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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.

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NOMENCLATURE

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

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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 M[1] 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 drawdowns[2]. 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

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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".

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).

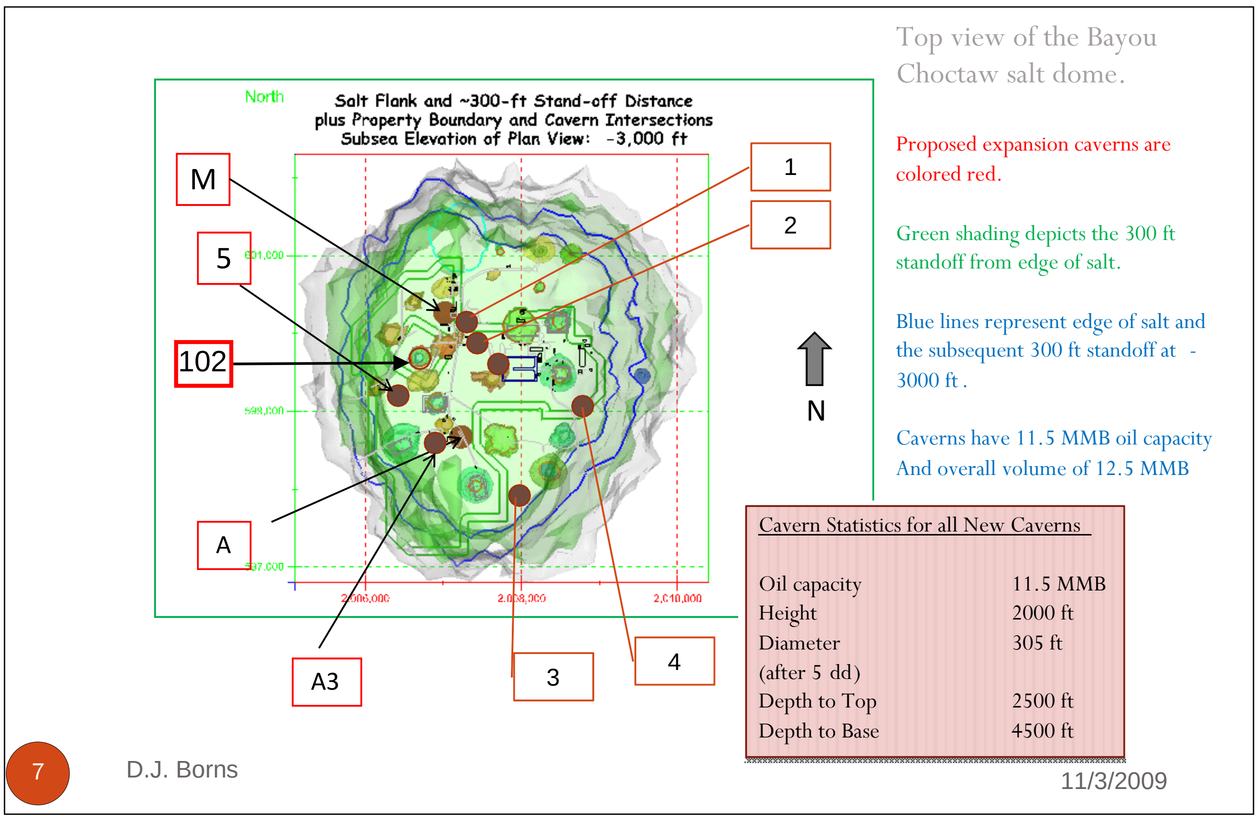

Figure 1: Proposed locations of expansion caverns at Bayou Choctaw. Also shown are the required standoff distances from dome edge (green shading), the proposed expansion caverns (brown), the edge of salt and the subsequent 300 ft standoff at -3000 ft (blue lines) and DOE property boundaries (green lines)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

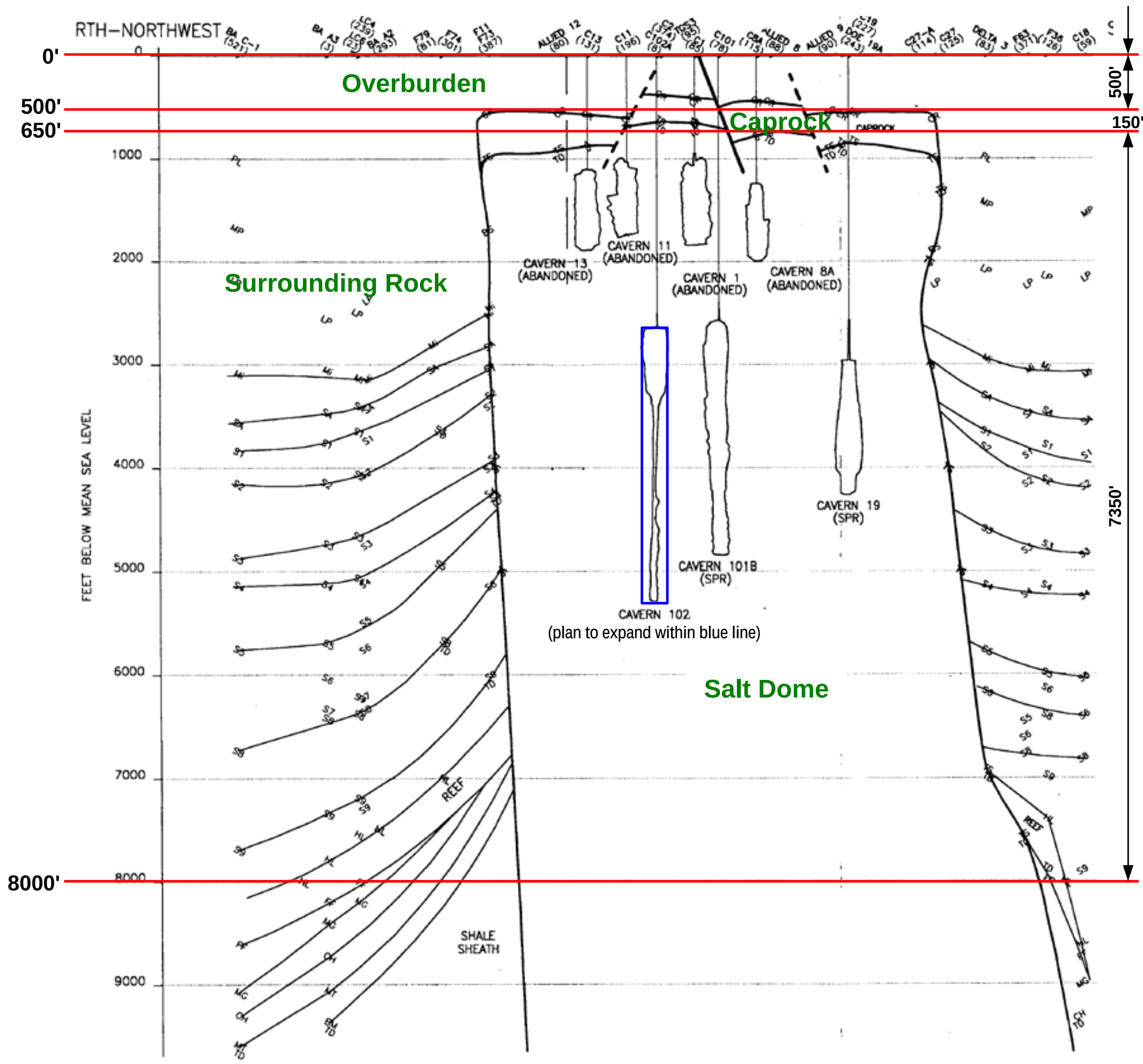

Figure 2: Stratigraphy near the Bayou Choctaw salt dome [Neal et al., 1993] and the thickness of each layer used for modeling. Blue line box approximates the converted maximum size of Cavern 102.

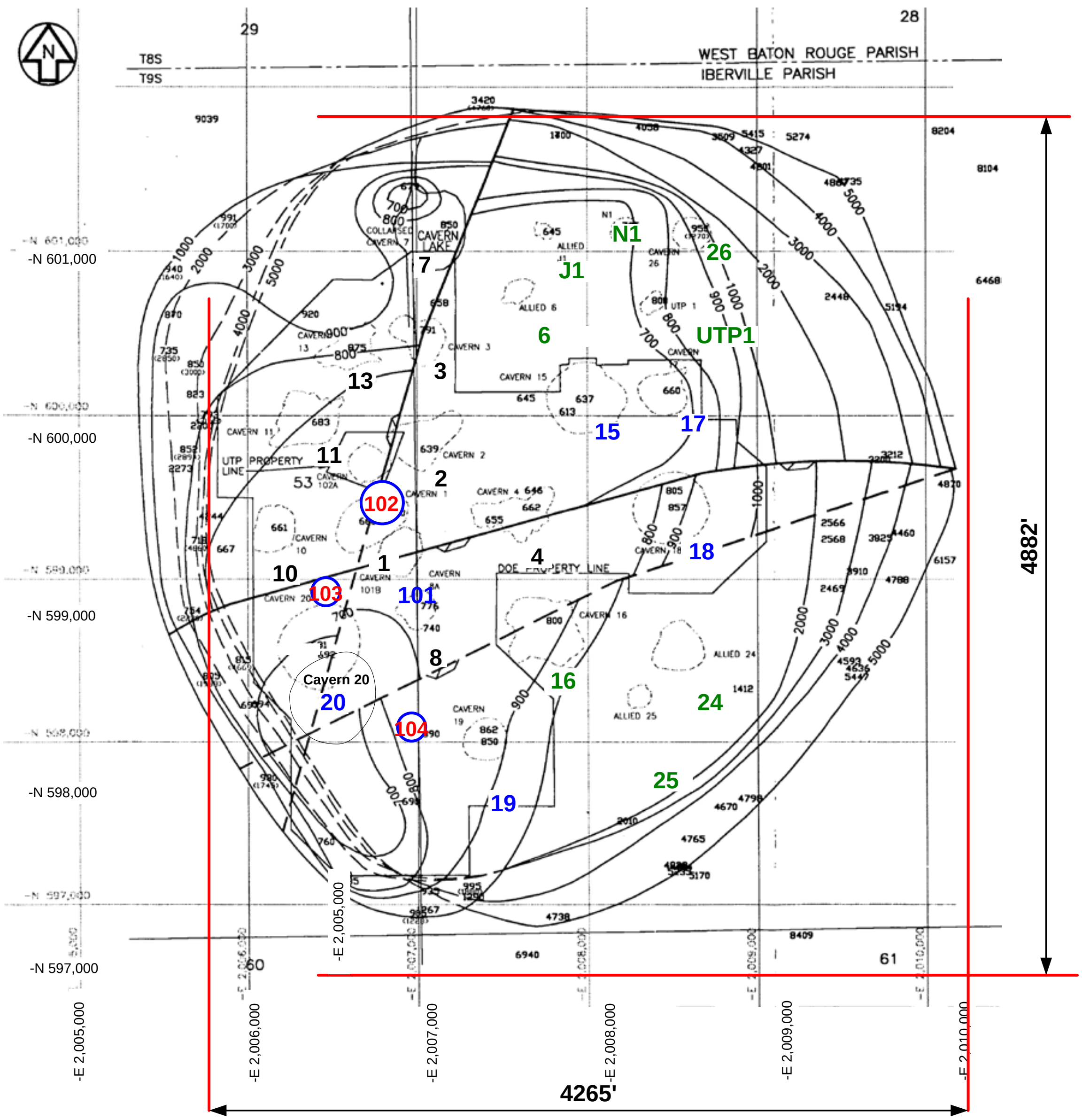

Figure 3: Plan view of the Bayou Choctaw site [Neal et al., 1993] at 4000 ft below mean sea level. Red lines indicate the extents used to determine major and minor diameters of salt dome for modeling. The blue circles with red fonts show the proposed two new cavern locations (103 and 104) and one converted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

UTM Coordinate of West Edge at 4000 ft BMSL	E	2,005,738	ft
UTM Coordinate of East Edge at 4000 ft BMSL	E	2,010,000	ft
UTM Coordinate of South Edge at 4000 ft BMSL	N	597,000	ft
UTM Coordinate of North Edge at 4000 ft BMSL	N	601,881	ft
UTM Coordinate of Center at 4000 ft BMSL	E	2,007,869	ft
UTM Coordinate of Center at 4000 ft BMSL	N	599,440	ft
Major Diameter at 4000 ft BMSL		4,881	ft
Minor Diameter at 4000 ft BMSL		4,262	ft
Avg. Elevation Top Salt		-650	ft
Avg. Elevation Top Caprock		-500	ft

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:

$$\dot{\varepsilon} = A\left(\frac{\sigma}{\mu}\right)^n \exp\left(-\frac{Q}{RT}\right) \tag{1}$$

where, $\dot{\varepsilon} =$ creep strain rate,
$\sigma =$ von Mises equivalent stress,
$\mu =$ shear modulus = E/2(1+ν), where E is Young's modulus and ν 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.

Parameter	Unit	Value	References
Young's modulus (E)	psi	4.496×10^6	Krieg, 1984
Density (ρ)	lb/ft^3	143.6	Krieg, 1984
Poisson's ratio (v)	-	0.25	Krieg, 1984
Elastic modulus reduction factor (RF)	-	12.5	Morgan and Krieg, 1988
Bulk modulus (K)	psi	2.397×10^5	Calculated using E and v
Two mu (2μ)	psi	2.878×10^5	Calculated using E and v
Power law creep constant (A)	Pa^{-n}/s	5.79×10^{-36}	Krieg, 1984
Structure multiplication factor (SMF)	-	0.12	Park et al., 2006
Calibrated power law creep constant (A_C)	Pa^{-n}/s	0.695×10^{-36}	Park et al., 2006
Stress exponent (n)	-	4.9	Krieg, 1984
Thermal constant (Q)	cal/mol	12000	Krieg, 1984
Universal gas constant (R)	cal/(mol·K)	1.987	
Input thermal constant (Q/R)	K	6039	

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 6×10^4 to 1×10^7 psi [Carmichael, 1984]. For simplifying the analysis, a median value of the Young's modulus of sandstone, 5×10^6 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]

	Unit	Overburden	Caprock	Surrounding Rock
Young's modulus	psi	1.450×10^4	2.277×10^6	5×10^6
Density	lb/ft^3	117.0	144.8	156.1
Poisson's ratio	-	0.33	0.29	0.33

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].

Cavern Number	X coordinate of center	Y coordinate of center	Initial gross volume	Gross volume after 5 drawdowns	Elevation† of cavern top	Elevation of cavern bottom	Cavern height	Initial diameter	Diameter after 5 drawdowns
	ft	ft	MMB	MMB	ft	ft	ft	ft	ft
Cavern 1	-1002	-27	8.4	N/A	-950	-1810	860	250	N/A
Cavern 2	-817	369	9.0	N/A	-715	-1590	875	260	N/A
Cavern 3	-821	1082	5.0	N/A	-890	-1875	985	200	N/A
Cavern 4	-212	12	6.0	N/A	-620	-1710	1090	280	N/A
Allied 6	-192	1353	0.8	N/A	-1195	-1562	367	126	N/A
Cavern 7	-786	1679	4.0	N/A	-440	-1560	1120	160	N/A
Cavern 8	-811	-604	3.1	N/A	-1235	-1976	741	200	N/A
Cavern 10	-1706	-118	6.4	N/A	-990	-1902	912	200	N/A
Cavern 11	-1458	521	9.5	N/A	-1030	-1800	770	280	N/A
Cavern 13	-1241	969	4.3	N/A	-1103	-1880	777	240	N/A
Cavern 15	92	669	16. 5	33.1	-2605	-3296	691	412	585
Cavern 16	-68	-675	10.5	N/A	-2612	-3228	616	349	N/A
Cavern 17	573	736	12.2	24.5	-2600	-4023	1423	238	350
Cavern 18	609	43	17.4	35.1	-2125	-4219	2094	244	346
Cavern 19	-477	-1362	12. 7	25.5	-2935	-4228	1293	260	375
Cavern 20	-1561	-936	9.2	18.5	-3830	-4225	395	514	578
Allied 24	664	-798	5.6	N/A	-3100	-4337	1237	179	N/A
Allied 25	451	-1167	7.1	N/A	-3575	-5790	2215	151	N/A
Cavern 26	747	1669	0.7	N/A	-3076	-3470	394	113	N/A
Cavern 101	-951	-325	13.1	26.3	-2550	-4830	2280	201	287
Cavern 102	-1169	270	4.2	N/A	-2640	-5340	2700	105.5	N/A
Allied J1	-92	1682	0.8	N/A	-2854	-3945	1091	70	N/A
Allied N1	358	1686	0.5	N/A	-2670	-3590	920	62	N/A
UTP 1	369	1223	1.4	N/A	-2360	-3502	1142	94	N/A

†: Elevation from the surface.

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

Cavern Number	X coordinate of center	Y coordinate of center	Initial gross volume	Gross volume after 5 drawdowns	Elevation of cavern top	Elevation of cavern bottom	Cavern height	Initial diameter	Diameter after 5 drawdowns
	ft	ft	MMB	MMB	ft	ft	ft	ft	ft
Cavern 102	-1169	270	23.6	47.5	-2640	-5340	2700	250	355
Cavern 103	-1469	-290	12.9	26.0	-2500	-4500	2000	215	305
Cavern 104	-937	-1010	12.9	26.0	-2500	-4500	2000	215	305

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.

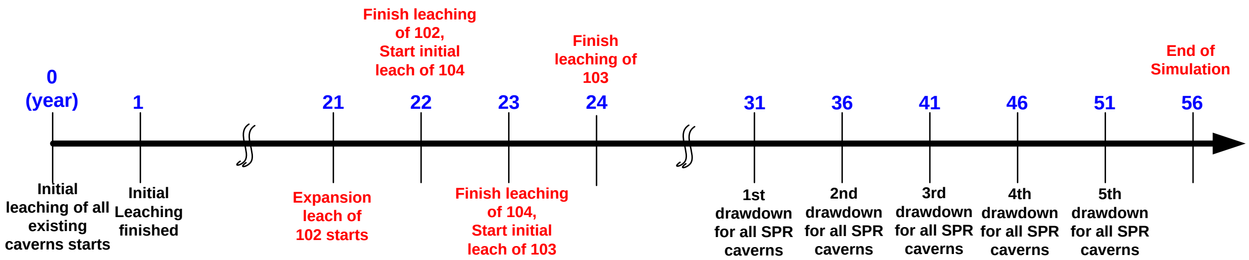

Figure 4: The time sequence for the simulation.

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 occured 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 conditions. 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.

Cavern	Operating Pressure Range (psi)		
	Low	High	Average Pressure
Cavern 15	815	990	903
Cavern 17	815	990	903
Cavern 18	690	740	715
Cavern 19	900	950	925
Cavern 20	825	875	850
Cavern 101	825	1000	913
Cavern 102	-	-	913
Cavern 103	-	-	913
Cavern 104	-	-	913

In general, the SPR caverns are most susceptible to structural instability when a workover[3] 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].

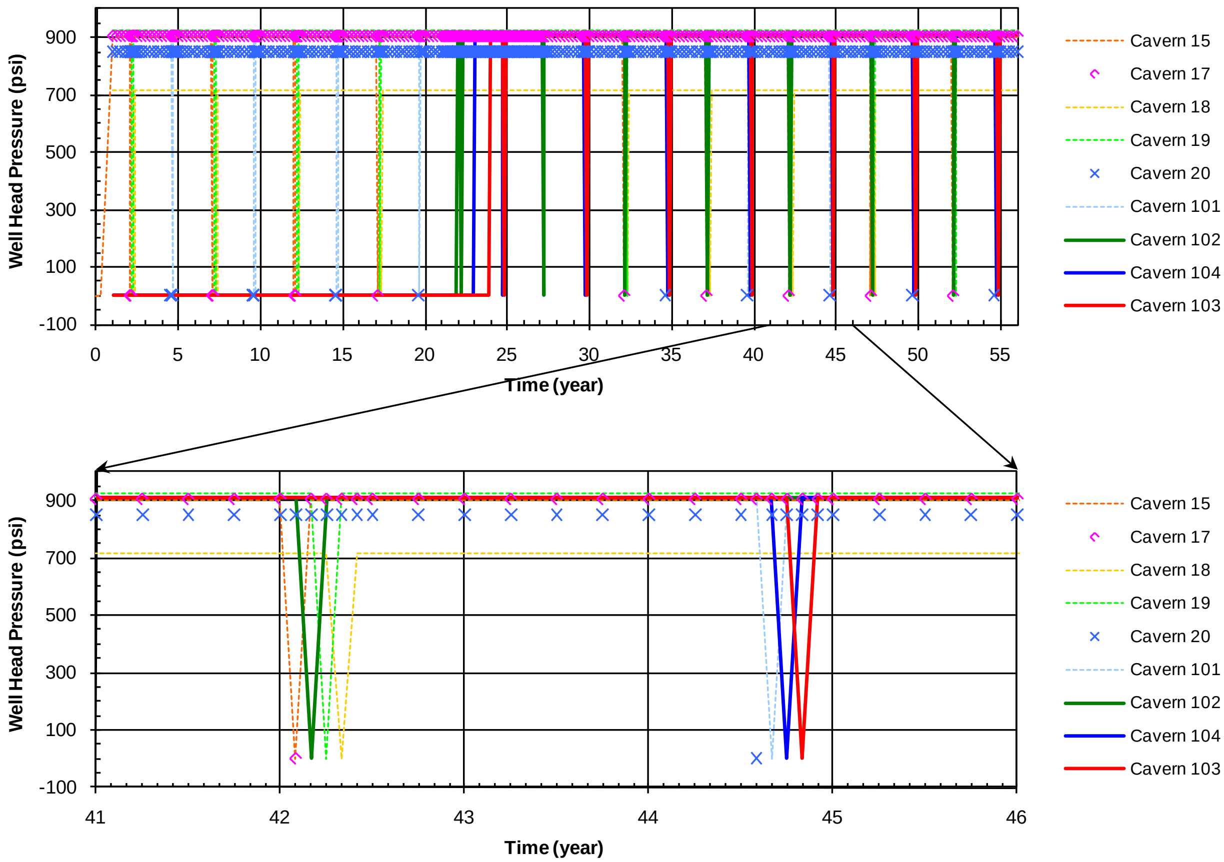

Figure 5: Wellhead histories of each SPR cavern for Scenario 1.

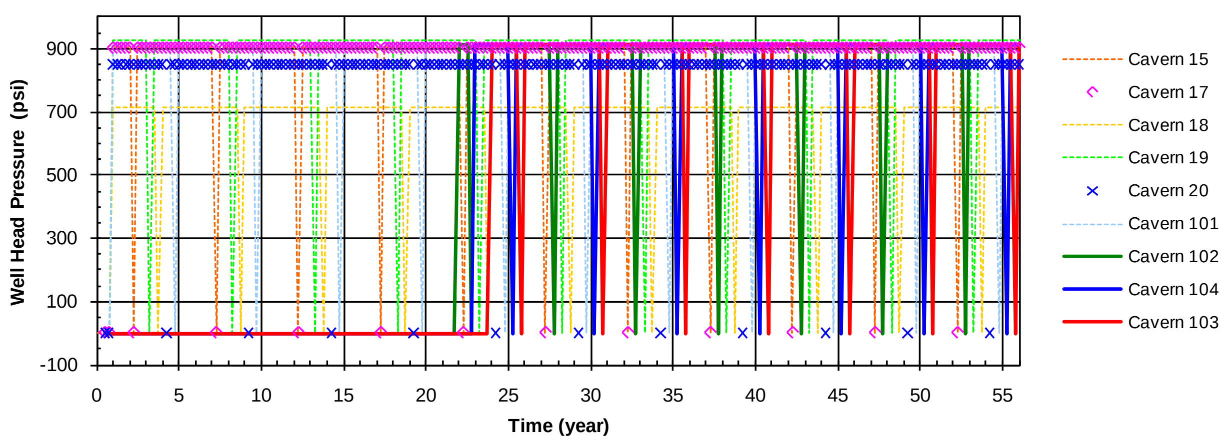

Figure 6: Wellhead histories of each SPR cavern for Scenario 2.

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.

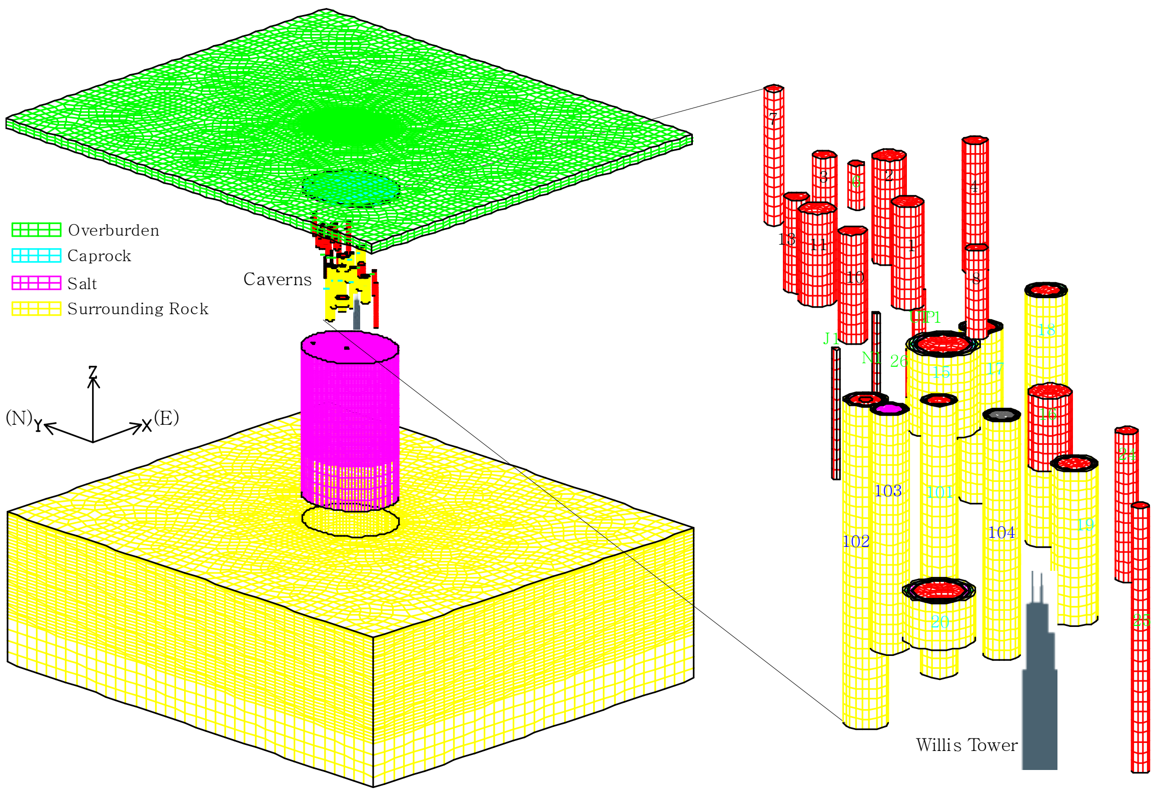

Figure 7: Overview of the finite element mesh of the stratigraphy and cavern field at Bayou Choctaw and the cavern geometry within the salt dome. For comparison purposes to show how large the caverns are, a silhouette of the Willis Tower is shown.

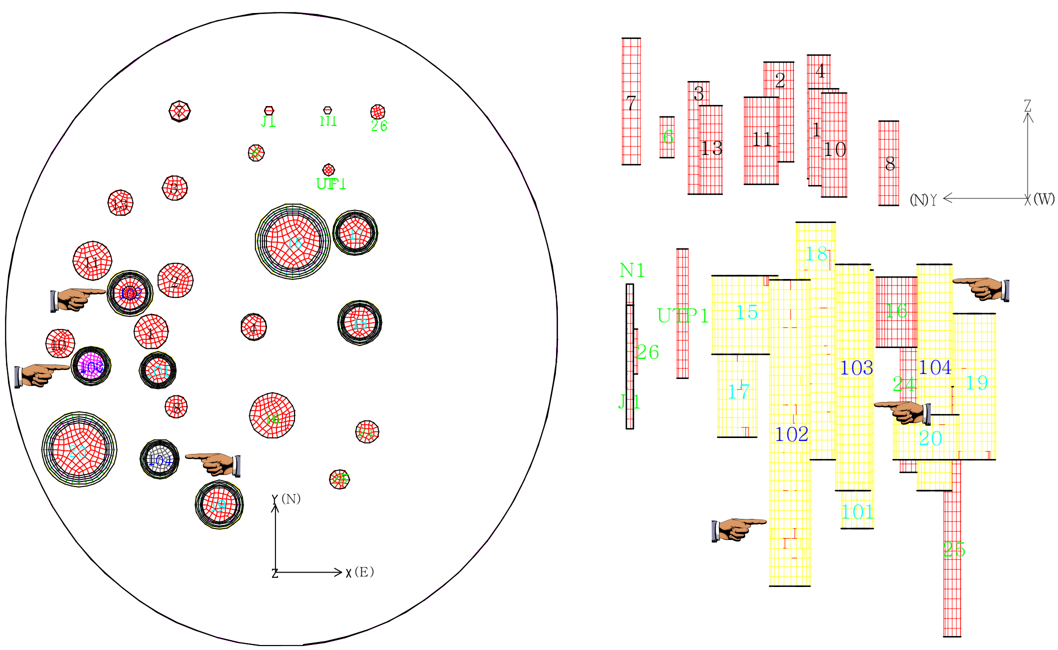

Figure 8: Plan view of cavern layout and side view of cavern geometry. Hands are pointing to the two new caverns, 103 and 104, and the expanded Cavern 102.

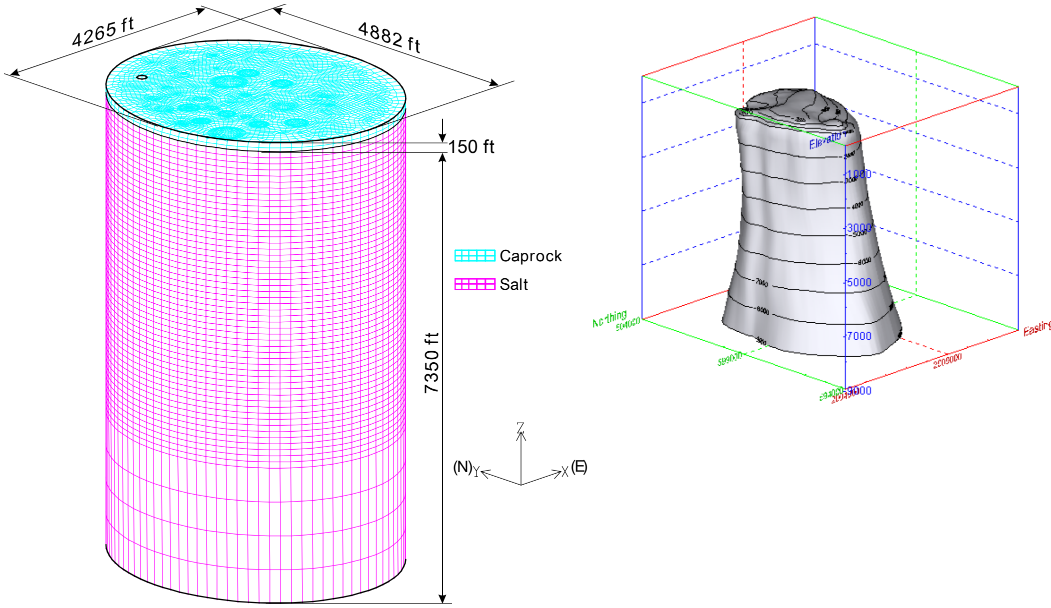

Figure 9: Mesh for salt dome and caprock (left). The three dimensional representation of the salt dome (right) is from Rautman and Stein [2004].

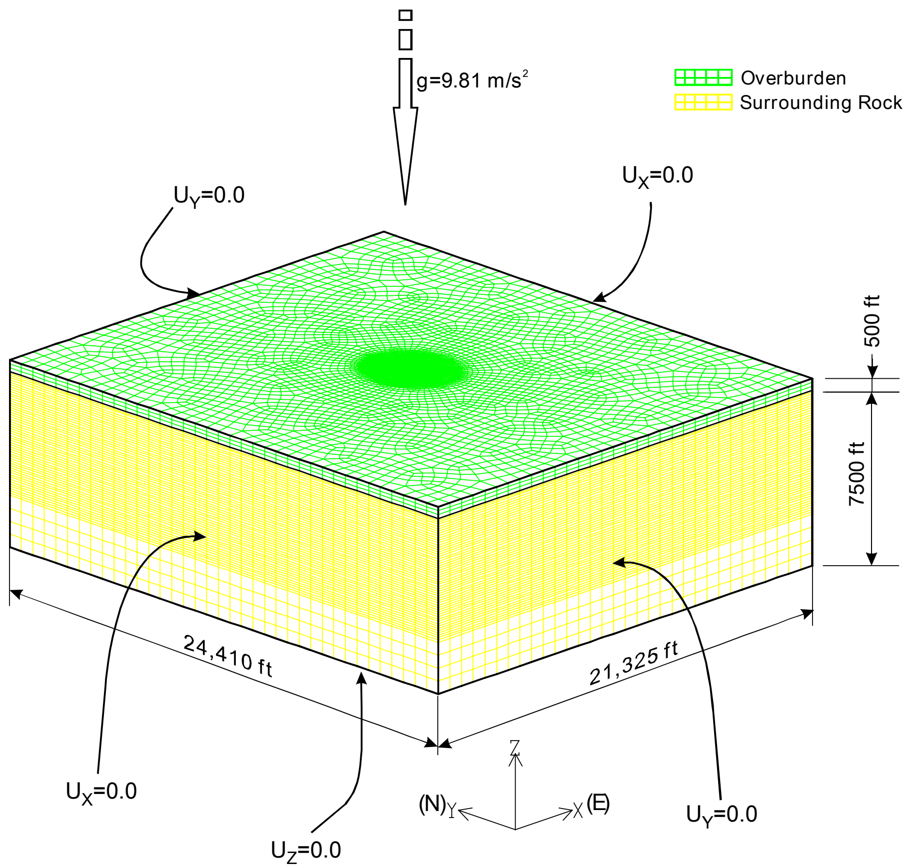

Figure 10: Finite mesh discretization and boundary conditions at Bayou Choctaw.

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;

$$D = \frac{0.257 \cdot I_1}{\sqrt{J_2}} \tag{2}$$

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

σ_1, σ_2, and σ_3 are the maximum, intermediate, and minimum principal stresses, respectively.

σ_m is the mean stress.

When $D \le 1$, 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

Code Name	Version	Use
APREPRO	2.07	Preprocessor
CUBIT	12.0	Mesh generation
EMERGE	1.50	Adds temperature to the mesh
JAS3D	2.4.C	FEM solver
ALGEBRA2	1.30	Postprocessor
BLOT II-2	1.66	Postprocessor

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)

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

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.

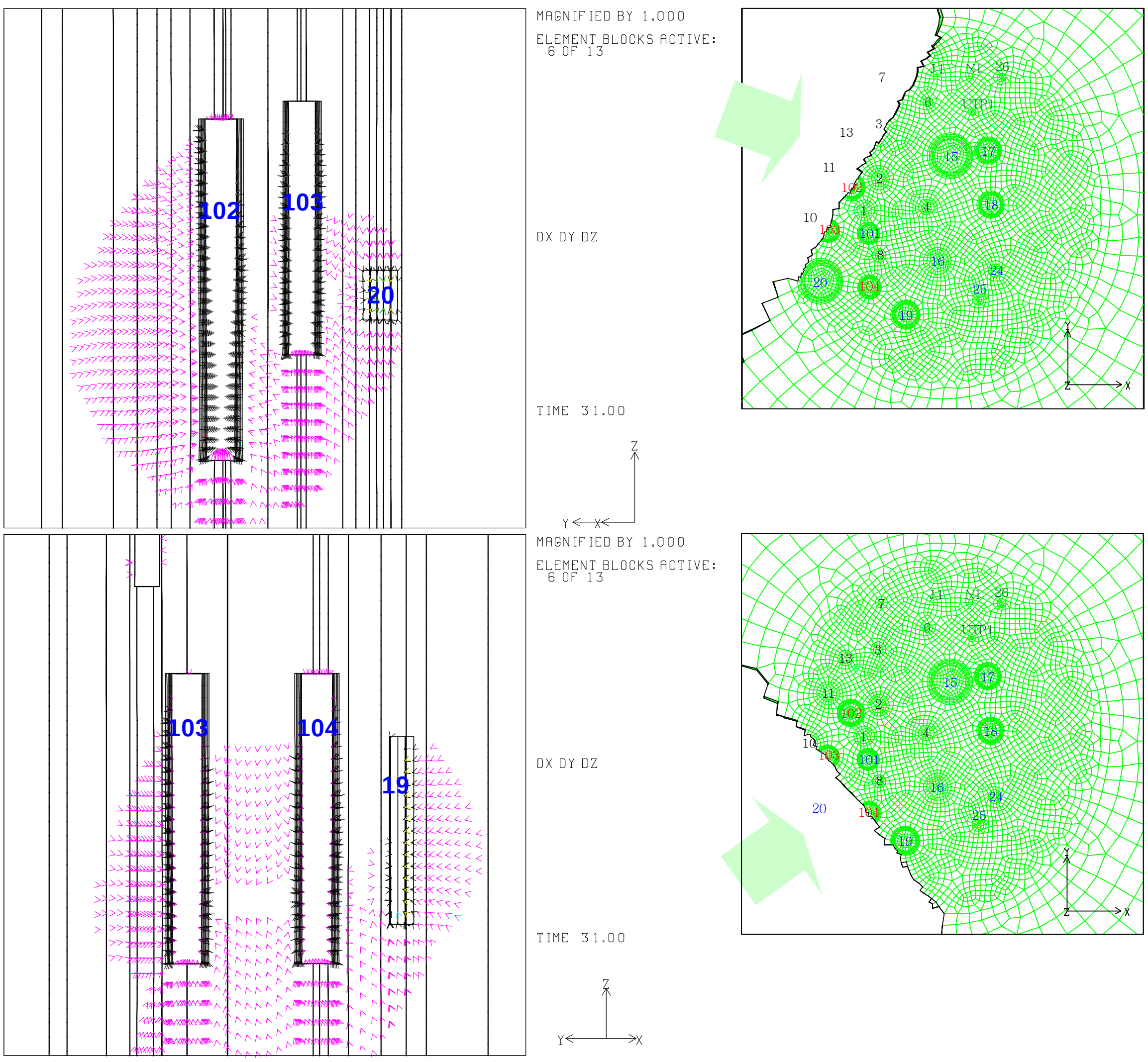

Figure 11: Displacement vectors around Caverns 102, 103, and 104 at 31 years for Scenario 1.

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.

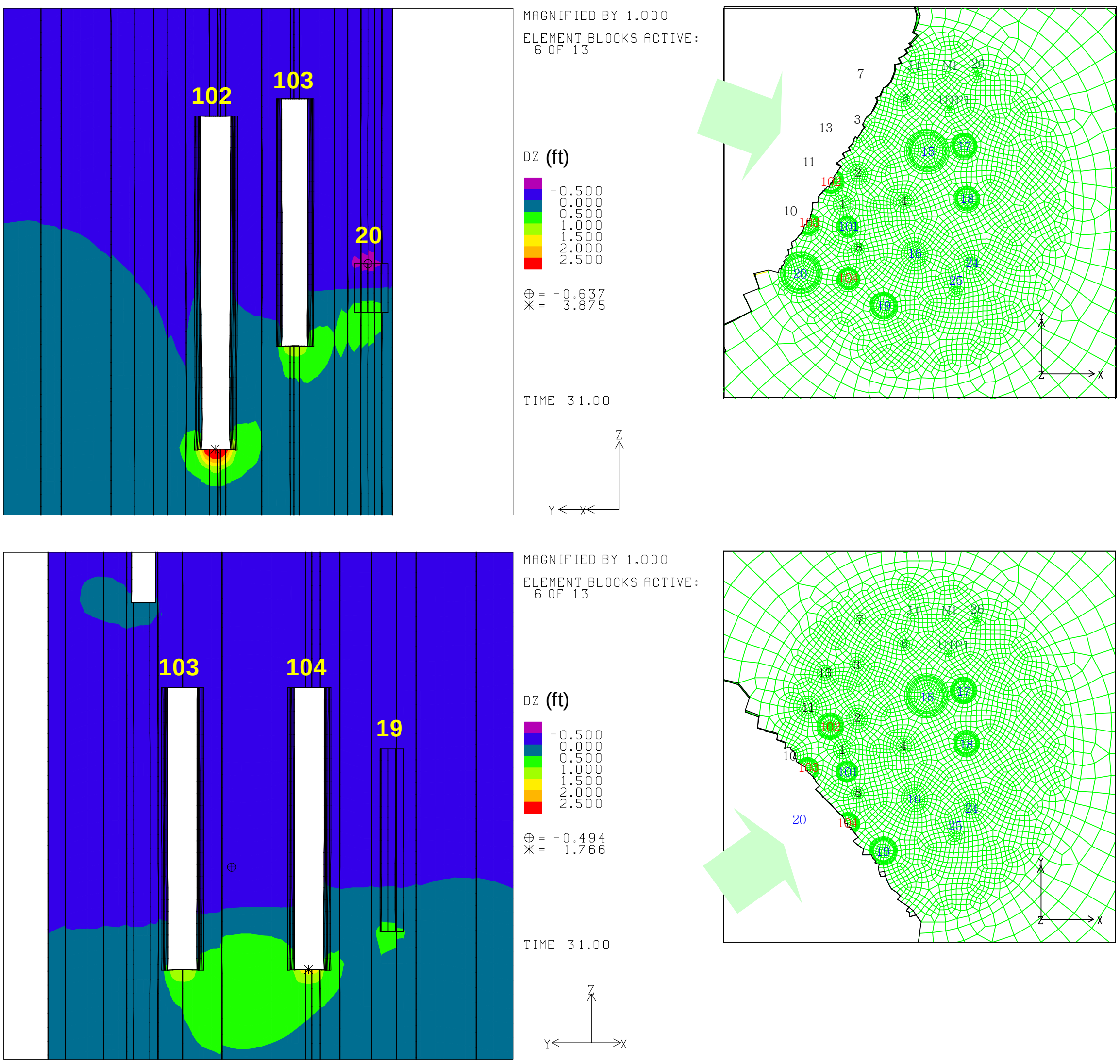

Figure 12: Vertical displacement contours around Caverns 103, 104, and 102 at 31 years for Scenario 1.

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.

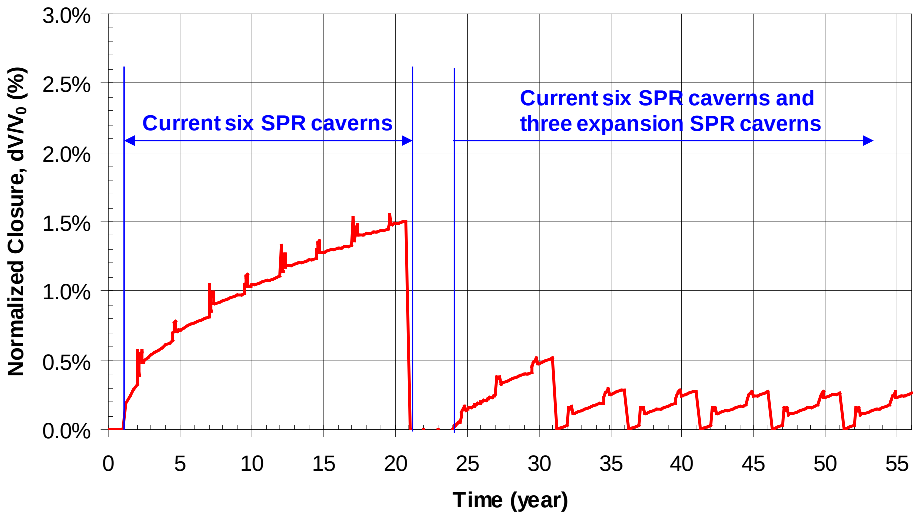

Figure 13: Predicted total volumetric closure normalized to overall storage volume for Scenario 1.

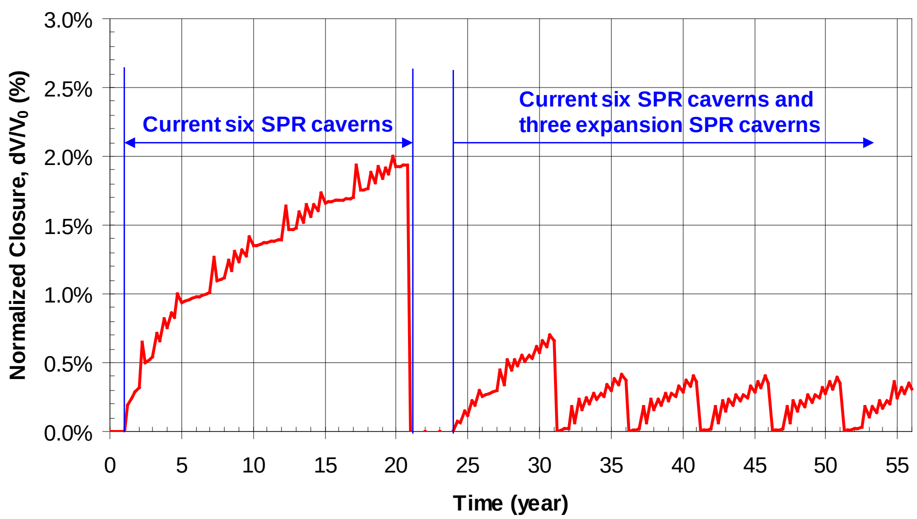

Figure 14: Predicted total volumetric closure normalized to overall storage volume for Scenario 2.

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.

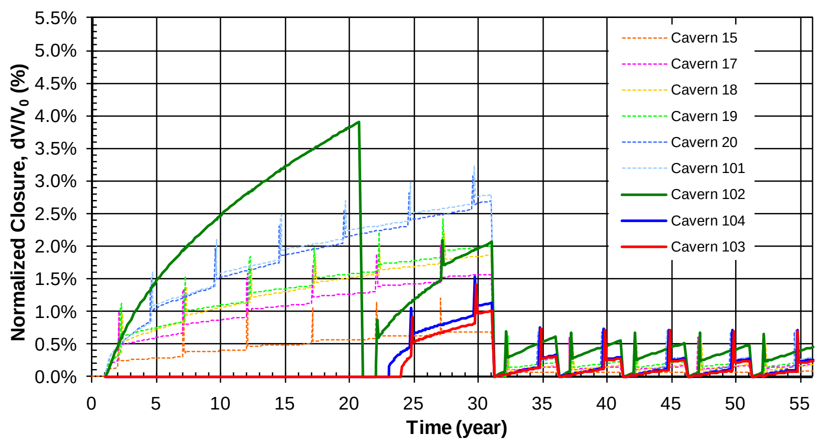

Figure 15: Normalized volumetric closure of each cavern with time for Scenario 1.

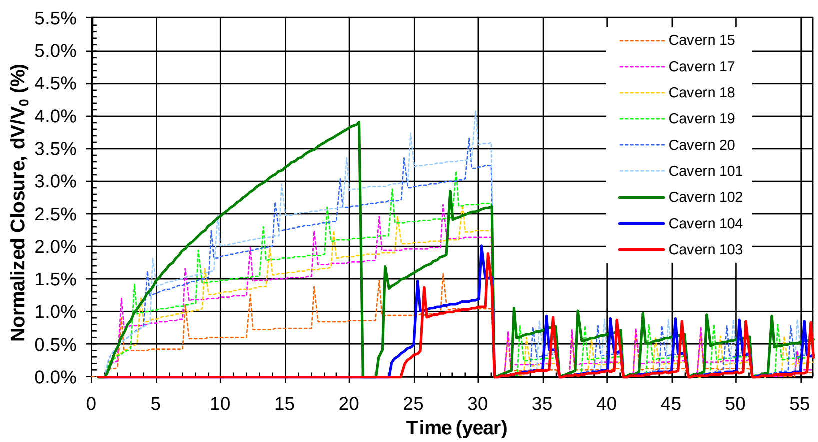

Figure 16: Normalized volumetric closure of each cavern with time for Scenario 2.

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.

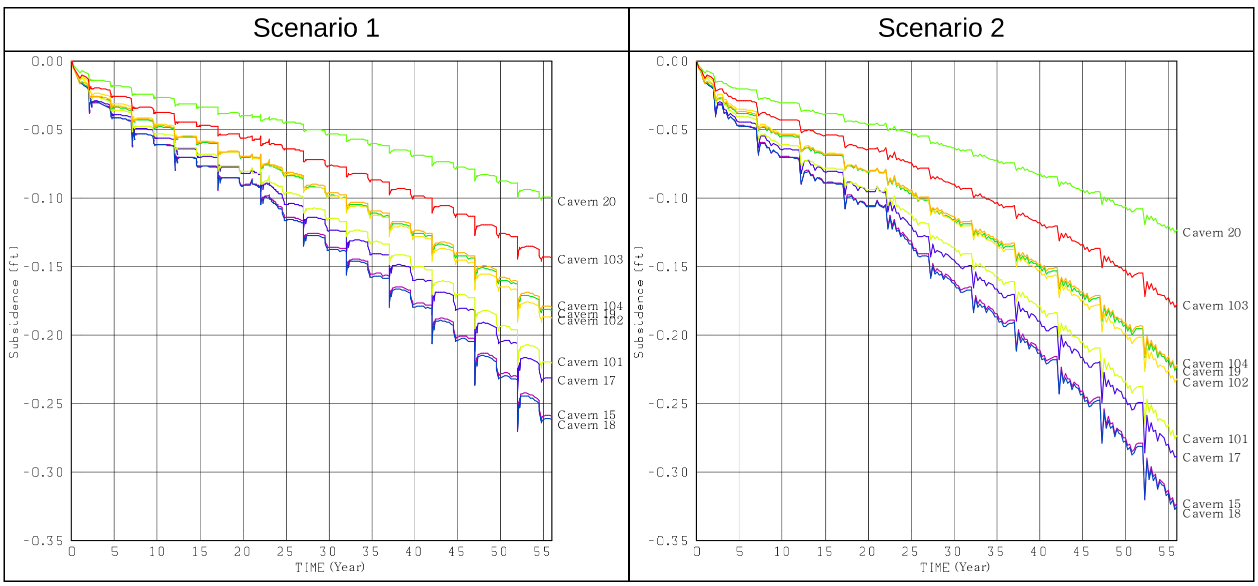

Figure 17: Predicted subsidence on the surface near the center of SPR caverns.

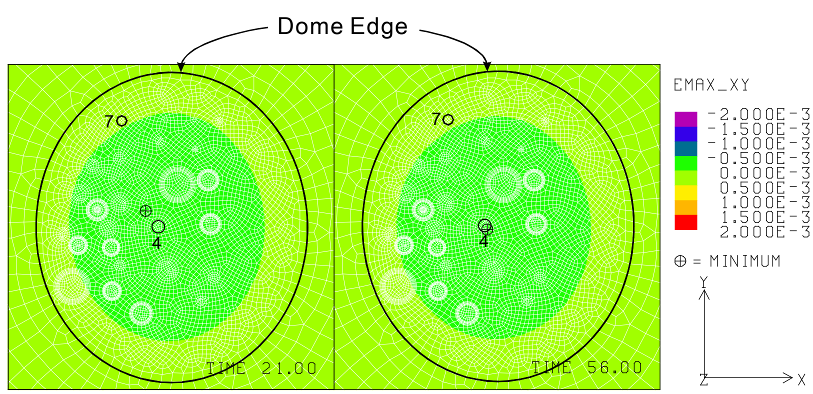

Figure 18: Predicted radial surface strains at 21 years and 56 years for Scenario 1.

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.

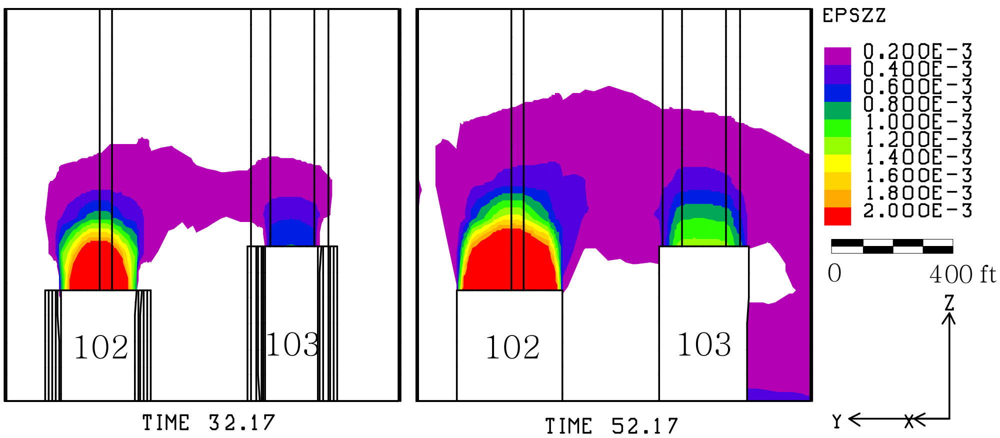

Figure 19: Vertical strain contours around Caverns 102 and 103 during workover of Cavern 102 after the initial leach (left) and the 5th drawdown leach (right) for Scenario 1.

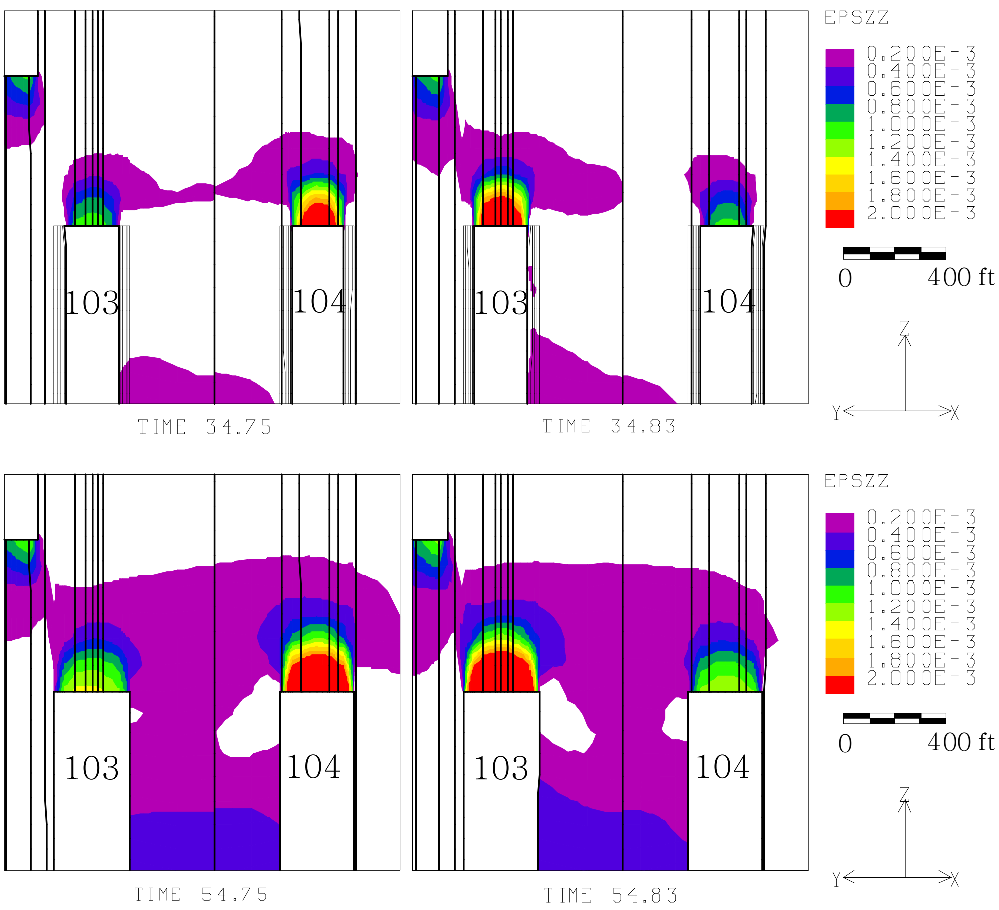

Figure 20: Vertical strain contours around Caverns 103 and 104 during workovers of Caverns 104 (left) and 103 (right) after the initial leach (top) and the 5th drawdown leach (bottom) for Scenario 1.

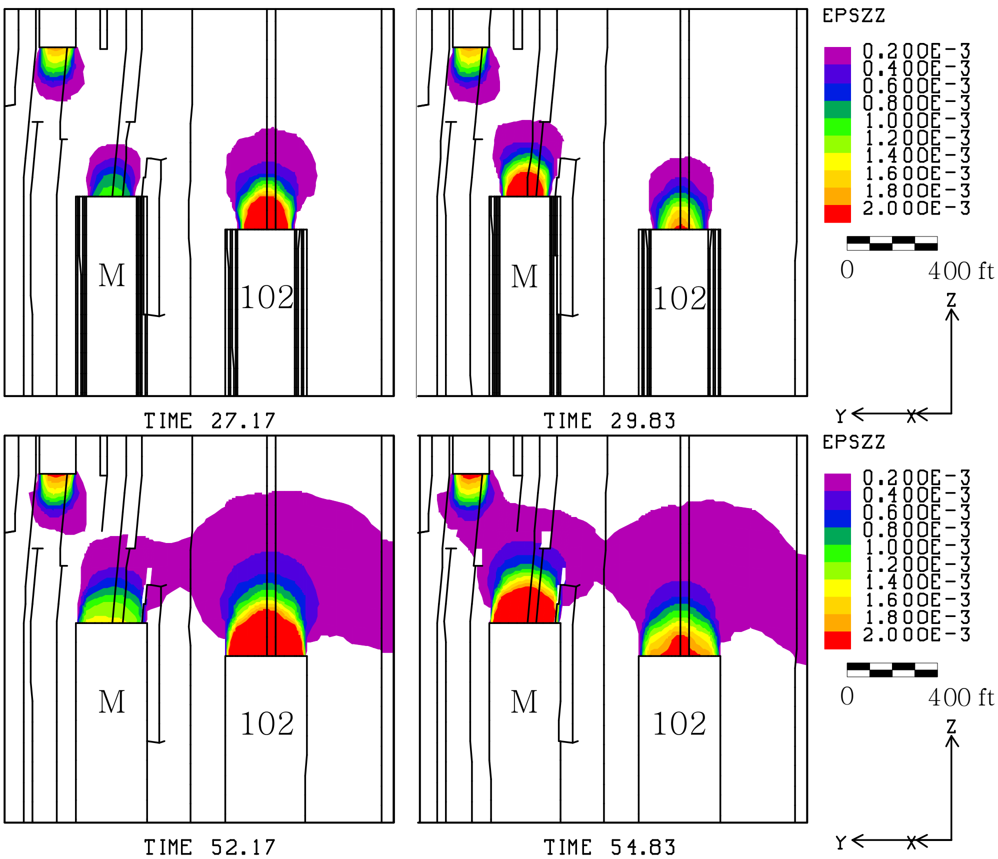

Figure 21: Vertical strain contours around Caverns M and 102 during workovers of Caverns M (left) and 102 (right) after the initial leach (top) and the 5th drawdown leach (bottom) for Scenario 1 derived from the previous analyses by Park and Ehgartner [2008].

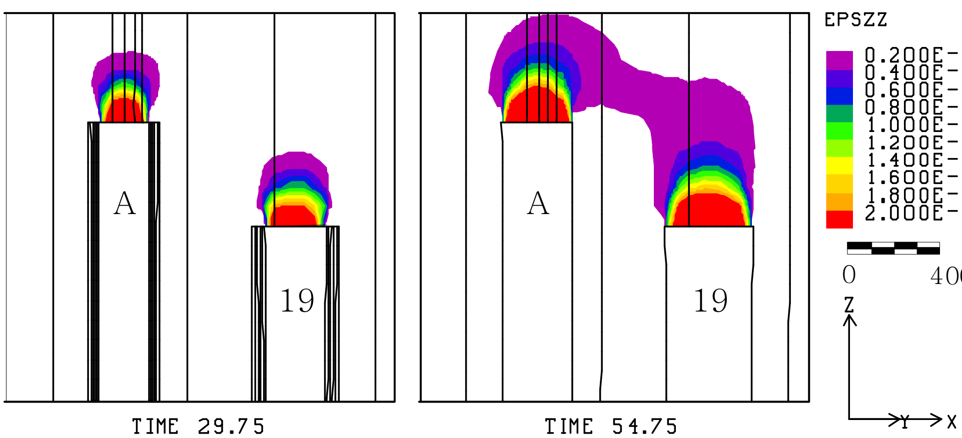

Figure 22: Vertical strain contours around Cavern A and 19 during workover of Cavern A after the initial leach (left) and the 5th drawdown leach (right) for Scenario 1 derived from the previous analyses by Park and Ehgartner [2008].

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 5th 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 4th 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.

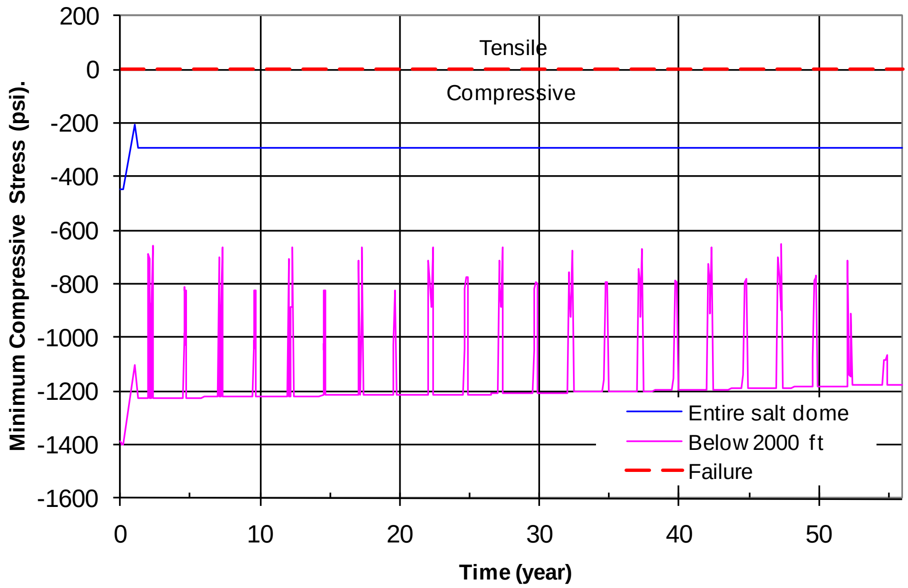


Figure 23: Minimum compressive stress history for Scenario 1.

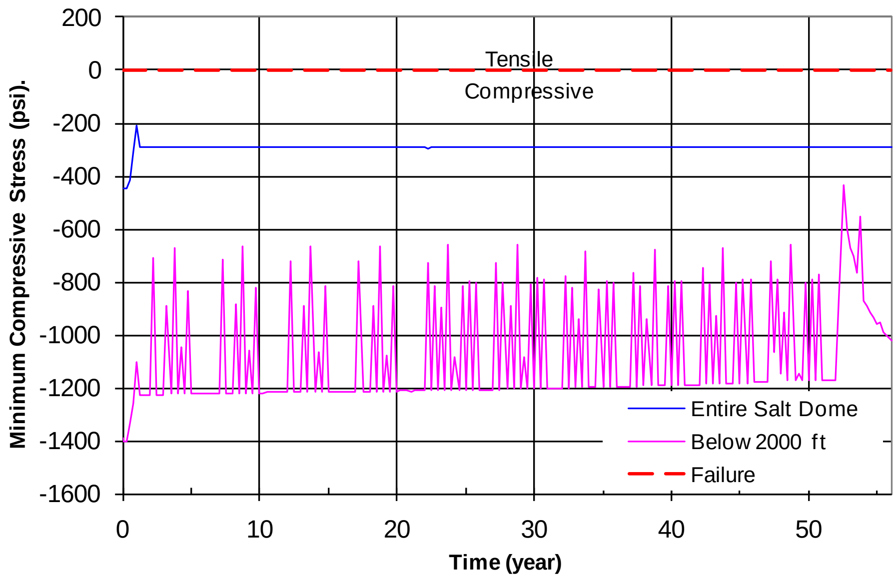


Figure 24: Minimum compressive stress history for Scenario 2.

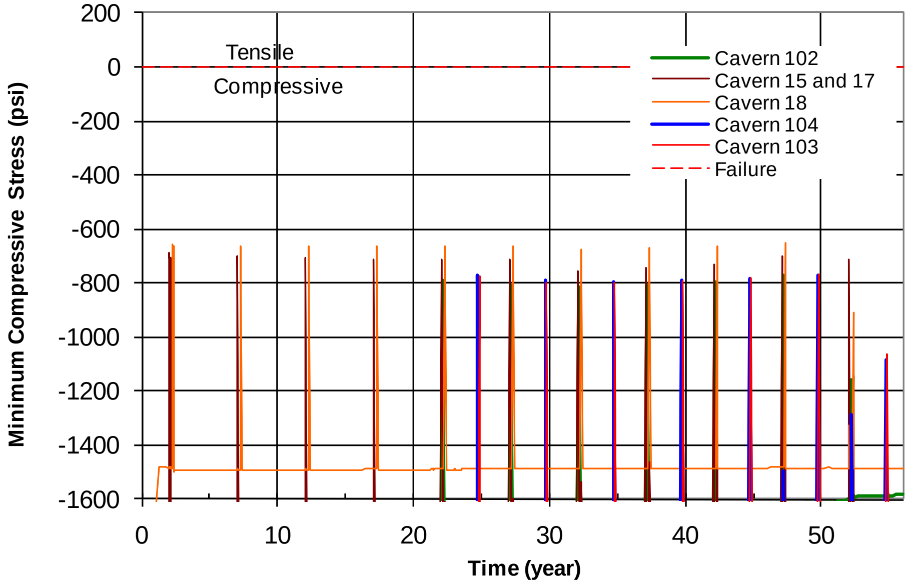


Figure 25: Minimum compressive stress history in the elements within 130 ft of cylindrical Caverns 15, 17, 18, 102, 103 and 104 (Scenario 1).

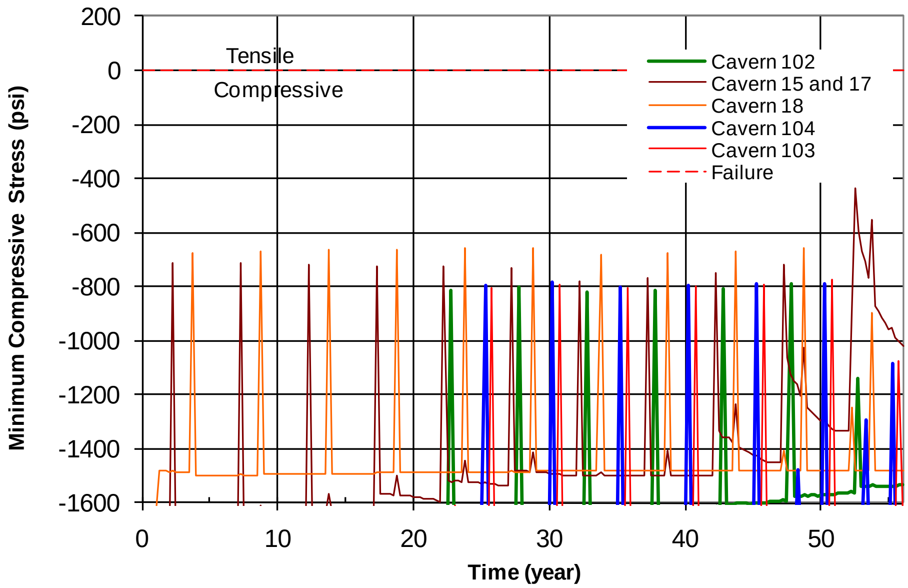


Figure 26: Minimum compressive stress history in the elements within 130 ft of cylindrical Caverns 15, 17, 18, 102, 103 and 104 (Scenario 2).

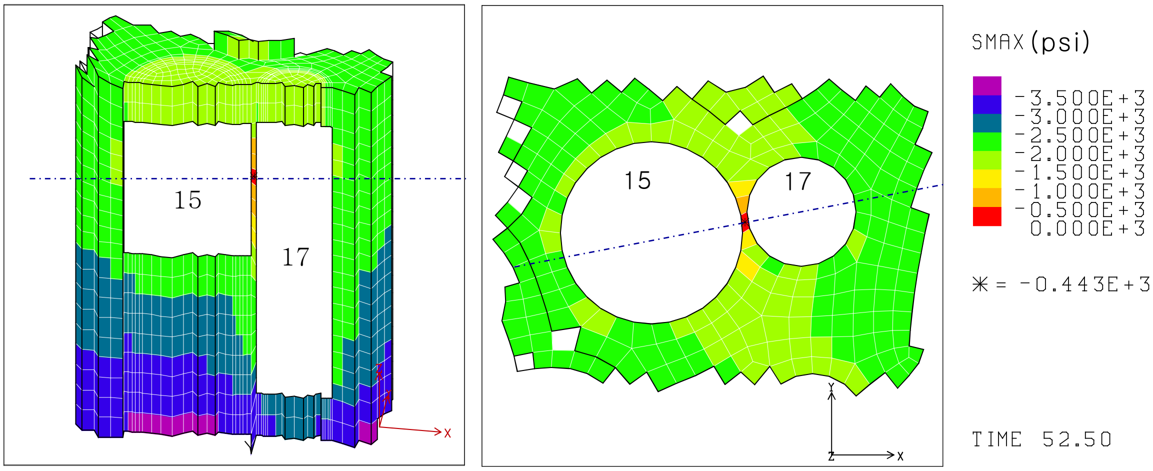


Figure 27: Compressive stress contours during workover of Caverns 15 & 17 after 5 leaches for Scenario 2, vertical cross-section through the centers of caverns (left) and horizontal cross-section at the elevation where the minimum compressive stress occurs (right). The blue lines show where the mesh was cut.

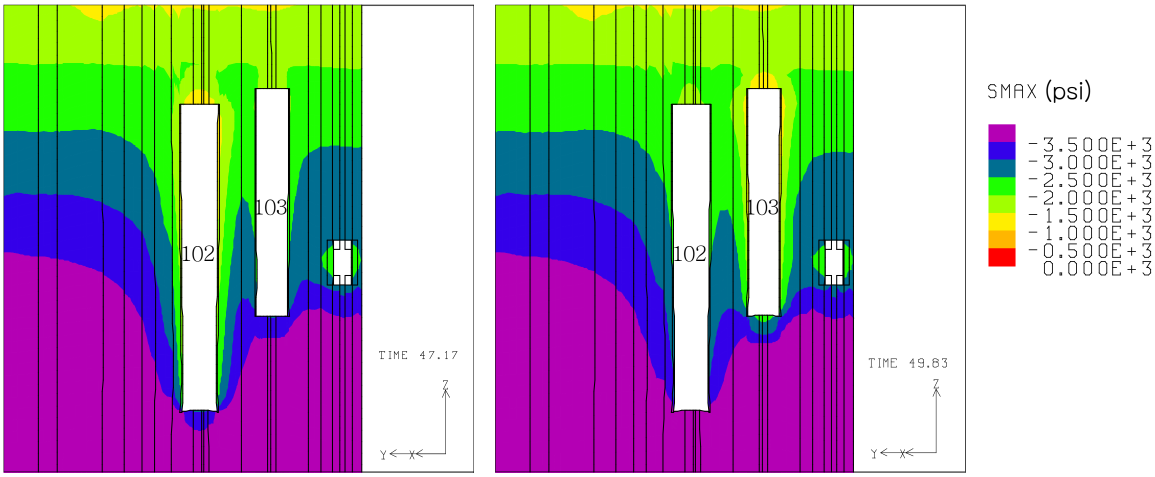


Figure 28: Compressive stress contours around Caverns 102 and 103 during workover of each cavern at 47.17 years and 49.83 years for Scenario 1.

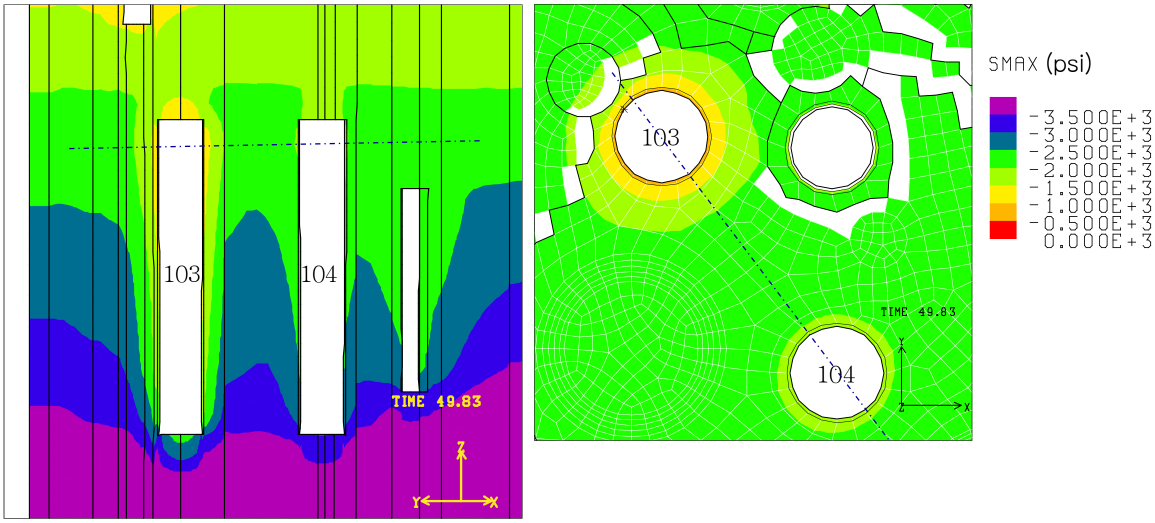


Figure 29: Compressive stress contours around vertical cross-sections of Caverns 103 and 104 (left) and horizontal cross-section at the center elevation of Caverns 103 and 104 (right) during workover of Cavern 103 at 49.83 years for Scenario 1. The blue lines in the horizontal section show where the mesh was cut.

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 Cavern 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 4th 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 4th and 5th 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 4th 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 5th 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

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.

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.

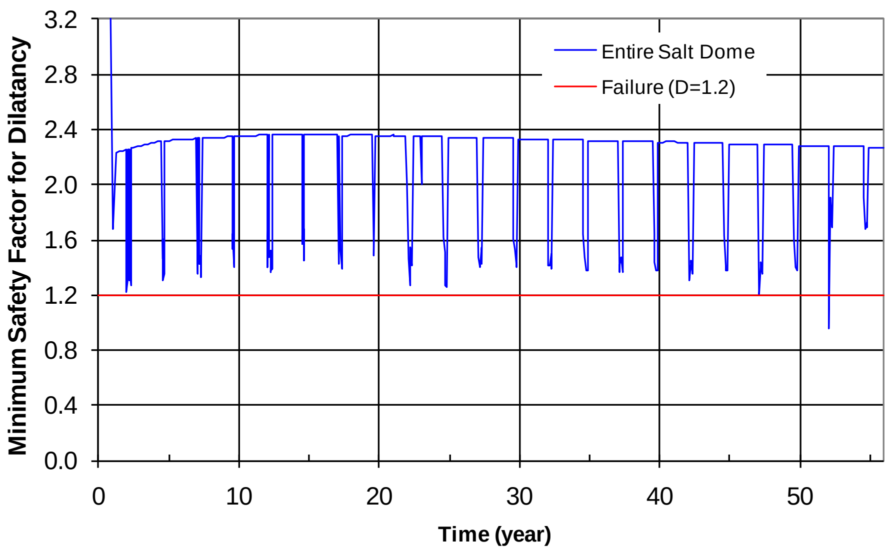


Figure 30: Minimum safety factor history against dilatant damage for Scenario 1.

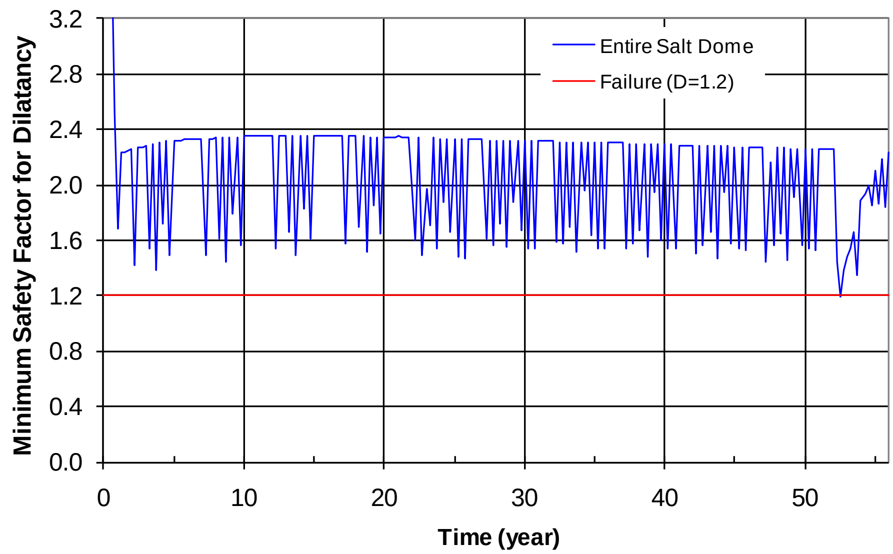


Figure 31: Minimum safety factor history against dilatant damage for Scenario 2.

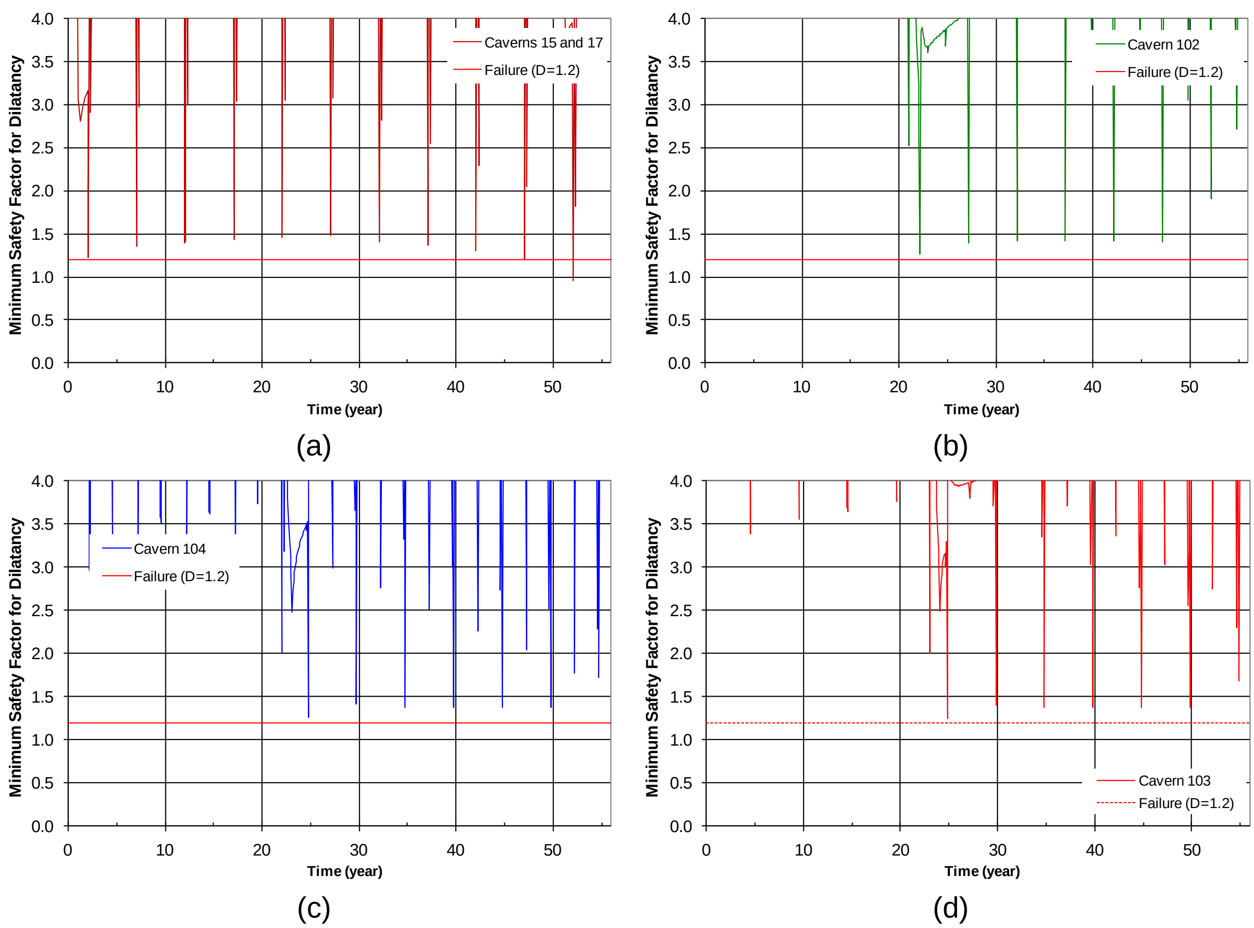


Figure 32: Minimum safety factor history against dilatant damage in the elements within 130 ft of Caverns 15, 17, 102, 103 and 104 for Scenario 1.

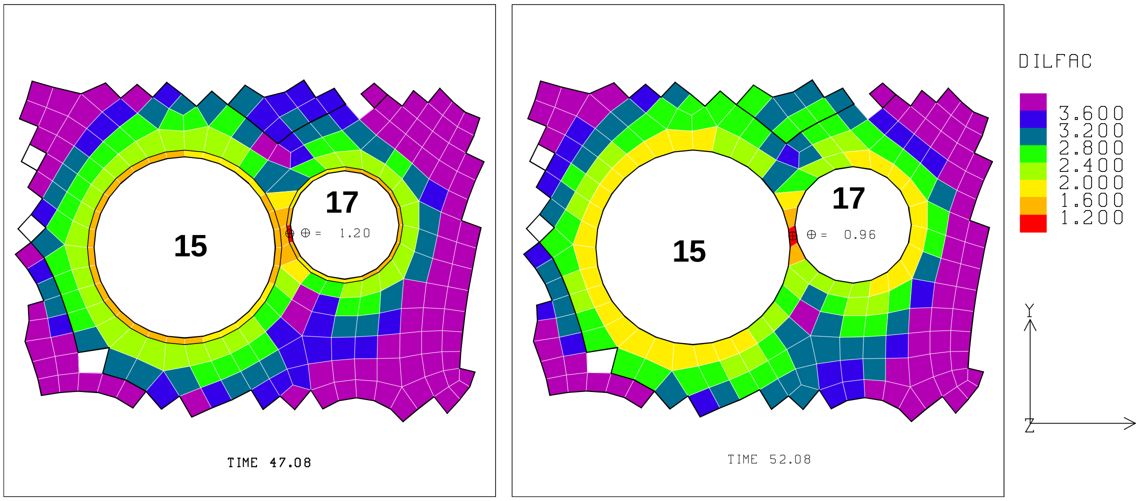


Figure 33: Safety factor contours against dilatant damage during workover of Caverns 15 and 17 after 4th (left) and 5th (right) leach, respectively, for Scenario 1 on the horizontal cross-section at the elevation where the minimum compressive stress occurs.

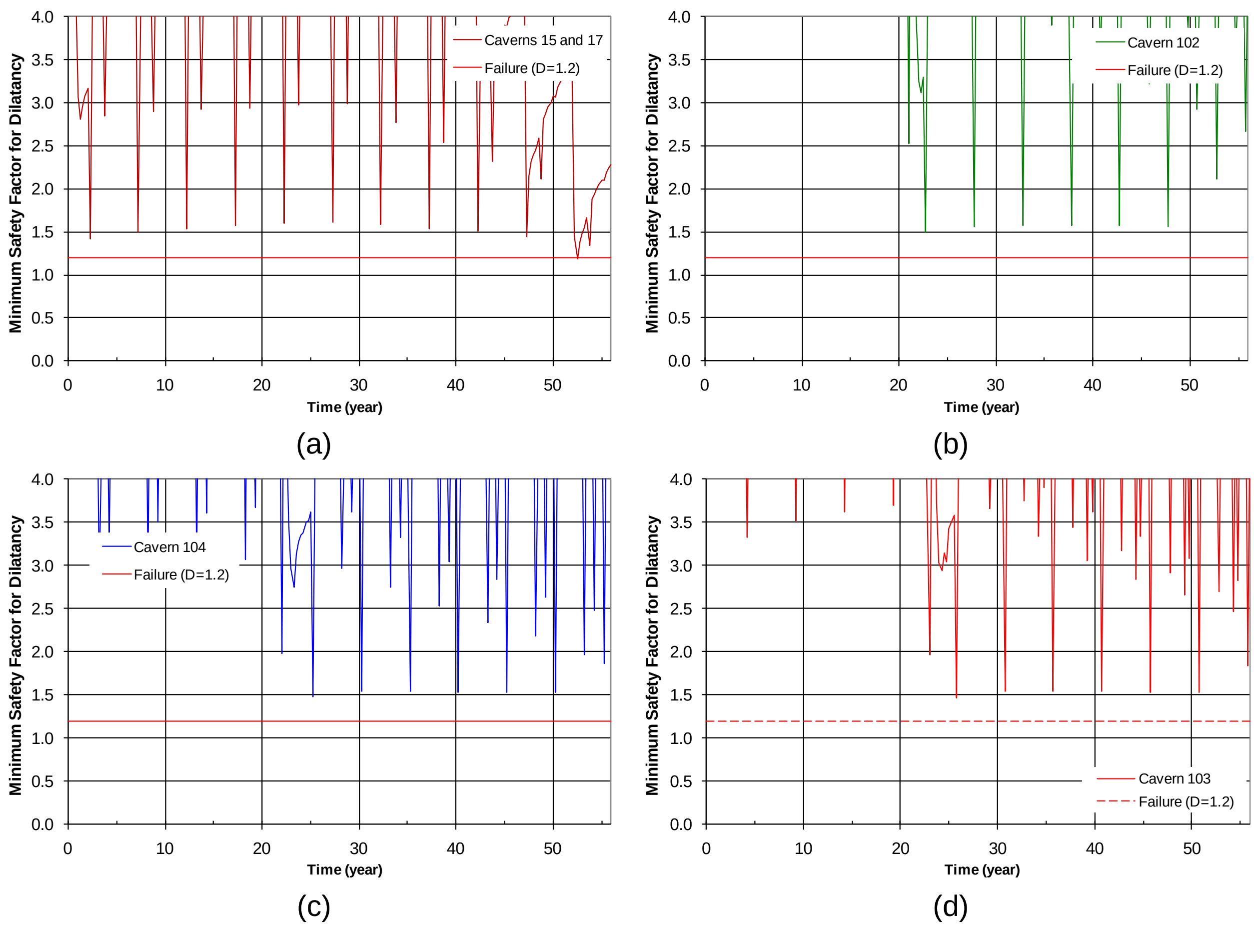
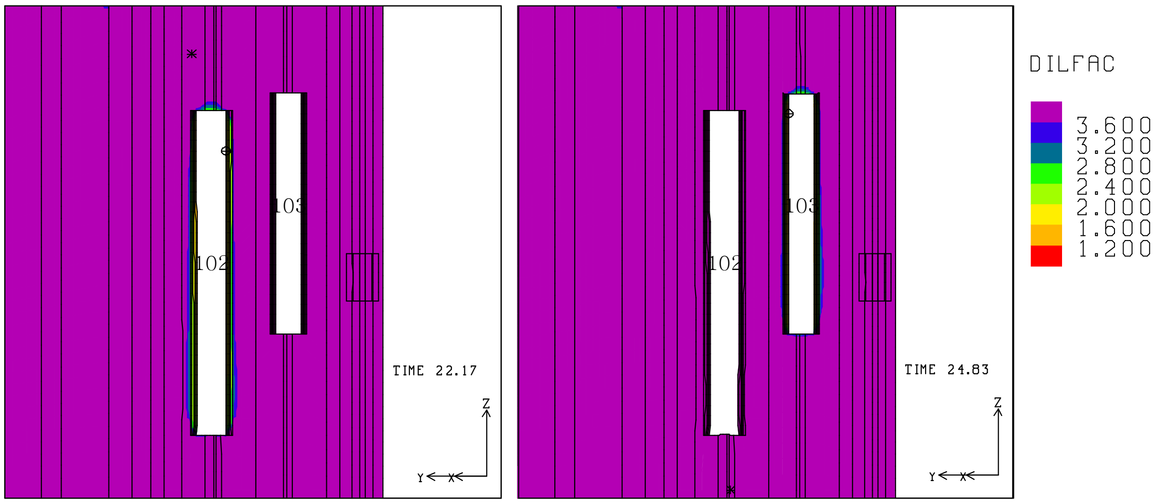


Figure 34: Minimum safety factor history against dilatant damage in the elements within 130 ft of Caverns 15, 17, 102, 103 and 104 for Scenario 2.



22.17 years (a)

24.83 years (b)

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.

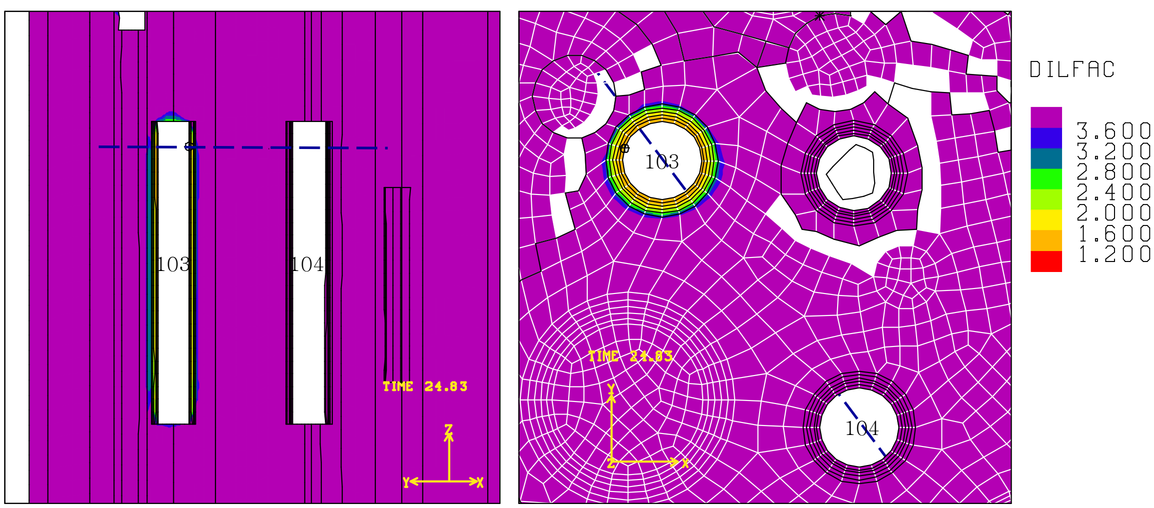


Figure 36: Safety factor contours against dilatant damage during first workover of Cavern 103 after the initial leach for Scenario 1. Vertical cross-section through the centers of Caverns 103 and 104 (left) and horizontal cross-section at the elevation where the minimum safety factor occurs (right). 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

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APPENDIX A: INPUT FOR JAS3D

Scenario 1

```
title
SPR Bayou Choctaw Exp. A3 and 5, 26cav5l_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=30.41666666666666667} days
$ DAYYR      = {DAYYR=365.} days
$ SECMON     = {SECMON=SECDAY*DAYMON} s
$ SECYR      = {SECYR=SECDAY*DAYYR} s
$ SECDEC     = {SECDEC=10.*SECYR} s
$ SECCEN     = {SECCEN=10.*SECDEC} s
$ SECMIL     = {SECMIL=10.*SECCEN} s
$ Initial leaches start
$     SECST  = {SECST=0.} s $ {SECST/SECYR} years
$ Time at the expansion leach for Cavern 102 starts
$     SECL102= {SECL102=SECST + 21.*SECYR} s $ {SECL102/SECYR} years
$ Times at the initial leachs for Caverns A and M start
$     SECILA = {SECILA=SECL102 + 1.*SECYR} s $ {SECILA/SECYR} years
$     SECILM = {SECILM=SECILA  + 1.*SECYR} s $ {SECILM/SECYR} years
$ Times at the leaches for all SPR caverns start
$     SEC1ST = {SEC1ST=SECST + 31.*SECYR} s  $ {SEC1ST/SECYR} years
$     SEC2ND = {SEC2ND=SEC1ST + 5.*SECYR} s  $ {SEC2ND/SECYR} years
$     SEC3RD = {SEC3RD=SEC2ND + 5.*SECYR} s  $ {SEC3RD/SECYR} years
$     SEC4TH = {SEC4TH=SEC3RD + 5.*SECYR} s  $ {SEC4TH/SECYR} years
$     SEC5TH = {SEC5TH=SEC4TH + 5.*SECYR} s  $ {SEC5TH/SECYR} years
$ Time at the simulaton completes
$     SECEND = {SECEND=SEC5TH + 5.*SECYR} s  $ {SECEND/SECYR} years


start time 0.0
  ITERATION PRINT, 20
  MAXIMUM ITERATIONS, 40000
  TARGET TOLERANCE, .00005
  ACCEPTABLE TOLERANCE .00001
  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={(SECYR-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 {DDE1=DDS1+0.5*SECYR} $ {DDE1/SECYR} years - drawdown ends
  time steps, {2*ITS}    $ 1 step={2.*SECYR/(2*ITS)/SECMON} months
  PLOT every, 3          $ every {3.*2.*SECYR/(2*ITS)/SECMON} months
  print every, {2*ITS}
  write restart frequency, 0
next time {DDS2=DDE1+2.*SECYR} $ {DDS2/SECYR} years - Cav.20,101 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 {DDE2=DDS2+0.5*SECYR} $ {DDE2/SECYR} years - drawdown ends
  time steps, {2*ITS}    $ 1 step={2.*SECYR/(2*ITS)/SECMON} months
  PLOT every, 3          $ every {3.*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
  PLOT every, 1          $ every {0.5*SECYR/(HYR*3)/SECDAY} days
  print every, {HYR*3}
  write restart frequency, 0
next time {DDE1+TRM}     $ {(DDE1+TRM)/SECYR} years - drawdown ends
  time steps, {2*ITS}    $ 1 step={2.*SECYR/(2*ITS)/SECMON} months
  PLOT every, 3          $ every {3.*2.*SECYR/(2*ITS)/SECMON} months
  print every, {2*ITS}
  write restart frequency, 0
next time {DDS2+TRM}    $ {(DDS2+TRM)/SECYR} years - Cav.20,101 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 {DDE2+TRM}     $ {(DDE2+TRM)/SECYR} years - drawdown ends
  time steps, {2*ITS}    $ 1 step={2.*SECYR/(2*ITS)/SECMON} months
  PLOT every, 3          $ every {3.*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 {DDE1+2.*TRM}     $ {(DDE1+2.*TRM)/SECYR} years - drawdown ends
  time steps, {2*ITS}    $ 1 step={2.*SECYR/(2*ITS)/SECMON} months
  PLOT every, 3          $ every {3.*2.*SECYR/(2*ITS)/SECMON} months
  print every, {2*ITS}
  write restart frequency, 0
next time {DDS2+2.*TRM}    $ {(DDS2+2.*TRM)/SECYR} years - Cav.20,101 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 {DDE2+2.*TRM}     $ {(DDE2+2.*TRM)/SECYR} years - drawdown ends
  time steps, {2*ITS}    $ 1 step={2.*SECYR/(2*ITS)/SECMON} months
  PLOT every, 3          $ every {3.*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)/SECMON} months
  PLOT every, 1          $ every {0.5*SECYR/(HYR)/SECMON} months
```

```
  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/(2*ITS)/SECMON} months
  PLOT every, 3          $ every {3.*2.*SECYR/(2*ITS)/SECMON} months
  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} months
  PLOT every, 1          $ every {0.5*SECYR/(HYR)/SECMON} months
  print every, {HYR}
  write restart frequency, 0
next time {DDE2+3.*TRM}     $ {(DDE2+3.*TRM)/SECYR} years - drawdown ends
  time steps, {ITS}    $ 1 step={2.*SECYR/(2*ITS)/SECMON} months
  PLOT every, 3          $ every {3.*2.*SECYR/(2*ITS)/SECMON} months
  print every, {ITS}
  write restart frequency, 0
$ {4*TRM/SECYR} years =20 years
next time {SECL102} $ Expansion leach of 102 starts: {SECL102/SECYR} years
  time steps, {ITS}    $ 1 step={(SECILA-SECL102)/ITS/SECMON} months
  write restart every, 0
  PLOT every, 1
  print every, {ITS}
next time {SECILA} $ 102 done, initial leach for A starts: {SECILA/SECYR} years
  time steps, {ITS}    $ 1 step={(SECILM-SECILA)/ITS/SECMON} months
  write restart every, 0
  PLOT every, 1
  print every, {ITS}
next time {SECILM} $ A done, initial leach for M starts: {SECILM/SECYR} years
  time steps, {ITS}    $ 1 step={(SECILM+SECYR-SECILM)/ITS/SECMON} months
  write restart every, 0
  PLOT every, 1
  print every, {ITS}
next time {SECILM+SECYR} $ M done: {(SECILM+SECYR)/SECYR} years
  time steps, {3*ITS}    $ 1 step={((DDS1+5.*TRM)-(SECILM+SECYR))/(3*ITS)/SECMON} months
  write restart every, 0
  PLOT every, 1
  print every, {3*ITS}
$ {5*TRM/SECYR} years = 25 years
next time {DDS1+5.*TRM}  $ {(DDS1+5.*TRM)/SECYR} years - Cav.15,17,102,19,18 drawdown starts
  time steps, {HYR}    $ 1 step={0.5*SECYR/(HYR)/SECMON} months
  PLOT every, 1          $ every {0.5*SECYR/(HYR)/SECMON} months
  print every, {HYR}
  write restart frequency, 0
next time {DDE1+5.*TRM}     $ {(DDE1+5.*TRM)/SECYR} years - drawdown ends
  time steps, {2*ITS}    $ 1 step={2.*SECYR/(2*ITS)/SECMON} months
  PLOT every, 3          $ every {3.*2.*SECYR/(2*ITS)/SECMON} months
  print every, {2*ITS}
  write restart frequency, 0
next time {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} months
  PLOT every, 1          $ every {0.5*SECYR/(HYR)/SECMON} months
  print every, {HYR}
  write restart frequency, 0
next time {DDE2+5.*TRM}     $ {(DDE2+5.*TRM)/SECYR} years - drawdown ends
  time steps, {2*ITS}    $ 1 step={2.*SECYR/(2*ITS)/SECMON} months
  PLOT every, 3          $ every {3.*2.*SECYR/(2*ITS)/SECMON} months
  print every, {2*ITS}
  write restart frequency, 0
$ {6*TRM/SECYR} years = 30 years
next time {DDS1+6.*TRM}  $ {(DDS1+6.*TRM)/SECYR} years - Cav.15,17,102,19,18 drawdown starts
  time steps, {HYR}    $ 1 step={0.5*SECYR/(HYR)/SECMON} months
  PLOT every, 1          $ every {0.5*SECYR/(HYR)/SECMON} months
  print every, {HYR}
  write restart frequency, 0
next time {DDE1+6.*TRM}     $ {(DDE1+6.*TRM)/SECYR} years - drawdown ends
  time steps, {2*ITS}    $ 1 step={2.*SECYR/(2*ITS)/SECMON} months
  PLOT every, 3          $ every {3.*2.*SECYR/(2*ITS)/SECMON} months
  print every, {2*ITS}
  write restart frequency, 0
next time {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} months
  PLOT every, 1          $ every {0.5*SECYR/(HYR)/SECMON} months
  print every, {HYR}
  write restart frequency, 0
next time {DDE2+6.*TRM}     $ {(DDE2+6.*TRM)/SECYR} years - drawdown ends
  time steps, {2*ITS}    $ 1 step={2.*SECYR/(2*ITS)/SECMON} months
  PLOT every, 3          $ every {3.*2.*SECYR/(2*ITS)/SECMON} months
  print every, {2*ITS}
```

```
  write restart frequency, 0
$ {7*TRM/SECYR} years = 35 years
next time {DDS1+7.*TRM}  $ {(DDS1+7.*TRM)/SECYR} years - Cav.15,17,102,19,18 drawdown starts
  time steps, {HYR}    $ 1 step={0.5*SECYR/(HYR)/SECMON} months
  PLOT every, 1         $ every {0.5*SECYR/(HYR)/SECMON} months
  print every, {HYR}
  write restart frequency, 0
next time {DDE1+7.*TRM}     $ {(DDE1+7.*TRM)/SECYR} years - drawdown ends
  time steps, {2*ITS}    $ 1 step={2.*SECYR/(2*ITS)/SECMON} months
  PLOT every, 3          $ every {3.*2.*SECYR/(2*ITS)/SECMON} months
  print every, {2*ITS}
  write restart frequency, 0
next time {DDS2+7.*TRM}    $ {(DDS2+7.*TRM)/SECYR} years - Cav.20,101,106(A),107(SPR 5) drawdown
      starts
  time steps, {HYR}    $ 1 step={0.5*SECYR/(HYR)/SECMON} months
  PLOT every, 1          $ every {0.5*SECYR/(HYR)/SECMON} months
  print every, {HYR}
  write restart frequency, 0
next time {DDE2+7.*TRM}     $ {(DDE2+7.*TRM)/SECYR} years - drawdown ends
  time steps, {2*ITS}    $ 1 step={2.*SECYR/(2*ITS)/SECMON} months
  PLOT every, 3          $ every {3.*2.*SECYR/(2*ITS)/SECMON} months
  print every, {2*ITS}
  write restart frequency, 0
$ {8*TRM/SECYR} years = 40 years
next time {DDS1+8.*TRM}  $ {(DDS1+8.*TRM)/SECYR} years - Cav.15,17,102,19,18 drawdown starts
  time steps, {HYR}    $ 1 step={0.5*SECYR/(HYR)/SECMON} months
  PLOT every, 1          $ every {0.5*SECYR/(HYR)/SECMON} months
  print every, {HYR}
  write restart frequency, 0
next time {DDE1+8.*TRM}     $ {(DDE1+8.*TRM)/SECYR} years - drawdown ends
  time steps, {2*ITS}    $ 1 step={2.*SECYR/(2*ITS)/SECMON} months
  PLOT every, 3          $ every {3.*2.*SECYR/(2*ITS)/SECMON} months
  print every, {2*ITS}
  write restart frequency, 0
next time {DDS2+8.*TRM}    $ {(DDS2+8.*TRM)/SECYR} years - Cav.20,101,106(A),107(SPR 5) drawdown
      starts
  time steps, {HYR}    $ 1 step={0.5*SECYR/(HYR)/SECMON} months
  PLOT every, 1          $ every {0.5*SECYR/(HYR)/SECMON} months
  print every, {HYR}
  write restart frequency, 0
next time {DDE2+8.*TRM}     $ {(DDE2+8.*TRM)/SECYR} years - drawdown ends
  time steps, {2*ITS}    $ 1 step={2.*SECYR/(2*ITS)/SECMON} months
  PLOT every, 3          $ every {3.*2.*SECYR/(2*ITS)/SECMON} months
  print every, {2*ITS}
  write restart frequency, 0
$ {9*TRM/SECYR} years = 45 years
next time {DDS1+9.*TRM}  $ {(DDS1+9.*TRM)/SECYR} years - Cav.15,17,102,19,18 drawdown starts
  time steps, {HYR}    $ 1 step={0.5*SECYR/(HYR)/SECMON} months
  PLOT every, 1          $ every {0.5*SECYR/(HYR)/SECMON} months
  print every, {HYR}
  write restart frequency, 0
next time {DDE1+9.*TRM}     $ {(DDE1+9.*TRM)/SECYR} years - drawdown ends
  time steps, {2*ITS}    $ 1 step={2.*SECYR/(2*ITS)/SECMON} months
  PLOT every, 3          $ every {3.*2.*SECYR/(2*ITS)/SECMON} months
  print every, {2*ITS}
  write restart frequency, 0
next time {DDS2+9.*TRM}    $ {(DDS2+9.*TRM)/SECYR} years - Cav.20,101,106(A),107(SPR 5) drawdown
      starts
  time steps, {HYR}    $ 1 step={0.5*SECYR/(HYR)/SECMON} months
  PLOT every, 1          $ every {0.5*SECYR/(HYR)/SECMON} months
  print every, {HYR}
  write restart frequency, 0
next time {DDE2+9.*TRM}     $ {(DDE2+9.*TRM)/SECYR} years - drawdown ends
  time steps, {2*ITS}    $ 1 step={2.*SECYR/(2*ITS)/SECMON} months
  PLOT every, 3          $ every {3.*2.*SECYR/(2*ITS)/SECMON} months
  print every, {2*ITS}
  write restart frequency, 0
$ {10*TRM/SECYR} years = 50 years
next time {DDS1+10.*TRM}  $ {(DDS1+10.*TRM)/SECYR} years - Cav.15,17,102,19,18 drawdown starts
  time steps, {HYR}    $ 1 step={0.5*SECYR/(HYR)/SECMON} months
  PLOT every, 1          $ every {0.5*SECYR/(HYR)/SECMON} months
  print every, {HYR}
  write restart frequency, 0
next time {DDE1+10.*TRM}     $ {(DDE1+10.*TRM)/SECYR} years - drawdown ends
  time steps, {2*ITS}    $ 1 step={2.*SECYR/(2*ITS)/SECMON} months
  PLOT every, 3          $ every {3.*2.*SECYR/(2*ITS)/SECMON} months
  print every, {2*ITS}
  write restart frequency, 0
next  time  {DDS2+10.*TRM}      $  {(DDS2+10.*TRM)/SECYR}  years  -  Cav.20,101,106(A3),107(SPR  5)
      drawdown starts
  time steps, {HYR}    $ 1 step={0.5*SECYR/(HYR)/SECMON} months
```

```
  PLOT every, 1          $ every {0.5*SECYR/(HYR)/SECMON} months
  print every, {HYR}
  write restart frequency, 0
next time {DDE2+10.*TRM}     $ {(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 displacement Z 2 $ Bottom of mesh
no displacement x 3 $ West side
no displacement x 4 $ East side
no displacement y 5 $ South side
no displacement y 6 $ North side


$ Pressures on side set are the initial cavern pressure
pressure   10 user 1. $ 1$ pressure in cavern   1
pressure   20 user 1. $ 2$ pressure in cavern   2
pressure   30 user 1. $ 3$ pressure in cavern   3
pressure   40 user 1. $ 4$ pressure in cavern   4
pressure   60 user 1. $ 5$ pressure in cavern   6
pressure   70 user 1. $ 6$ pressure in cavern   7 Wall
pressure   71 user 1. $ 6$ pressure in cavern   7 Floor and Roof
pressure   80 user 1. $ 7$ pressure in cavern   8
pressure  100 user 1. $ 8$ pressure in cavern  10
pressure  110 user 1. $ 9$ pressure in cavern  11
pressure  130 user 1. $10$ pressure in cavern  13
pressure  150 user 1. $11$ pressure in cavern  15
pressure  160 user 1. $12$ pressure in cavern  16
pressure  170 user 1. $13$ pressure in cavern  17
pressure  180 user 1. $14$ pressure in cavern  18
pressure  190 user 1. $15$ pressure in cavern  19
pressure  200 user 1. $16$ pressure in cavern  20
pressure  240 user 1. $17$ pressure in cavern  24
pressure  250 user 1. $18$ pressure in cavern  25
pressure  260 user 1. $19$ pressure in cavern  26
pressure 1010 user 1. $20$ pressure in cavern 101
pressure 1020 user 1. $21$ pressure in cavern 102 before expansion
pressure 1026 user 1. $22$ pressure in cavern 102 after expansion
pressure 1030 user 1. $23$ pressure in cavern 103(J1)
pressure 1040 user 1. $24$ pressure in cavern 104(N1)
pressure 1050 user 1. $25$ pressure in cavern 105(UTP1)
pressure 1060 user 1. $26$ pressure in cavern 106(A3)
pressure 1070 user 1. $27$ 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
```

```
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(A3)
pressure 1073 user 1. $ pressure in cavern 107(SPR 5)

$ 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.
  magnitude 1.0
  use function 3
end gravity


material 1, power law creep, {rho1}    $ Salt1
 bulk modulus = {K1/RF}
 two mu = {2*mu1/RF}
 creep constant = {SMF*A}
 stress exponent = {n}
 thermal constant = {Q/R}
END
$ {thick1=2240.28}


$active  limits,  10,  0.0,{SECST-1*SECYR/ITS}  $  {(SECST-1*SECYR/ITS)/SECYR}  years  $  Initial
      leaching of caverns
active limits, 10, 0.0,{IEXST=0.01} $ {SECST-1*SECYR/ITS} $ 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,{SECL102} $ Expansion leach for 102 at {SECL102/SECYR} 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,{SECILA} $ Initial leach for A at {SECILA/SECYR} 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,{SECILM} $ Initial leach for M at {SECILM/SECYR} 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,{SEC1ST} $ 1st leach at {SEC1ST/SECYR} 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}
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 = {2*mu1/RF}
 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 = {2*mu1/RF}
 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 = {2*mu1/RF}
 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 = {2*mu1/RF}
 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
```

```
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 USIGYY=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 USIGYY=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 USIGYY=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 USIGYY=Function Z 1, 1., material 106
initial value USIGZZ=Function Z 1, 1., material 107
initial value USIGXX=Function Z 1, 1., material 107
initial value USIGYY=Function Z 1, 1., material 107

$ {sigover = -rho3*9.81*thick3}           $ Vertical stress at botttom of overburden or top of
      caprock
$ {sigcr   = sigover - rho2*9.81*thick2} $ Vertical stress at botttom of caprock or top of salt
$ {sigbot  = sigcr - rho1*9.81*thick1}   $ Vertical stress at bottom of salt

function 1 linear      $ initial stress function for overburden (mat.3), caprock (mat. 2), and
      salt (mat. 1, and 10-15)
  {-thick1 - thick2 - thick3} {sigbot}   $ Bottom of salt
  {-thick2 - thick3}          {sigcr}    $ Bottom of caprock or top of salt
  {-thick3}                   {sigover}  $ Botttom of overburden or top of caprock
  0.0                         0.0        $ Top of overburden
end function 1

function 2 linear     $ initial stress function for surrounding rock (mat. 4)
  {-thick1 - thick2 - thick3} {sigover - rho4*9.81*thick4} $ Bottom of salt
  {-thick3}                      {sigover}                      $ Bottom of Overburden or top of
      caprock
end function 2

function 3  $ Gravity Function
     0.            1.0
 {SECEND}                1.0
end function 3

exit
```

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):
```

```
$ 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, 1992)
$ Density={rho3=1874.},Poisson's Ratio={nu3=0.33}(Hoffman and Ehgartner, 1992)
$
$Surrounding Rock (Material 4):
$ Young's Modulus={E4}(Carmichael, 1984)
$ Density={rho4=2500.},Poisson's Ratio={nu4=0.33}(Lama and Vutukuri, 1978)

$ Time at the initial leaches begin
$     bgn_s  = {bgn_s=0.} s
$ Time at the expansion leach for Cavern 102 starts
$     EL102_s= {EL102_s=bgn_s + 21.*yr_s} s $ {EL102_s/yr_s} years
$ Times at the initial leachs for Caverns A and M start
$     ILA_s = {ILA_s=EL102_s + 1.*yr_s} s  $ {ILA_s/yr_s} years
$     ILM_s = {ILM_s=ILA_s + 1.*yr_s} s    $ {ILM_s/yr_s} years
$ Times at the leaches for all SPR caverns start
$     D1st_s = {D1st_s=bgn_s + 31.*yr_s} s $ {D1st_s/yr_s} years
$     D2nd_s = {D2nd_s=D1st_s + 5.*yr_s} s $ {D2nd_s/yr_s} years
$     D3rd_s = {D3rd_s=D2nd_s + 5.*yr_s} s $ {D3rd_s/yr_s} years
$     D4th_s = {D4th_s=D3rd_s + 5.*yr_s} s $ {D4th_s/yr_s} years
$     D5th_s = {D5th_s=D4th_s + 5.*yr_s} s $ {D5th_s/yr_s} years
$Time at the simulaton completes
$     end_s  = {end_s =D5th_s + 5.*yr_s} s $ {end_s/yr_s} years

$ number of nodes = {nnod = 603216.}
$=======
start time 0.0
  ITERATION PRINT, 20
  MAXIMUM ITERATIONS, {nnod}  $ number of nodes
  TARGET TOLERANCE, 5.e-5  $ was 5.e-5
  ACCEPTABLE TOLERANCE 1.e-5  $ was 1.e-5
  predictor scale factor, 0.0,0.0
  time steps, 1   $1 step={d_s/1/d_s} day
  PLOT every, 1
  print every, 1
  write restart frequency, 0
next time {1.*d_s}  $ 1 days
  time steps, 9   $1 step={(10.*d_s-1.*d_s)/9/d_s} day
  PLOT every, 9
  print every, 9
  write restart frequency, 0
next time {10.*d_s}  $ 10 days
  time steps, 4   $1 step={(mon_s-10.*d_s)/4/d_s} days
  PLOT every, 4
  print every, 1
  write restart frequency, 0
next time {mon_s}    $ 1 month
  time steps, {ITS=12}  $1 step={(3.*mon_s-mon_s)/ITS/d_s} days
  PLOT every, {ITS}
  print every, {ITS}
  write restart frequency, 0
next time {3.*mon_s} $ 3 months
  time steps, 9      $1 step={(bgn_s+yr_s-3.*mon_s)/9/d_s} days
  PLOT every, 3
  print every, 9
$----
next time {bgn_s+yr_s} $ Change to oil/brine/liquid in caverns: {(bgn_s+yr_s)/yr_s} years
  time steps, {20*ITS}    $ 1 step={(EL102_s-(bgn_s+yr_s))/(20*ITS)/mon_s} months
  write restart every, 0
  PLOT every, 3
  print every, {ITS}
next time {EL102_s} $ Expansion leach of 102 starts: {EL102_s/yr_s} years
  time steps, {ITS}    $ 1 step={(ILA_s-EL102_s)/ITS/mon_s} months
  write restart every, 0
  PLOT every, 3
  print every, {ITS}
next time {ILA_s} $ 102 done, initial leach for A starts: {ILA_s/yr_s} years
  time steps, {ITS}    $ 1 step={(ILM_s-ILA_s)/ITS/mon_s} months
  write restart every, 0
  PLOT every, 3
  print every, {ITS}
next time {ILM_s} $ A done, initial leach for M starts: {ILM_s/yr_s} years
  time steps, {ITS}    $ 1 step={(ILM_s+yr_s-ILM_s)/ITS/mon_s} months
  write restart every, 0
  PLOT every, 3
  print every, {ITS}
next time {ILM_s+yr_s} $ M done: {(ILM_s+yr_s)/yr_s} years
  time steps, {32*ITS}    $ 1 step={(end_s-(ILM_s+yr_s))/(32*ITS)/mon_s} months
```

```
  write restart every, 0
  PLOT every, 3
  print every, {ITS}
end time  {end_s} $ {(end_s-bgn_s)/yr_s} years since simulation starts
$=======
$ Output
thermal stress external, tmpnod
plot state, EqCS, temp
plot nodal, displacement, tmpnod
plot element, sig, vonmis, eps, pressure

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

$ Pressures on side set are the initial cavern pressure
pressure   10 user 1. $ 1$ pressure in cavern   1
pressure   20 user 1. $ 2$ pressure in cavern   2
pressure   30 user 1. $ 3$ pressure in cavern   3
pressure   40 user 1. $ 4$ pressure in cavern   4
pressure   60 user 1. $ 5$ pressure in cavern   6
pressure   70 user 1. $ 6$ pressure in cavern   7 Wall
pressure   71 user 1. $ 6$ pressure in cavern   7 Floor and Roof
pressure   80 user 1. $ 7$ pressure in cavern   8
pressure  100 user 1. $ 8$ pressure in cavern  10
pressure  110 user 1. $ 9$ pressure in cavern  11
pressure  130 user 1. $10$ pressure in cavern  13
pressure  150 user 1. $11$ pressure in cavern  15
pressure  160 user 1. $12$ pressure in cavern  16
pressure  170 user 1. $13$ pressure in cavern  17
pressure  180 user 1. $14$ pressure in cavern  18
pressure  190 user 1. $15$ pressure in cavern  19
pressure  200 user 1. $16$ pressure in cavern  20
pressure  240 user 1. $17$ pressure in cavern  24
pressure  250 user 1. $18$ pressure in cavern  25
pressure  260 user 1. $19$ pressure in cavern  26
pressure 1010 user 1. $20$ pressure in cavern 101
pressure 1020 user 1. $21$ pressure in cavern 102 before expansion
pressure 1026 user 1. $22$ pressure in cavern 102 after expansion
pressure 1030 user 1. $23$ pressure in cavern 103(J1)
pressure 1040 user 1. $24$ pressure in cavern 104(N1)
pressure 1050 user 1. $25$ pressure in cavern 105(UTP1)
pressure 1060 user 1. $26$ pressure in cavern 106(A)
pressure 1070 user 1. $27$ 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)
pressure 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)
pressure 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)
pressure 1073 user 1. $ pressure in cavern 107(M)
```

```
$ 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}
```

```
END

active limits, 12, 0.0,{D2nd_s} $ 2nd leach at {D2nd_s/yr_s} years
material 12, 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, 13, 0.0,{D3rd_s} $ 3rd leach at {D3rd_s/yr_s} years
material 13, 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, 14, 0.0,{D4th_s} $ 4th leach at {D4th_s/yr_s} years
material 14, 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, 15, 0.0,{D5th_s} $ 5th leach at {D5th_s/yr_s} years
material 15, 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

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

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

material 4, elastic, {rho4}    $ Farfield (sandstone)
 youngs modulus = {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 USIGYY=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 USIGYY=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 USIGYY=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 USIGYY=Function Z 1, 1., material 106
initial value USIGZZ=Function Z 1, 1., material 107
initial value USIGXX=Function Z 1, 1., material 107
initial value USIGYY=Function Z 1, 1., material 107

$ {sigv_OB = -rho3*9.81*t_OB} Pa $ Vertical stress at botttom of overburden or top of caprock
$ {sigv_CR = sigv_OB - rho2*9.81*t_CR} Pa $ Vertical stress at botttom of caprock or top of salt
$ {sigv_SD = sigv_CR - rho1*9.81*h_SD} Pa $ Vertical stress at bottom of salt
$ {sigv_SR = sigv_OB - rho4*9.81*t_SR} Pa $ Vertical stress at bottom of surrounding rock

$ ASCENDING ORDER IS REQUIRED FOR DEFINING FUNCTION
function 1 linear $ initial stress function for overburden (mat.3), caprock (mat.2), and salt
      (mat.1)
  {-h_SD - t_CR - t_OB} {sigv_SD}  $ Bottom of salt
  {-t_CR - t_OB}        {sigv_CR}  $ Bottom of caprock or top of salt
  {-t_OB}               {sigv_OB}  $ Botttom of overburden or top of caprock
  0.0                   0.0        $ Top of overburden
end function 1

function 2 linear     $ initial stress function for surrounding rock (mat. 4)
  {-h_SD - t_CR - t_OB} {sigv_SR}  $ Bottom of surrounding rock
  {-t_OB}               {sigv_OB}  $ Bottom of Overburden or top of surrounding rock
  0.0                   0.0        $ Top of overburden
end function 2

function 3  $ Gravity and normal displacement function
     0.            1.0
 {end_s}           1.0
end function 3

exit

[units.txt]

$Unit conversion:
$
$Length:
$ ft   = {ft_m=0.3048} m
$ m    = {m_ft=1/ft_m} ft
$
$Pressure:
$ MPa  = {MPa_Pa  = 1E6} Pa
$ Pa   = {Pa_MPa  = 1/MPa_Pa} MPa
$
$Time:
$ min  = {min_s   = 60           } s
$ h    = {h_min   = 60           } min
$ d    = {d_h     = 24           } h
$ mon  = {mon_d   = 30.4166666667} d
$ yr   = {yr_d    = 365          } d
$ dec  = {dec_yr  = 10           } yr
$ cen  = {cen_dec = 10           } dec
$ mil  = {mil_cen = 10           } cen
$ h    = {h_s     = h_min*min_s  } s
$ d    = {d_s     = d_h*h_s      } s
$ mon  = {mon_s   = mon_d*d_s    } s
$ yr   = {yr_s    = yr_d*d_s     } s
$ dec  = {dec_s   = dec_yr*yr_s  } s
$ cen  = {cen_s   = cen_dec*dec_s} s
$ mil  = {mil_s   = mil_cen*cen_s} s
$

[thickness.txt]

$ Thicknesses of each layer
$
$ thickness of overburden:    t_OB={t_OB=500*ft_m} m
$ thickness of caprock:       t_CR={t_CR=150*ft_m} m
$ height of salt dome:        h_SD={h_SD=7350*ft_m} m
$ thickness of surrounding rock:     t_SR={t_SR=t_CR+h_SD} m
```

[References]

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Hogan, R. G., 1980, *Strategic Petroleum Reserve (SPR) Geological Site Characterization Report Bayou Choctaw Salt Dome*, SAND80-7140, Sandia National Laboratories, Albuquerque, New Mexico.

Krieg, R.D., 1984, *Reference Stratigraphy and Rock Properties for the Waste Isolation Pilot Plant (WIPP) Project*, SAND83-1908, Sandia National Laboratories, Albuquerque, NM 87185.

Lama, R. D. and V. S. Vutukuri, 1978, *Handbook on Mechanical Properties of Rocks – Testing Techniques and Results*, Series on Rock and Soil Mechanics, Vol. 3, No.2, Trans Tech Publications.

Morgan, H.S. and R.D. Krieg, 1988. *A Comparison of Unified Creep-Plasticity and Conventional Creep Models for Rock Salt Based on Predictions of Creep Behavior Measured in Several in Situ and Bench-Scale Experiments*, SAND87-1867, Sandia National Laboratories, Albuquerque, NM 87185 and Livermore, CA 94550.

APPENDIX B: USER-SUPPLIED SUBROUTINE

Scenario 1:

```
C $Id: usrpbc.f,v 5.0 1998/08/07 21:42:02 mlblanf Exp $
C
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 expaned 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 ***********************************************************************
C
C   DESCRIPTION:
C     This routine provides pressure boundary conditions to JAS3D
C
C   FORMAL PARAMETERS:
C     FAC      REAL        Array which must be returned
C                          with the required face pressure
C     CORDES   REAL        Nodal coordinate array
C     KSFLG    INTEGER     Side set ID for this pressure BC
C     SCALE    REAL        Pressure scale factor from input record
C     NE       INTEGER     Number of faces having this pressure BC
C     TIME     REAL        Problem time
C     NESNS    INTEGER     Number of Element Side Nodes
C     NEBLK    INTEGER     Number of Elements per Vector Block
C     NSPC     INTEGER     Number of Spatial Coordinate Components
C
C   CALLED BY: EXLOAD, called once per iteration for each user-defined
C                      pressure BC
C
C ***********************************************************************
C234567890123456789012345678901234567890123456789012345678901234567890
C
      INCLUDE 'precision.blk'
      INCLUDE 'rcdata.blk'
      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
      SECMIL=10.*SECCEN
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
      SECL102 = SECST + 21.*SECYR
C --- Times at the initial leachs for Caverns A and M start
      SECILA = SECL102 + 1.*SECYR
      SECILM = SECILA  + 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
```

```
      SEC5TH = 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=AINT(TIMEYR)
      A2=AINT(A1/5.)
      A3=A2*5.+1.
      A4=TIMEYR-A3
      if (A1.GE.5.and.A4.LE.0.) A4=A4+5.
C
C initialize the drawdown flags
C
      FINIO = .FALSE.
      FINIT = .FALSE.
      F1ST  = .FALSE.
      F2ND  = .FALSE.
      F3RD  = .FALSE.
      F4TH  = .FALSE.
      F5TH  = .FALSE.
C
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=.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
      HOROVR=RGOVR*(OVRNU/(1-OVRNU))
      VEROVR=RGOVR
C
C z-locations for layer interfaces, m
      ZSURF=0.
      ZOVR=-152.
      ZCAP=-198.
C
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.1065) THEN
        PHEAD=913.0*6894.757
      ELSEIF(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
C Set zero on the face
      DO 10 I = 1,NE
        FAC(I)=0.0
   10 CONTINUE
C
```

```
      S1 = SCALE
C
      DO 1000 I = 1,NE
C
C Coordinates of the center of the face
C
        XFAC = PFORTH*(CORDES(1,I,1) + CORDES(2,I,1) +
     *                 CORDES(3,I,1) + CORDES(4,I,1))
        YFAC = PFORTH*(CORDES(1,I,2) + CORDES(2,I,2) +
     *                 CORDES(3,I,2) + CORDES(4,I,2))
        ZFAC = PFORTH*(CORDES(1,I,3) + CORDES(2,I,3) +
     *                 CORDES(3,I,3) + CORDES(4,I,3))
C
        PLITHO = DEADLOAD + RGSALT*(ZCAP-ZFAC)
        PH2O =   RGH2O*(ZSURF-ZFAC)
        POIL  =  RGOIL*(ZSURF-ZFAC)
        PBRI = RGBRINE*(ZSURF-ZFAC)
        PPROP = RGPROP*(ZSURF-ZFAC)
        PETHY = RGETHY*(ZSURF-ZFAC)
        PLNG  = RGLNG *(ZSURF-ZFAC)
        PETHA = RGETHA*(ZSURF-ZFAC)
        POVRH = HOROVR*(ZSURF-ZFAC)
        POVRV = VEROVR*(ZSURF-ZFAC)
C
        PHH2O =  PH2O +PHEAD
        PHOIL =  POIL +PHEAD
        PHBRI =  PBRI +PHEAD
        PHPROP = PPROP+PHEAD
        PHETHY = PETHY+PHEAD
        PHLNG  = PLNG +PHEAD
        PHETHA = PETHA+PHEAD
        PHOVRH = POVRH+PHEAD
        PHOVRV = POVRV+PHEAD
C
C23456789112345678921234567893123456789412345678951234567896123456789712
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.
C
      IF (KSFLG.NE.1026) GO TO 50
        IF (TIME.LT.SECL102) GO TO 1001
        IF (TIME.LE.(SECL102+SECYR+SECDAY)) THEN
          PWELL=(PHH2O-PLITHO)*(TIME-SECL102)/SECYR + PLITHO
         FINIO = .TRUE.
          GO TO 69
        ELSE
          PWELL=PHOIL
         FINIT = .TRUE.
          GO TO 54
        ENDIF
   50 IF (KSFLG.NE.1060) GO TO 51
        IF (TIME.LT.SECILA) GO TO 1001
        IF (TIME.LE.(SECILA+SECYR+SECDAY)) THEN
          PWELL=(PHH2O-PLITHO)*(TIME-SECILA)/SECYR + PLITHO
         FINIO = .TRUE.
          GO TO 69
        ELSE
          PWELL=PHOIL
         FINIT = .TRUE.
          GO TO 54
        ENDIF
   51 IF (KSFLG.NE.1070) GO TO 52
        IF (TIME.LT.SECILM) GO TO 1001
        IF (TIME.LE.(SECILM+SECYR+SECDAY)) THEN
          PWELL=(PHH2O-PLITHO)*(TIME-SECILM)/SECYR + PLITHO
         FINIO = .TRUE.
          GO TO 69
        ELSE
          PWELL=PHOIL
         FINIT = .TRUE.
          GO TO 54
        ENDIF
C
C --- Revised pressure calculation of changing to other liquid 1 year
C --- after the stabilization.
C
   52 IF (TIME.LE.(SECST+SECYR+SECDAY)) THEN
          PWELL=(PHH2O-PLITHO)*(TIME-SECST)/SECYR + PLITHO
C
C --- Set zero on 1020 after the expansion of cavern 102 starts.
```

```
C
        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)
     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
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
C23456789112345678921234567893123456789412345678951234567896123456789712
C
C --- Determine which drawdown the simulation is at
C
      IF ((KSFLG.EQ.  10) .OR. (KSFLG.EQ.  20) .OR. (KSFLG.EQ.  30)
     1.OR.(KSFLG.EQ.  40) .OR. (KSFLG.EQ.  60) .OR. (KSFLG.EQ.  70)
     2.OR.(KSFLG.EQ.  80) .OR. (KSFLG.EQ. 100) .OR. (KSFLG.EQ. 110)
     3.OR.(KSFLG.EQ. 130) .OR. (KSFLG.EQ. 150) .OR. (KSFLG.EQ. 160)
     4.OR.(KSFLG.EQ. 170) .OR. (KSFLG.EQ. 180) .OR. (KSFLG.EQ. 190)
     5.OR.(KSFLG.EQ. 200) .OR. (KSFLG.EQ. 240) .OR. (KSFLG.EQ. 250)
     6.OR.(KSFLG.EQ. 260) .OR. (KSFLG.EQ.1010) .OR. (KSFLG.EQ.1020)
     7.OR.(KSFLG.EQ.1030) .OR. (KSFLG.EQ.1040) .OR. (KSFLG.EQ.1050)
     8.OR.(KSFLG.EQ.  71)
     9) 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 months)
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.155))  PWELL=PWELL-PHEAD
C Cavern 17 is regarded as 1st group
      IF ((A4.GE.1.0001.AND.A4.LE.1.0834).AND.
     1    (KSFLG.GE.170.AND.KSFLG.LE.175))  PWELL=PWELL-PHEAD
C Cavern 102 is regarded as 2nd group
      IF ((A4.GE.1.0834.AND.A4.LE.1.1667).AND.
     1    (KSFLG.GE.1021.AND.KSFLG.LE.1026))  PWELL=PWELL-PHEAD
C Cavern 19 is regarded as 3rd group
      IF ((A4.GE.1.1667.AND.A4.LE.1.2501).AND.
     1    (KSFLG.GE.190.AND.KSFLG.LE.195))  PWELL=PWELL-PHEAD
C Cavern 18 is regarded as 4th group
      IF ((A4.GE.1.2501.AND.A4.LE.1.3334).AND.
     1    (KSFLG.GE.180.AND.KSFLG.LE.185))  PWELL=PWELL-PHEAD
C
C Cavern 20 is regarded as 5th group
      IF ((A4.GE.3.5001.AND.A4.LE.3.5834).AND.
     1    (KSFLG.GE.200.AND.KSFLG.LE.205))  PWELL=PWELL-PHEAD
C Cavern 101 is regarded as 6th group
      IF ((A4.GE.3.5834.AND.A4.LE.3.6667).AND.
     1    (KSFLG.GE.1010.AND.KSFLG.LE.1015))  PWELL=PWELL-PHEAD
C Cavern 106(A) is regarded as 7th group
      IF ((A4.GE.3.6667.AND.A4.LE.3.7501 ).AND.
     1    (KSFLG.GE.1060.AND.KSFLG.LE.1065))  PWELL=PWELL-PHEAD
C Cavern 107(M) is regarded as 8th group
      IF ((A4.GE.3.7501.AND.A4.LE.3.8334).AND.
     1    (KSFLG.GE.1070.AND.KSFLG.LE.1075))  PWELL=PWELL-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 ((TIME.GT.SEC5TH).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 ((time.ge.(SECST- 950.*SECYR).and.time.le.(SECST+ 2.0*SECDAY))
     *.or.(time.ge.(SECST+ 0.24*SECYR).and.time.le.(SECST+ 0.26*SECYR))
     *.or.(time.ge.(SECST+ 0.99*SECYR).and.time.le.(SECST+ 1.01*SECYR))
     *.or.(time.ge.(SECST+ 1.99*SECYR).and.time.le.(SECST+ 2.51*SECYR))
     *.or.(time.ge.(SECST+ 4.49*SECYR).and.time.le.(SECST+ 5.01*SECYR))
     *.or.(time.ge.(SECST+20.99*SECYR).and.time.le.(SECST+22.34*SECYR))
     *.or.(time.ge.(SECST+24.49*SECYR).and.time.le.(SECST+24.83*SECYR))
     *.or.(time.ge.(SECST+25.99*SECYR).and.time.le.(SECST+27.34*SECYR))
     *.or.(time.ge.(SECST+29.49*SECYR).and.time.le.(SECST+29.83*SECYR))
     *.or.(time.ge.(SECST+44.49*SECYR).and.time.le.(SECST+44.83*SECYR))
     *.or.(time.ge.(SECST+50.99*SECYR).and.time.le.(SECST+52.34*SECYR))
     *.or.(time.ge.(SECST+55.99*SECYR).and.time.le.(SECST+56.51*SECYR))
     *) then
C
        if ((NE.LT.32).and.(KSFLG.eq.20))
     *    write(*,"(' Years ',1x,'  A4  ',1x,'NE',1x,
     *   '  ZFAC ',1x,'KSFLG',1x,' FAC(NE) '1x,
     *   '  PLITHO ',1x,'  PHH2O  ',1x,'   PHBRI ',1x,'  PHOVRH ',1x,
     *   '  PHOVRV ',1x,'   POIL  ',1x,'  PHEAD  ')")
        if ((NE.LT.32).or.((KSFLG.eq.1026).and.(ZFAC.gt.-805.)))
     *    write(*,"(F7.4,1x,F6.3,1x,I2,1X,F7.1,1X,I5,1X,
     *      8(E9.3,1X))") TIMEYR,A4,NE,ZFAC,KSFLG,
     *      FAC(NE),PLITHO,PHH2O,PHBRI,PHOVRH,PHOVRV,POIL,PHEAD
      endif
      RETURN
```

```
      END
```

Scenario 2:

```
C $Id: usrpbc.f,v 5.0 1998/08/07 21:42:02 mlblanf Exp $
C
C $Modified for Bayou Choctaw by B.Y.Park, 12/02/2009
C Convert Cavern 102 to SPR and add Caverns A3 and 5 as SPR for Scenario 2
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 expaned 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 **********************************************************************
C
C   DESCRIPTION:
C     This routine provides pressure boundary conditions to JAS3D
C
C   FORMAL PARAMETERS:
C     FAC       REAL          Array which must be returned
C                             with the required face pressure
C     CORDES    REAL          Nodal coordinate array
C     KSFLG     INTEGER       Side set ID for this pressure BC
C     SCALE     REAL          Pressure scale factor from input record
C     NE        INTEGER       Number of faces having this pressure BC
C     TIME      REAL          Problem time
C     NESNS     INTEGER       Number of Element Side Nodes
C     NEBLK     INTEGER       Number of Elements per Vector Block
C     NSPC      INTEGER       Number of Spatial Coordinate Components
C
C   CALLED BY: EXLOAD, called once per iteration for each user-defined
C                      pressure BC
C
C **********************************************************************
C234567890123456789012345678901234567890123456789012345678901234567890
C
      INCLUDE 'precision.blk'
      INCLUDE 'rcdata.blk'
      INCLUDE 'numbers.blk'
C
C declare logical variables for drawdown flags
C
      LOGICAL FINIO,FINIT,F1ST,F2ND,F3RD,F4TH,F5TH
C declare real variables in units_fortran.txt
      Real min_s,h_min,d_h,mon_d,yr_d,dec_yr,cen_dec,mil_cen
     *     h_s,d_s,mon_s,yr_s,dec_s,cen_s,mil_s,ILA_s,ILM_s
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
      INCLUDE 'units_fortran.txt'
C
C Define times at each event - BYP 7/30/2007
C --- Time at the initial leaches start (except expanded caverns)
      bgn_s=0.
C --- Time at the expansion leach for Cavern 102 starts
      EL102_s = bgn_s + 21.*yr_s
C --- Times at the initial leachs for Caverns A and M start
      ILA_s = EL102_s + 1.*yr_s
      ILM_s = ILA_s  + 1.*yr_s
C --- 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
C Skip for stabilizing process of lithologies BYP 9.20.2006
      IF (TIME.LT.bgn_s) GO TO 1001
C Truncates Time
      TIMEYR=(TIME-bgn_s)/yr_s
      A1=AINT(TIMEYR)
```

```
      A2=AINT(A1/5.)
      A3=A2*5.+1.
      A4=TIMEYR-A3
      if (A1.GE.5.and.A4.LE.0.) A4=A4+5.
C
C initialize the drawdown flags
C
      FINIO = .FALSE.
      FINIT = .FALSE.
      F1ST  = .FALSE.
      F2ND  = .FALSE.
      F3RD  = .FALSE.
      F4TH  = .FALSE.
      F5TH  = .FALSE.
C
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=.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
      HOROVR=RGOVR*(OVRNU/(1-OVRNU))
      VEROVR=RGOVR
C
C z-locations for layer interfaces, m
      ZSURF=0.
      ZOVR=-152.
      ZCAP=-198.
C
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.1065) THEN
        PHEAD=913.0*6894.757
      ELSEIF(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
C Set zero on the face
      DO 10 I = 1,NE
        FAC(I)=0.0
   10 CONTINUE
C
      S1 = SCALE
C
      DO 1000 I = 1,NE
C
C Coordinates of the center of the face
C
```

```
        XFAC = PFORTH*(CORDES(1,I,1) + CORDES(2,I,1) +
     *               CORDES(3,I,1) + CORDES(4,I,1))
        YFAC = PFORTH*(CORDES(1,I,2) + CORDES(2,I,2) +
     *               CORDES(3,I,2) + CORDES(4,I,2))
        ZFAC = PFORTH*(CORDES(1,I,3) + CORDES(2,I,3) +
     *               CORDES(3,I,3) + CORDES(4,I,3))
C
        PLITHO = DEADLOAD + RGSALT*(ZCAP-ZFAC)
        PH2O =   RGH2O*(ZSURF-ZFAC)
        POIL  =  RGOIL*(ZSURF-ZFAC)
        PBRI = RGBRINE*(ZSURF-ZFAC)
        PPROP = RGPROP*(ZSURF-ZFAC)
        PETHY = RGETHY*(ZSURF-ZFAC)
        PLNG  = RGLNG *(ZSURF-ZFAC)
        PETHA = RGETHA*(ZSURF-ZFAC)
        POVRH = HOROVR*(ZSURF-ZFAC)
        POVRV = VEROVR*(ZSURF-ZFAC)
C
        PHH2O =  PH2O +PHEAD
        PHOIL =  POIL +PHEAD
        PHBRI =  PBRI +PHEAD
        PHPROP = PPROP+PHEAD
        PHETHY = PETHY+PHEAD
        PHLNG  = PLNG +PHEAD
        PHETHA = PETHA+PHEAD
        PHOVRH = POVRH+PHEAD
        PHOVRV = POVRV+PHEAD
C
C23456789112345678921234567893123456789412345678951234567896123456789712
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.
C
      IF (KSFLG.NE.1026) GO TO 50
        IF (TIME.LT.EL102_s) GO TO 1001
        IF (TIME.LE.(EL102_s+yr_s+d_s)) THEN
          PWELL=(PHH2O-PLITHO)*(TIME-EL102_s)/yr_s + PLITHO
         FINIO = .TRUE.
          GO TO 69
        ELSE
          PWELL=PHOIL
         FINIT = .TRUE.
          GO TO 54
        ENDIF
   50 IF (KSFLG.NE.1060) GO TO 51
        IF (TIME.LT.ILA_s) GO TO 1001
        IF (TIME.LE.(ILA_s+yr_s+d_s)) THEN
          PWELL=(PHH2O-PLITHO)*(TIME-ILA_s)/yr_s + PLITHO
         FINIO = .TRUE.
          GO TO 69
        ELSE
          PWELL=PHOIL
         FINIT = .TRUE.
          GO TO 54
        ENDIF
   51 IF (KSFLG.NE.1070) GO TO 52
        IF (TIME.LT.ILM_s) GO TO 1001
        IF (TIME.LE.(ILM_s+yr_s+d_s)) THEN
          PWELL=(PHH2O-PLITHO)*(TIME-ILM_s)/yr_s + PLITHO
         FINIO = .TRUE.
          GO TO 69
        ELSE
          PWELL=PHOIL
         FINIT = .TRUE.
          GO TO 54
        ENDIF
C
C --- Revised pressure calculation of changing to other liquid 1 year
C --- after the stabilization.
C
   52 IF (TIME.LE.(bgn_s+yr_s+d_s)) THEN
          PWELL=(PHH2O-PLITHO)*(TIME-bgn_s)/yr_s + PLITHO
C
C --- Set zero on 1020 after the expansion of cavern 102 starts.
C
        ELSEIF ((KSFLG.EQ.1020).AND.(TIME.GE.EL102_s)) 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)
     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
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
C2345678911234567892123456789312345678941234567895123456789612345678971 2
C
C --- Determine which drawdown the simulation is at
C
      IF ((KSFLG.EQ.  10) .OR. (KSFLG.EQ.  20) .OR. (KSFLG.EQ.  30)
     1.OR.(KSFLG.EQ.  40) .OR. (KSFLG.EQ.  60) .OR. (KSFLG.EQ.  70)
     2.OR.(KSFLG.EQ.  80) .OR. (KSFLG.EQ. 100) .OR. (KSFLG.EQ. 110)
     3.OR.(KSFLG.EQ. 130) .OR. (KSFLG.EQ. 150) .OR. (KSFLG.EQ. 160)
     4.OR.(KSFLG.EQ. 170) .OR. (KSFLG.EQ. 180) .OR. (KSFLG.EQ. 190)
     5.OR.(KSFLG.EQ. 200) .OR. (KSFLG.EQ. 240) .OR. (KSFLG.EQ. 250)
     6.OR.(KSFLG.EQ. 260) .OR. (KSFLG.EQ.1010) .OR. (KSFLG.EQ.1020)
     7.OR.(KSFLG.EQ.1030) .OR. (KSFLG.EQ.1040) .OR. (KSFLG.EQ.1050)
     8.OR.(KSFLG.EQ.  71)
     9) 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 3 months)
C --- Caverns 15 and 17 currently maintain equal pressures at all time
C --- including the workover periods.
C
   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.
     1    (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.
     1    (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.
     1    (KSFLG.GE.190.AND.KSFLG.LE.195))  PWELL=PWELL-PHEAD
C Cavern 18 is regarded as 4th group
      IF ((A4.GE.2.5001.AND.A4.LE.2.7501).AND.
     1    (KSFLG.GE.180.AND.KSFLG.LE.185))  PWELL=PWELL-PHEAD
C
C Cavern 20 is regarded as 5th group
      IF ((A4.GE.3.0001.AND.A4.LE.3.2501).AND.
     1    (KSFLG.GE.200.AND.KSFLG.LE.205))  PWELL=PWELL-PHEAD
C Cavern 101 is regarded as 6th group
      IF ((A4.GE.3.5001.AND.A4.LE.3.7501).AND.
     1    (KSFLG.GE.1010.AND.KSFLG.LE.1015))  PWELL=PWELL-PHEAD
C Cavern 106(A) is regarded as 7th group
      IF ((A4.GE.4.0001.AND.A4.LE.4.2501 ).AND.
     1    (KSFLG.GE.1060.AND.KSFLG.LE.1065))  PWELL=PWELL-PHEAD
C Cavern 107(M) is regarded as 8th group
      IF ((A4.GE.4.5001.AND.A4.LE.4.7501).AND.
     1    (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
C2345678911234567892123456789312345678941234567895123456789612345678971 2
 1001 CONTINUE
      if ((time.ge.(bgn_s- 900.*yr_s).and.time.le.(bgn_s+ 2.0*d_s))
     *.or.(time.ge.(bgn_s+ 0.44*yr_s).and.time.le.(bgn_s+ 0.54*yr_s))
     *.or.(time.ge.(bgn_s+ 0.99*yr_s).and.time.le.(bgn_s+ 1.01*yr_s))
     *.or.(time.ge.(bgn_s+ 1.99*yr_s).and.time.le.(bgn_s+ 2.51*yr_s))
     *.or.(time.ge.(bgn_s+ 4.49*yr_s).and.time.le.(bgn_s+ 5.01*yr_s))
     *.or.(time.ge.(bgn_s+20.99*yr_s).and.time.le.(bgn_s+24.51*yr_s))
     *.or.(time.ge.(bgn_s+30.99*yr_s).and.time.le.(bgn_s+32.51*yr_s))
     *.or.(time.ge.(bgn_s+35.99*yr_s).and.time.le.(bgn_s+37.51*yr_s))
     *.or.(time.ge.(bgn_s+40.99*yr_s).and.time.le.(bgn_s+42.51*yr_s))
     *.or.(time.ge.(bgn_s+45.99*yr_s).and.time.le.(bgn_s+47.51*yr_s))
     *.or.(time.ge.(bgn_s+50.99*yr_s).and.time.le.(bgn_s+52.51*yr_s))
     *.or.(time.ge.(bgn_s+55.99*yr_s).and.time.le.(bgn_s+56.51*yr_s))
     *) then
C
        if ((NE.LT.32).and.(KSFLG.eq.20))
     *    write(*,"(' Years ',1x,'  A4  ',1x,'NE',1x,
     *   '  ZFAC ',1x,'KSFLG',1x,' FAC(NE) '1x,
     *   '  PLITHO ',1x,'  PHH20  ',1x,'   PHBRI ',1x,'  PHOVRH ',1x,
     *   '  PHOVRV ',1x,'   POIL  ',1x,'  PHEAD  ')")
        if ((NE.LT.32).or.((KSFLG.eq.1026).and.(ZFAC.gt.-805.)))
     *    write(*,"(F7.4,1x,F6.3,1x,I2,1X,F7.1,1X,I5,1X,
     *      8(E9.3,1X))") TIMEYR,A4,NE,ZFAC,KSFLG,
     *      FAC(NE),PLITHO,PHH2O,PHBRI,PHOVRH,PHOVRV,POIL,PHEAD
      endif
      RETURN
      END
```

APPENDIX C: FORTRAN SCRIPT FOR TEMPERATURE AT EACH NODE

```
      program load
      parameter (ntimes=2,numnod=508028)
      dimension 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./
C
      numen=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(j)*0.0251
      write(9,901) i, j, numnod, z(j), 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,numen)
         if (i.ge.ntimes) go to 1
         go to 3
 1    continue
C
      close(8)
      stop
 500  write(*,900) j,numnod
 900  format("*** Number of nodes in nodes file does not match ",
     1 "numnod in source code!! ***",i6,1x,i6)
      stop 1
      end
```

[References]

Ballard, S. and Ehgartner, B.L., 2000, CAVEMAN Version 3.0: System for SPR Cavern Pressure Analysis, SAND2000-1751, Sandia National Laboratories, Albuquerque, NM 87185-0750.

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 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 {-(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 radius {REW_D} minor radius {RNS_D}
volume {V_DM=V_BR+1} move x 0 y 0 z {Z_SD=-(H_SD+H_CR)/2-H_OB}
#
# create cavern 1 (Abandoned)
create cylinder height {H_01=262.13} radius {R0_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 {R0_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 {R0_03=29.06}
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 (Inacive)
create cylinder height {H_04=332.23} radius {R0_04=30.18}
volume {V_04=V_03+1} move x {X_04=  -64.47} y {Y_04=   3.61} z {Z_04=-H_OB-H_CR-H_04/2}
#
# create Allied 6 (UTP)
create cylinder height {H_06=111.86} radius {R0_06=19.26}
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 (Inactive)
create cylinder height {H_07=341.38} radius {R0_07=24.38}
volume {V_07=V_06+1} move x {X_07= -239.49} y {Y_07= 511.63} z {Z_07=-H_OB-H_07/2}
#
# create cavern 8A (Abandoned)
create cylinder height {H_08=225.86} radius {R0_08=26.44}
volume {V_08=V_07+1} move x {X_08= -247.24} y {Y_08=-184.18} z {Z_08=-489.36}
#
# create cavern 10 (Abandoned)
create cylinder height {H_10=277.98} radius {R0_10=34.13}
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 {R0_11=45.26}
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 {R0_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=V_13+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=V_15+11} 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=37.68}
volume {V_17=V_16+1} 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=V_17+11} 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 {R0_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 {R0_19}
create cylinder height {H_19} radius {R1_19=R0_19*sqrt(IR)}
subtract volume {V_19+1} from volume {V_19+2}
### 2nd drawdown
create cylinder height {H_19} radius {R1_19}
create cylinder height {H_19} radius {R2_19=R1_19*sqrt(IR)}
subtract volume {V_19+3} from volume {V_19+4}
### 3rd drawdown
create cylinder height {H_19} radius {R2_19}
create cylinder height {H_19} radius {R3_19=R2_19*sqrt(IR)}
subtract volume {V_19+5} from volume {V_19+6}
### 4th drawdown
create cylinder height {H_19} radius {R3_19}
create cylinder height {H_19} radius {R4_19=R3_19*sqrt(IR)}
subtract volume {V_19+7} from volume {V_19+8}
### 5th drawdown
create cylinder height {H_19} radius {R4_19}
create cylinder height {H_19} radius {R5_19=R4_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 {R0_20=62.10}
volume {V_20=V_19+11} move x {X_20=-475.77} y {Y_20=-285.19} z {Z_20=-1227.58}
### 1st drawdown
create cylinder height {H_20} radius {R0_20}
create cylinder height {H_20} radius {R1_20=R0_20*sqrt(IR)}
subtract volume {V_20+1} from volume {V_20+2}
### 2nd drawdown
create cylinder height {H_20} radius {R1_20}
create cylinder height {H_20} radius {R2_20=R1_20*sqrt(IR)}
subtract volume {V_20+3} from volume {V_20+4}
### 3rd drawdown
create cylinder height {H_20} radius {R2_20}
create cylinder height {H_20} radius {R3_20=R2_20*sqrt(IR)}
subtract volume {V_20+5} from volume {V_20+6}
### 4th drawdown
create cylinder height {H_20} radius {R3_20}
create cylinder height {H_20} radius {R4_20=R3_20*sqrt(IR)}
subtract volume {V_20+7} from volume {V_20+8}
### 5th drawdown
create cylinder height {H_20} radius {R4_20}
create cylinder height {H_20} radius {R5_20=R4_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 {R0_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 {R0_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 {R0_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 {R0_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 {R0_101}
create cylinder height {H_101} radius {R1_101=R0_101*sqrt(IR)}
subtract volume {V_101+1} from volume {V_101+2}
```

```
### 2nd drawdown
create cylinder height {H_101} radius {R1_101}
create cylinder height {H_101} radius {R2_101=R1_101*sqrt(IR)}
subtract volume {V_101+3} from volume {V_101+4}
### 3rd drawdown
create cylinder height {H_101} radius {R2_101}
create cylinder height {H_101} radius {R3_101=R2_101*sqrt(IR)}
subtract volume {V_101+5} from volume {V_101+6}
### 4th drawdown
create cylinder height {H_101} radius {R3_101}
create cylinder height {H_101} radius {R4_101=R3_101*sqrt(IR)}
subtract volume {V_101+7} from volume {V_101+8}
### 5th drawdown
create cylinder height {H_101} radius {R4_101}
create cylinder height {H_101} radius {R5_101=R4_101*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 {R0_102=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 {R0_102}
create cylinder height {H_102} radius {R1_102=R0_102*sqrt(IR)}
subtract volume {V_102+1} from volume {V_102+2}
### 2nd drawdown
create cylinder height {H_102} radius {R1_102}
create cylinder height {H_102} radius {R2_102=R1_102*sqrt(IR)}
subtract volume {V_102+3} from volume {V_102+4}
### 3rd drawdown
create cylinder height {H_102} radius {R2_102}
create cylinder height {H_102} radius {R3_102=R2_102*sqrt(IR)}
subtract volume {V_102+5} from volume {V_102+6}
### 4th drawdown
create cylinder height {H_102} radius {R3_102}
create cylinder height {H_102} radius {R4_102=R3_102*sqrt(IR)}
subtract volume {V_102+7} from volume {V_102+8}
### 5th drawdown
create cylinder height {H_102} radius {R4_102}
create cylinder height {H_102} radius {R5_102=R4_102*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 {R0_J1=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 {R0_N1= 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 {R0_U1=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 {R0_A=32.77}
volume {V_A=V_U1+ 1} move x {X_A=-285.61} y {Y_A=-307.99} z {Z_A=-1066.80}
## 1st drawdown
create cylinder height {H_A} radius {R0_A}
create cylinder height {H_A} radius {R1_A=R0_A*sqrt(IR)}
subtract volume {V_A+1} from volume {V_A+2}
### 2nd drawdown
create cylinder height {H_A} radius {R1_A}
create cylinder height {H_A} radius {R2_A=R1_A*sqrt(IR)}
subtract volume {V_A+3} from volume {V_A+4}
### 3rd drawdown
create cylinder height {H_A} radius {R2_A}
create cylinder height {H_A} radius {R3_A=R2_A*sqrt(IR)}
subtract volume {V_A+5} from volume {V_A+6}
### 4th drawdown
create cylinder height {H_A} radius {R3_A}
create cylinder height {H_A} radius {R4_A=R3_A*sqrt(IR)}
subtract volume {V_A+7} from volume {V_A+8}
### 5th drawdown
```

```
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
volume {V_A+2} {V_A+4} {V_A+6} {V_A+8} {V_A+10} \
       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=-447.77} y {Y_M=-88.54} z {Z_M=Z_A}
### 1st drawdown
create cylinder height {H_M} radius {R0_M}
create cylinder height {H_M} radius {R1_M=R0_M*sqrt(IR)}
subtract volume {V_M+1} from volume {V_M+2}
### 2nd drawdown
create cylinder height {H_M} radius {R1_M}
create cylinder height {H_M} radius {R2_M=R1_M*sqrt(IR)}
subtract volume {V_M+3} from volume {V_M+4}
### 3rd drawdown
create cylinder height {H_M} radius {R2_M}
create cylinder height {H_M} radius {R3_M=R2_M*sqrt(IR)}
subtract volume {V_M+5} from volume {V_M+6}
### 4th drawdown
create cylinder height {H_M} radius {R3_M}
create cylinder height {H_M} radius {R4_M=R3_M*sqrt(IR)}
subtract volume {V_M+7} from volume {V_M+8}
### 5th drawdown
create cylinder height {H_M} radius {R4_M}
create cylinder height {H_M} radius {R5_M=R4_M*sqrt(IR)}
subtract volume {V_M+9} from volume {V_M+10}
### move to exact location
volume {V_M+2} {V_M+4} {V_M+6} {V_M+8} {V_M+10} \
       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 1 121 with sheet extended from surface 520
## related to dome in overburden (volume 126)
# delete duplicated volumes (volume 2 120 122)
delete volume 125 127 124
# then volumes of overburden are 126 (dome)   1 (surrounding)
# volumes of caprock are           2 (dome) 119 (surrounding)
# volumes of mid part are        122 (dome) 123 (surrounding)
# volumes of lower part are      120 (dome) 121 (surrounding)
zoom volume 122
#
# create 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
```

```
### then volume of cavern 7 is 158 in caprock, 161 in salt
#### cavern 8 (volume 9, 166)
webcut volume 126 2 122 120 with sheet extended from surface 28
webcut volume 164 with plane surface 30
webcut volume 166 with plane surface 29
delete volume 167
#### cavern 10 (volume 10, 172)
webcut volume 126 2 122 120 with sheet extended from 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 sheet extended from 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 sheet extended from 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\A_M 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 sheet extended from surface 40
webcut volume 126 2 122 120 with sheet extended from surface 46
webcut volume 126 2 122 120 with sheet extended from surface 55
webcut volume 126 2 122 120 with sheet extended from surface 64
webcut volume 126 2 122 120 with sheet extended from surface 73
webcut volume 126 2 122 120 with sheet extended from 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 sheet extended from 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 sheet extended from surface 91
webcut volume 126 2 122 120 with sheet extended from surface 97
webcut volume 126 2 122 120 with sheet extended from surface 106
webcut volume 126 2 122 120 with sheet extended from surface 115
webcut volume 126 2 122 120 with sheet extended from surface 124
webcut volume 126 2 122 120 with sheet extended from surface 133
webcut volume 230 234 238 242 246 250 with plane surface 93
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 sheet extended from surface 139
webcut volume 126 2 122 120 with sheet extended from surface 145
webcut volume 126 2 122 120 with sheet extended from surface 154
webcut volume 126 2 122 120 with sheet extended from surface 163
webcut volume 126 2 122 120 with sheet extended from surface 172
webcut volume 126 2 122 120 with sheet extended from surface 181
webcut volume 266 270 274 278 282 286 with plane surface 141
webcut volume 288 289 290 291 292 293 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 sheet extended from surface 187
webcut volume 126 2 122 120 with sheet extended from surface 193
webcut volume 126 2 122 120 with sheet extended from surface 202
webcut volume 126 2 122 120 with sheet extended from surface 211
webcut volume 126 2 122 120 with sheet extended from surface 220
webcut volume 126 2 122 120 with sheet extended from 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 58 60 62 64 66 68 360 361 362 363 364 365
webcut volume 126 2 122 120 with sheet extended from surface 235
webcut volume 126 2 122 120 with sheet extended from surface 241
webcut volume 126 2 122 120 with sheet extended from surface 250
webcut volume 126 2 122 120 with sheet extended from surface 259
webcut volume 126 2 122 120 with sheet extended from surface 268
webcut volume 126 2 122 120 with sheet extended from 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 sheet extended from 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 385 with plane surface 291
webcut volume 387 with plane surface 290
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 413 414 415 416 417 418 with plane surface 293
delete volume 419 420 421 422 423 424
#### cavern 102A (volume 83 85 87 89 91 93 449 450 451 452 453 454
webcut volume 126 2 122 120 with sheet extended from surface 340
webcut volume 126 2 122 120 with sheet extended from surface 346
webcut volume 126 2 122 120 with sheet extended from surface 355
webcut volume 126 2 122 120 with sheet extended from surface 364
webcut volume 126 2 122 120 with sheet extended from surface 373
webcut volume 126 2 122 120 with sheet extended from surface 382
webcut volume 427 431 435 439 443 447 with plane surface 342
webcut volume 449 450 451 452 453 454 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 463 with plane surface 390
webcut volume 465 with plane surface 389
delete volume 466
#### cavern N1 (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 481 485 489 493 497 501 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
#######
# merge 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 {RI_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
merge all
# +6
# draw volume 551  83  85  87  89  91  93 (Cavern 102)
# draw volume 555 427 431 435 439 443 447 (upper part of cavern 102)
# draw volume 557 449 450 451 452 453 454 (lower part of cavern 102)
# draw volume 556 428 432 436 440 444 448 (most lower part)
#
# Mesh caverns manually first
# Use round off to get integer for interval of mesh
#
## Cavern 1 (volume 3)
surface 11 interval {RI_01=10}
mesh surface 11
surface 10 interval {HI_01=10}
mesh volume 3
#
### Note that "\" doesn't work in the aprepro script
## Cavern 2 (volume 4)
surface 14 interval \
   {(fmod(R0_02*RI_01,R0_01)<0.5 ? int(R0_02/R0_01*RI_01) : int(R0_02/R0_01*RI_01)+1)}
mesh surface 14
surface 13 interval \
   {(fmod(H_02*HI_01,H_01)<0.5 ? int(H_02/H_01*HI_01) : int(H_02/H_01*HI_01)+1)}
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) : int(R0_03/R0_01*RI_01)+1)-1}
mesh surface 17
surface 16 interval \
   {(fmod(H_03*HI_01,H_01)<0.5 ? int(H_03/H_01*HI_01) : int(H_03/H_01*HI_01)+1)}
mesh volume 5
#
## Cavern 4 (volume 6)
surface 20 interval \
   {(fmod(R0_04*RI_01,R0_01)<0.5 ? int(R0_04/R0_01*RI_01) : int(R0_04/R0_01*RI_01)+1)}
mesh surface 20
surface 19 interval \
   {(fmod(H_04*HI_01,H_01)<0.5 ? int(H_04/H_01*HI_01) : int(H_04/H_01*HI_01)+1)}
mesh volume 6
#
## Allied 6 (volume 7)
surface 23 interval \
   {(fmod(R0_06*RI_01,R0_01)<0.5 ? int(R0_06/R0_01*RI_01) : int(R0_06/R0_01*RI_01)+1)}
mesh surface 23
surface 22 interval \
   {(fmod(H_06*HI_01,H_01)<0.5 ? int(H_06/H_01*HI_01) : int(H_06/H_01*HI_01)+1)}
mesh volume 7
#
## Cavern 7 (volume 158, 161)
surface 715 interval \
   {(fmod(R0_07*RI_01,R0_01)<0.5 ? int(R0_07/R0_01*RI_01) : int(R0_07/R0_01*RI_01)+1)}
mesh surface 715
surface 738 interval \
   {(fmod((H_07-H_CR)*HI_01,H_01)<0.5     ?     int((H_07-H_CR)/H_01*HI_01)     :     int((H_07-
H_CR)/H_01*HI_01)+1)}
surface  717 interval \
   {(fmod(H_CR*HI_01,H_01)<0.5 ? int(H_CR/H_01*HI_01) : int(H_CR/H_01*HI_01)+1)}
mesh volume 158 161
#
## Cavern 8A (volume 9)
surface 29 interval \
   {(fmod(R0_08*RI_01,R0_01)<0.5 ? int(R0_08/R0_01*RI_01) : int(R0_08/R0_01*RI_01)+1)}
mesh surface 29
surface 28 interval \
   {(fmod(H_08*HI_01,H_01)<0.5 ? int(H_08/H_01*HI_01) : int(H_08/H_01*HI_01)+1)}
mesh volume 9
#
## Cavern 10 (volume 10)
surface 32 interval \
   {(fmod(R0_10*RI_01,R0_01)<0.5 ? int(R0_10/R0_01*RI_01) : int(R0_10/R0_01*RI_01)+1)}
mesh surface 32
surface 31 interval \
   {(fmod(H_10*HI_01,H_01)<0.5 ? int(H_10/H_01*HI_01) : int(H_10/H_01*HI_01)+1)}
```

```
mesh volume 10
#
## Cavern 11 (volume 11)
surface 35 interval \
   {(fmod(R0_11*RI_01,R0_01)<0.5 ? int(R0_11/R0_01*RI_01) : int(R0_11/R0_01*RI_01)+1)}
mesh surface 35
surface 34 interval \
   {(fmod(H_11*HI_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(R0_13*RI_01,R0_01)<0.5 ? int(R0_13/R0_01*RI_01) : int(R0_13/R0_01*RI_01)+1)}
mesh surface 38
surface 37 interval \
   {(fmod(H_13*HI_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(R0_15*RI_01,R0_01)<0.5 ? int(R0_15/R0_01*RI_01) : int(R0_15/R0_01*RI_01)+1)}
mesh surface 41 50 59 68 77 86
surface 40 46 55 64 73 82 interval \
   {(fmod(H_15*HI_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(R0_16*RI_01,R0_01)<0.5 ? int(R0_16/R0_01*RI_01) : int(R0_16/R0_01*RI_01)+1)}
mesh surface 89
surface 88 interval \
   {(fmod(H_16*HI_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  92 101 110 119 128 137 interval \
   {(fmod(R0_17*RI_01,R0_01)<0.5 ? int(R0_17/R0_01*RI_01) : int(R0_17/R0_01*RI_01)+1)}
mesh surface 92 101 110 119 128 137
surface  91  97 106 115 124 133 interval \
   {(fmod(H_17*HI_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(R0_18*RI_01,R0_01)<0.5 ? int(R0_18/R0_01*RI_01) : int(R0_18/R0_01*RI_01)+1)}
mesh surface 140 149 158 167 176 185
surface 139 145 154 163 172 181 \
   interval {(fmod(H_18*HI_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(R0_19*RI_01,R0_01)<0.5 ? int(R0_19/R0_01*RI_01) : int(R0_19/R0_01*RI_01)+1)}
mesh surface 188 197 206 215 224 233
surface 187 193 202 211 220 229 interval \
   {(fmod(H_19*HI_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(R0_20*RI_01,R0_01)<0.5 ? int(R0_20/R0_01*RI_01) : int(R0_20/R0_01*RI_01)+1)}
mesh surface 236 245 254 263 272 281
surface 235 241 250 259 268 277 interval \
   {(fmod(H_20*HI_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(R0_24*RI_01,R0_01)<0.5 ? int(R0_24/R0_01*RI_01) : int(R0_24/R0_01*RI_01)+1)}
mesh surface 284
surface 283 interval \
   {(fmod(H_24*HI_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(R0_25*RI_01,R0_01)<0.5 ? int(R0_25/R0_01*RI_01) : int(R0_25/R0_01*RI_01)+1)}
mesh surface 287
surface 286 2016 interval \
   {(fmod(H_25*HI_01,H_01)<0.5 ? int(H_25/H_01*HI_01) : int(H_25/H_01*HI_01)+1)}
mesh volume 70 380
```

```
#
## Cavern 26 (volume 71)
surface 290 interval \
   {(fmod(R0_26*RI_01,R0_01)<0.5 ? int(R0_26/R0_01*RI_01) : int(R0_26/R0_01*RI_01)+1)}
mesh surface 290
surface 289 interval \
   {(fmod(H_26*HI_01,H_01)<0.5 ? int(H_26/H_01*HI_01) : int(H_26/H_01*HI_01)+1)}
mesh volume 71
#
## Cavern 101B (volume 72 74 76 78 80 82)
surface 293 302 311 320 329 338 interval \
   {(fmod(R0_101*RI_01,R0_01)<0.5 ? int(R0_101/R0_01*RI_01) : int(R0_101/R0_01*RI_01)+1)}
mesh surface 293 302 311 320 329 338
surface 292 298 307 316 325 334 interval \
   {(fmod(H_101*HI_01,H_01)<0.5 ? int(H_101/H_01*HI_01) : int(H_101/H_01*HI_01)+1)}
mesh volume 72 74 76 78 80 82
#
## Cavern 102A (volume 551  83  85  87  89  91  93)
surface 3071 3077 350 359 368 377 386 interval \
   {(fmod(R0_102*RI_01,R0_01)<0.5 ? int(R0_102/R0_01*RI_01) : int(R0_102/R0_01*RI_01)+1)}
mesh surface 3071 3077 350 359 368 377 386
surface 3070 340 346 355 364 373 382 interval \
   {(fmod(H_102*HI_01,H_01)<0.5 ? int(H_102/H_01*HI_01) : int(H_102/H_01*HI_01)+1)}
mesh volume 551 83 85 87 89 91 93
#
## Allied J1 (volume 94) (?strange: interval = 1, it has to be 3 like N1)
surface 389 interval \
   {(fmod(R0_J1*RI_01,R0_01)<0.5 ? int(R0_J1/R0_01*RI_01) : int(R0_J1/R0_01*RI_01)+1)}
mesh surface 389
surface 388 interval \
   {(fmod(H_J1*HI_01,H_01)<0.5 ? int(H_J1/H_01*HI_01) : int(H_J1/H_01*HI_01)+1)}
mesh volume 94
#
## Allied N1 (volume 95)
surface 392 interval \
   {(fmod(R0_N1*RI_01,R0_01)<0.5 ? int(R0_N1/R0_01*RI_01) : int(R0_N1/R0_01*RI_01)+1)}
mesh surface 392
surface 391 interval \
   {(fmod(H_N1*HI_01,H_01)<0.5 ? int(H_N1/H_01*HI_01) : int(H_N1/H_01*HI_01)+1)}
mesh volume 95
#
## UTP1 (volume 96)
surface 395 interval \
   {(fmod(R0_U1*RI_01,R0_01)<0.5 ? int(R0_U1/R0_01*RI_01) : int(R0_U1/R0_01*RI_01)+1)}
mesh surface 395
surface 394 interval \
   {(fmod(H_U1*HI_01,H_01)<0.5 ? int(H_U1/H_01*HI_01) : int(H_U1/H_01*HI_01)+1)}
mesh volume 96
#
## Cavern A3 (volume 97 99 101 103 105 107)
surface 398 407 416 425 434 443 interval \
   {1+(fmod(R0_A*RI_01,R0_01)<0.5 ? int(R0_A/R0_01*RI_01) : int(R0_A/R0_01*RI_01)+1)}
mesh surface 398 407 416 425 434 443
surface 397 403 412 421 430 439 interval \
   {(fmod(H_A*HI_01,H_01)<0.5 ? int(H_A/H_01*HI_01) : int(H_A/H_01*HI_01)+1)}
mesh volume 97 99 101 103 105 107
#
## Cavern 5 (volume 108 110 112 114 116 118 539 540 541 542 543 544)
surface 446 455 464 473 482 491 interval \
   {1+(fmod(R0_M*RI_01,R0_01)<0.5 ? int(R0_M/R0_01*RI_01) : int(R0_M/R0_01*RI_01)+1)}
mesh surface 446 455 464 473 482 491
surface 445 451 460 469 478 487 interval \
   {(fmod(H_M*HI_01,H_01)<0.5 ? int(H_M/H_01*HI_01) : int(H_M/H_01*HI_01)+1)}
mesh volume 108 110 112 114 116 118
#
# Define groups and meshing
##
### Bottom elevation of caprock {BE_CR=-H_OB-H_CR}
### Bottom elevation of mid dome{BE_MD=Z_25-H_25/2}
group "near_caverns" add vol all with z_coord < {BE_CR} and z_coord > {BE_MD}
### find volumes in Group defined by the prior script
#
vol 123 in near_caverns size 200
vol in near_caverns except vol 123 size 38
vol all in near_caverns scheme auto
surface 520 interval \
   {(fmod(H_SD*HI_01,H_01)<0.5 ? int(H_SD/H_01*HI_01) : int(H_SD/H_01*HI_01)+1)}
mesh vol 122
mesh vol all in near_caverns
##
group "above_caverns" add vol all with z_coord > {BE_CR}
```

```
vol all in above_caverns size 80
vol all in above_caverns scheme auto
mesh vol all in above_caverns
##
group "below_caverns" add vol all with z_coord < {BE_MD}
vol all in below_caverns size 160
vol all in below_caverns scheme auto
mesh vol all in below_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 58, 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 293, 302 to 303, 306 to 307, 310 to 311, 314 to 315,\
   318 to 319, 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, 463 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,\
   181, 187, 191, 195, 199, 203, 207, 223, 229, 233, 237, 241,\
   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, 228, 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)
```

```
#14# Cavern  18 (volume 36 38 40 42 44 46)
#15# Cavern  19A(volume 47 49 51 53 55 57)
#16# Cavern  20A(volume 58 60 62 64 66 68)
#17# Allied  24 (Volume 69)
#18# Allied  25 (Volume 70)
#19# Cavern  26 (Volume 71)
#20# Cavern 101B(volume 72 74 76 78 80 82)
#21# Cavern 102A(Volume 551 83 85 87 89 91 93)
#22# Allied  J1 (Volume 94)
#23# Allied  N1 (Volume 95)
#24# UTP1       (Volume 96)
#25# Cavern A3  (volume 97 99 101 103 105 107)
#26# Cavern 5   (volume 108 110 112 114 116 118)


### SO FAR ####################################################################
block  10 volume 3 4 5 6 7 158 161 9 10 11 12 13 24 25 36 47 58 69 70 71 \
                72 551 94 95 96                # volume of initial leach
block  11 volume 15 27 38 49 60 74 85  99 110  # volume of 1st leach
block  12 volume 17 29 40 51 62 76 87 101 112  # volume of 2nd leach
block  13 volume 19 31 42 53 64 78 89 103 114  # volume of 3rd leach
block  14 volume 21 33 44 55 66 80 91 105 116  # volume of 4th leach
block  15 volume 23 35 46 57 68 82 93 107 118  # volume of 5th leach
block 102 volume  83 # volume of expansion leach of Cavern 102
block 106 volume  97 # volume of initial leach of Cavern A
block 107 volume 108 # volume of initial leach of Cavern M
#
# Side set
# Print this file and refer to "webcut volume"
# to find the roof and floor surface number
# volume   2 is caprock
# volume 122 is dome
# draw block 1
#
## Cavern 1 (draw Volume 3, 132, 130)
sideset  10 surface 10 wrt volume 122 # wall  at initial
sideset  10 surface 11 wrt volume 132 # floor at initial
sideset  10 surface 12 wrt volume 130 # roof  at initial
#
## cavern 2 (draw volume 4, 138, 136)
sideset  20 surface 13 wrt volume 122 # wall  at initial
sideset  20 surface 14 wrt volume 138 # floor at initial
sideset  20 surface 15 wrt volume 136 # roof  at initial
#
## Cavern 3 (draw Volume 5, 144, 142)
sideset  30 surface 16 wrt volume 122 # wall  at initial
sideset  30 surface 17 wrt volume 144 # floor at initial
sideset  30 surface 18 wrt volume 142 # roof  at initial
#
## cavern 4 (draw volume 6, 148, 147)
sideset  40 surface 19 wrt volume 122 # wall  at initial
sideset  40 surface 20 wrt volume 148 # floor at initial
sideset  40 surface 21 wrt volume 147 # roof  at initial
#
## Allied 6 (draw volume 7, 155, 153)
sideset  60 surface 22 wrt volume 122 # wall  at initial
sideset  60 surface 23 wrt volume 155 # floor at initial
sideset  60 surface 24 wrt volume 153 # roof  at initial
#
## Cavern 7 (draw Volume 157,158,159,160,161: 158 in caprock, 161 in salt)
sideset  70 surface  717 wrt volume   2 # wall  at initial in caprock
sideset  71 surface  715 wrt volume 157 # roof  at initial
sideset  70 surface  738 wrt volume 122 # wall  at initial in salt
sideset  71 surface  735 wrt volume 159 # floor at initial
#
## Cavern 8A (draw volume 9, 164, 166)
sideset  80 surface 28 wrt volume 122 # wall  at initial
sideset  80 surface 29 wrt volume 166 # floor at initial
sideset  80 surface 30 wrt volume 164 # roof  at initial
#
## Cavern 10 (draw Volume 10, 172, 170)
sideset 100 surface 31 wrt volume 122 # wall  at initial
sideset 100 surface 32 wrt volume 172 # floor at initial
sideset 100 surface 33 wrt volume 170 # roof  at initial
#
## Cavern 11 (draw Volume 11, 178, 176)
sideset 110 surface 34 wrt volume 122 # wall  at initial
sideset 110 surface 35 wrt volume 178 # floor at initial
sideset 110 surface 36 wrt volume 176 # roof  at initial
##--- Hereafter refer to C:\Sandia.dat\SPR\BC_exp\Calculation\A_M to A3_5.xls
## Cavern 13 (draw Volume 12 184 182
```

```
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 \
# 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 50 wrt volume 211 # floor after 1st leach
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 154 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 59 wrt volume 212 # floor after 2nd 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 77 wrt volume 214 # floor after 4th leach
sideset 154 surface 78 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
sideset 155 surface 86 wrt volume 215 # floor after 5th leach
sideset 155 surface 87 wrt volume 208 # roof after 5th leach
#
## Cavern 16 (draw Volume 24 226 224
sideset 160 surface 88 wrt volume 122 # wall at initial
sideset 160 surface 89 wrt volume 226 # floor at initial
sideset 160 surface 90 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 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 290 # floor after 2nd leach
sideset 185 surface 159 wrt volume 274 # roof after 2nd leach
sideset 185 surface 167 wrt volume 291 # floor after 3rd leach
sideset 185 surface 168 wrt volume 278 # roof after 3rd leach
sideset 185 surface 176 wrt volume 292 # floor 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
# 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 206 wrt volume 326 # floor after 2nd 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 224 wrt volume 328 # floor after 4th leach
sideset 195 surface 225 wrt volume 318 # roof after 4th leach
sideset 195 surface 233 wrt volume 329 # floor after 5th 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 80 82 413 414 415 416 417 418 391 395 399 403 407 411
# 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 1014 surface 325 wrt volume 82 # wall after 4th leach
sideset 1014 surface 293 wrt volume 413 # floor at initial
sideset 1014 surface 294 wrt volume 391 # roof at initial
sideset 1014 surface 302 wrt volume 414 # floor after 1st leach
sideset 1014 surface 303 wrt volume 395 # roof after 1st leach
sideset 1014 surface 311 wrt volume 415 # floor after 2nd leach
sideset 1014 surface 312 wrt volume 399 # roof after 2nd leach
sideset 1014 surface 320 wrt volume 416 # floor after 3rd leach
sideset 1014 surface 321 wrt volume 403 # roof after 3rd leach
sideset 1014 surface 329 wrt volume 417 # floor after 4th leach
sideset 1014 surface 330 wrt volume 407 # roof after 4th 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
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 340 wrt volume 85 # wall 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 346 wrt volume 87 # wall 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 355 wrt volume 89 # wall 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 1022 surface 359 wrt volume 451 # floor at initial
sideset 1022 surface 360 wrt volume 435 # roof at initial

sideset 1023 surface 364 wrt volume 91 # wall 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 1023 surface 359 wrt volume 451 # floor at initial
sideset 1023 surface 360 wrt volume 435 # roof at initial
sideset 1023 surface 368 wrt volume 452 # floor at initial
sideset 1023 surface 369 wrt volume 439 # roof at initial

sideset 1024 surface 373 wrt volume 93 # wall at initial
sideset 1024 surface 3071 wrt volume 557 # floor at initial
sideset 1024 surface 3072 wrt volume 555 # roof at initial
sideset 1024 surface 3077 wrt volume 449 # floor at initial
sideset 1024 surface 3078 wrt volume 427 # roof at initial
sideset 1024 surface 350 wrt volume 450 # floor at initial
sideset 1024 surface 351 wrt volume 431 # roof at initial
sideset 1024 surface 359 wrt volume 451 # floor at initial
sideset 1024 surface 360 wrt volume 435 # roof at initial
sideset 1024 surface 368 wrt volume 452 # floor at initial
sideset 1024 surface 369 wrt volume 439 # roof at initial
sideset 1024 surface 377 wrt volume 453 # floor at initial
sideset 1024 surface 378 wrt volume 443 # roof at initial

sideset 1025 surface 382 wrt volume 122 # wall at initial
sideset 1025 surface 3071 wrt volume 557 # floor at initial
sideset 1025 surface 3072 wrt volume 555 # roof at initial
sideset 1025 surface 3077 wrt volume 449 # floor at initial
sideset 1025 surface 3078 wrt volume 427 # roof at initial
sideset 1025 surface 350 wrt volume 450 # floor at initial
sideset 1025 surface 351 wrt volume 431 # roof at initial
sideset 1025 surface 359 wrt volume 451 # floor at initial
sideset 1025 surface 360 wrt volume 435 # roof at initial
sideset 1025 surface 368 wrt volume 452 # floor at initial
sideset 1025 surface 369 wrt volume 439 # roof at initial
sideset 1025 surface 377 wrt volume 453 # floor at initial
sideset 1025 surface 378 wrt volume 443 # roof at initial
sideset 1025 surface 386 wrt volume 454 # floor at initial
sideset 1025 surface 387 wrt volume 447 # roof at initial
#
## Allied J1 (draw volume 94 465 463
sideset 1030 surface 388 wrt volume 122 # wall at initial
sideset 1030 surface 389 wrt volume 465 # floor at initial
sideset 1030 surface 390 wrt volume 463 # roof at initial
#
## Allied N1 (draw volume 95 471 469
sideset 1040 surface 391 wrt volume 122 # wall at initial
sideset 1040 surface 392 wrt volume 471 # floor at initial
sideset 1040 surface 393 wrt volume 469 # roof at initial
#
## UTP1 (draw volume 96 477 475
sideset 1050 surface 394 wrt volume 122 # wall at initial
sideset 1050 surface 395 wrt volume 477 # floor at initial
sideset 1050 surface 396 wrt volume 475 # roof at initial
#
## Cavern A3 (draw volume 97 99 101 103 105 107 503 504 505 506 507 508 481 485 489 493 497 501
# 503 504 505 506 507 508
# 481 485 489 493 497 501
sideset 1060 surface 397 wrt volume 99 # wall at initial
sideset 1060 surface 398 wrt volume 503 # floor at initial
sideset 1060 surface 399 wrt volume 481 # roof at initial

sideset 1061 surface 403 wrt volume 101 # wall after 1st leach
sideset 1061 surface 398 wrt volume 503 # floor at initial
sideset 1061 surface 399 wrt volume 481 # roof at initial
sideset 1061 surface 407 wrt volume 504 # floor after 1st leach
sideset 1061 surface 408 wrt volume 485 # roof after 1st leach

sideset 1062 surface 412 wrt volume 103 # wall after 2nd leach
sideset 1062 surface 398 wrt volume 503 # floor at initial
sideset 1062 surface 399 wrt volume 481 # roof at initial
sideset 1062 surface 407 wrt volume 504 # floor after 1st leach
sideset 1062 surface 408 wrt volume 485 # roof after 1st leach
sideset 1062 surface 416 wrt volume 505 # floor after 2nd leach
sideset 1062 surface 417 wrt volume 489 # roof after 2nd leach

sideset 1063 surface 421 wrt volume 105 # wall after 3rd leach
sideset 1063 surface 398 wrt volume 503 # floor at initial
sideset 1063 surface 399 wrt volume 481 # roof at initial
sideset 1063 surface 407 wrt volume 504 # floor after 1st leach
sideset 1063 surface 408 wrt volume 485 # roof after 1st leach
sideset 1063 surface 416 wrt volume 505 # floor after 2nd leach
sideset 1063 surface 417 wrt volume 489 # roof after 2nd leach
sideset 1063 surface 425 wrt volume 506 # floor after 3rd leach
sideset 1063 surface 426 wrt volume 493 # roof after 3rd leach
```

```
sideset 1064 surface 430 wrt volume 107 # wall after 4th leach
sideset 1064 surface 398 wrt volume 503 # floor at initial
sideset 1064 surface 399 wrt volume 481 # roof at initial
sideset 1064 surface 407 wrt volume 504 # floor after 1st leach
sideset 1064 surface 408 wrt volume 485 # roof after 1st leach
sideset 1064 surface 416 wrt volume 505 # floor after 2nd leach
sideset 1064 surface 417 wrt volume 489 # roof after 2nd leach
sideset 1064 surface 425 wrt volume 506 # floor after 3rd leach
sideset 1064 surface 426 wrt volume 493 # roof after 3rd leach
sideset 1064 surface 434 wrt volume 507 # floor after 4th leach
sideset 1064 surface 435 wrt volume 497 # roof after 4th leach

sideset 1065 surface 439 wrt volume 122 # wall after 5th leach
sideset 1065 surface 398 wrt volume 503 # floor at initial
sideset 1065 surface 399 wrt volume 481 # roof at initial
sideset 1065 surface 407 wrt volume 504 # floor after 1st leach
sideset 1065 surface 408 wrt volume 485 # roof after 1st leach
sideset 1065 surface 416 wrt volume 505 # floor after 2nd leach
sideset 1065 surface 417 wrt volume 489 # roof after 2nd leach
sideset 1065 surface 425 wrt volume 506 # floor after 3rd leach
sideset 1065 surface 426 wrt volume 493 # roof after 3rd leach
sideset 1065 surface 434 wrt volume 507 # floor after 4th leach
sideset 1065 surface 435 wrt volume 497 # roof after 4th leach
sideset 1065 surface 443 wrt volume 508 # floor after 5th leach
sideset 1065 surface 444 wrt volume 501 # roof after 5th leach
# 22
## Cavern 5 (draw volume 108 110 112 114 116 118 539 540 541 542 543 544 517 521 525 529 533 537
# 539 540 541 542 543 544
# 517 521 525 529 533 537
sideset 1070 surface 445 wrt volume 110 # wall at initial
sideset 1070 surface 446 wrt volume 539 # floor at initial
sideset 1070 surface 447 wrt volume 517 # roof at initial

sideset 1071 surface 451 wrt volume 112 # wall after 1st leach
sideset 1071 surface 446 wrt volume 539 # floor at initial
sideset 1071 surface 447 wrt volume 517 # roof at initial
sideset 1071 surface 455 wrt volume 540 # floor after 1st leach
sideset 1071 surface 456 wrt volume 521 # roof after 1st leach

sideset 1072 surface 460 wrt volume 114 # wall after 2nd leach
sideset 1072 surface 446 wrt volume 539 # floor at initial
sideset 1072 surface 447 wrt volume 517 # roof at initial
sideset 1072 surface 455 wrt volume 540 # floor after 1st leach
sideset 1072 surface 456 wrt volume 521 # roof after 1st leach
sideset 1072 surface 464 wrt volume 541 # floor after 2nd leach
sideset 1072 surface 465 wrt volume 525 # roof after 2nd leach

sideset 1073 surface 469 wrt volume 116 # wall after 3rd leach
sideset 1073 surface 446 wrt volume 539 # floor at initial
sideset 1073 surface 447 wrt volume 517 # roof at initial
sideset 1073 surface 455 wrt volume 540 # floor after 1st leach
sideset 1073 surface 456 wrt volume 521 # roof after 1st leach
sideset 1073 surface 464 wrt volume 541 # floor after 2nd leach
sideset 1073 surface 465 wrt volume 525 # roof after 2nd leach
sideset 1073 surface 473 wrt volume 542 # floor after 3rd leach
sideset 1073 surface 474 wrt volume 529 # roof after 3rd leach

sideset 1074 surface 478 wrt volume 118 # wall after 4th leach
sideset 1074 surface 446 wrt volume 539 # floor at initial
sideset 1074 surface 447 wrt volume 517 # roof at initial
sideset 1074 surface 455 wrt volume 540 # floor after 1st leach
sideset 1074 surface 456 wrt volume 521 # roof after 1st leach
sideset 1074 surface 464 wrt volume 541 # floor after 2nd leach
sideset 1074 surface 465 wrt volume 525 # roof after 2nd leach
sideset 1074 surface 473 wrt volume 542 # floor after 3rd leach
sideset 1074 surface 474 wrt volume 529 # roof after 3rd leach
sideset 1074 surface 482 wrt volume 543 # floor after 4th leach
sideset 1074 surface 483 wrt volume 533 # roof after 4th leach

sideset 1075 surface 487 wrt volume 122 # wall after 5th leach
sideset 1075 surface 446 wrt volume 539 # floor at initial
sideset 1075 surface 447 wrt volume 517 # roof at initial
sideset 1075 surface 455 wrt volume 540 # floor after 1st leach
sideset 1075 surface 456 wrt volume 521 # roof after 1st leach
sideset 1075 surface 464 wrt volume 541 # floor after 2nd leach
sideset 1075 surface 465 wrt volume 525 # roof after 2nd leach
sideset 1075 surface 473 wrt volume 542 # floor after 3rd leach
sideset 1075 surface 474 wrt volume 529 # roof after 3rd leach
sideset 1075 surface 482 wrt volume 543 # floor after 4th leach
sideset 1075 surface 483 wrt volume 533 # roof after 4th leach
sideset 1075 surface 491 wrt volume 544 # floor after 5th leach
```

```
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
c2345678901234567890123456789012345678901234567890123456789012345678901 2
C======================================================================

C   --*** EX2EX1V2 *** EXODUS II to EXODUS I translator
C   --   Written by Lynn Clements (RE/SPEC) - 01/15/92
C   --   Updated to ExodusII V2.0 Specs by V.R. Yarberry 11/2/93
C   --   Bayou Choctaw, Expansion Caverns in Cylinderical Shape
C   --   Modified by Byoung-Yoon Park (SNL) - 12/10/2009
C   --
C   --EX2EX1V2 reads the EXODUS II V2.02 and V2.03
C   --regular and history files and writes an EXODUS I database file.
C   --
C   --Expects the output database on unit 11.

      include 'exodusII.inc'
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)

      CHARACTER*8 QAINFO(6)
      PARAMETER (MAXQA = 100, MAXINF = 100)
c      CHARACTER*32 QAREC(4,MAXQA)
c      CHARACTER*80 INFO(MAXINF)

C ... Names read in are 32-characters long
      CHARACTER*(mxstln) MAMECO(6)
      CHARACTER*(mxstln) MAMES(256)
C ... Names written out are 8-characters long, truncate with no warning
      CHARACTER*8 NAMECO(6)
      CHARACTER*8 NAMELB(256)
      CHARACTER*8 NAMES(256)

      CHARACTER*80 TITLE

      DIMENSION A(1), ia(1)
C      --A - the dynamic memory base array
      equivalence (a(1), ia(1))
      CHARACTER*1 c(1)
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),
     1 vol0(nx2),chvol(nx2)
      real volcav(nx2,nx4),time(nx4)
      common /nodec/ hx(8),hy(8),hz(8)
      character*1 comma(nx2)
      character*6 displx,disply,displz
c

      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,disply,displz /'DISPLX','DISPLY','DISPLZ'/
      data (comma(i),i=1,nx2) /nx2*','/
C
      data (ssid(i,1),i=1,nx2) /10,20,30,40,60,70,71,
     1 80,100,110,130,
     2 150,151,152,153,154,155,160,
     3 170,171,172,173,174,175,
```

```
     4 180,181,182,183,184,185,
     5 190,191,192,193,194,195,
     6 200,201,202,203,204,205,240,250,260,
     7 1010,1011,1012,1013,1014,1015,
     8 1020,1026,1021,1022,1023,1024,1025,1030,1040,1050,
     9 1060,1061,1062,1063,1064,1065,
     * 1070,1071,1072,1073,1074,1075/
c ------ Radius of cavern from [BC_26cav5l_cylinder_HI10.txt]
      data (r0(i),i=1,nx2) /40.32,41.37,29.06,30.18,19.26,2*24.38,
     1 26.44,34.13,45.26,30.35,
     2 62.86,67.41,72.29,77.52,83.13,89.15,53.17,
     3 37.68,40.41,43.33,46.47,49.83,53.44,
     4 37.19,39.88,42.77,45.86,49.18,52.74,
     5 40.33,43.25,46.38,49.74,53.34,57.20,
     6 62.10,66.59,71.42,76.58,82.13,88.07,27.39,23.04,17.30,
     7 30.83,33.06,35.45,38.02,40.77,43.72,
     8 16.07,38.10,40.86,43.82,46.99,50.39,54.03,10.68, 9.04,14.32,
     9 32.77,35.14,37.69,40.41,43.34,46.48,
     * 32.77,35.14,37.69,40.41,43.34,46.48/
c ------ Height of cavern from [BC_26cav5l_cylinder_HI10.txt]
      data (h0(i),i=1,nx2) /262.13,266.70,300.23,332.23,111.86,
     * 341.38, 10.,
     1 225.86,277.98,234.70,236.83,
     2 6*210.62,187.76,
     3 6*433.73,
     4 6*638.25,
     5 6*394.11,
     6 6*120.40,377.04,675.13,120.09,
     7 6*694.94,
     8 7*822.66,332.54,280.42,348.08,
     9 6*609.60,
     * 6*609.60/
      data (th0(i),i=1,nx2) /73*360./
c ------ xc and yc are center coordinate of caverns
c ------ Get from from [BC_26cav5l_cylinder_HI10.txt]
      data (xc(i),i=1,nx2) /-305.47,-249.04,-250.36,-64.47,
     * -58.54,2*-239.49,
     1 -247.24,-519.85,-444.26,-378.27,
     2 6*27.94,-20.68,
     3 6*174.77,
     4 6*185.64,
     5 6*-145.25,
     6 6*-475.77,202.37,137.51,227.67,
     7 6*-289.91,
     8 7*-356.33,-28.06,109.10,112.46,
     9 6*-285.61,
     * 6*-447.77/
      data (yc(i),i=1,nx2) /-8.18,112.38,329.78,3.61,
     * 412.25,2*511.63,
     1 -184.18,-36.08,158.69,295.42,
     2 6*203.83,-205.60,
     3 6*224.44,
     4 6*13.17,
     5 6*-415.07,
     6 6*-285.19,-243.38,-355.82,508.57,
     7 6*-99.08,
     8 7*82.15,512.53,513.75,372.63,
     9 6*-307.99,
     * 6*-88.54/
c ------ zc is vertical center of caverns
c ------ Get from from [BC_26cav5l_cylinder_HI10.txt]
      data (zc(i),i=1,nx2) /-420.62,-351.28,-421.39,-364.24,
     * -420.17,2*-332.9,
     1 -489.36,-440.74,-431.29,-454.61,
     2 6*-899.31,-890.02,
     3 6*-1009.35,
     4 6*-966.83,
     5 6*-1091.64,
     6 6*-1227.58,-1133.40,-1427.23,-997.61,
     7 6*-1124.71,
     8 7*-1216.00,-1036.17,-954.02,-893.37,
     9 6*-1066.80,
     * 6*-1066.80/
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, EXLBVR, idummy, exlibversion, name, nerr)
      write(*,'(A,F6.3)')'ExodusII Library version ',
     1         exlibversion

      CALL MDINIT (A)
      CALL MCINIT (C)
      CALL MDSTAT (NERR, MEM)
      IF (NERR .GT. 0) GOTO 130

      MDEBUG = .false.
      if (MDEBUG) then
         call mlist()
      end if
c
c       make netCDF and exodus errors not show up
c
c      call ncpopt (0)
      call exopts (0,ierr)
c
c      open the netcdf file
c

      net = 11
      call exname (net, netfil, lnam)
c
c -- SRS - changed netfil(1:lnam) to interactive input of file name
c
C -- modified for compiling in SEALS by JEB on 10/10/2007
      write(*,'(a)') 'Name of EXODUS input file:',netfil(1:lnam)
C
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, nerr)
         goto 140
      endif

      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
C       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
      endif

      write(*,*) 'Output file name: ',ndbfil(1:lnam)
c
c      get initialization parameters from regular netcdf file
c
      CALL EXGINI (netid, title, ndim, numnp, numel,
     &       nelblk, numnps, numess, nerr)
      if (nerr .lt. 0) then
        call exopts (EXVRBS,ierr)
        call exerr('volcav', 'Error from exgini', ierr)
        goto 140
      endif
      if (numnp.ne.nx0) then
          call exerr('volcav', 'Error: nx0 .ne. numnp', -1)
         write(*,'(A)') 'Error: nx0 .ne. numnp'
         write(*,*) nx0,numnp
           goto 140
         endif
      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'
          write(*,*) nx2,numess
            goto 140
          endif
c
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
c       get the length of the side sets node list
c
         CALL EXINQ (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
c       get the length of the side sets distribution factor list
c
          CALL EXINQ (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
c       get the length of the side sets element list
c
          CALL EXINQ (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
c        write the initialization information to the EXODUS 1.0 database
c --- commented by SRS
c       CALL DBOINI (NDB, TITLE, NDIM, NUMNP, NUMEL, NELBLK,
c     &   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   --Read the coordinates
       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(*,*)' ************************* NDIM: ',ndim
         CALL EXGCOR(netid, a(kxn), a(kyn), a(kzn), nerr)
          if (nerr .lt. 0) then
            call exopts (EXVRBS,ierr)
            call exerr('volcav', 'Error from exgcor', ierr)
            goto 140
          endif
```

```
c-SRS        CALL DBOXYZ (NDB, NDIM, NUMNP, A(KXN), A(KYN), A(KZN))

c-JEB        CALL MDDEL ('XN')
c-JEB        CALL MDDEL ('YN')
c-JEB        CALL MDDEL ('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

c-SRS        CALL DBOXYZ (NDB, NDIM, NUMNP, A(KXN), A(KYN), dummy)

c-JEB        CALL MDDEL ('XN')
c-JEB        CALL MDDEL ('YN')
      ENDIF

      do 10 i=1,numnp
 10   x(i)=a(kxn+i-1)
      do 11 i=1,numnp
 11   y(i)=a(kyn+i-1)
      if (ndim.gt.2) then
        do 12 i=1,numnp
 12     z(i)=a(kzn+i-1)
      endif
      write(*,*) kxn,kyn,kzn
      write(*,*) x(1),y(1),z(1)
      write(*,*) x(numnp),y(numnp),z(numnp)

C   --Read the element order map
      write(*,'(A)') 'Reading element order map'
      CALL MDRSRV ('MAPEL', KMAPEL, NUMEL)
      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
      go to 28
      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

c      CALL DBOMAP (NDB, NUMEL, A(KMAPEL))
c      write(*,*) a(kmapel+3),ia(kmapel+3),kmapel
c      write(*,*) kmapel
c-delete this line when ready      call getar1d (ia(KMAPEL),mapeo,numel)
      CALL MDDEL ('MAPEL')
c
c       Read in the element block ID array
c
      write(*,'(A)') '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(*,'(A)') 'Reading element blocks'
```

```
      CALL MDRSRV ('NUMELB', KNELB, NELBLK)
      CALL MDRSRV ('LINK', KLINK, 0)
      CALL MDRSRV ('ATRIB', KATRIB, 0)
      CALL MDSTAT (NERR, MEM)
c      write(*,*) knelb,klink,katrib
      IF (NERR .GT. 0) GOTO 130

      nel = 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)
            goto 140
         endif
         namelb(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)
              goto 140
           endif
         end if

         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)
              goto 140
           endif
         end if

         CALL MDSTAT (NERR, MEM)
         IF (NERR .GT. 0) GOTO 130

c-SRS         CALL DBOELB (NDB, IELB, IELB,
c-SRS     &      a(kidelb+ielb-1), A(KNELB+IELB-1), NUMLNK, NUMATR,
c-SRS     &      A(KLINK), A(KATRIB))

         nel=nel+num
         CALL MDLONG ('LINK', klink, 0)
         CALL MDLONG ('ATRIB', katrib, 0)

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))
      END IF

C   --Read the node sets
      write(*,'(A)') 'Reading node sets'
      write(15,'(A)') 'Reading node sets'

      CALL MDRSRV ('IDNPS',  KIDNS, NUMNPS)  ! Node set ids array
      CALL MDRSRV ('NNNPS', KNNNS, NUMNPS)   ! Node set node count array
      CALL MDRSRV ('NDNPS', KNDNS, NUMNPS)   ! Node set df count array
      CALL MDRSRV ('IXNNPS', KIXNNS, NUMNPS) ! Node set nodes index array
      CALL MDRSRV ('IXDNPS', KIXDNS, NUMNPS) ! Node set df 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(*,*) kidns,knnns,kndns,kixnns,kixdns,klstns,kfacns,kxfacn

      if (numnps .gt. 0) then
```

```
         call exgcns (netid, a(kidns), a(knnns), a(kndns), a(kixnns),
     &                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
C     Massage node sets distribution factors to include '1' for node sets
C       without Dfs by walking KNDNS array, checking for 0, and filling where
C       necessary.
C
      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 ('IXNNPS')
      CALL MDDEL ('IXDNPS')
      CALL MDDEL ('LSTNPS')
      CALL MDDEL ('FACNPS')
      CALL MDDEL ('XFACNP')
      CALL MDSTAT (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(*,*)'side set id array size: ',numess
      CALL MDRSRV ('NEESS', KNESS, NUMESS)   ! number of ss elems array
c     write(*,*)'number of side set elements  array size: ',numess
      CALL MDRSRV ('NDESS', KNDSS, NUMESS)   ! number of dist factors array
c     write(*,*)'number of dist factors array size: ',numess
      CALL MDRSRV ('NNESS', KNNSS, NUMESS)   ! number of nodes array
c     write(*,*)'number of side set nodes array size: ',numess
      CALL MDRSRV ('IXEESS', KIXESS, NUMESS) ! index into elements array
c     write(*,*)'index into side set elements array size: ',numess
      CALL MDRSRV ('IXDESS', KIXDSS, NUMESS) ! index into dist factors array
c     write(*,*)'index into side set dist factors  array size: ',numess
      CALL MDRSRV ('IXNESS', KIXNSS, NUMESS) ! index into nodes array
c     write(*,*)'index into side set nodes array size: ',numess
      CALL MDRSRV ('LTEESS', KLTESS, LESSEL) ! element list
c     write(*,*)'side set element list array size: ',lessel
      CALL MDRSRV ('LTNESS', KLTNSS, LESSNL) ! node list (21 is max possible)
c     write(*,*)'side set node list array size: ',lessnl
      CALL MDRSRV ('LTNNSS', KLTNNS, LESSEL) ! node count array
c     write(*,*)'side set node count array size: ',lessel
      CALL MDRSRV ('LTSESS', KLTSSS, LESSEL) ! side list
c     write(*,*)'side set side list array size: ',lessel
      CALL MDRSRV ('FACESS', KFACSS, LESSDL) ! dist factors list
c     write(*,*)'side set dist factors list array size: ',lessdl
      CALL MDRSRV ('XFACES', KXFACS, LESSNL) ! dist factors list(w/all DF)
      CALL MDSTAT (NERR, MEM)
      IF (NERR .GT. 0) GOTO 130

      if (numess .gt. 0) then
        call exgcss (netid, a(kidss), a(kness), a(kndss),
     &                a(kixess), a(kixdss),
     &                a(kltess), a(kltsss), a(kfacss), 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

        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 elem blks

          ia(kixnss+i)=nodcnt+1                            ! update index array

          call exgsp(netid,ia(kidss+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(kidss+i)
         write(15,*)'SS ID: ',ia(kidss+i)
         write(*,*)' # of sides: ',nsess
         write(15,*)' # of sides: ',nsess
         i1=0
         do 86 i0=1,nx2
         if (ssid(i0,1).eq.ia(kidss+i)) then
            i1=i0
            ssid(i0,2)=nsess
            ssid(i0,3)=nodcnt+1
            go to 87
         endif
   86    continue
   87    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(kidss+i),a(kltnns+isoff),
     &               a(kltnss+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
            nness=nness+ia(kltnns+isoff+ii)         ! calculate next index
102       continue
c         write(*,*)' # of nodes: ',nness
          write(*,*) nodcnt,nness
          write(15,*) nodcnt,nness
          do 234 j=1,nness
          ssnodes(nodcnt+j)=ia(kltnss+nodcnt+j-1)
 234      continue
          do 235 j=1,nness,12
 235      write(15,*) (ssnodes(nodcnt+j0),j0=j,j+11)
          ia(knnss+i)=nness
          nodcnt=nodcnt+nness
          isoff=isoff+nsess
104     continue
      endif
C
C     Massage side sets distribution factors to include '1' for side sets
C       without Dfs by walking KNDSS array, checking for 0, and filling where
C       necessary.
C
      do 110 i=0, numess-1
        if (ia(kndss+i) .eq. 0) then
          do 106 ii=0, ia(knnss+i)-1
            a(kxfacs+ia(kixnss+i)-1+ii) = 1.0! Force unity distribution factor
106       continue
        else
          do 108 ii=0, ia(knnss+i)-1
            a(kxfacs+ia(kixnss+i)-1+ii) = a(kfacss+ia(kixdss+i)-1+ii)
108       continue
        endif
110     continue

c-SRS       CALL DBOESS (NDB, NUMESS, LESSEL, LESSNL,
c-SRS     &   A(KIDSS), A(KNESS), A(KNNSS), A(KIXESS), A(KIXNSS),
c-SRS     &   A(KLTESS), A(KLTNSS), A(KXFACS))

      CALL MDDEL ('IDESS')
      CALL MDDEL ('NEESS')
```

```
      CALL MDDEL ('NDESS')
      CALL MDDEL ('NNESS')
      CALL MDDEL ('IXEESS')
      CALL MDDEL ('IXDESS')
      CALL MDDEL ('IXNESS')
      CALL MDDEL ('LTEESS')
      CALL MDDEL ('LTNESS')
      CALL MDDEL ('LTNNSS')
      CALL MDDEL ('LTSESS')
      CALL MDDEL ('FACESS')
      CALL MDDEL ('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 mcrsrv('QARECS', kqarec, 4*nqarec*8)
        call mcrsrv('QATMP', kqatmp, 4*nqarec*mxstln)
        call mcstat(nerr, mem)
        if (nerr .ne. 0) goto 130
      else
        kqarec = 1
      end if
      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 mcrsrv('INFO', kinfo, ninfo*mxlnln)
        call mcstat(nerr, mem)
        if (nerr .ne. 0) goto 130
      else
        kinfo = 1
      end if
      if (ninfo .gt. MAXINF) ninfo = 0

      call rdqain (netid, nqarec, c(kqatmp), ninfo, c(kinfo))

      if (nqarec .gt. 0)
     &    call resize (nqarec, c(kqarec), c(kqatmp))

c-SRS      IF (NQAREC .GE. 0) THEN
c-SRS         CALL DBOQA (NDB, NQAREC, c(kqarec), NINFO, c(kinfo))
c-SRS      END IF


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

      call exgvp (netid, 'e', nvarel, nerr)
      if (nerr .lt. 0) then
         call exopts (EXVRBS,ierr)
         call exerr('volcav', 'Error from exgvp', ierr)
         goto 140
      endif
c
C   --Read in the number of global variable names
c
      write(*,'(A)') 'Reading number of global variable names'
      call exgvp (netid, 'g', nvargl, nerr)
      if (nerr .lt. 0) then
         call exopts (EXVRBS,ierr)
         call exerr('volcav', 'Error from exgvp', ierr)
         goto 140
      endif
c
C   --Read in the number of nodal variable names
```

```
c
      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 mdrsrv ('ISEVOK', kievok, nvarel*nelblk)
      CALL MDSTAT (NERR, MEM)
      IF (NERR .GT. 0) GOTO 130
c
c       read in the element variable truth table
c
      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
c
c       read in the element variable names
c
      ixev = 1
      if (nvarel .gt. 0) then
        call exgvan (netid, 'e', nvarel,mames(ixev), nerr)
        if (nerr .lt. 0) then
           call exopts (EXVRBS,ierr)
           call exerr('volcav', 'Error from exgvan', ierr)
           goto 140
        endif
      end if
c
c       read in the global variable names
c
      ixgv = ixev + nvarel
      if (nvargl .gt. 0) then
        call exgvan (netid, 'g', nvargl,mames(ixgv), nerr)
        if (nerr .lt. 0) then
           call exopts (EXVRBS,ierr)
           call exerr('volcav', 'Error from exgvan', ierr)
           goto 140
        endif
      end if
c
c       read in the nodal variable names
c
      ixnv = ixgv + nvargl
      if (nvarnp .gt. 0) then
        call exgvan (netid, 'n', nvarnp, mames(ixnv), nerr)
        if (nerr .lt. 0) then
           call exopts (EXVRBS,ierr)
           call exerr('volcav', 'Error from exgvan', ierr)
           goto 140
        endif
      end if
c
c       read coordinate names
c
      call exgcon (netid, mameco, 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,
     &      NUMNPS, LNPSNL, NUMESS, LESSEL, LESSNL,
     &      NVARHI, NVARGL, NVARNP, NVAREL)

      do 111 i=1, ndim
```

```
        nameco(i) = mameco(i)(:8)
 111  continue
      idx=0
      idy=0
      idz=0
      do 112 i=1, (nvarhi+nvargl+nvarnp+nvarel)
        names(i) = mames(i)(:8)
        write(*,*) names(i)
        if (displx.eq.names(i)(:6)) idx=i-nvarel-nvargl
        if (disply.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
c --- calculate original volumes
c
      degrad=3.141592653/180.
      do 113 i=1,nx2
        vol0(i)=0.5*degrad*th0(i)*h0(i)*r0(i)**2
  113 continue

c      CALL DBONAM (NDB, NDIM, NELBLK, NVARHI, NVARGL, NVARNP, NVAREL,
c     &   nameco, namelb,
c     &   names(ixhv), names(ixgv), names(ixnv), names(ixev),
c     &   A(KIEVOK))



      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
c       read in the number of history time steps and the number of
C       whole time steps
c
      call exinq (netid, EXTIMS, 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.gt.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 exinq (hisid, EXTIMS, nhtime, s, name, nerr)
        numstp = nhtime
        if (nerr .gt. 0) goto 140
      endif

c
c       read the time step information
c
      write(*,'(A)') 'Reading time step information'

      istep = 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
c      write(*,'(A)') 'Inside 300 loop'
      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=wtime

        write (*,'(4x,"processing time step ", i4)') ihstep
        write (15,'(4x,"processing time step ", i4)') ihstep
c
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
c          If a whole time step, do global, nodal, and element
c          variables for the time step.
c
        if ((whotim) .or. (wtime .eq. htime)) then

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

c
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
c           get the nodal variable values
c
          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
210       continue

c
c           get element variable values
c
          if (nvarel .gt. 0) then
            ielo=0
            j0=0
            do 250 k = 1,nelblk
              l=(k-1)*nvarel
              do 240 j=1, nvarel
c
c                If truth table indicates element values are available
c                for the element variable, get the values for the
c                element variable.
c
```

```
               if(a(kievok+l +j-1) .ne. 0) then
                 call exgev (netid, istep, j, a(kidelb+k-1),
     &                a(knelb+k-1), a(kvarel+ielo), nerr)
                 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
c ------ calculate new element variable IMPULSE for all elements
c
       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=ssid(i,2)
       nnodes=nsides*4
       write(15,900) ssid(i,1),nsides,nnodes
  900 format('Side set number ',i3,', number of sides = ',i6,
     1       ', number of nodes = ',i6)
       j0=ssid(i,3)
       j1=j0+nnodes-1
       do 91 j=j0,j1,4
         jm1=j-1
         do 92 jj=1,4
         n0=ssnodes(jm1+jj)
c         if (ihstep.eq.69) write(15,*) jm1+jj,n0,x(n0),y(n0),z(n0),
c    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=xc(i)-hx(1)
         b0=yc(i)-hy(1)
         c0=zc(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!! **',
     1        ihstep,i,n0,x(n0),y(n0),z(n0),fac,hvol
         chvol(i)=chvol(i)+fac*hvol
   91  continue
c -- if i=1, then side set is top surface
C -- for Bayou Choctaw, if i=7, then side set is top and bottom surface of cav. 7
       if (i.eq.7) then
         volcav(i,ihstep)=chvol(i)
       else
         volcav(i,ihstep)=vol0(i)-chvol(i)
       endif
       write(15,*) ihstep,i,vol0(i),chvol(i),volcav(i,ihstep)
   90  continue
       wyear=wtime/3600/24/365
       write(16,901) wtime,wyear,(comma(n),volcav(n,ihstep),n=1,numess)
```

```
  901   format(e12.5,',',F9.4,73(a1,f10.1))

c        CALL DBOSTE (NDB, ihstep, NVARHI, NVARGL, NVARNP, NUMNP,
c     &      NVAREL, NELBLK, a(knelb), a(kievok),
c     &      HTIME, WHOTIM, A(KVARHI), A(KVARGL), A(KVARNP),
c     &      A(KVAREL))


300   continue

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

120   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

  130 CONTINUE
      CALL MEMERR
      GOTO 140

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

999   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
c  Jacobian 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
```

```
      aj8=b17-b28
      aj9=c17-c28
c
c   Jacobian
c
      aj5968=aj5*aj9-aj6*aj8
      aj6749=aj6*aj7-aj4*aj9
      aj4857=aj4*aj8-aj5*aj7
c
      hvol=o64th*(aj1*aj5968+aj2*aj6749+aj3*aj4857)
c
      return
      end
c

      subroutine mlist()
      call mdlist(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

C=======================================================================
      SUBROUTINE RESIZE (NQAREC, QAREC, QATMP)
C=======================================================================
C   --
C   --RESIZE - resizes the qa records from length 32 to 8
C   --
C   --Parameters:
C   --   NQAREC - IN - the number of QA records
C   --   QAREC  - IN - the QA records containing size = 8
C   --   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
tmin 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.*ABS(PRE2)
'
' Compute Maximum Squr(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=SJ2/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=SJ2/GX
RATIOS=DPOTS-CUT
DILS=IFLZ(RATIOS,CUT,RATIOS+CUT)
SHRFAC=1/DILS
minshr=smin(SHRFAC)
'
maxsj2=smax(sj2)
minfx=smin(fx)
mingx=smin(gx)
'
' Define time in terms of years
'
TIME=TIME/3.1536e7
'
' Delete unneeded variables
'
delete PRE PRE1 PRE2 SJ2 I1 RATIO RATIOS DIL DILS FX GX
delete CUT m1 m2
end
```

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