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Analysis of the Stability of Large-Diameter Caverns for the Strategic Petroleum Reserve

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Abstract

The U.S. Strategic Petroleum Reserve (SPR) stores crude oil in 62 caverns located at four different sites in Texas (Bryan Mound and Big Hill) and Louisiana (Bayou Choctaw and West Hackberry). The petroleum is stored in solution-mined caverns in salt dome formations. The SPR sites are varied in terms of cavern structure and layout. Most of the caverns at these sites were built as vertical cylinders of reasonably uniform cavern dimensions (radius, height, shape, and depth) and spacing. However, several caverns at these sites, particularly those constructed prior to SPR ownership, are characterized by diverse cavern characteristics. Sometimes these unusual cavern shapes present technical problems due to the resulting increased subsidence and shear stresses. Cavern 6 at the West Hackberry site has an unusual dish-like shape with a large rim around the circumference. The diameter of Cavern 6 at the ceiling ranges from 1120 to 1240 feet. It is also in close proximity to Cavern 9, which is hourglass-shaped. Because of the shape of the cavern and the creep behavior of salt, Cavern 6 is prone to wellbore casing failures caused by tensile strains. In addition, Cavern 6 has a greater potential for tensile cracking of salt at the perimeter of the cavern during a period of increasing pressure, such as at the end of a workover procedure.

This report presents a case study of how computational analyses may be used in conjunction with site data to advise site operations responding to a wellbore casing failure. One of the wells in Cavern 6 was recently compromised. SPR operations instituted a workover procedure to allow repair of the well casing. To minimize the amount of creep-induced loss in storage capacity, the field operators wish to increase the pressure in Cavern 6 to normal operating pressure as quickly as possible after completion of the well repair activities. However, results from preliminary analyses created a concern about the rate at which Cavern 6 could be repressurized; if the pressure is increased too much or too quickly, tensile cracking at the perimeter of the cavern may occur, particularly in that portion of the cavern closest to Cavern 9. To provide guidance to field operators, additional geomechanical calculations were performed to determine the structural integrity of Cavern 6 in response to different pressurization rates and maximum pressures. The calculations utilized a realistic three-dimensional model of the geometries of the caverns, and high-performance analytical codes using a multi-mechanism deformation material model. The results of the calculations indicate a significant effect of pressurization rate on the stress response of the surrounding salt, suggesting that a conservative approach be used for repressurization. These analyses resulted in operational guidance to the SPR that permits increasing the pressure quickly to an intermediate value to minimize storage loss, and then slowly increasing the pressure to a maximum operating pressure. These calculations indicate how high-performance geomechanical analyses may be used to support field operation activities and assure cavern integrity.

Key words: Caverns for Liquid Storage, Cavern Operation, Computer Modeling, Instrumentation and Monitoring, Louisiana, Rock Mechanics, Salt Domes, Strategic Petroleum Reserve, Well Casing

Introduction

The U.S. Strategic Petroleum Reserve (SPR) stores crude oil in 62 caverns located at four different sites in Texas (Bryan Mound and Big Hill) and Louisiana (Bayou Choctaw and West Hackberry). The petroleum is stored in solution-mined caverns in salt dome formations. West Hackberry is located in the extreme southwestern corner of Louisiana, some 15 miles from the Louisiana/Texas border to the west and the Gulf of Mexico to the south (Munson, 2006). The geological characteristics related to the West Hackberry site were first described by Whiting (1980). The updated three-dimensional models of Rautman et al. (2004) used more refined analysis of the data and produced models of the dome that differed slightly from the earlier models. The West Hackberry dome consists of the more-or-less typical geologic sequence of rocks. With increasing depth below the ground surface, initially there is roughly 1500 ft of soil and unconsolidated gravel, sand, and mud, followed by approximately 400 ft of caprock, consisting of anhydrite and carbonate (a conversion product of anhydrite). Generally, the upper portions of the caprock consist of the anhydrite conversion products of gypsum and dolomite, while the lower portion of the caprock is the initial anhydrite residue from the solution of the original domal material. The caprock is generally lens shaped with the thickest part of the lens over the central portion of the dome, tapering to thin edges toward the periphery of the dome.

At the West Hackberry site, the five caverns known as Phase 1 – Caverns 6, 7, 8, 9, and 11 – were created as early as 1946 and were used for brining and brine storage before the SPR took ownership of them in 1981. After that time, seventeen other storage caverns (numbered 101 to 117) were created over an eight-year period. The post-1981 caverns were built via solution mining, and all have a generally cylindrical shape (more specifically, frustums with the larger diameter at the top) of approximately 2000 feet height and 100-150 feet in radius. The Phase 1 caverns, however, were originally built for brine storage, and thus they were constructed with little concern about the long-term stability of the cavern shape. Cavern 6 at the West Hackberry site has an unusual dish-like shape with a large rim around the circumference. It is also in close proximity to Cavern 9, an hourglass-shaped cavern. A profile view of Cavern 6 is shown in Figure 1, and a representation of Caverns 6 and 9 drawn in their full volume and proximity is shown in Figure 2. High resolution sonar measurements performed on Cavern 6 in 1980 are listed in Table 1 along with the average and maximum ceiling spans. The sonars of Cavern 6, taken from the three different Cavern 6 wells, are in close agreement and show that the ceiling of Cavern 9 is located 230 feet from its edge. The closest point of approach is with the lower lobe of Cavern 9, at approximately 200 feet.

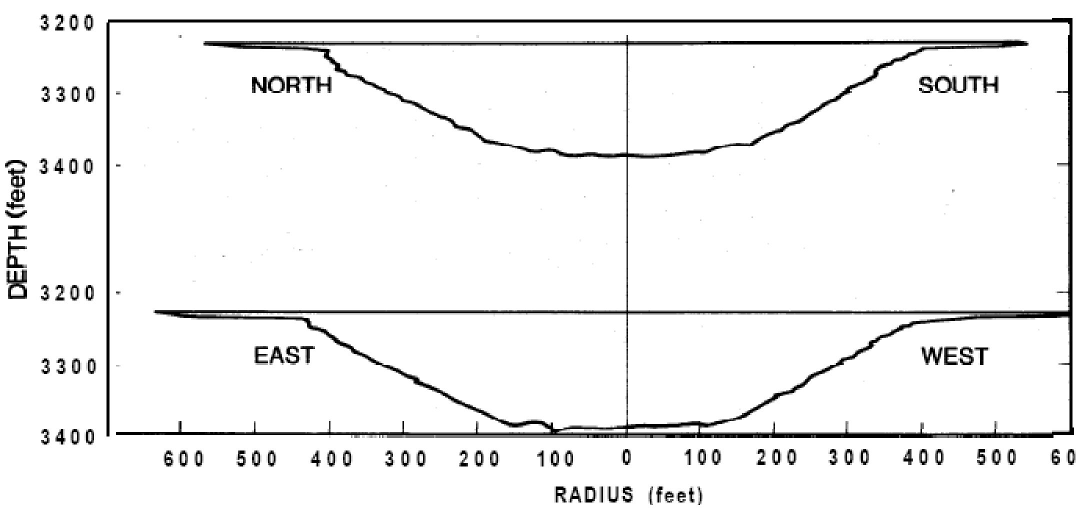


Figure 1. Profile of Cavern 6 based on 1980-1982 sonars.

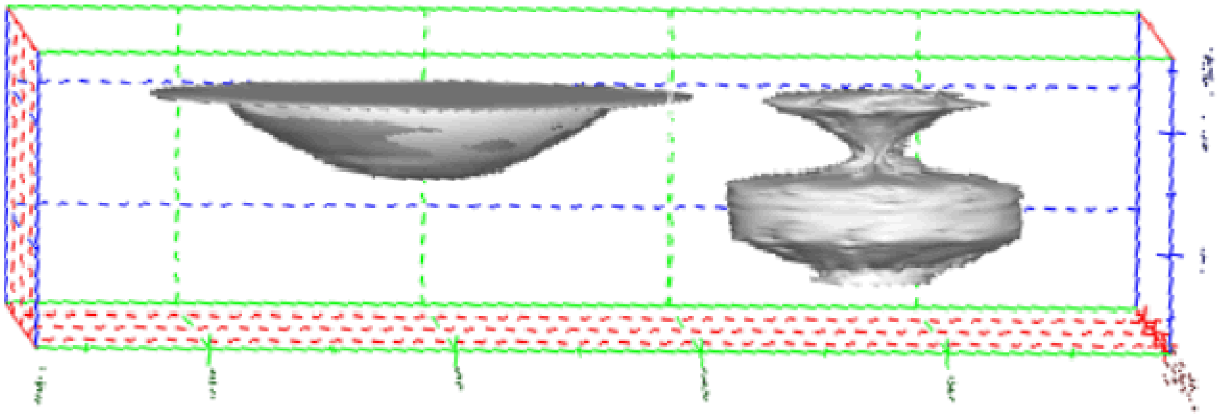


Figure 2. Caverns 6 (left) and 9 (right), from the most recent (1982) sonar and strapping data.

Table 1. Measured Spans of WH Cavern 6.

	Well	Avg. Ceiling Span, ft	Maximum Ceiling Span, ft
5/21/1980	6	1158	1243
5/21/1981	6	1145	1231
3/21/1980	6c	1124	1212
3/21/1980	6b	1129	1187

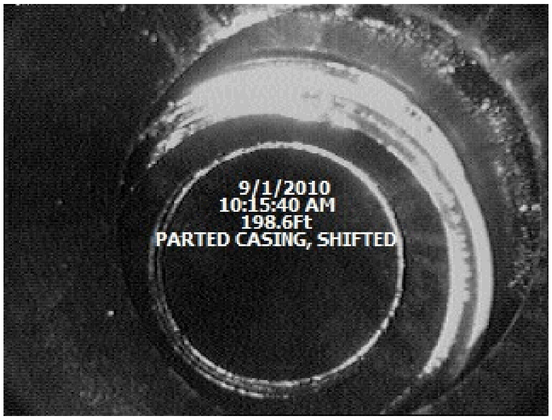
Mechanical analyses of the West Hackberry site were recently published (Sobolik and Ehgartner, 2009), and they indicate that the dish-like shape of Cavern 6 make it prone to significant subsidence during normal operations, and may potentially be at risk of dilatant and tensile damage around the cavern perimeter during repressurization after a workover. The analyses in Sobolik and Ehgartner (2009) modeled the salt's creep behavior with the power law creep model along with a reduced elastic modulus. While this approach gives good results of long-term behavior, it probably overestimates the mechanical reaction of the salt to changes in pressure over a short period of time. Recently, Sandia improved its implementation of the M-D multi-mechanism deformation (M-D) model (Sobolik et al. 2010), which is a rigorous mathematical description of both transient and steady-state creep phenomena. The M-D model provides a more realistic model of the transient behavior of salt under pressure change conditions such as a workover.

Recent problems with the integrity of Well 6 led to a workover of the cavern. Because of concerns of potential tensile cracking around the perimeter of Cavern 6 upon repressurization, a new set of calculations was performed on West Hackberry utilizing the M-D model. The results of the predictions are described below. The primary recommendation derived from the calculations is that the wellhead pressure in Cavern 6 may be raised to 700 psi over a 3-day period, but then the rate of pressure increase must be drastically reduced until the desired operating pressure is reached.

Description of Event at West Hackberry Cavern 6

Cavern 6 has 3 cemented and cased wells, two of which also have liners due to earlier well failures. The most recent well failure occurred in the remaining unlined well. The 7-inch production casing was logged using a Multi-Sensor Caliper as part of an ongoing program to determine the condition of SPR wellbores. The caliper survey run on August 23, 2010 and confirming camera images taken on September 1, 2010 provided compelling evidence of parted casing and severe deformation within the WH-6 cased wellbore, particularly at depths of approximately 195 feet and 2,550 feet subsurface. Figure 3 shows some images of the damaged wellbore. The damage is a result of tensile strains generated along the axis of the wellbore due to cavern creep and subsidence.

The decision was made to plug and abandon the damaged well. The process required an extended workover period. The wellhead pressure was reduced to atmospheric starting on September 28, 2010, and cementing the wellbore to the Bradenhead Flange was not achieved until January 5, 2011.



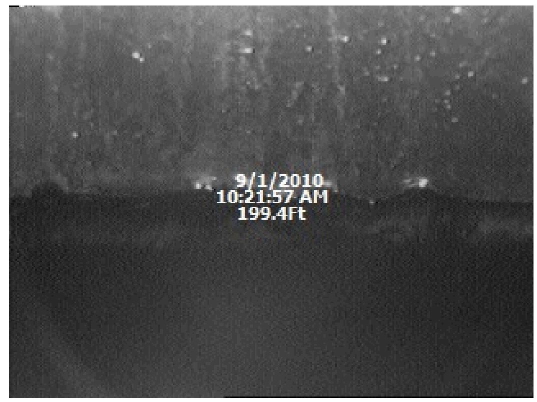


Figure 3. Camera shots showing parted casing (left- looking down well, right- sidewall image) just above collar at 199.5 ft (courtesy DM Petroleum Operations Co.)

Results of Earlier Analyses

An earlier set of analyses was performed of the mechanical behavior of the caverns at the West Hackberry site (Sobolik and Ehgartner, 2009). These analyses indicated several concerns about Caverns 6 and 9:

- Because of the dish-like shape of Cavern 6, the perimeter of the cavern is at risk of dilatant and tensile damage, particularly at the end of a workover operation. This potential will increase with the first and second leaching operations, but may be abated with the later expansions as the cavern takes on a more cylindrical shape.
- Because of expected tensile cracking potential near Cavern 6, the close proximity of Cavern 9 (200 feet at their closest point) poses a risk of inter-cavern communications. The potential exists for a crack to propagate from Cavern 6 and intersect Cavern 9, causing cavern pressures to equilibrate. An operational scenario of having Cavern 9 in workover mode during the breach would pose a serious risk to operational safety and containment of oil. A breach when Cavern 6 is fully repressurized (the most likely condition) could abruptly pressurize Cavern 9 and potentially result in oil loss in the absence of a wellhead or if the blowout preventer faulted. This could pose a safety risk to the workover crew and potential environmental damage.
- Cavern 9 has a middle section with a smaller radius, giving a cross-section of the cavern the look of a bell with a mid-cavern ledge. This ledge and the cavern wall underneath supporting the ledge are also locations with a significant potential for dilatant damage during workover operations. This analysis designs a cavern enlargement process that gradually eliminates the ledge, resulting in a final bell shape with no enlargement in the radius over the majority of the cavern. This cavern enlargement procedure favorably eliminates the ledge, but in reality the leached shaped of the cavern may differ, and other leaching scenarios may result in interference with Cavern 6 or a heightened potential for dilatant damage.
- Workovers performed on Cavern 9 wells should be performed no sooner than one year after the completion of a workover in Cavern 6. This period will allow the stressed salt around Cavern 6 enough time to heal and attain near-hydrostatic stress values, so to minimize the possibility of cracking the salt between Caverns 6 and 9. Performing the workovers in the opposite order (Cavern

9, then Cavern 6) does not appear to need such a stringent requirement, although it may be prudent to keep the same delay.

Because of the results of these previous analyses, the SPR site office was already sensitive to the potential integrity issues regarding Cavern 6. Therefore, in response to the decision by the SPR site office to initiate a workover on Cavern 6, a new set of calculations was performed to develop recommedations for the repressurization of the cavern. These analyses were performed with the same computational mesh, boundary conditions, and cavern operating conditions as the Sobolik and Ehgartner (2009) analyses, but with greater detail given to the rate of repressurization, and with an improved material model for the salt.

Description of Model

This analysis utilized JAS3D, Version 2.0.F (Blanford et al., 2001), a three-dimensional finite element program developed by Sandia National Laboratories, and designed to solve large quasi-static nonlinear mechanics problems. Several constitutive material models are incorporated into the program, including models that account for elasticity, viscoelasticity, several types of hardening plasticity, strain rate dependent behavior, damage, internal state variables, deviatoric creep, and incompressibility. The continuum mechanics modeled by JAS3D are based on two fundamental governing equations. The kinematics are based on the conservation of momentum equation, which can be solved either for quasi-static or dynamic conditions (a quasi-static procedure was used for these analyses). The stress-strain relationships are posed in terms of the conventional Cauchy stress.

Historically, three-dimensional geomechanical simulations of the behavior of the caverns at SPR facilities have been performed using a power law creep model, which evaluates only the secondary steady-state salt creep mechanism. Because the transient creep mechanism is not represented in this model, the common practice has been to use a reduction factor for the elastic modulus. Using this method, and calibrating the creep coefficient to field data such as cavern closure and surface subsidence, analysis agreement with observed phenomena has ranged from adequate to very good, depending upon the degree of homogeneity at a particular site. However, the power law creep model used in this manner is not well-suited for modeling short-term events such as pressure changes due to a workover. The artificially low elastic modulus causes an over-estimation of the deformation response to depressurization and repressurization, and also incorrectly models the stress equilibration response of the salt after such an event.

Recently, enhancements have been completed to the integration algorithm within the model to create a more stable implementation of the multi-mechanism deformation (M-D) model (Sobolik et al., 2010). The M-D model is a rigorous mathematical description of both transient and steady-state creep phenomena. It was originally developed by Munson and Dawson (1979, 1982, and 1984) and later extended by Munson et al. (1989). This constitutive model considers three well recognized fundamental features of a creeping material: a steady state creep rate, a transient strain limit, and both a work-hardening and recovery time rate of change (*i.e.,* curvature). Because of the highly non-linear nature of the curvature of the transient strain response, this model has been difficult to integrate in a fully three-dimensional calculation for a model with hundreds of thousands of elements. Many published papers exist presenting two-dimensional calculations using the M-D model, but three-dimensional, large-scale simulations have been more difficult due to the model's high nonlinearity. Full descriptions of the M-D model and the integration algorithm enhancements are provided in Sobolik et al. (2010).

The previous analyses of the mechanical behavior of the caverns at West Hackberry (Sobolik and Ehgartner, 2009) used the power law creep model. For those analyses, a computational domain was developed for the West Hackberry cavern field that encompasses the eastern half of the salt dome, with a vertical symmetry plane through six WH caverns (110, 109, 103, 101, 105, and 117). The mesh for the computational model is illustrated in Figures 4 and 5. Figure 4 shows the entire mesh used for these calculations, and Figure 5 shows the same view with the overburden and caprock removed to expose the salt formation. Four material blocks were used in the model to describe the stratigraphy: the overburden, caprock, salt dome and sandstone surrounding the salt dome. The overburden is made of sand, and the caprock layer is made of gypsum or limestone. Figure 6 shows two views of the layout of the meshed caverns used for these calculations, which includes the six half caverns listed above, which are spaced approximately 230 m (150 feet) center-to-center, plus full cavern representations for 108 and the Phase 1 caverns (6, 7, 8, 9, and 11). The figures show the caverns at their current volumes plus five additional extraction layers, which represent proposed additional salt leaching operations to grow the existing West Hackberry caverns.

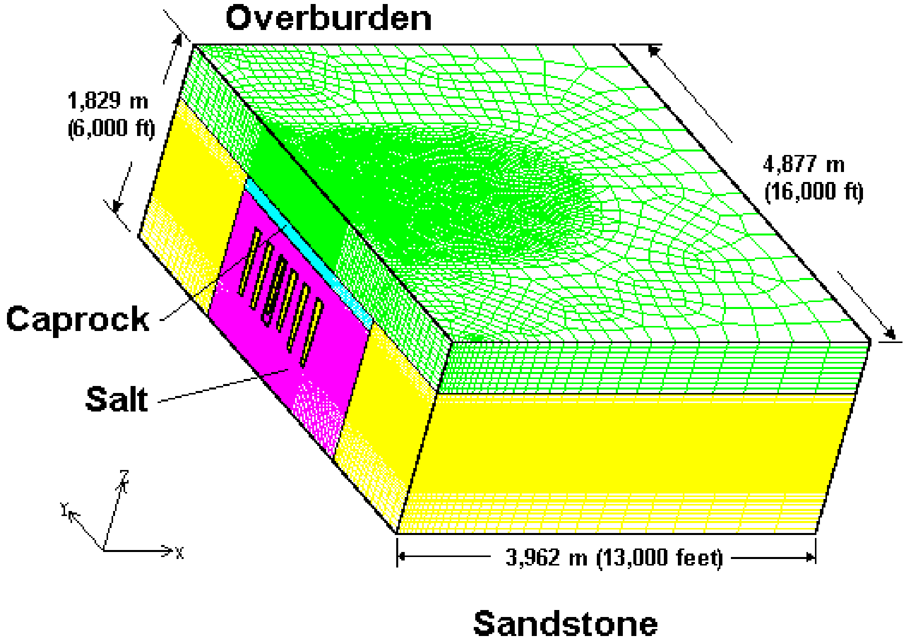


Figure 4. Computational mesh used for the West Hackberry calculations.

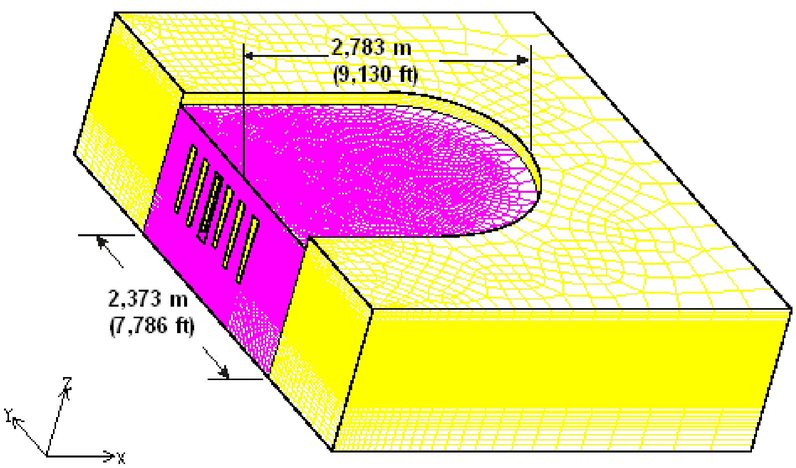


Figure 5. Computational mesh showing the salt formation and surrounding sandstone.

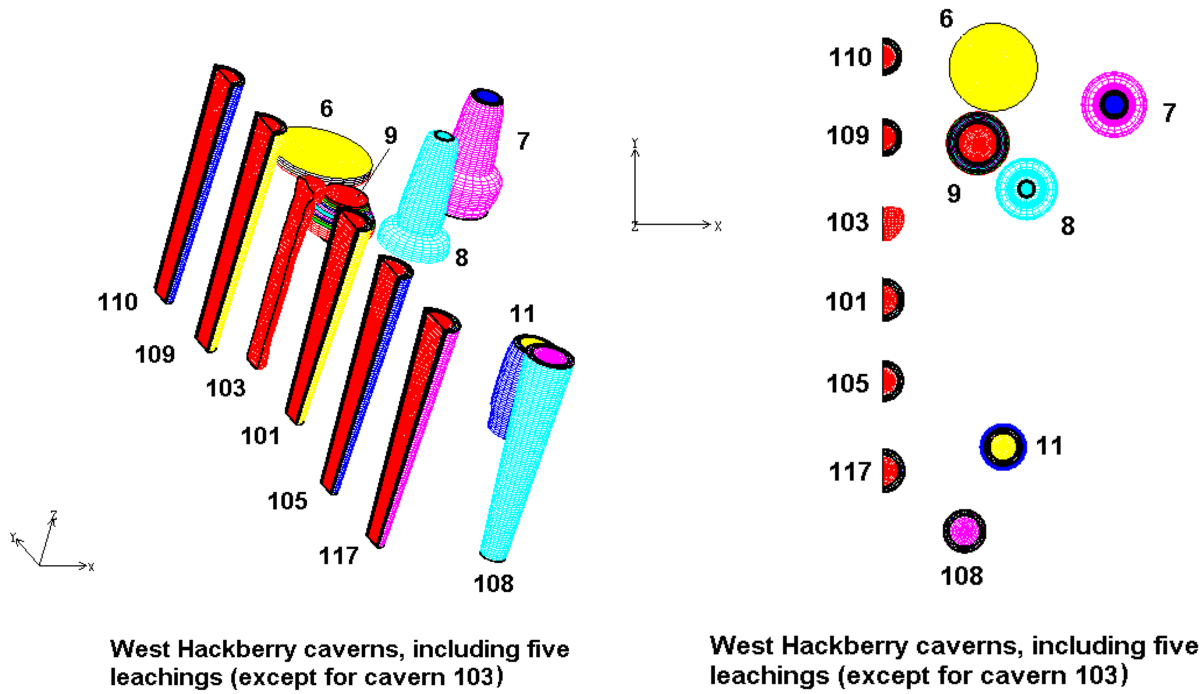


Figure 6. West Hackberry caverns included in the computational mesh (two views).

Description of Analysis

The 1980 sonar data from Cavern 6 indicate that the approximately 200-feet wide "rim" encircling the cavern has been present since at least 1980, and was about 10 feet thick at the edge of the dish or bowl portion of the cavern. Unfortunately, the 1982 sonar measurements are the last data taken of the cavern profile. The current condition of the rim of Cavern 6 is not known. This may be important for two reasons. One, the extension of the flat wide volume of the cavern may increase the already-high fracture potential around the perimeter, and consequently cause the cavern ceiling to subside more. Two, because of the geometry of the cavern, it is possible that the rim has been pinched off from the rest of the cavern, potentially trapping oil in the pinched section or in pockets near the rim that are at higher elevations than the access holes in the cavern ceiling. Therefore, there are three probable current conditions of the rim around Cavern 6:

- The rim is highly compressed, but there is still enough oil in it to allow pressure communication from the main cavern out to the edge of the rim; or
- The rim is completely pinched off at the edge of the main part of the cavern, meaning there is in essence no more rim; or
- The rim is pinched off somewhere between the main cavern and the original rim edge.

Mechanical simulations were performed with JAS3D and the M-D model assuming either communication with the edge of the rim, or that the rim no longer exists. The analyses were identical to those performed for Sobolik and Ehgartner (2009), except that the M-D model was used instead of the power law creep model, and the pressure changes during the workover period for Cavern 6 were altered. For all the analyses, the wellhead pressure in Cavern 6 was dropped from its normal operating pressure of 900 psi to 0 psi for the workover in 120 hours (5 days), and then held at 0 psi for an additional 55 days before repressurization. The parameters used for the M-D model are listed in Table 2. The properties were developed from Munson (1998), with a multiplier of 1.2 added to K_0 to better match subsidence and cavern closure data from West Hackberry. Five sets of calculations were performed:

- Cavern with rim, raise wellhead pressure from 0 to 900 psi in 24 hours (1 day).
- Cavern with rim, raise wellhead pressure from 0 to 900 psi in 72 hours (3 days).
- Cavern with rim, raise wellhead pressure from 0 to 900 psi in 120 hours (5 days).
- Cavern with a closed rim, raise wellhead pressure from 0 to 900 psi in 72 hours (3 days).
- Cavern with rim, with a staged repressurization: raise wellhead pressure from 0 to 700 psi in 72 hours (3 days), followed by a seven-day period raising the pressure to 850 psi.

Table 2. M-D Model Mechanical Properties Used for West Hackberry Salt.

Property	West Hackberry, soft salt properties
Density, kg/m^3	2300 (144 lb/ft^3)
Elastic modulus, GPa	31.0 (4.50 $\times 10^6$ psi)
Shear modulus G, GPa	12.4 (1.80 $\times 10^6$ psi)
Poisson's ratio	0.25
Primary Creep Constant A_1, sec^{-1}	9.81 $\times 10^{22}$
Exponent n_1	5.5
Q_1, cal/mol	25000
Secondary Creep Constant A_2, sec^{-1}	1.13 $\times 10^{13}$
Exponent n_2	5.0
Q_2, cal/mol	10000
B_1, sec^{-1}	7.121$\times 10^6$
B_2, sec^{-1}	3.55$\times 10^{-2}$
σ_0, MPa	20.57 (2983 psi)
q	5335
m	3.0
K_0	7.53$\times 10^5$
c	0.009198
α	-17.37
β	-7.738
δ	0.58

Figure 7 shows the maximum stress around the perimeter of the cavern during repressurization. For the simulations that assume communication with the edge of the rim still exists, the maximum stress is at the edge of the rim; for the case with a closed rim, the stress occurs at the perimeter of the main bowl of the cavern. The "x" on each curve indicates when each simulation reaches 700 psi wellhead pressure. Note that for the three cases with a rim and a steady repressurization, the maximum stress become tensile when the wellhead pressure reaches its maximum simulation pressure of 900 psi. Note also that there is some improvement as the repressurization period increases. For the case with a closed rim, the maximum stress nears but does not become tensile at its maximum wellhead pressure. This result is significant, because the results for the same calculation using the power law creep model in Sobolik and Ehgartner (2009) indicated that tensile stresses would occur during this process; the M-D model, which handles transient stress effects more realistically, shows that tension should not occur, although one might still believe it comes uncomfortably close to tension. For the case of the staged repressurization, the maximum stress reaches its maximum value of 300 psi in compression at 10 days and 850 psi wellhead pressure, and then begins to re-equilibrate to in situ stress. These results indicate that the best approach for repressurization is to relatively quickly (i.e., in 3 days) increase the wellhead pressure to 700 psi to mitigate further storage capacity loss, then take a much longer time (at least seven days) to increase the wellhead pressure to the minimum of the normal operating range or 850 psi. Figure 8 shows the resulting stress re-equilibration for up to 450 days after the end of the workover. Note that the maximum stress has not reached the in situ value before the end of the analysis at 450 days. Because of the proximity of Cavern 9, this result reinforces the recommendation to wait at least one year between workovers of Caverns 6 and 9.

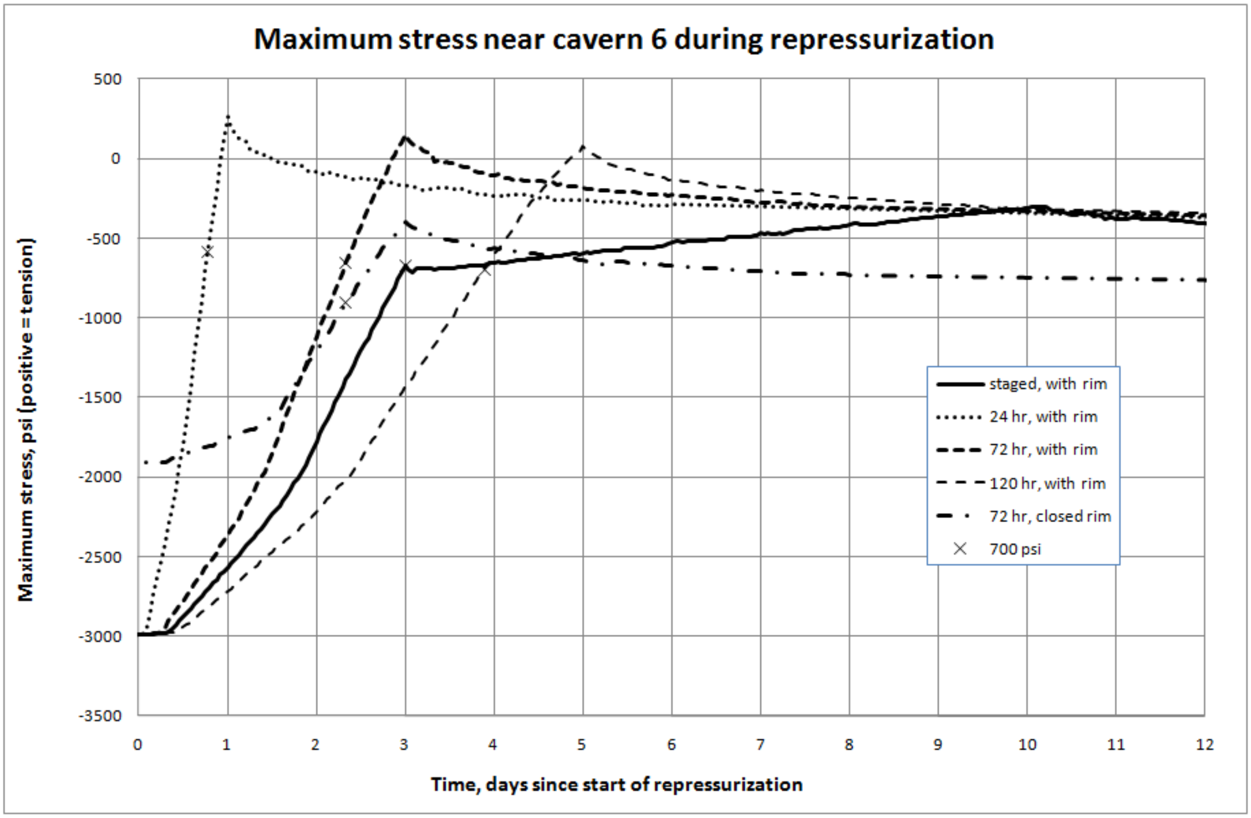


Figure 7. Maximum stress around Cavern 6 during repressurization.

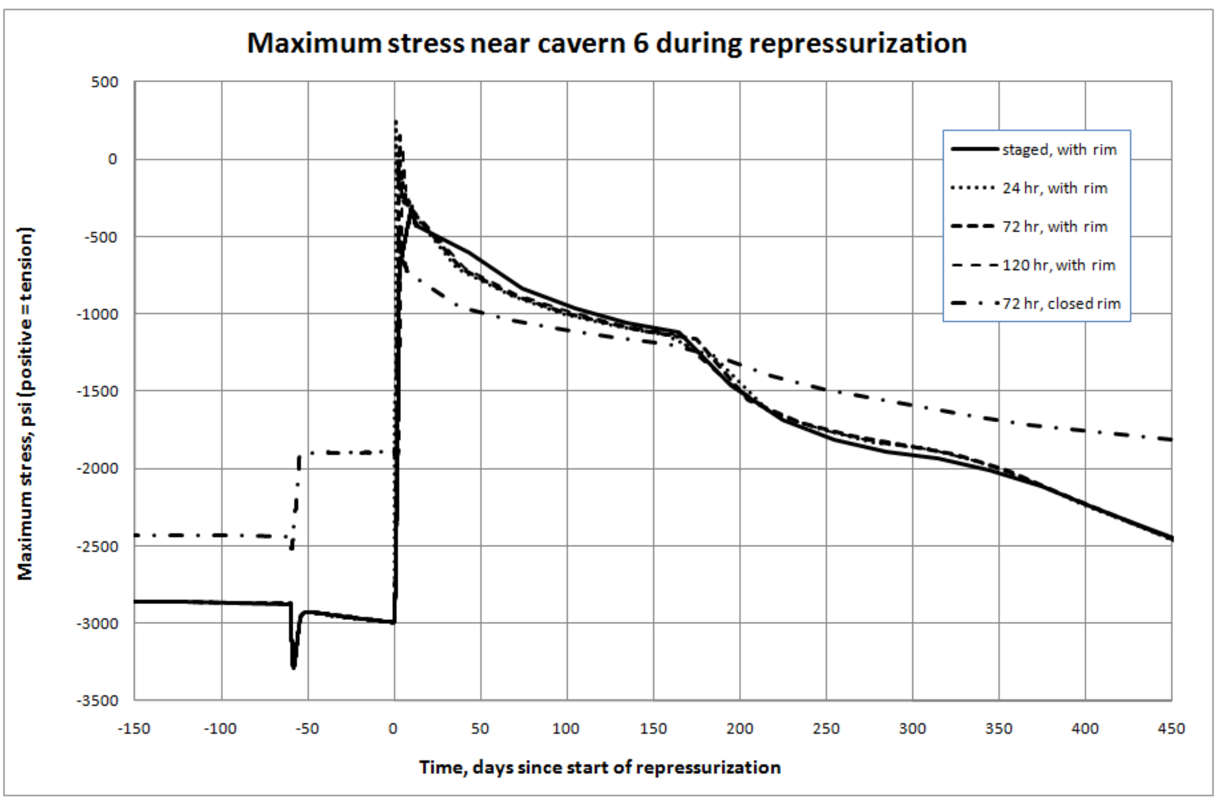


Figure 8. Maximum stress around Cavern 6 over a year after repressurization.

Figure 9 shows the minimum value of dilatant damage factor obtained for each of the five simulations. A value of 1 indicates the onset of dilatant damage; typically, it is desired to keep the damage factor above 1.5. For the three cases with a rim and steady repressurization, the damage factor drops below 1, indicating the onset of damage. Fortunately, when the pressure increase ends, stress equilibration begins immediately and the damage factor rises back above 1 very quickly. For the case of no rim, the damage factor briefly drops below 1.5 at the maximum wellhead pressure, and then recovers. This result also differs from the result using the power law creep model, which predicted a damage factor below 1 for the same cavern geometry. For the case using staged repressurization, a minimum value of the damage factor of 1.34 is reached shortly after the maximum wellhead pressure is achieved at 10 days. This result demonstrates that at least seven days should be allowed to increase the wellhead pressure from 700 psi to 850 psi.

The results presented here show that the pressure in Cavern 6 can be raised fairly quickly to 700 psi. This will help to minimize storage volume loss due to creep. Then a much slower pressure rise is warranted to prevent damage to the salt around the cavern. This repressurization process has not been violated by previous workovers for Cavern 6; Figure 10 shows historic repressurization data from previous workovers along with the current recommended limit to re-pressurize.

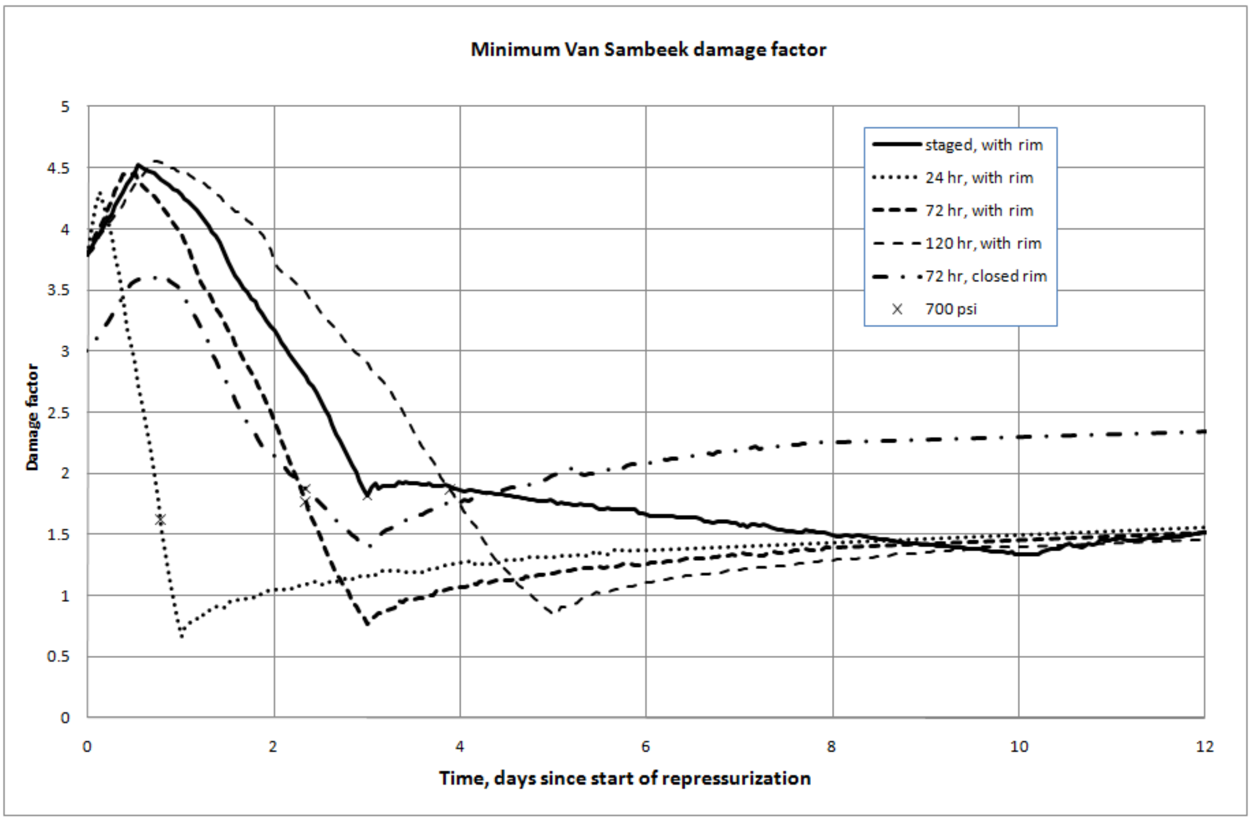


Figure 9. Minimum dilatant damage factor around Cavern 6 during repressurization.

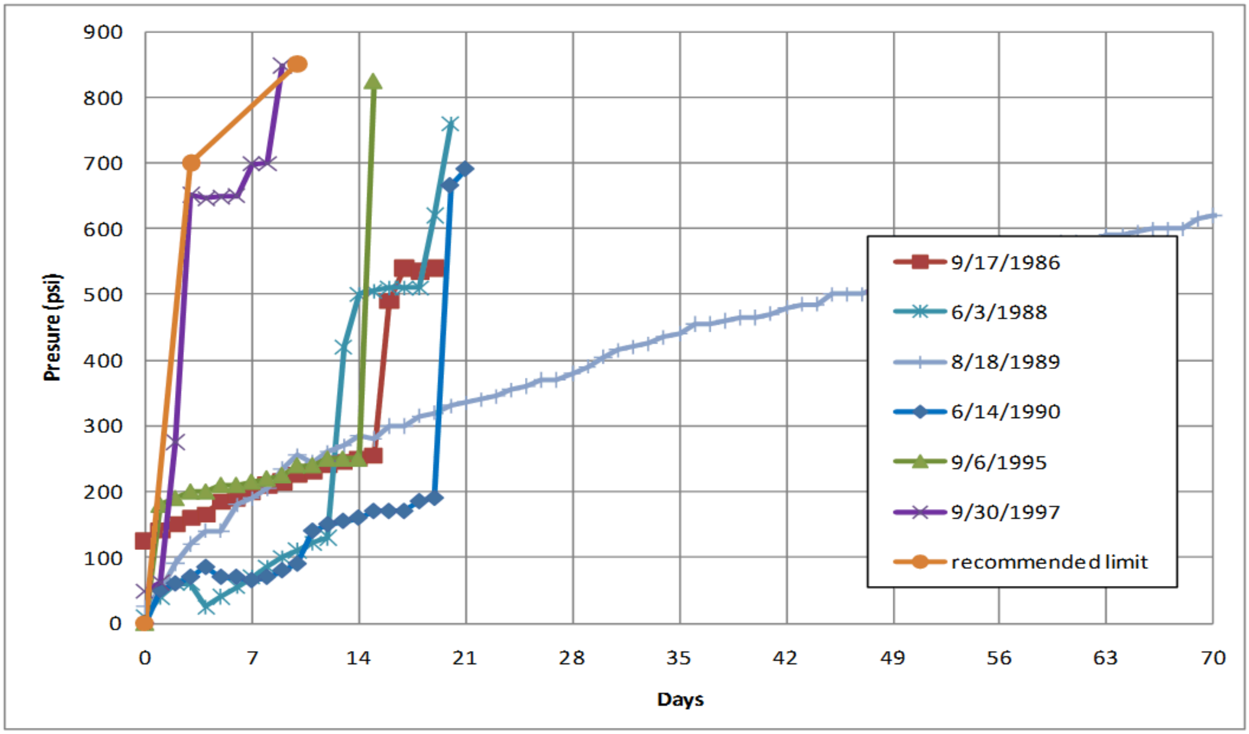


Figure 10. Re-pressurization histories following previous workovers of Cavern 6.

Conclusions

Based on the results presented here and in Sobolik and Ehgartner (2009), the following recommendations were made regarding Caverns 6 and 9 and the successful plugging and abandonment of Well 6:

- Following a workover, repressurization of the cavern must be performed slowly to avoid tensile fracturing at the roof. The wellhead pressure in Cavern 6 can be re-pressurized to 700 psi over three days, followed by an additional seven-day period (minimum; longer would be better) to raise the wellhead pressure to 850 psi. The initial and more rapid pressure increase will help mitigate creep closure losses in the cavern. The subsequent and more sensitive pressure rate must be slower to avoid tensile fracturing at the edge of the large flat diameter roof.

In addition the analyses noted that:

- Workovers performed on Caverns 9 should be performed no sooner than one year after the completion of a workover in Cavern 6. This period will allow the stressed salt around Cavern 6 enough time re-equilibrate and attain near-hydrostatic stress values, so to minimize the possibility of cracking the salt between Caverns 6 and 9, and reduce the possibility of damage under the ledge in Cavern 9 during its workover.
- Leaching of the salt ledge in Cavern 9 will improve its stability. As a result, Cavern 9 should be given priority in future oil drawdowns that inject freshwater.
- The causative mechanism of the well failures was determined to be subsidence induced ground strains along the axis of the wellbore due to salt creep and cavern closure.

Following the completion of wellbore cementing on January 5, 2011, the repressurization of the cavern started on January 14, 2011 and lasted throughout January following the recommendations in this report. The wellhead pressure in Cavern 6 was raised to 700 psi over three days, followed by an additional ten-day period to raise the wellhead pressure to the low end of its normal operating range, 850 psi on January 31, 2011. Based on all indications from well pressure measurements from Caverns 6 and 9, there has been no event indicative of additional well damage or loss of cavern integrity since the workover was completed.

The analysis demonstrates the capability to apply complex, three-dimensional geomechanical computations to make recommendations to field operations in a short time frame. The computational model presented here is mature, with a mesh containing realistic geometries for the caverns and salt dome, a functional M-D model, and operating pressure scenarios that can be modified to fit current and new scenarios. The model was able to predict the well failures that occurred in the field.

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