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3-D Finite Element Analyses of the Egan Cavern Field

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3-D Finite Element Analyses of the Egan Cavern Field

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Abstract

Three-dimensional finite element analyses were performed for the two gas-filled storage caverns at the Egan field, Jennings dome, Louisiana. The effects of cavern enlargement on surface subsidence, storage loss, and cavern stability were investigated. The finite element model simulated the leaching of caverns to 6 and 8 billion cubic feet (BCF) and examined their performance at various operating conditions. Operating pressures varied from 0.15 psi/ft to 0.9 psi/ft at the bottom of the lowest cemented casing. The analysis also examined the stability of the web or pillar of salt between the caverns under differential pressure loadings.

The 50-year simulations were performed using JAC3D, a three dimensional finite element analysis code for nonlinear quasistatic solids. A damage criterion based on the onset of dilatancy was used to evaluate cavern instability. Dilation results from the development of microfractures in salt and, hence, potential increases in permeability. Its onset occurs well before large scale failure. The analyses predicted stable caverns throughout the 50-year period for the range of pressures investigated. Some localized salt damage was predicted near the bottom walls of the caverns if the caverns are operated at minimum pressure for long periods of time. Volumetric cavern closures over time due to creep were moderate to excessive depending on the salt creep properties and operating pressures. However, subsidence above the cavern field was small and should pose no problem to surface facilities.

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Contents

1	INTRODUCTION	1
2	PROBLEM DESCRIPTION.....	1
	2.1 Cavern Geometry	1
	2.2 Model History	1
	2.3 Structural Model	5
	2.4 Thermal Model	11
	2.5 Constitutive Models and Material Properties	12
	2.6 Structural Stability of Rock Salt	13
3	ANALYSIS RESULTS	14
	3.1 Cavern Deformation	14
	3.2 Storage Loss.....	17
	3.3 Subsidence	17
	3.4 Cavern Stability	21
4	CONCLUSIONS.....	36
5	REFERENCES	38

Tables

Table 1. Time and Pressure History of the Two-Cavern Analysis	2
Table 2. Cavern Size for each Analysis Case Study	2
Table 3. Structural Properties of Overburden, Caprock, and Salt.....	13
Table 4. Peak Values of Principal Stress and Dilatancy	36

Figures

Figure 1. Profile of Jennings Dome Showing Location of Egan Caverns 1 and 2	3
Figure 2. Predicted Geometries of Caverns 1 and 2 at 6 and 8 BCF	4
Figure 3. Plane of Symmetry used in the Finite-Element Model	5
Figure 4. Finite Element Mesh.....	7
Figure 5. Case #1 and #3 – Cavern Mesh	9
Figure 6. Case #2 – Cavern Mesh.....	9
Figure 7. Case #1 – Deformed Caverns at 50 years.....	15
Figure 8. Case #2 – Deformed Caverns at 50 years.....	15
Figure 9. Case #3 – Deformed Caverns at 10 years.....	16
Figure 10. Case #3 – Deformed Caverns at 20 years.....	16
Figure 11. Case #1 – Storage Loss.....	18
Figure 12. Case #2 – Storage Loss.....	18
Figure 13. Case #3 – Storage Loss.....	19
Figure 14. Case #1 – Ground Surface Subsidence.....	19
Figure 15. Case #2 – Ground Surface Subsidence.....	20
Figure 16. Case #3 – Ground Surface Subsidence.....	20
Figure 17. Case #1 – Maximum Principal Stresses at 15, 20, 25, and 30 years	23
Figure 18. Case #1 – Dilatancy Safety Factors (D) at 15, 20, 25, and 30 years	23
Figure 19. Case #2 – Maximum Principal Stresses at 15, 20, 25, and 30 years	25
Figure 20. Case #2 – Dilatancy Safety Factors (D) at 15, 20, 25, and 30 years	25
Figure 21. Case #3 – Maximum Principal Stresses at 6, 10, 15, and 20 years	27
Figure 22. Case #3 – Dilatancy Safety Factors (D) at 6, 10, 15, and 20 years	27
Figure 23. Case #1 – Maximum Principal Stresses, Cavern 1.....	30
Figure 24. Case #1 – Maximum Principal Stresses, Cavern 2.....	30
Figure 25. Case #2 – Maximum Principal Stresses, Cavern 1.....	31
Figure 26. Case #2 – Maximum Principal Stresses, Cavern 2.....	31
Figure 27. Case #3 – Maximum Principal Stresses, Cavern 1.....	32
Figure 28. Case #3 – Maximum Principal Stresses, Cavern 2.....	32
Figure 29. Case #1 – Dilatancy Safety Factor, Cavern 1.....	33
Figure 30. Case #1 – Dilatancy Safety Factor, Cavern 2.....	33
Figure 31. Case #2 – Dilatancy Safety Factor, Cavern 1.....	34
Figure 32. Case #2 – Dilatancy Safety Factor, Cavern 2.....	34
Figure 33. Case #3 – Dilatancy Safety Factor, Cavern 1.....	35
Figure 34. Case #3 – Dilatancy Safety Factor, Cavern 2.....	35

1 INTRODUCTION

Three-dimensional (3-D) finite-element geomechanics analyses were performed for the expansion of the Egan Gas Cavern Field at Jennings Dome, Louisiana. The field initially consisted of one cavern which was enlarged to a 6 billion cubic feet (BCF) working gas capacity. Leaching then commenced on Cavern 2, located 800 ft. away. In this report, the stability of final cavern sizes of 6 and 8 BCF are evaluated. The locations of the caverns are shown in Figure 1.

The two cavern field necessitated the use of a 3-D structural model (Hoffman, 1993a). The analyses predicted surface subsidence, volumetric cavern closure, and cavern stability over a 50-year period for various operating cavern pressure conditions, varying from 0.15 to 0.90 psi/ft at the casing shoe, approximately 100 feet above the ceiling of the cavern.

The finite element model is described in the following section. Next, the analysis results are presented in terms of cavern performance and integrity. Finally, the conclusions of the investigation are presented in the last section.

2 PROBLEM DESCRIPTION

2.1 Cavern Geometry

The cavern geometries are based on leaching prediction simulations as shown in Figure 2. The caverns are approximately 3850 feet deep at the roof and stand approximately 1300 feet high. The enlargement from 6 to 8 BCF occurs in the lower section of the caverns, i.e., the body of the cavern bulges outward somewhat.

The finite element models used for this study include a typical domal stratigraphy of salt, caprock and overburden, as illustrated in Figure 1. The overburden and caprock are idealized at an average thickness of 2500 ft and 500 ft-thick, respectively. Since the caverns are located in the central portion of the dome, a symmetry plane can be used in the model. The location of this symmetry plane is illustrated in Figure 3.

2.2 Model History

The analysis history was simulated where Cavern 1 is initially 6 BCF and Cavern 2 does not exist. After 4 years, two possible cavern sizes for Cavern 2 (6 and 8 BCF) are examined. The analysis concludes by enlarging Cavern 1 and examining different scenarios for operating pressure as shown in Table 1. The range in gas operating pressure was equal to 0.15 and 0.9 psi/ft at the casing shoe. The casing shoe was assumed to be located 100 ft above the cavern roof. A constant uniform gas pressure was used during the low, typical, and high pressure periods in the analyses. The variation in cavern size and salt properties for the three different Cases studied are shown in Table 2.

Table 1. Time and Pressure History of the Two-Cavern Analysis

Time (yrs)	Cavern 1	Cavern 2	Comment
0	6 BCF		start analyses using typical operating pressure
4		6 or 8 BCF	Examine option of adding a new 6 BCF cavern (Case #1) or 8 BCF cavern (Case #2)
6	8 BCF		Enlarge Cavern 1 to 8 BCF
10 – 15	Low Pressure	High Pressure	Examine web stability under maximum pressure differential between caverns
15 – 20	High Pressure	Low Pressure	Examine web stability for other pressure scenario
20 – 25	Low Pressure	Low Pressure	Induce maximum creep using adverse operating conditions
25 – 30	High Pressure	High Pressure	Examine sensitivity of subsidence and cavern closure to increased pressure
30 – 50	Typical Pressure	Typical Pressure	return caverns to typical operating conditions and examine long-term performance
50			Stop analyses, repeat worst case with fast creeping salt properties from WIPP (Case #3)

Typical Pressure = 0.50 psi/ft = 1875 psi

Low Pressure = 0.15 psi/ft = 563 psi

High Pressure = 0.90 psi/ft = 3375 psi

Table 2. Cavern Size for each Analysis Case Study

Case	#1		#2		#3 *	
Salt	Jennings		Jennings		WIPP (fast creeping salt)	
Time	Cavern 1	Cavern 2	Cavern 1	Cavern 2	Cavern 1	Cavern 2
0-4 years	6 BCF	None	6 BCF	None	6 BCF	None
4-6 years	6 BCF	6 BCF	6 BCF	8 BCF	6 BCF	6 BCF
6-50 years	8 BCF	6 BCF	8 BCF	8 BCF	8 BCF	6 BCF

* The cavern sizes for this Case were chosen after completing Case #1 and #2

Figure 1. Profile of Jennings Dome Showing Location of Egan Caverns 1 and 2

6 BCF WORKING GAS

8 BCF WORKING GAS

Figure 2. Predicted Geometries of Caverns 1 and 2 at 6 and 8 BCF

Figure 3. Plane of Symmetry used in the Finite-Element Model

2.3 Structural Model

Sandia has a long history of research and development in nonlinear large strain finite element codes and the application of these codes to geomechanics problems and cavern analyses similar to the ones solved in this report (Hoffman, 1993b). Sandia's quasistatic finite element technology is based on iterative solvers and has been extensively developed for large problems involving geometric and material nonlinearities. The use of iterative solvers and experience with nonlinear material response provides a base technology that offers efficient solution of very large complex geomechanics problems. The finite element code used in the present calculations, JAC3D (Biffle, 1992), uses an eight-node hexahedral Lagrangian uniform strain element with hourglass stiffness to control zero energy modes. A nonlinear conjugate gradient method is used to solve the nonlinear system of equations. This efficient solution scheme is considerably faster than the direct solvers which are used in most commercial codes.

Because of vertical symmetry, only one-half of the model is represented by the finite element mesh, as illustrated in Figure 4. The model, constructed of 8-node hexahedral elements consists of 48,274 nodes and 44,020 elements for analysis Cases #1 and #3. For Case #2, a larger Cavern 2 (8 BCF) resulted in a slightly smaller model consisting of 47,324 nodes and 43,060 elements. The finite element mesh showing detail around both Caverns for Case #1 and #3 is illustrated in Figure 5. Similarly, the Caverns for Case #2 are detailed in Figure 6. In both these Figures, Cavern 1 shows an inner mesh of a different color. This inner mesh represents the difference between a 6 BCF Cavern and an 8 BCF Cavern. As described earlier and shown in Tables 1 and 2, Cavern 1 is initially a 6 BCF Cavern and is enlarged to an 8 BCF Cavern. This was accomplished by giving these elements a different material ID and using the element death option in JAC3D. The death option allows the analysis to continue using the same mesh but the material properties are eliminated and nodal movement is no longer restricted to the material restraints. The shapes of the Caverns in Figures 5 and 6 are comparable to the predicted cavern outlines shown in Figure 2.

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Figure 4. Finite Element Mesh

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Figure 5. Case #1 and #3 – Cavern Mesh

Figure 6. Case #2 – Cavern Mesh

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Displacements were constrained in the direction normal to the vertical plane of symmetry and the bottom of the mesh. The far field boundary (curved boundary) is 4,000 feet from the center point between the two caverns (a distance representing the edge of the dome) and was constrained only with a depth-dependent horizontal pressure.

A uniform pressure distribution was applied to the inside of the caverns to simulate gas storage. When a cavern was enlarged during the analysis (6 BCF to 8 BCF), the pressure surface changed from the smaller cavern surface to the larger cavern surface. The density of the gas was ignored. In reality, the stored gas will provide an increase in pressure with depth. Ignoring this effect is conservative since the additional pressure resulting from the density of the gas would result in reduced salt stresses and slower creep at the base of the cavern.

In addition to the pressure loads, gravitational body forces are applied to the rock. To ensure initial equilibrium, elevation-dependent initial stresses are applied to each element in the model based on the density of the overburden, caprock, and salt. In the elastic materials (overburden and caprock), the vertical stress component at a given location was applied based on the weight of the material above that point. The horizontal component was applied to be consistent with a vertically loaded elastic material in equilibrium. Under these load conditions, the resulting ratio of horizontal to vertical stress components is defined as follows:

$$\frac{\sigma_h}{\sigma_v} = \frac{\nu}{1 - \nu}$$

where ν is the Poisson's ratio of the material. For the salt, an initial stress state was assumed in which the vertical and horizontal stress components are equal to the weight of the overlying material (lithostatic).

2.4 Thermal Model

The geothermal or *in-situ* temperature at Jennings dome was assumed to be 80 °F at the ground surface and increase at 0.012 °F per foot of depth. At the mid height (-4,500 ft) the corresponding temperature is 134 °F. A constant temperature of 134 °F was applied to all elements in the model. A constant temperature was considered reasonable because the gas inside the cavern will circulate and keep the walls of the cavern relatively the same. In addition, the elements along the cavern wall experience the highest change in stress and hence creep. The temperature is important because the creep response of the salt is temperature dependent. Radial temperature gradients due to cavern cooling were not considered in these calculations. Previous 2D cavern studies have shown the predicted cavern deformation to be insensitive to radial thermal gradients developed by cooling effects of the cavern product (Hoffman, 1992).

2.5 Constitutive Models and Material Properties

The geotechnical properties for Jennings salt were measured at two different laboratories (Wawersik and Zimmerer, 1993; Humbert and Vouille, 1994). A creep indicator test showed the salt to creep similar to Bryan Mound salt, a previously tested domal salt. For this reason Bryan Mound properties were selected as the baseline properties for the salt in Case study #1 and #2. However, the Jennings and Bryan Mound salts are the slowest creeping salts tested to date at Sandia and creep properties can vary within a dome. The testing by Humbert and Vouille (1994) showed some variability of salt creep at Jennings dome. Therefore, to be prudent, in addition to simulations using the expected Jennings properties, the properties of clean salt from the Waste Isolation Pilot Plant (WIPP) were used for Case study #3. The WIPP salt is well characterized and has a relatively fast creep rate. The creep properties of WIPP salt represent a conservative upper bound to those that could occur at Jennings.

The domal salt exhibits both elastic and creep behavior. The creep constitutive model used for this material is determined from the effective stress as follows:

$$\dot{\epsilon}^{cr} = A \sigma^n \exp\left(-\frac{Q}{RT}\right)$$

where

$\dot{\epsilon}^{cr}$ is the creep strain rate,

A and n are constants determined from fitting the model to creep data,

σ is the effective or von Mises stress,

Q is the effective activation energy (Cal/mole),

R is the universal gas constant (1.987 Cal/mole-K), and

T is absolute temperature.

The creep constants for salt are given in Table 3 and correspond to parameters for the Jennings or Bryan Mound salt (Wawersik and Zeuch, 1984) and Waste Isolation Pilot Plant salt (Krieg, 1984).

The overburden and caprock were modeled as elastic materials using the properties listed in Table 3. The properties assume a homogeneous material with typical properties of shale and sand (Touloukian and Ho, 1981; Carmichael, 1984) representing caprock, and overburden respectively.

Table 3. Structural Properties of Overburden, Caprock, and Salt

Materials	Young's Modulus, E (ksf)	Poisson's Ratio, ν	Density, ρ (k/ft ³)	Structure Factor, A (ksf ⁻ⁿ /sec)	Stress Exponent n	Activation Energy, Q (kcal/mole)
Overburden	2,000	0.33	0.1168	--	--	--
Caprock	146,000	0.29	0.1559	--	--	--
Jennings Salt	648,000	0.25	0.1434	4.26×10^{-11}	4.54	15.17
WIPP Salt	648,000	0.25	0.1434	1.33×10^{-12}	4.90	12.03

2.6 Structural Stability of Rock Salt

This study evaluated the potential for damage to or around the caverns based on two different criteria: tensile failure and dilatant damage. For the purposes of these analyses, the tensile strength of the salt was conservatively assumed to be zero. Tensile cracking in rock salt tends to initiate perpendicular to the largest tensile stress in the rock sample. The largest tensile stress is one of the principal stresses. Because the maximum principal stress is the algebraically largest of the three principal stresses (in 3D space) and the largest normal stress in any direction, the potential for tensile failure exists if the maximum principal stress is tensile or numerically positive.

Dilatancy is considered the onset of damage to the salt resulting in significant increases in permeability. An attempt was made to measure the dilatancy of Jennings salt in the laboratory testing. There was considerable uncertainty associated with the results (Ehgartner, 1994). Therefore, for purposes of these analyses, the dilatancy criterion will be taken from the literature which shows a very consistent ratio of 0.25 between the second invariant of the deviatoric stress and the first invariant of stress (Ehgartner, 1997).

The dilatant damage criterion is used to delineate potential zones of dilatancy in the salt formation surrounding the storage facility. Dilatancy is attributed to microfracturing or changes in the pore structure of the salt, resulting in an increase in permeability and, hence, a flow path through or into the salt. The potential for dilatant damage is defined by a "damage" safety factor (D) which is expressed as follows:

$$D = \frac{I_1}{4\sqrt{J_2}}$$

where J_2 is the second invariant of the deviatoric stress tensor, and I_1 is the first invariant of the stress tensor ($I_1 = 3\sigma_m$, where σ_m is the mean stress). When D is equal to or less than one, the shear stresses in the salt are large compared to the mean stress and the potential for dilatant behavior is high (Speirs, 1988; Van Sambeek 1993). Hunsche

(1992) suggests that dilatancy is linked to creep rupture. He contends that as rock salt dilates, its structure loosens and may fail after some time due to creep rupture.

It should be clearly stated that the above dilatation criteria is not used in the present study to quantify damage, but merely to identify regions with a high potential for damage. This criteria identifies regions where the deviatoric stress is high and the mean stress is low, a stress state conducive to dilation. No comprehensive constitutive model exists at this time which can predict damage evolution in a reasonable computation time for a 3D problem of this size. Hence, the post-processed dilatation criteria was used as a conservative engineering approach to estimate possible regions of salt dilation. Much can be inferred from this criterion. For example, if the dilatant damage safety factor is decreasing with time, it can be concluded that the potential for damage is increasing. Hence, salt healing (a reduction in dilatancy) is not likely to occur. Second, if the predicted damage is growing in both size and magnitude, then the damaged region (fracture or dilation) may continue to grow. Similarly, if a tensile region is predicted to be growing in both size and magnitude, the resulting fractures, although not explicitly modeled, should also grow.

3 ANALYSIS RESULTS

3.1 Cavern Deformation

For Case #1 and #2, the analysis was performed using the Jennings salt properties for up to 50 years when the analysis was stopped. The final deformed shapes ($t = 50$ years) of the two caverns are shown in Figures 7 and 8. When compared to the original cavern meshes shown in Figures 5 and 6, no major changes in geometry are observable.

When Case #3 was run using the faster creeping WIPP salt properties, deformations at the base of the caverns after 20 years were large enough at the lower corner of the cavern that the sides and base of the caverns began to overlap. At this point, the analysis was stopped because surface contact algorithms were not included in the model. Deformation rates would be expected to slow once the walls of the cavern begin to contact the floor.

The deformed mesh for Case #3 at $t=10$ years is shown in Figure 9. At this point the deformations are relatively small. This is because only typical operating pressures were applied to the inside the caverns. Over the next ten years (10-20) each cavern alternately experienced a low operating pressure for 5 year. This low internal pressure resulted in high creep rates causing the cavern to close in much faster. The final deformed shapes ($t = 20$ years) for Case #3 are shown in Figure 10. As is expected, the majority of the deformation occurs in the lower half of the cavern where the creep rate is highest because of increased stress levels.

Figure 7. Case #1 – Deformed Caverns at 50 years

Figure 8. Case #2 – Deformed Caverns at 50 years

Figure 9. Case #3 – Deformed Caverns at 10 years

Figure 10. Case #3 – Deformed Caverns at 20 years

3.2 Storage Loss

Figures 11, 12, and 13 show the percentage of initial cavern storage volume as a function of time for Cases #1, #2 and #3 respectively. For both Cases #1 and #2, Cavern 1 reduces to about 85% of its initial volume and Cavern 2 reduces to about 86% of its initial volume after 50 years. The 1% difference is attributable to the four year delay in the creation of Cavern 2. Even though Cavern 2 is larger in Case #2 (8 BCF) than it was in Case #1 (6 BCF), the percentage loss was nearly the same.

For Cases #1 and #2 the rates of storage loss are very similar. When operating at high pressures the caverns experience almost no change in volume. When operating at typical pressures the caverns only loose about 1% of the storage volume every 5 to 10 years. At low operating pressures the caverns loose about 1% per year.

The much faster creeping WIPP salt properties (Case #3) had a significant effect on the storage loss of the Egan Caverns. After only 10 years and operating at typical operating pressures the volume reduced to 85% in Cavern 1 and 86% in Cavern 2. This is the same as the volume loss in both Cases #1 and #2 (using Jennings salt properties) after 50 years. For Case #3 after 20 years, Cavern 1 reduced to 45% of it's initial volume and Cavern 2 reduced to 46% of its initial volume. Once again this small difference was due mostly to the delay in the creation of Cavern 2.

The rates of storage loss were also significantly higher in Case #3. When operating at high pressures the caverns experience almost no change in volume. When operating at typical pressures the caverns loose about $1\frac{1}{2}$ to 2 % of the storage volume per year. At low operating pressures the caverns loose about 8% per year.

3.3 Subsidence

The ground surface subsidence above both caverns to the edge of the model is plotted in Figures 14, 15, and 16 for Cases #1, #2 and #3 respectively. For Case #1 and #2 the subsidence is plotted at 10, 30, and 50 years. For these two Cases there is almost no surface subsidence after 10 years. After 30 years the subsidence reaches 0.10 feet at the center point between caverns in Case #1 and 0.125 feet in Case #2. After 50 years the subsidence increases slightly to 0.13 feet in Case #1 and 0.16 feet in Case #2.

The faster creeping WIPP salt properties resulted in higher surface subsidence in Case #3 as shown in Figure 16. For this Case, subsidence was plotted at 10 and 20 years. At 10 years the subsidence at the center point between caverns reached 0.14 feet. After 20 years the subsidence reached 0.85 feet at the center.

For all the surface subsidence plots, the subsidence is nearly symmetric, forming a single surface depression, about the center point and extending to the edges of the model. This is due primarily to the depth of the Caverns (3,850 feet deep at the top) and relatively close distance between the two caverns (800 feet). Some surface subsidence is shown to be occurring above the edge of the dome, 4,000 feet away from the center of the model. This is probably realistic because the outer edge of the model is not mechanically

Figure 11. Case #1 – Storage Loss

Figure 12. Case #2 – Storage Loss

Figure 13. Case #3 – Storage Loss

Figure 14. Case #1 – Ground Surface Subsidence

Figure 15. Case #2 – Ground Surface Subsidence

Figure 16. Case #3 – Ground Surface Subsidence

constrained in any direction, but has a depth dependent lateral pressure applied to match the insitu stress conditions occurring at the edge of the model.

3.4 Cavern Stability

As described in Section 2.6 of this report, this study evaluated the potential for damage to or around the caverns based on two criteria: tensile failure and dilatant damage. The tensile strength of the salt was conservatively assumed to be zero and the largest tensile stress is the maximum principal stress. Therefore, if the maximum principal stress is positive, the potential for tensile failure exists. Dilatancy was also described in Section 2.6 of this report and was considered the onset of damage to the salt resulting in potentially significant increases in permeability. When the "damage" safety factor D is equal to or less than one, the potential for dilatant behavior is considered to be high.

Contour plots of the maximum principal stresses and dilatancy safety factors (D) are plotted in: Figures 17 and 18 for Case #1, Figures 19 and 20 for Case #2, and Figures 21 and 22 for Case #3. For Cases #1 and #2 the contours are plotted at 15, 20, 25, and 30 years. For Case #3 the contours are plotted at 6, 10, 15 and 20 years, again because the analysis was stopped after 20 years.

Comparing the maximum principal stress contours, particularly at 15 and 20 years, for all three Cases, there is not much difference in the magnitude or distribution of stresses. There also appears to be very little if any stress interactions between the caverns. When comparing the dilatancy contours at 15 and 20 years for all three cases, there is little difference in the magnitude or variation in the dilatant safety factor.

In all the maximum principal stress contours for all three Cases, the entire Cavern wall from top to bottom is showing stresses in the highest range plotted between -1,000 psi and 0 psi when a cavern is operating at low pressures. This implies that when operating at a low pressure (0.15psi/ft) this entire area, although still in compression, is the most vulnerable to tensile failure. It is interesting to note that the contours follow the shape of the caverns very well and there does not appear to be significantly higher stresses in the lower portion of the caverns as is typically the case when caverns are modeled as perfect cylinders (Hoffman, 1993b).

Similarly, the dilatancy contours for all three cases show the minimum safety factor 'D' between 1 and 1.5 over nearly the entire cavern wall when operation at low pressures. Again, this implies that for low operating pressures the entire cavern wall is most vulnerable to dilatant behavior.

For all these contour plots, both the maximum principal stresses and dilatancy safety factors appear very similar when comparing the site specific salt properties in Cases #1 and #2 to the faster creeping salt (WIPP) in Case #3. Comparing the actual peak values at the element level, results in a slightly different conclusion.

Most of the maximum principal stresses and dilatant safety factors occurred near the bottom of the cavern approximately 20 feet above the base. In addition, the values in the

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Figure 18. Case #1 – Dilatancy Safety Factors (D) at 15, 20, 25, and 30 years

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Figure 19. Case #2 – Maximum Principal Stresses at 15, 20, 25, and 30 years

Figure 20. Case #2 – Dilatancy Safety Factors (D) at 15, 20, 25, and 30 years

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Figure 21. Case #3 – Maximum Principal Stresses at 6, 10, 15, and 20 years

Figure 22. Case #3 – Dilatancy Safety Factors (D) at 6, 10, 15, and 20 years

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elements at the shoulder level of the cavern (the point in the bottle shaped cavern where the neck joins the body) sometimes showed increased stresses and lower dilatancy factors. Elements at these levels on both sides of each cavern were selected for monitoring the maximum principal stress and dilatancy safety factor history.

The maximum principal stresses for these locations in Caverns 1 and 2 for Case #1 are shown in Figures 23 and 24 respectively. The maximum stress in this Case is -323 psi and it occurs at 25 years into the analysis. The maximum principal stresses in Caverns 1 and 2 for Case #2 are shown in Figures 25 and 26 respectively. The maximum stress in this Case is -426 psi and it also occurs at 25 years. The maximum principal stresses in Caverns 1 and 2 for Case #3 are shown in Figures 27 and 28 respectively. The maximum stress in this Case is -171 psi and it occurs at 18 years.

The dilatant safety factor 'D' for the most vulnerable locations in Caverns 1 and 2 for Case #1 are shown in Figures 29 and 30 respectively. The minimum factor in this Case is 1.08 and it occurred at 25 years into the analysis. The dilatant safety factor in Cavern 1 and 2 for Case #2 are shown in Figures 31 and 32 respectively. The minimum factor in this Case is 1.15 and it occurred at 21 years. The dilatant safety factors in Caverns 1 and 2 for Case #3 are shown in Figures 33 and 34 respectively. The minimum factor in this Case is 0.92 and it occurred at 18 years.

A summary of all the maximum principal stresses and minimum dilatancy safety factors (D) are summarized in Table 4. The peak values are shown for each Case and also at the base of the cavern and near the shoulder. Peak values at the shoulder are usually not as high or low as near the base but if failure occurs at the shoulder it could have greater consequences than it were to occur near the base.

As shown in Table 4, the maximum principal stress was higher (-323 psi) in Case #1 than in Case #2 (-426 psi). These values are slightly below the minimum gas pressure exerted on the cavern walls (-563 psi), but well above the assumed tensile strength of salt (0 psi). Also, the dilatancy safety factor was much closer to 1.0 in Case #1 (1.08) than it was in Case #2 (1.15). This is why the Case #1 cavern geometries were chosen for the Case #3 analysis.

In the Case #3 analysis using the faster creeping WIPP salt properties, the maximum principal stress was higher (-171 psi) and the dilatancy factor dipped below 1 to 0.92 when the cavern was operated at low pressure. This indicates the potential for dilatant behavior exists if the salt at Jennings unexpectedly creeps like WIPP salt. However, this would probably be localized to a small area near the base. The values for stress and dilatancy at the shoulder of the Caverns in Case #3 actually improved compared to Cases #1 and #2 as shown in Table 4.

Figure 23. Case #1 – Maximum Principal Stresses, Cavern 1

Figure 24. Case #1 – Maximum Principal Stresses, Cavern 2

Figure 25. Case #2 – Maximum Principal Stresses, Cavern 1

Figure 26. Case #2 – Maximum Principal Stresses, Cavern 2

Figure 27. Case #3 – Maximum Principal Stresses, Cavern 1

Figure 28. Case #3 – Maximum Principal Stresses, Cavern 2

Figure 29. Case #1 – Dilatancy Safety Factor, Cavern 1

Figure 30. Case #1 – Dilatancy Safety Factor, Cavern 2

Figure 31. Case #2 – Dilatancy Safety Factor, Cavern 1

Figure 32. Case #2 – Dilatancy Safety Factor, Cavern 2

Figure 33. Case #3 – Dilatancy Safety Factor, Cavern 1

Figure 34. Case #3 – Dilatancy Safety Factor, Cavern 2

Table 4. Peak Values of Principal Stress and Dilatancy

Case	Maximum Principal Stress (psi)		Minimum Dilatancy Safety Factor, D	
	at Shoulder	At Base	at Shoulder	at Base
# 1	-609	-323	1.16	1.08
# 2	-605	-426	1.17	1.15
# 3	-628	-171	1.30	0.92

4 CONCLUSIONS

Three-dimensional finite element analyses were performed for the two gas-filled storage caverns at the Egan field, Jennings dome, Louisiana. The effects of cavern enlargement on surface subsidence, storage loss, and cavern stability were investigated. The finite element model simulated the leaching of caverns to 6 and 8 BCF and examined their performance at various operating conditions. Operating pressures varied from 0.15 psi/ft to 0.9 psi/ft at the lowest cemented casing seat, which is a typical industry standard for referencing gas pressures in caverns. The analysis also examined the stability of the web or pillar of salt between the caverns under differential loading.

The 50 year simulations were performed using JAC3D, a three dimensional finite element analysis code for nonlinear quasistatic solids. The results show that volumetric cavern closures over time due to creep were moderate and subsidence above the cavern field was small and should pose no problem to surface facilities. Cavern closure is predicted to be approximately 15% after 50 years of operation and the resulting subsidence amounts to only 0.16 ft at the surface when using the Jennings salt creep properties. When using the much faster creeping WIPP salt properties, the Cavern closure was about 55% after 20 years and the surface subsidence was about 0.85 feet.

A damage criterion based on the onset of tensile failure and dilatancy was used to investigate cavern stability. Tensile failure was assumed to occur if the maximum principal stress was no longer in compression or is positive. This assumes that the salt has no tensile strength, which is a conservative assumption. In this analysis, no tensile failure of the salt was predicted.

Dilatant behavior reflects the development of microfractures in salt and hence potential increases in permeability. Its onset occurs well before large scale failure. Some localized dilatant damage was predicted near the bottom walls of the caverns when the caverns are operated at minimum pressure and the salt is assumed to creep like WIPP salt (much

faster than actually measured in laboratory testing). No dilatant damage was predicted for any of the pressure scenarios in the site specific Jennings salt.

The analysis predicted very little cavern interaction which suggests that the caverns are conservatively spaced. This resulted in no potential for web instability between caverns even when operated at different pressure extremes. In addition, stress perturbations did not extend very far above the roof of the caverns, thus showing the caverns are located sufficiently below the top of the salt. The analyses predict very little difference between Case #1 and #2 (Cavern 2 at 6 versus 8 BCF, respectively) or any significant changes due to the enlargement of Cavern 1 from 6 to 8 BCF. In summary, the predicted damage factors of the Egan caverns suggest stable caverns up through a time period of 50 years.

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