 294 wrt volume 391 # roof at initial
sideset 1011 surface 302 wrt volume 414 # floor after 1st leach
sideset 1011 surface 303 wrt volume 395 # roof after 1st leach
sideset 1012 surface 307 wrt volume 78 # wall after 2nd leach
sideset 1012 surface 293 wrt volume 413 # floor at initial
sideset 1012 surface 294 wrt volume 391 # roof at initial
sideset 1012 surface 302 wrt volume 414 # floor after 1st leach
sideset 1012 surface 303 wrt volume 395 # roof after 1st leach
sideset 1012 surface 311 wrt volume 415 # floor after 2nd leach
sideset 1012 surface 312 wrt volume 399 # roof after 2nd leach
sideset 1013 surface 316 wrt volume 80 # wall after 3rd leach
sideset 1013 surface 293 wrt volume 413 # floor at initial
sideset 1013 surface 294 wrt volume 391 # roof at initial
sideset 1013 surface 302 wrt volume 414 # floor after 1st leach
sideset 1013 surface 303 wrt volume 395 # roof after 1st leach
sideset 1013 surface 311 wrt volume 415 # floor after 2nd leach
sideset 1013 surface 312 wrt volume 399 # roof after 2nd leach
sideset 1013 surface 320 wrt volume 416 # floor after 3rd leach
sideset 1013 surface 321 wrt volume 403 # roof after 3rd leach
sideset 1013 surface 329 wrt volume 417 # floor after 4th leach
sideset 1013 surface 330 wrt volume 407 # roof after 4th leach
sideset 1014 surface 325 wrt volume 82 # wall after 5th leach
sideset 1014 surface 329 wrt volume 418 # floor after 5th leach
sideset 1014 surface 330 wrt volume 407 # roof after 5th leach
sideset 1015 surface 334 wrt volume 122 # wall after 5th leach
sideset 1015 surface 293 wrt volume 413 # floor at initial
sideset 1015 surface 294 wrt volume 391 # roof at initial
sideset 1015 surface 302 wrt volume 414 # floor after 1st leach
sideset 1015 surface 303 wrt volume 395 # roof after 1st leach
sideset 1015 surface 311 wrt volume 415 # floor after 2nd leach
sideset 1015 surface 312 wrt volume 399 # roof after 2nd leach
sideset 1015 surface 320 wrt volume 416 # floor after 3rd leach
sideset 1015 surface 321 wrt volume 403 # roof after 3rd leach
sideset 1015 surface 329 wrt volume 417 # floor after 4th leach
sideset 1015 surface 330 wrt volume 407 # roof after 4th leach
sideset 1015 surface 338 wrt volume 418 # floor after 5th leach
sideset 1015 surface 339 wrt volume 411 # roof after 5th leach
# - 9 - 236
## Cavern 102A (draw volume 551 83 85 87 89 91 93 557 449 450 451 452 453 454 555 427 431 435 439
557 449 450 451 452 453 454 555 427 431 435 439
443 447
# 557 449 450 451 452 453 454
# 555 427 431 435 439 443 447
sideset 1020 surface 3070 wrt volume 83 # wall at initial
sideset 1020 surface 3071 wrt volume 557 # floor at initial
sideset 1020 surface 3072 wrt volume 555 # roof at initial
sideset 1026 surface 3071 wrt volume 557 # floor at initial
sideset 1026 surface 3072 wrt volume 555 # roof at initial
sideset 1026 surface 3077 wrt volume 449 # floor at initial
sideset 1026 surface 3078 wrt volume 427 # roof at initial
sideset 1021 surface 3071 wrt volume 557 # floor at initial
sideset 1021 surface 3072 wrt volume 555 # roof at initial
sideset 1021 surface 3077 wrt volume 449 # floor at initial
sideset 1021 surface 3078 wrt volume 427 # roof at initial
sideset 1021 surface 350 wrt volume 450 # floor at initial
sideset 1021 surface 351 wrt volume 431 # roof at initial
sideset 1022 surface 3071 wrt volume 557 # floor at initial
sideset 1022 surface 3072 wrt volume 555 # roof at initial
sideset 1022 surface 3077 wrt volume 449 # floor at initial
sideset 1022 surface 3078 wrt volume 427 # roof at initial
sideset 1022 surface 350 wrt volume 450 # floor at initial
sideset 1022 surface 351 wrt volume 431 # roof at initial
sideset 1023 surface 3071 wrt volume 557 # floor at initial
sideset 1023 surface 3072 wrt volume 555 # roof at initial
sideset 1023 surface 3077 wrt volume 449 # floor at initial
sideset 1023 surface 3078 wrt volume 427 # roof at initial
sideset 1023 surface 350 wrt volume 450 # floor at initial
sideset 1023 surface 351 wrt volume 431 # roof at initial
sideset 1075 surface 492 wrt volume 537 # roof after 5th leach
#
# Block set (Ctrl + Drag Right button on the screen for V.12.0)
# Toggle select Enclosed/Extended, Select XRay has to be on.
# Node set (Ctrl + Drag left of mouse on the screen)
## Top of body
nodeset 1 Surface 545, 560, 592, 624, 656, 684, 716, 744, 776, 808,
840, 872, 896, 920, 944, 968, 992, 1084, 1116, 1140, 1164, 1188,
1212, 1236, 1328, 1352, 1376, 1400, 1424, 1448, 1540, 1564, 1588,
1612, 1636, 1660, 1752, 1776, 1800, 1824, 1848, 1872, 1964, 1996,
2024, 2056, 2080, 2104, 2128, 2152, 2176, 2292, 2316, 2340, 2364,
2388, 2480, 2512, 2544, 2576, 2600, 2624, 2648, 2672, 2696, 2788,
2812, 2836, 2860, 2884, 2905, 2908, 3081, 3084
## Bottom set
nodeset 2 Surface 551, 578, 610, 642, 674, 702, 734, 762, 794, 826,
858, 890, 914, 938, 962, 986, 1010, 1102, 1134, 1158, 1182, 1206,
1230, 1254, 1346, 1370, 1394, 1418, 1442, 1466, 1558, 1582, 1606,
1630, 1654, 1678, 1770, 1794, 1818, 1842, 1866, 1890, 1982, 2014,
2042, 2074, 2098, 2122, 2146, 2170, 2194, 2310, 2334, 2358, 2382,
2406, 2498, 2530, 2562, 2594, 2618, 2642, 2666, 2690, 2714, 2806,
2830, 2854, 2878, 2902, 2923, 2926, 3099, 3102
## Left set (West side)
nodeset 3 Surface 495, 508, 523, 530
## Right set (East side)
nodeset 4 Surface 497, 510, 525, 527
## Front set (South side)
nodeset 5 Surface 496, 509, 522, 529
## Back set (North side)
nodeset 6 Surface 494, 511, 524, 528
APPENDIX E: USER-SUPPLIED SUBROUTINE TO CALCULATE THE VOLUME CHANGE

PROGRAM VOLCAV2
C
C ----- user input parameters:
C -----   nx0   = number of nodes
C -----   nx1   = number of elements
C -----   nx2   = number of side sets (or larger) = numess
C -----   nx3   = length of node list in the side sets
C -----   nx4   = number of time steps (or larger)
parameter (nx0=508028, nx1=495564, nx2=73, nx3=152800, nx4=500)
C
CHARACTER*8 QAINFO(6)
PARAMETER (MAXQA = 100, MAXINF = 100)
CHARACTER*32 QAREC(4, MAXQA)
CHARACTER*80 INFO(MAXINF)
CHARACTER*(mxstln) MAMECO(6)
CHARACTER*(mxstln) MAMES(256)
CHARACTER*8 NAMECO(6)
CHARACTER*8 NAMELB(256)
CHARACTER*8 NAMES(256)
CHARACTER*80 TITLE
DIMENSION A(1), ia(1)
equivalence (a(1), ia(1))
CHARACTER*1 c(1)

C ------- arrays added by SRS
C ------- data from exodus file
dimension x(nx0), y(nx0), z(nx0)
integer ssid(nx2,3), ssnodes(nx3)
real r0(nx2), h0(nx2), th0(nx2), xc(nx2), yc(nx2), zc(nx2),
v0(nx2), chvol(nx2)
real volcav(nx2,nx4), time(nx4)
common /nodec/ hx(8), hy(8), hz(8)
character*5 STRA, STRB
character*8 STR8
character*256 netfil, ndbfil, errmsg
character*(mxstln) name, cdummy
LOGICAL WHOTIM
real wtime, htime
integer hisid, cpuws, iows
LOGICAL MDEBUG
DATA (QAINFO(I), I=1,3) / 'EX2EX1V2', '09/29/98', 'V 2.04' /
data iin, iout /5, 6/
data cpuws, iows /0, 0/
data displx, displx, displx /
data (comma(i), i=1, nx2) /'DISPLX', 'DISPLY', 'DISPLZ' /
data (comma(i), i=1, nx2) /nx2*','/
C
C ------- arrays added by SRS
C ------- data from exodus file
dimension x(nx0), y(nx0), z(nx0)
integer ssid(nx2,3), ssnodes(nx3)
real r0(nx2), h0(nx2), th0(nx2), xc(nx2), yc(nx2), zc(nx2),
v0(nx2), chvol(nx2)
real volcav(nx2,nx4), time(nx4)
common /nodec/ hx(8), hy(8), hz(8)
character*5 STRA, STRB
character*8 STR8
character*256 netfil, ndbfil, errmsg
character*(mxstln) name, cdummy
LOGICAL WHOTIM
real wtime, htime
integer hisid, cpuws, iows
LOGICAL MDEBUG
DATA (QAINFO(I), I=1,3) / 'EX2EX1V2', '09/29/98', 'V 2.04' /
data iin, iout /5, 6/
data cpuws, iows /0, 0/
data displx, displx, displx /
data (comma(i), i=1, nx2) /'DISPLX', 'DISPLY', 'DISPLZ' /
data (comma(i), i=1, nx2) /nx2*','/
c ------ Radius of cavern from [BC_26cav5l_cylinder_HI10.txt]
data (r(i), i=1, nx2) / 40.32, 41.37, 29.06, 30.18, 19.26, 24.38, 26.44, 34.13, 45.26, 30.35, 62.86, 67.41, 72.29, 77.52, 83.13, 89.15, 53.17, 37.68, 40.41, 43.33, 46.47, 49.83, 53.44, 40.39, 42.77, 45.86, 49.18, 52.74, 50.35, 62.10, 66.59, 71.42, 76.58, 82.13, 88.07, 27.39, 39.30, 30.83, 33.06, 35.45, 38.02, 40.77, 43.72, 16.07, 38.10, 40.86, 43.82, 46.99, 50.39, 54.03, 10.68, 10.04, 14.32, 32.77, 35.14, 37.69, 40.41, 43.34, 46.48, 341.38, 10.22, 10.23, 10.24, 10.25, 10.30, 10.40, 10.50, 10.60, 10.61, 10.62, 10.63, 10.64, 10.65.

C open(15, file='volcav.out')
open(16, file='volcav.csv')

CALL STRTUP (QAINFO)
CALL BANNER (0, QAINFO, 'EXODUS II V2.03 TO EXODUS I DATABASE')
& ' TRANSLATOR', ' ', ' ')  
call exinq (netid, EXLVR, idummy, exlibversion, name, nerr)  
write(*,'(A,F6.3)')'ExodusII Library version ',  
  exlibversion  

CALL MDINIT (A)  
CALL MCINIT (C)  
CALL MDSTAT (NERR, MEM)  
IF (NERR .GT. 0) GOTO 130  
MDEBUG = .false.  
if (MDEBUG) then  
call mlst()  
end if  

make netCDF and exodus errors not show up  
call ncpopt (0)  
call exopts (0,ierr)  
c open the netcdf file  

net = 11  
call exname (net, netfil, lnam)  

--- SRS - changed netfil(1:lnam) to interactive input of file name  

C --- modified for compiling in SEALS by JEB on 10/10/2007  
write(*,'(a)') 'Name of EXODUS input file:',netfil(1:lnam)  
C  
read(*,*) netfil  
netid = EXOPEN(netfil(1:lnam), EXREAD, cpuws, iows, vers, nerr)  
if (nerr .lt. 0) then  
write(errmsg,'("could not open input file, error=",i3)')nerr  
call exopts (EXVRBS,ierr)  
call exerr ('volcav', errmsg, ierr)  
goto 140  
end if  
write(15,*) 'Input file name: ',netfil(1:lnam)  
call exinq (netid, EXVERS, idummy, exversion, name, nerr)  
write(*,'(A,F6.3)')  
& 'This database was created by ExodusII version ', exversion  
C - SRS - removed history section here  
open the output database and write the initial variables  

NDB = 20  
call exname (ndb, ndbfil, lnam)  

CALL OPNFIL (NDB, 'U', 'U', 0, IERR)  
if (ierr .gt. 0) then  
write(errmsg,'("error opening output file ", a)')ndbfil(1:lnam)  
call exopts (EXVRBS,ierr)  
call exerr ('volcav', errmsg, ierr)  
goto 140  
end if  
write(*,*) 'Output file name: ',ndbfil(1:lnam)  
call exinq (netid, EXVERS, idummy, exversion, name, nerr)  
write(*,'(A,F6.3)')  
& 'This database was created by ExodusII version ', exversion  
C - SRS - removed history section here  
open the output database and write the initial variables  

get initialization parameters from regular netcdf file  

CALL EXGNI (netid, title, ndim, numnp, numel,  
& nelblk, nummps, numess, nerr)  
if (nerr .lt. 0) then  
call exopts (EXVRBS,ierr)  
call exerr ('volcav', 'Error from exgini', ierr)  
goto 140  
end if  
if (numnp.ne.nx0) then  
call exerr ('volcav', 'Error: nx0 .ne. numnp', -1)  
write(*(,'(A)') 'Error: nx0 .ne. numnp'  
write(*,*) nx0,numnp  
goto 140  
end if  
if (numel.ne.nx1) then  
call exerr ('volcav', 'Error: nx1 .ne. numel', -1)  
write(*(,'(A)') 'Error: nx1 .ne. numel'  
write(*,*) nx1,numel
goto 140
endif
if (numess.gt.nx2) then
  call exerr('volcav', 'Error: nx2 .lt. numess', -1)
  write(*,'(A)') 'Error: nx2 .lt. numnps'
  goto 140
endif

c
get the length of the node sets node list
c
if (numnps .gt. 0) then
  CALL EXINQ (netid, EXNSNL, lnpsnl, dummy, cdummy, nerr)
  if (nerr .lt. 0) then
    call exopts (EXVRBS,ierr)
    call exerr('volcav', 'Error from exqini', ierr)
    goto 140
  endif
else
  lnpsnl = 0
endif

c
if (numess .gt. 0) then
c
get the length of the side sets node list
c
CALL EXI NO (netid, EXSSNL, lessnl, dummy, cdummy, nerr)
if (nerr .lt. 0) then
  call exopts (EXVRBS,ierr)
  call exerr('volcav', 'Error from exqini', ierr)
  goto 140
endif

c
get the length of the side sets distribution factor list
c
CALL EXI NO (netid, EXSSDF, lessdl, dummy, cdummy, nerr)
if (nerr .lt. 0) then
  call exopts (EXVRBS,ierr)
  call exerr('volcav', 'Error from exqini', ierr)
  goto 140
endif

c
if (numess .gt. 0) then
c
get the length of the side sets element list
c
CALL EXI NO (netid, EXSSEL, lessel, dummy, cdummy, nerr)
if (nerr .lt. 0) then
  call exopts (EXVRBS,ierr)
  call exerr('volcav', 'Error from exqini', ierr)
  goto 140
endif
else
  lessnl = 0
  lessel = 0
  lessdl = 0
endif
c
-- Write the initialization information to the EXODUS 1.0 database---
c
-- Commented by SRS
c
CALL DBOINI (NDB, TITLE, NDIM, NUMNP, NUMEL, NELBLK,
&   NUMNPS, LNPSNL, NUMESS, LESSEL, LESSNL)
c
CALL DBPINI ('TIS', NDB, TITLE, NDIM, NUMNP, NUMEL, NELBLK,
&   NUMNPS, LNPSNL, NUMESS, LESSEL, LESSNL,
&   IDUM, IDUM, IDUM, IDUM)
c
C --- Read the coordinates
c
write(*,'(A)') 'Reading coordinates'
CALL MDRSRV ('XN', KXN, NUMNP)
CALL MDRSRV ('YN', KYN, NUMNP)
IF (NDIM .GE. 3) THEN
  CALL MDRSRV ('ZN', KZN, NUMNP)
  CALL MDSTAT (NERR, MEM)
  IF (NERR .GT. 0) GOTO 130
  C
  write(*,'(A)') 'Error from mdrsrv', ierr
go to 140
endif

c-SRS        CALL DBOXYZ (NDB, NDIM, NUMNP, A(KXN), A(KYN), A(KZN))
c-JEB        CALL MDEL ('XN')
c-JEB        CALL MDEL ('YN')
c-JEB        CALL MDEL ('ZN')
ELSE
  CALL EXGCOR(netid, a(kxn), a(kyn), dummy, nerr)
  if (nerr .lt. 0) then
    call exopts (EXVRBS, ierr)
    call exerr('volcav', 'Error from exgcor', ierr)
  goto 140
endif
endif
C   --Read the element order map
write(*,*) kxn,kyn,kzn
write(*,*) x(1),y(1),z(1)
write(*,*) x(numnp),y(numnp),z(numnp)
c      CALL MDRSRV ('MAPEL', KMAPEL, NUMEL)
c      CALL MDSTAT (NERR, MEM)
 IF (NERR .GT. 0) GOTO 130
CALL EXGMAP (netid, a(KMAPEL), nerr)
c      write(*,*) nerr
      do 29 i=2,numel
        do 29 j=1,i-1
          if (ia(kmapel+i-1).eq.ia(kmapel+j-1)) then
            write(*,'(A)') '**************************'
            write(*,'(A)') 'Element order map contains duplicate element IDs'
            write(*,'(A)') '**** Setting nerr to 17 ****'
            nerr=17
          endif
        29 continue
      28 if (nerr .ne. 0) then
        if (nerr .eq. 17) then
          C   -- no element order map in the EXODUS II file; create a dummy one
          do 30 i=1,numel
            ia(KMAPEL+i-1) = i
          30          continue
        else
          goto 140
        endif
      endif
      CALL DBOMAP (NDB, NUMEL, A(KMAPEL))
C      write(*,*) a(kmapel+3),ia(kmapel+3),kmapel
      c-delete this line when ready      call getar1d (ia(KMAPEL),mapeo,numel)
      CALL MDEL ('MAPEL')
c
C   --Read in the element block ID array
write(*,*) 'Reading element block ID array'
call MDRSRV ('IDELB', kidelb, nelblk)
call exgebi (netid, a(kidelb), ierr)
if (nerr .lt. 0) then
  call exopts (EXVRBS, ierr)
  call exerr('volcav', 'Error from exgebi', ierr)
  goto 140
endif
c   --Read the element block
write(*,*) 'Reading element block'
CALL MDRSRV ("NUMELB", KNELB, NELBLK)
CALL MDRSRV ("LNK", KLINK, 0)
CALL MDRSRV ("ATRIB", KATRIB, 0)
CALL MDSTAT (NERR, MEM)
c
write(*,*) knelb, klink, katrib
IF (NERR .GT. 0) GOTO 130

nie = 0
DO 50 IELB = 1, NELBLK

CALL EXGELB (netid, a(kidelb+ielb-1), name, a(knelb+ielb-1), numlnk, numatr, nerr)
if (nerr .lt. 0) then
    call exopts (EXVRBS,ierr)
call exerr('volcav', 'Error from exgelb', ierr)
go to 140
endif

nameelb(ielb) = name(:8)
call getin (a(knelb+ielb-1), num)
if (numlnk .gt. 0) then
    CALL MDLONG ('LINK', KLINK, num*numlnk)
    CALL EXGELC (netid, a(kidelb+ielb-1), a(klink), nerr)
    if (nerr .lt. 0) then
        call exopts (EXVRBS,ierr)
call exerr('volcav', 'Error from exgelc', ierr)
go to 140
    endif
endif
if (numatr .gt. 0) then
    CALL MDLONG ('ATRIB', KATRIB, num*numatr)
    CALL EXGEAT (netid, a(kidelb+ielb-1), a(katrib), nerr)
    if (nerr .lt. 0) then
        call exopts (EXVRBS,ierr)
call exerr('volcav', 'Error from exgeat', ierr)
go to 140
    endif
endif

CALL MDSTAT (NERR, MEM)
IF (NERR .GT. 0) GOTO 130
c
50 CONTINUE
CALL MDDEL ('LINK')
CALL MDDEL ('ATRIB')
IF (NEL .NE. NUMEL) THEN
    CALL INTSTR (1, 0, NEL, STRA, LSTRA)
    CALL INTSTR (1, 0, NUMEL, STRB, LSTRB)
    CALL PRTERR ('WARNING', 'NUMBER OF ELEMENTS IN BLOCK = ' // STRA(:LSTRA)
                   // ' does not match TOTAL = ' // STRB(:LSTRB))
ENDIF
C--Read the node sets
write(*,'(A)') 'Reading node sets'
c
write(15,'(A)') 'Reading node sets'

CALL MDRSRV ("IDNPS", KIDNS, NUMNPS) ! Node set ids array
CALL MDRSRV ("NNNPS", KNNS, NUMNPS) ! Node set node count array
CALL MDRSRV ("KDNPS", KDNNS, NUMNPS) ! Node set df count array
CALL MDRSRV ("KXNPS", IXNNS, NUMNPS) ! Node set node index array
CALL MDRSRV ("LSTNPS", KLSTNS, LNPSNL) ! Node set node list array
CALL MDRSRV ("FACNPS", KFACNS, LNPSNL) ! Node set df list array
CALL MDRSRV ("XFACNP", KXFACN, LNPSNL) ! Expanded df list array
CALL MDSTAT (NERR, MEM)
c
write(*,*) ki dns, knnns, kdnns, ki xdns, kl stns, kfacns, kxfacn
if (numnps .gt. 0) then
call exgcns (netid, a(kidns), a(knnns), a(kndns), a(kxns),
&                    a(kixdns), a(klstns), a(kfacns), nerr)
if (nerr .lt. 0) then
  call exopts (EXVRBS,ierr)
  call exerr('volcav', 'Error from exgcns', ierr)
goto 140
endif
endif

C Message node sets distribution factors to include '1' for node sets
without Dfs by walking KNDNS array, checking for 0, and filling where
necessary.

do 64 i=0, numnps-1
if (ia(kndns+i) .eq. 0) then
  do 60 ii=0, ia(knnns+i)-1
    a(kxfacn+ia(kixnns+i)-1+ii) = 1.0! Force unity distribution factor
  60 continue
else
  do 62 ii=0, ia(kndns+i)-1
    a(kxfacn+ia(kixnns+i)-1+ii) = a(kfacns+ia(kixdns+i)-1+ii)
  62 continue
endif
64 continue

c-SRS      CALL DBONPS (NDB, NUMNPS, LNPSNL,
c-SRS     &   A(KIDNS), A(KNNNS), A(KIXNNS), A(KLSTNS), A(KXFACN))
CALL MDDEL ('IDNPS')
CALL MDDEL ('NNNPS')
CALL MDDEL ('NDNPS')
CALL MDDEL ('IXNPS')
CALL MDDEL ('LSTNPS')
CALL MDDEL ('FACNPS')
CALL MDDEL ('XFACNP')
CALL MOSTAT (NERR, MEM)
write(15,'(A)') '   Node sets processing complete'
IF (NERR .GT. 0) GOTO 130
C   --Read the side sets
   write(*,'(A)') 'Reading side sets'
   CALL MDRSRV ('IDESS', KIDSS, NUMESS) ! side set id array
c   write(*,'(A)')'number of side set elements array size: ',numess
   CALL MDRSRV ('NEESS', KNESS, NUMESS) ! number of ss elems array
c   write(*,'(A)')'number of side set elements array size: ',numess
   CALL MDRSRV ('NDESS', KNDSS, NUMESS) ! number of dist factors array
c   write(*,'(A)')'number of side set nodes array size: ',numess
   CALL MDRSRV ('NNESS', KNNSS, NUMESS) ! number of nodes array
c   write(*,'(A)')'number of side set nodes array size: ',numess
   CALL MDRSRV ('IXDESS', KIXDSS, NUMESS) ! index into dist factors array
c   write(*,'(A)')'index into side set nodes array size: ',numess
   CALL MDRSRV ('IXNESS', KIXNSS, NUMESS) ! index into nodes array
c   write(*,'(A)')'index into side set nodes array size: ',numess
   CALL MDRSRV ('LTEESS', KLTESS, LESSEL) ! element list
c   write(*,'(A)')'element list array size: ',lessel
   CALL MDRSRV ('LTNESS', KLTNSS, LESSNL) ! node list (21 is max possible)
c   write(*,'(A)')'node list count array size: ',lessnl
   CALL MDRSRV ('LTNNS', KLTNNS, LESSEL) ! node count array
c   write(*,'(A)')'node count array size: ',lessel
   CALL MDRSRV ('LTSESS', KLTSSS, LESSDL) ! side list
c   write(*,'(A)')'side list array size: ',lessdl
   CALL MDRSRV ('FACESS', KFACSS, LESSDL) ! dist factors list
c   write(*,'(A)')'dist factors list array size: ',lessdl
   CALL MDRSRV ('XFACES', KXFACS, LESSNL) ! dist factors list(all DF)
   CALL MOSTAT (NERR, MEM)
IF (NERR .GT. 0) GOTO 130
if (numess .gt. 0) then
  call exgcss (netid, a(kidss), a(kness), a(kndss),
&                    a(kixss), a(kxds), a(kltrss), a(kfacs), nerr)
  if (nerr .lt. 0) then
    call exopts (EXVRBS,ierr)
    call exerr('volcav', 'Error from exgcss', ierr)
goto 140
endif
C Convert sides to nodes

```fortran
isoff = 0  ! offset into element list for current side set
nodcnt = 0  ! node count for current side set
do 104 i = 0, numess - 1  ! loop thru ss element blocks
    ia(kiennss+i) = nodcnt + 1  ! update index array

    call exgsp(netid, ia(kiidss+i), nsess, ndess, nerr) ! get num of sides & df
    if (nerr .lt. 0) then
        call exopts (EXVRBS, ierr)
        call exerr('volcav', 'Error from exgsp', ierr)
        goto 140
    endif

    write(*,*) 'SS ID: ', ia(kiidss+i)
    write(15,*) 'SS ID: ', ia(kiidss+i)
    write(*,*) ' # of sides: ', nsess
    write(15,*) ' # of sides: ', nsess
    i1 = 0
    do 86 i0 = 1, nx2
        if (ssid(i0,1).eq. ia(kiidss+i)) then
            i1 = i0
            ssid(i0,2) = nsess
            ssid(i0,3) = nodcnt + 1
            go to 87
        endif
     86 continue
     87 continue
     endif
     if(i1.eq.0) then
         write(*,*) '*** mismatched side set IDs, loop 86'
         stop 1
     endif

c         write(*,*)' # of dist factors: ', ndess
     call exgssn(netid, ia(kiidss+i), a(klttss+nodcnt),
                   a(klttss+nodcnt), nerr)  ! get side set nodes
     if (nerr .lt. 0) then
         call exopts (EXVRBS, ierr)
         call exerr('volcav', 'Error from exgssn', ierr)
         goto 140
     endif

     nness = 0
     do 102 ii = 0, nsess - 1    ! sum node counts to calculate next index
         nness = nness + ia(klttss+nodcnt+ii)
     102 continue
     c         write(*,*)' # of nodes: ', nness
     call exssn(netid, ia(kiidss+i), a(klttss+nodcnt),
                a(klttss+nodcnt), nerr)  ! get side set nodes
     if (nerr .lt. 0) then
         call exopts (EXVRBS, ierr)
         call exerr('volcav', 'Error from exssn', ierr)
         goto 140
     endif

     nness = 0
     do 102 ii = 0, nsess - 1
         nness = nness + ia(klttss+nodcnt+ii)
     102 continue
     c         write(*,*)' # of nodes: ', nness
     do 234 j = 1, nness
         ssnodes(nodcnt+j) = a(klttss+nodcnt+j-1)
     234 continue
     do 235 j = 1, nness, 12
         write(15,*) (ssnodes(nodcnt+j0), j0 = j, j+11)
     235 continue
     ia(knnss+i) = nness
     nodcnt = nodcnt + nness
     i1off = i1off + nsess
     104 continue

C Massage side sets distribution factors to include '1' for side sets without Dfs by walking KNNSS array, checking for 0, and filling where necessary.
C
    do 110 i = 0, numess - 1
        if (ia(knns+i).eq.0) then
            do 106 ii = 0, ia(knns+i)-1
                a(kxfacs+a(kixnss+i)-1+ii) = 1.0! Force unity distribution factor
            106 continue
        else
            do 108 ii = 0, ia(knns+i) - 1
                a(kxfacs+a(kixnss+i)-1+ii) = a(kfacs+a(kixdss+i)-1+ii)
            108 continue
        endif
    110 continue
```

C calls DBOESS (NDB, NUMESS, LESSEL, LESSNL,
C & A(KI DSS), A(KNNESS), A(KKNNS), A(KI XESS), A(KI XNSS),
C & A(KL TESS), A(KLT TSS), A(KXFACS))

CALL MDDEL ('IDESS')
CALL MDDEL ('NEESS')
CALL MODEL ('NDESS')
CALL MODEL ('NNESS')
CALL MODEL ('XDESS')
CALL MODEL ('XNESS')
CALL MODEL ('IXDESS')
CALL MODEL ('IXNESS')
CALL MODEL ('LTEESS')
CALL MODEL ('LTNESS')
CALL MODEL ('LTNNSS')
CALL MODEL ('LTSESS')
CALL MODEL ('FACESS')
CALL MODEL ('XFACES')

C -- Read the QA records
write(*,'(A)') 'Reading QA records'

nqarec = 0
CALL EXINQ (netid, EXQA, nqarec, r, name, nerr)
if (nerr .lt. 0) then
  call EXOPTS (EXVRBS, ierr)
  call EXERR('volcav', 'Error from exinq', ierr)
  goto 140
endif
if (nqarec .gt. 0 .and. nqarec .le. MAXQA) then
  CALL MCSRVR('QARECS', kqarec, 4*nqarec*8)
  CALL MCSRVR('QATMP', kqatmp, 4*nqarec*mxstln)
  CALL MCSTAT(nerr, mem)
  if (nerr .ne. 0) goto 130
else
  kqarec = 1
endif
if (nqarec .gt. MAXQA) nqarec = 0

ninfo = 0
CALL EXINQ (netid, EXINFO, ninfo, r, name, nerr)
if (nerr .lt. 0) then
  call EXOPTS (EXVRBS, ierr)
  call EXERR('volcav', 'Error from exinq', ierr)
  goto 140
endif
if (ninfo .gt. 0 .and. ninfo .le. MAXINF) then
  CALL MCSRVR('INFO', kinfo, ninfo*mxlnln)
  CALL MCSTAT(nerr, mem)
  if (nerr .ne. 0) goto 130
else
  kinfo = 1
endif
if (ninfo .gt. MAXINF) ninfo = 0

CALL RDQA (netid, nqarec, c(kqatmp), ninfo, c(kinfo))
if (nqarec .gt. 0)
  call resize (nqarec, c(kqarec), c(kqatmp))
endif

C -- Read in the number of element variable names
write(*,'(A)') 'Reading number of element variable names'

CALL EXGV (netid, 'e', nvarel, nerr)
if (nerr .lt. 0) then
  call EXOPTS (EXVRBS, ierr)
  call EXERR('volcav', 'Error from exgv', ierr)
  goto 140
endif

C -- Read in the number of global variable names
write(*,'(A)') 'Reading number of global variable names'

CALL EXGV (netid, 'g', nvargl, nerr)
if (nerr .lt. 0) then
  call EXOPTS (EXVRBS, ierr)
  call EXERR('volcav', 'Error from exgv', ierr)
  goto 140
endif

C -- Read in the number of nodal variable names
write(*,'(A)') 'Reading number of nodal variable names'
call exgvp (netid, 'n', nvarnp, nerr)
if (nerr .lt. 0) then
   call exopts (EXVRBS, ierr)
   call exerr('volcav', 'Error from exgvp', ierr)
goto 140
endif
nvarhi = 0
call mdsrv ('ISEVOK', kievok, nvarel*nelblk)
call mdstat (nerr, mem)
if (nerr .gt. 0) goto 130
write(*,'(A)') 'Reading element variable truth table'
call exgvtt (netid, nelblk, nvarel, a(kievok), nerr)
if (nerr .gt. 0) then
   if (nvarel .gt. 0) then
      write (*,'(4x,"must have element variable truth table")')
goto 140
   endif
endif
if (nerr .lt. 0) then
   call exopts (EXVRBS, ierr)
   call exerr('volcav', 'Error from exgvtt', ierr)
goto 140
endif
write(*,'(A)') 'Reading element variable names'
ixev = 1
if (nvarel .gt. 0) then
   call exgvan (netid, 'e', nvarel, names(ixev), nerr)
   if (nerr .lt. 0) then
      call exopts (EXVRBS, ierr)
      call exerr('volcav', 'Error from exgvan', ierr)
goto 140
   endif
endif
write(*,'(A)') 'Reading global variable names'
ixgv = ixev + nvarel
if (nvargl .gt. 0) then
   call exgvan (netid, 'g', nvargl, names(ixgv), nerr)
   if (nerr .lt. 0) then
      call exopts (EXVRBS, ierr)
      call exerr('volcav', 'Error from exgvan', ierr)
goto 140
   endif
endif
write(*,'(A)') 'Reading nodal variable names'
ixnv = ixgv + nvargl
if (nvarnp .gt. 0) then
   call exgvan (netid, 'n', nvarnp, names(ixnv), nerr)
   if (nerr .lt. 0) then
      call exopts (EXVRBS, ierr)
      call exerr('volcav', 'Error from exgvan', ierr)
goto 140
   endif
endif
write(*,'(A)') 'Reading coordinate names'
call exgcon (netid, nameco, nerr)
if (nerr .lt. 0) then
   call exopts (EXVRBS, ierr)
   call exerr('volcav', 'Error from exgcon', ierr)
goto 140
endif
CALL DBPINI ('V', NTXT, TITLE, NDIM, NUMNP, NUMEL, NELBLK, & NUMVPS, NMAXN, NNUMS, LESSEL, LESSNL, & NVARGL, NVAREL, NVARNP, NNAME)
do 111 i = 1, ndim
nameco(i) = nameco(i)(:8)
111 continue
i dx=0
dy=0
idz=0
do 112 i=1, (nvarhi +nvargl +nvarnp +nvarel)
names(i) = names(i)(:8)
write(*,*) names(i)
if (di splx .eq. names(i)(:6)) idx = i-nvarel-nvargl
if (dyspl y .eq. names(i)(:6)) idy = i-nvarel-nvargl
if (displz .eq. names(i)(:6)) idz = i-nvarel-nvargl
112 continue
write(*,*) idx, idy, idz
c --- calculate original volumes
degrad=3.141592653/180.
do 113 i=1, nx2
vol(i) = 0.5*degrad*th(i)*h0(i)*r0(i)**2
113 continue
CALL DBONAM (NDB, NDIM, NELBLK, NVARHI, NVARGL, NVARNP, NVA REL,
& nameco, namelb,
& names(ixhv), names(ixgv), names(ixnv), names(ixev),
& A(KI EVOK))
CALL MDRSRV ('VARHI', KVARHI, NVARHI)
CALL MDRSRV ('VARGL', KVARGL, NVARGL)
CALL MDRSRV ('VARNP', KVARNP, NVARNP * NUMNP)
CALL MDRSRV ('VAREL', KVAREL, NVAREL * NUMEL)
CALL MDSTAT (NERR, MEM)
IF (NERR .GT. 0) GOTO 130
c      read in the number of history time steps and the number of
C       whole time steps
c call exonq (netid, EXTI MS, ntime, s, name, nerr)
if (nerr .lt. 0) then
   call exopts (EXVRBS,ierr)
   call exerr('volcav', 'Error from exqini', ierr)
goto 140
endif
if (ntime .eq. 0) then
   write(errmsg,'("GENESIS file - no time steps written")')
   call exerr('volcav', errmsg, EXPMSG)
goto 140
endif
numstp = ntime
if (numstp .lt. nx4) then
   call exerr('volcav', 'Error: nx4 .lt. numstp', -1)
   write(*,'(A)') 'Error: nx4 .lt. numstp'
   write(*,*) nx4, numstp
   goto 140
endif
if (nvarhi .gt. 0) then
   call exonq (hisid, EXTI MS, nhtime, s, name, nerr)
   numstp = nhtime
   if (nerr .gt. 0) goto 140
endif
c      read the time step information
write(*,*,'(A)') 'Reading time step information'
isetp = 0
call exgtim(netid, istep+1, wtime, nerr)
if (nerr .lt. 0) then
   call exopts (EXVRBS,ierr)
   call exerr('volcav', 'Error from exgtim', ierr)
goto 140
endif
c      write(*,*) istep, wtime
write(16,902) (comma(n), ssid(n,1), n=1,numess)
902 format('Time(s)',',','Time(y)',73(a1,i4))
do 300 ihstep=1, numstp, oldtim

    write (*,'(4x,"processing time step ", i4)') ihstep
    write (15,'(4x,"processing time step ", i4)') ihstep

c
    get history information

c if (nvarhi .gt. 0) then
    whotim = .false.
    call exgtim(hisid, ihstep, htime, nerr)
    if (nerr .lt. 0) then
        call exopts (EXVRBS,ierr)
        call exerr('volcav', 'Error from exgtim', ierr)
        goto 140
    endif
    call exggv (hisid, ihstep, nvarhi, a(kvarhi), nerr)
    if (nerr .lt. 0) then
        call exopts (EXVRBS,ierr)
        call exerr('volcav', 'Error from exggv', ierr)
        goto 140
    endif
    else
    whotim = .true.
    call exgtim(netid, ihstep, wtime, nerr)
    if (nerr .lt. 0) then
        call exopts (EXVRBS,ierr)
        call exerr('volcav', 'Error from exgtim', ierr)
        goto 140
    endif
    htime = wtime
end if

c
    If a whole time step, do global, nodal, and element variables for the time step.

c if (((whotim) .or. (wtime .eq. htime)) then

    whotim = .true.
    istep = istep + 1
    write(*,*) ihstep, istep, htime, wtime, oldtim

c
    get the global variable values

c if (nvargl .gt. 0) then
    call exggv (netid, istep, nvargl, a(kvargl), nerr)
    if (nerr .lt. 0) then
        call exopts (EXVRBS,ierr)
        call exerr('volcav', 'Error from exggv', ierr)
        goto 140
    endif
end if

c
    get the nodal variable values

do 210 j = 1, nvarnp
    call exgnv (netid, istep, j, numnp, a(kvarnp+(j-1)*numnp), nerr)
    if (nerr .lt. 0) then
        call exopts (EXVRBS,ierr)
        call exerr('volcav', 'Error from exgnv', ierr)
        goto 140
    endif
    continue
210

c
    get element variable values

c if (nvarel .gt. 0) then
    iel=0
    j=0
    do 250 k = 1, nelblk
        l=(k-1)*nvarel
        do 240 j = 1, nvarel
            if (true) then
                get the values for the element variable.
if(a(kievok+i+1) .ne. 0) then
call exgev( netid, istep, j, a(kidelb+k-1),
& a(knelb+k-1), a(kvarel+ielo), nerr)
end if
if (nerr .lt. 0) then
call exopts (EXVRBS,ierr)
call exerr('volcav', 'Error from exgev', ierr)
goto 140
endif
call getin (a(knelb+k-1),num)
ielo = ielo+num
end if
240 continue
250 continue
end if
else
whotim=.false.
end if

c ------ calculate new element variable IMPULSE for all elements

time(ihstep)=wtime
write (15,'(4x,"time ", e11.5)') wtime
jvx=kvarnp+(idx-1)*numnp
jvy=kvarnp+(idy-1)*numnp
jvz=kvarnp+(idz-1)*numnp
do 90 i=1,numess
chvol(i)=0.0
nsides=nsi(d(i),2)
nodes=nsides*4
write(15,900) ssid(i,1),nsides,nnodes
900 format('Side set number ',i3,'
number of sides = ',i6,
'number of nodes = ',i6)
j0= ssid(i,3)
j1=j0+nnodes-1
do 91 j=j0,j1,4
   n0= ssnodes(jm1+jj)
c     if (ihstep.eq.69) write(15,*) jm1+jj,n0,x(n0),y(n0),z(n0),
a     1  a(jvx+n0-1),a(jvy+n0-1),a(jvz+n0-1)
hx(jj)=x(n0)
hy(jj)=y(n0)
hz(jj)=z(n0)
hx(jj+4)=x(n0)+a(jvx+n0-1)
hy(jj+4)=y(n0)+a(jvy+n0-1)
hz(jj+4)=z(n0)+a(jvz+n0-1)
dx=dx+a(jvx+n0-1)
dy=dy+a(jvy+n0-1)
dz=dz+a(jvz+n0-1)
92 continue

c ---- calculate volume of hexahedron from displacements
call hexvol(hvol)
c ---- make sure volume vector is calculated correctly
fac=1.0
a0=x(c(i)-hx(1))
b0=y(c(i)-hy(1))
c0=z(c(i)-hz(1))
a1=hx(2)-hx(1)
b1=hy(2)-hy(1)
c1=hz(2)-hz(1)
a2=hx(4)-hx(1)
b2=hy(4)-hy(1)
c2=hz(4)-hz(1)
dot = a0*(b1*c2-b2*c1)+b0*(c1*a2-c2*a1)+c0*(a1*b2-a2*b1)
if (dot .lt. 0.) fac=-1.
if (fac.lt.0.) write(15,*) '** Problem!! **
& ihstep,i,n0,x(n0),y(n0),z(n0),fac,hvol
chvol(i)=chvol(i)+fac*hvol
91 continue

c --- calculate volume of hexahedron for all elements

c ---- calculate volume of hexahedron from displacements

wyear=wtime/3600/24/365
write(16,901) wtime,wyear,(comma(n),volcav(n,ihstep),n=1,numess)
format(e12.5, ',', F9.4, 73(a1, f10.1))

CALL DBOSTE (NDB, ihsstep, NVARHI, NVARGL, NVARNP, NUMNP,
& NVAREL, NELBLK, a(knelb), a(kievok),
& HI ME, WHO TIM (A(KVARNP), A(KVARHI), A(KVARGL), A(KVARLP)))

continue

call MDDEL ('IDELB')
CALL MDDEL ('VARHI')
CALL MDDEL ('VARGL')
CALL MDDEL ('VARLP')
CALL MDDEL ('VAREL')
CALL MDDEL ('NUMELB')

CONTINUE
CALL INTSTR (1, 0, IHSTEP-1, STR8, LSTR)
WRITE (*, 10010) STR8(:LSTR)
10010 FORMAT (/ , 4X, A,
& ' time steps have been written to the database')
GOTO 140

CONTINUE
CALL MEMERR
GOTO 140

CONTINUE

CLOSE (NDB, IOSTAT=IDUM)
close(15)
close(16)
if (nvarhi .gt. 0) then
  if (hisid .ge. 0) call exclos (hisid, ierr)
endif

if (netid .ge. 0) call exclos (netid, ierr)

CALL WRAPUP (QAINFO(1))

END

subroutine hexvol (hvol)
c
common /nodec/ hx(8), hy(8), hz(8)
data o64th /0.0156250/
c
jacobi an matrix
c
x17=hx(7)-hx(1)
x28=hx(8)-hx(2)
x35=hx(5)-hx(3)
x46=hx(6)-hx(4)
y17=hy(7)-hy(1)
y28=hy(8)-hy(2)
y35=hy(5)-hy(3)
y46=hy(6)-hy(4)
z17=hz(7)-hz(1)
z28=hz(8)-hz(2)
z35=hz(5)-hz(3)
z46=hz(6)-hz(4)
c
aj1=x17+x28-x35-x46
aj2=y17+y28-y35-y46
aj3=z17+z28-z35-z46
a17=x17+x46
a28=x28+x35
b17=y17+y46
b28=y28+y35
c17=z17+z46
c28=z28+z35
c
aj4=a17+a28
aj5=b17+b28
aj6=c17+c28
aj7=a17-a28

111
aj 8=b17-b28
aj 9=c17-c28

Jacobi an

aj 5968=aj 5*aj 9-aj 6*aj 8
aj 6749=aj 6*aj 7-aj 4*aj 9
aj 4857=aj 4*aj 8-aj 5*aj 7

hvol =0.644h*(aj 1*aj 5968+aj 2*aj 6749+aj 3*aj 4857)

return
end

subroutine mliss()
call mliss(6)
return
end

subroutine rdqain (ndb, nqarec, qarec, ninfo, info)
include 'exodusII.inc'
integer ndb
character*(32) qarec(4,nqarec)
character*(80) info(ninfo)
if (nqarec .gt. 0) then
call exgqa (ndb, qarec, nerr)
if (nerr .lt. 0) then
call exopts (EXVRBS, ierr)
call exerr('volcav', 'Error from exgqa', ierr)
endif
endif
if (ninfo .gt. 0) then
call exginf (ndb, info, nerr)
if (nerr .lt. 0) then
call exopts (EXVRBS, ierr)
call exerr('volcav', 'Error from exginf', ierr)
endif
endif
return
end

SUBROUTINE RESIZE (NQAREC, QAREC, QATMP)
-- RESIZE - resizes the qa records from length 32 to 8
-- Parameters:
-- NQAREC - IN - the number of QA records
-- QAREC - IN - the QA records containing size = 8
-- QATMP - IN - the QA records containing size = 32

INTEGER NQAREC
CHARACTER*8 QAREC(4, NQAREC)
CHARACTER*32 QATMP(4, NQAREC)

IF (NQAREC .GT. 0) THEN
DO 50 I = 1, NQAREC
  DO 75 J = 1, 4
    QAREC(J,I) = QATMP(J,I)
  75 CONTINUE
50 CONTINUE
END IF
RETURN
END
APPENDIX F: ALGEBRA SCRIPT FOR POSTPROCESS

Subsidence, Principal Stress and Dilation below -2000 ft
Journalized by B.Y. Park on Apr. 19, 2006

ALLTIMES
min 86400

Difference from displacement at 1st time step
Unit conversion of m to ft

dx=(displx-displx:1)/0.3048
dy=(disply-disply:1)/0.3048
dz=(displz-displz:1)/0.3048

Select Salt Dome blocks 1 10 11 12 13 14 15 below -609.6 m
zoom -3250 3250 -3720 3720 -2438.4 -609.6

Compute Maximum Principal Stresses (psi)
smax=pmax(sigxx,sigyy,sigzz,sigxy,sigyz,sigzx)*1.45038e-4
smaxmx=smax(smax)

Compute Sqrt(J2) and I1
PRE=-(SIGXX+SIGYY+SIGZZ)/3.0
PRE1=ABS(PRE)-1.0e-6
PRE2=IFGZ(PRE1,PRE1,1.0e-6)
SJ2=VONMISES/SQRT(3.0)
I1=3.0*ABS(PRE2)

Compute Minimum Sqr(J2) and I1 (psi)
SJ2MAX=smax(SJ2)*1.45038e-4
I1MAX=smax(I1)*1.45038e-4

Compute Minimum Safety Factor for Dilatancy
Dilation Criterion (SPR rock mechanics test data)
FX=0.257*I1
DPOT=SIJ2/FX
CUT=0.01
RATIO=DPOT-CUT
DIL=IFLZ(RATIO,CUT,RATIO+CUT)
DILFAC=1/DIL
mindil=smin(dilfac)

Compute Minimum Safety Factor for Shear Failure
Shear Failure Criterion (Mises-Schleicher yield criterion)

m1=7.0E6   '(Pa)
m2=0.35
GX=m1+m2*(I1/3.)
DPOTS=SIJ2/GX
RATIO=DPOTS-CUT
DI LS=FLZI(RATIO QS, CUT, RATI O+CUT)
SHRFAC=1/DI LS
nshr=smin(n(SHRFAC))

Define time in terms of years
T1 ME=TI ME/3.1536e7

Delete unneeded variables
DELETE PRE PRE1 PRE2 SJ 1 1 RATIO O RATIO QS DI L DI LS FX GX
DELETE CUT m1 m2

end
DISTRIBUTION

2  U.S. Department of Energy
   Attn: D. Johnson, FE-42
   Strategic Petroleum Reserve
   1000 Independence Avenue SW
   Washington, D.C. 20585

Electronic copy only to Wayne Elias at Elias.Wayne@spr.doe.gov for distribution to DOE and DM

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