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Operation, Maintenance, and Monitoring of Large-Diameter Caverns in Oil Storage Facilities in Domal Salt

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ABSTRACT: This paper presents a study of operational and abandoned large-diameter caverns and their long-term implications for oil storage facilities in domal salt. Two caverns at the U.S. Strategic Petroleum Reserve's West Hackberry site, Caverns 6 and 9, present concerns due to their large diameters, unusual shapes and close proximity to each other. The Bryan Mound site has three caverns whose unusual shapes and dimensions have caused concerns about cavern collapse, sinkhole formation, and loss of accessibility to stored oil. This report presents a case study of how historical field data, computational geomechanical analyses, and the implementation of new instrumentation and historical data analyses may be used to develop site operation and monitoring plans for these caverns.

1 INTRODUCTION

The US Strategic Petroleum Reserve (SPR), operated by the U.S Department of Energy (DOE), 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.

This paper presents a study of five operational and abandoned large-diameter caverns and their long-term implications for oil storage facilities in domal salt. These five caverns are at two of the SPR sites. Two caverns at the West Hackberry site, Caverns 6 and 9, present concerns due to their unusual shapes and close proximity to each other. Cavern 6 has an unusual dish-like shape with a large rim around the circumference. The diameter of Cavern 6 at the roof ranges from 340 to 380 meters at the rim; the diameter of the bowl section is approximately 240 m. 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. Cavern 6 is in close proximity to Cavern 9, which is hourglass-shaped. Previous calculations indicated that the narrow section of Cavern 9 was vulnerable to dilatant shear stresses during workover procedures. The edges of the two caverns are 60 meters away at their closest point; this close proximity causes sympathetic stress response at one cavern to pressure changes in the other, which raises the concerns for cavern stability. Most recently, the large diameter of the roof of Cavern 6 has been determined to have dropped significantly enough that the existing boreholes near the center of the cavern are below the depth of the roof at the perimeter of the cavern by as much as 3 meters. Because of these factors, it was decided to remove oil from the cavern to complete diagnostic examinations; currently, it is believed that up to 27,000 cubic meters (170,000 barrels) may be trapped around the cavern perimeter.

The Bryan Mound site has three caverns whose unusual shapes and dimensions have caused concerns about cavern collapse, sinkhole formation, and loss of accessibility to stored oil. The abandoned Cavern 3 is a 400-m diameter cavern which was constructed for brine production and storage in the 1940s and plugged and abandoned in 1980. Surface subsidence measurements show an unexpectedly larger subsidence rate over Cavern 3 than the rest of the site, possibly indicating that this cavern may be losing pressure, which would affect boreholes for nearby storage caverns. Cavern 2 is a similar cavern of about 200m in diameter used for oil storage. Its location high in the salt dome raises concerns of long-term cavern stability. Cavern 5 is a giant, 38-

MMB cavern characterized by upper and lower lobes separated by a small neck. The geometry of the cavern creates difficulties in using fresh water to draw down the cavern for oil removal, as the possibility of a salt fall damaging the hanging string.

This paper presents a case study of how field data, computational geomechanical analyses, and the implementation of new instrumentation and historical data analyses may be used to develop site operation and monitoring plans for these caverns. The field data include cavern pressure monitoring, which provide real-time monitoring for potential casing leak detection, and periodic subsidence surveys, which help to characterize longer-term loss of fluid such as for Bryan Mound Cavern 3. The computational analyses utilized realistic three-dimensional models of the geometries of the caverns, and high-performance analytical codes using a multi-mechanism deformation material model. The results of the calculations are used to indicate a significant effect of pressurization rate on the stress response of the surrounding salt, suggesting that a conservative approach be used for repressurization for West Hackberry 6, or the potential for tensile stress formation above caverns close to the top of the salt dome. Data from newly-installed GPS and tiltmeters installed over Bryan Mound Cavern 3 provide continuous monitoring used for detecting underground events. Finally, the paper will discuss several new options being investigated for determining the existing shapes of these caverns, whose information will be used to develop strategies for locating and removing trapped oil and plans for long-term monitoring of the caverns.

2 WEST HACKBERRY CAVERNS 6 AND 9

2.1 *Description of West Hackberry site*

The SPR West Hackberry site is located in the extreme southwestern corner of Louisiana, some 24 km 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 a 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 480 m of soil and unconsolidated gravel, sand, and mud, followed by approximately 120 m 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 cavern geometries and spacings are illustrated in Figure 1. The post-1981 caverns were built via solution mining, and all have a generally cylindrical shape (typically with a larger diameter at the top) of approximately 600 m (2000 feet) height, 30-45 m (100-150 feet) in radius, and about 230 m spacing center-to-center. The Phase 1 caverns, however, were originally built for brine production, and thus they were constructed with less 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 2, and a representation of Caverns 6 and 9 drawn in their full volume and proximity is shown in Figure 3. High-resolution sonar measurements performed on Cavern 6 in 1980 are listed in Table 1 along with the average and maximum roof spans. The sonars of Cavern 6, taken from the three different Cavern 6 wells, are in close agreement and show that the roof of Cavern 9 is located 70 m (230 feet) from its edge. The closest point of approach is with the lower lobe of Cavern 9, at approximately 60 m (200 feet).

The West Hackberry site exhibits relatively homogeneous salt creep properties, and is shown to be a relatively fast-creeping salt from mechanical property testing of salt cores and site measurements of pressure changes induced by creep (Munson, 1998). The higher creep rate of the West Hackberry salt tends to diminish accumulation of tensile stresses in salt in the regions between the top of salt and tops of caverns, but also enhances tensile strain applied to the wellbore casing materials.

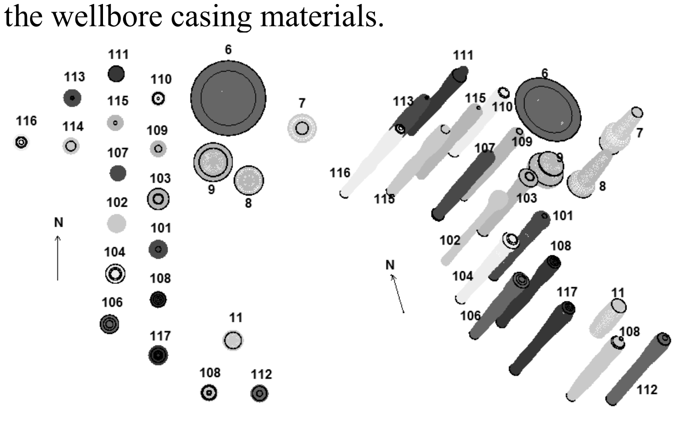

Figure 1. SPR West Hackberry Caverns (geometries obtained from sonars; two views).

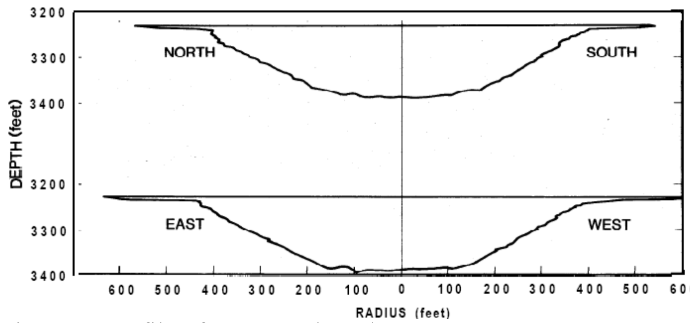

Figure 2. Profile of Cavern 6 based on 1980-1982 sonars.

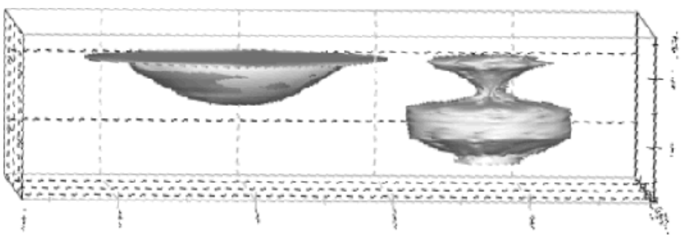
Figure 3. Caverns 6 (left) and 9 (right), from the most recent (1982) sonar and strapping data.

2.2 *Description of West Hackberry model*

Several mechanical analyses of the West Hackberry site have been published (Sobolik & Ehgartner 2009a, 2012a; Sobolik et al., 2010; Sobolik 2013). These analyses utilized first JAS3D, Version 2.0.F (Blanford et al. 2001), and then Adagio (SIERRA Team, 2010, 2011; Arguello et al., 2012), both three-dimensional finite element programs developed by Sandia National Laboratories, and designed to solve large quasi-static nonlinear mechanics problems.

The salt creep of the West Hackberry salt dome has been modeled using the multi-mechanism deformation (M-D) model. 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 nonlinear 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 computational domain developed for the West Hackberry cavern field 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.

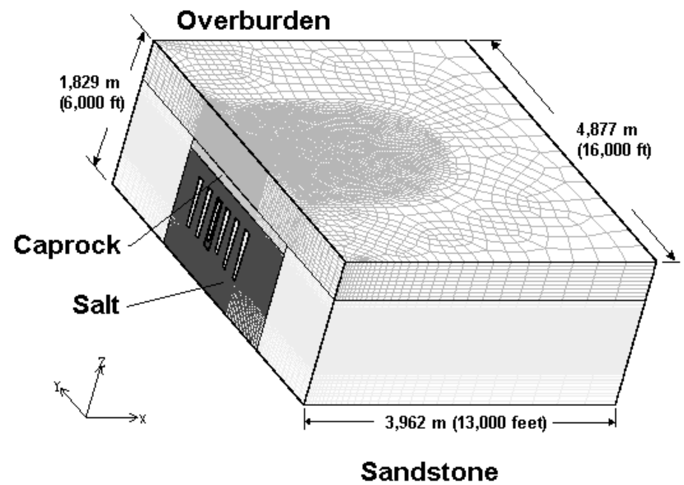

Figure 4. Computational mesh used for the West Hackberry calculations.

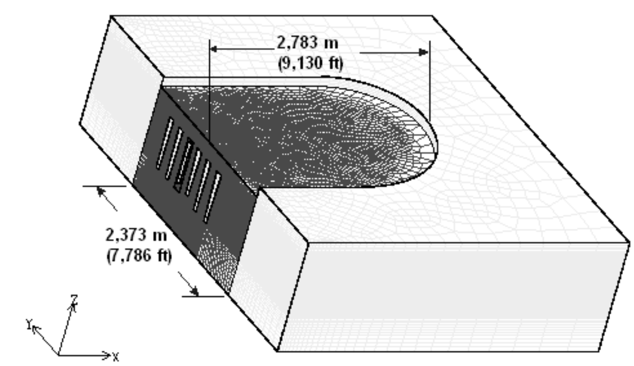

Figure 5. Computational mesh showing the West Hackberry salt formation and surrounding sandstone.

2.3 *Concerns for West Hackberry 6 and 9*

Several earlier sets of analyses have been performed of the mechanical behavior of the caverns at the West Hackberry site (Sobolik & Ehgartner 2009a, 2012a; Sobolik et al., 2010; Sobolik 2013). These analyses indicated several concerns about Caverns WH-6 and WH-9:

- WH-6 has been shown to be a stable cavern under normal operating pressures. However, because of the dish-like shape of WH-6, the perimeter of the cavern is at risk of dilatant and tensile damage during repressurization at the end of a workover operation.

- Because of expected tensile cracking potential near WH-6, the close proximity of WH-9 poses a risk of inter-cavern communications. The potential exists for a crack to propagate from WH-6 and intersect WH-9, causing cavern pressures to equilibrate. An operational scenario of having WH-9 in workover mode during the breach would pose a serious risk to operational safety and containment of oil. A breach when WH-6 is fully repressurized (the most likely condition) could abruptly pressurize WH-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.
- The roof of WH-6 has been predicted to subside by as much as 3.3 m (11 feet) over the life of the storage cavern. This sag has two detrimental effects: one, it applies significant tensile strains to the wellbore casings, which has apparently caused failure of two of the cavern's three wells; and two, the sag of the roof places oil in a toroidal region around the perimeter of the cavern above the bottom of the wellbores, and thus inaccessible through typical recovery via brine replacement. Uncertainty about the roof geometry makes it difficult to estimate the volume of oil that may be trapped in the cavern during full oil removal.
- The large diameter-to-height ratio of WH-6 raises the potential of cavern roof collapse at some point in the future, particularly if the cavern is not maintained at normal operating pressures of higher. However, because the top of the cavern is significantly below the top of the salt dome, the potential for a cavern collapse to cause sinkhole formation is considered highly unlikely. The proximity of WH-6 to other caverns makes it necessary for the cavern to be pressurized and monitored in the long-term if it is abandoned for oil storage.
- WH-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. Pressure change procedures on both caverns WH-6 and WH-9 must be planned to prevent fracture and microfracture formation.
- Workovers performed on WH-6 and nearby cavern WH-8 may also impact the rate at which strain is applied to the wellbores of WH-9.

In response to the concers about fracture formation between Caverns WH-6 and WH-9, recommendations for proper cavern repressurization procedures for WH-6 were developed from new geomechanical simulations (Sobolik, 2013).

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 recommendations for the repressurization of the cavern. These analyses were performed with the same computational mesh, boundary conditions, and cavern operating conditions as the Sobolik & Ehgartner (2009a) analyses, but with greater detail given to the rate of repressurization, and with an improved material model for the salt.

2.4 *Recent history of West Hackberry 6*

Recent problems with the integrity of wells at Cavern WH-6 have led to a series of actions, beginning with workovers of the cavern for wellbore remediation, to removing oil from the cavern for assessment of its current and future status. Prior to the events of September 2010, Cavern 6 had three cemented and cased wells (Wells 6, 6B and 6C), two of which also had liners due to earlier well failures. Well 6C had experienced a failure in 1988, and a 244 mm (9.625-inch) liner was installed in 1990 to repair the wellbore. Well 6B underwent a similar repair in 2002. In September 2010, a well failure occurred in the remaining unlined Well 6. The 178-mm (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 Well 6 cased wellbore, particularly at a depth of approximately 777 meters (2,550 feet subsurface). The damage was 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. Following the completion of wellbore cementing, the repressurization of the cavern started on January 14, 2011 and lasted throughout January following Sandia recommendations (Sobolik, 2013). Based on all indications from well pressure measurements from Caverns WH-6 and WH-9, there was no evidence of additional well damage or loss of cavern integrity until May 2012, indicating that the prescribed repressurization rate was not excessive. In May 2012, cavern pressure data indicated that a leak had occurred in WH-6. The wellhead pressure was reduced to zero, and it was discovered that Well 6C had failed in several locations. Over the next few months, as WH-6 was kept in workover mode, the natural pressurization rate due to creep observed in Cavern WH-9 had increased substantially. This elevated pressure increase in WH-9 raised a question about what happens if a workover on WH-9 is started within one year after depressuring WH-6 (which had previously been recommended against occurring). Additionally, the long-term workover in WH-6 exacerbates the existing problems of substantial vertical strain on the casing in Well 6B, and the additional loss of access to oil in the cavern due to roof subsidence.

Because of the issues regarding the wells at Cavern WH-6, the Cavern Integrity Working Group for the SPR West Hackberry site (including staff from the DOE SPR management team, DM Petroleum Operations Co. (now Fluor Federal Petroleum Operations), and Sandia) entered into a process to evaluate the long-term disposition of the cavern. The driving scenarios regarding the future use of WH-6 are well stability and oil accessibility; cavern stability, in the form of potential dilatant and tensile fracturing around the cavern, is a high but manageable concern. Based on the recent failure of the other two wells at Cavern 6, and on geomechanical calculations, Well 6B was determined to already be at a high risk of failure, and dropping the pressure in the cavern increases that risk. If Well 6B is lost (either in normal operations or during a workover), then the 0.95×10^6 m^3 (6×10^6 barrels, or 6 MMB) of oil in the cavern would have become inaccessible until another well can be drilled. Based on the cavern and well histories, and projected risks, the working group recommended emptying as much oil as possible from WH-6 using brine, then performing post-removal diagnostics, including a sonar scan of the cavern to map the roof and also estimate how much oil remains in the cavern. Planned diagnostics also included a multi-arm caliper to evaluate well deformation. During and after these operations, the Working Group are weighing the pros and cons of maintaining WH-6 for oil storage versus decommissioning, using the acquired geotechnical data and cost/benefit analyses. Decommissioning means the permanent removal of accessible oil from WH-6, and long-term pressure maintenance (with brine or some other fluid) and monitoring of the cavern. The oil removal process was begun on February 1, 2013; between then and April 2014, 5.8 MMB were removed, or approximately 91 percent of the original book inventory (Murray, 2014).

2.5 *Monitoring plan for West Hackberry 6 and 9*

There are three ongoing concerns regarding the operations at caverns WH-6 and WH-9: 1) the impact of long duration depressurizations of WH-6 while it is undergoing oil removal on operations on nearby cavern WH-9; 2) How much oil remains trapped in WH-6, and how may it be retrieved; and 3) establishing a program of long-term monitoring of WH-6 to anticipate possible future wellbore or cavern failure. Regarding the first concern, concurrent operations in WH-8 may affect wellbore stability in WH-9. Cavern WH-8 requires borehole diagnostic (well 8A) and remediation (wells 8 and 8B) work that require it to be depressurized for significantly greater than three months, which is the typical maximum workover period. This concern was augmented because of the close proximity of Cavern 8 to Cavern 9, and the reduced pressure in nearby Cavern 6 during its oil removal process. Although the previous geomechanical analyses were helpful to understand the interaction between these three caverns during workovers, they did not capture the unusual sequence of activities involving these caverns that have occurred in the past 2-3 years and would continue well into 2014. Therefore, additional modeling calculations simulating recent and scheduled workover activities were performed to determine the effect of extended simultaneous workover activities on Caverns 6, 8, and 9.

The workover schedule consisted of a 4-month workover on WH-9 beginning in late January 2014, with a concurrent 3-week workover in WH-6 beginning in late February. The simulations were also used to provide recommendations for maximum duration, depressurization and repressurization schedules, and maximum pressure differential for these caverns. Cavern stability can be described by two components: one, the stability of the cavern walls themselves, and the pillars between caverns, due to the pressure changes during cavern operations; and two, the stability of the wellbore casings during those operations.

As the caverns close due to creep, vertical strain is created along the borehole casings. The majority of the strain that is accumulated in the casing occurs during workovers, when the wellhead pressure is zero and the resulting lower cavern pressure allows creep closure to occur at a much faster rate than at normal operating conditions. In previous analyses, a prediction of 1.6 millistrains (mϵ) has been used as a limiting threshold value for strain accumulation. The 1.6- mϵ threshold indicates the point at which plastic deformation of the steel will occur; however, it does not indicate the point of failure for the steel (i.e., the point at which the casing is breeched and fluid may flow outside the casing). The failure strain for the casing steel itself will be at a higher strain than 1.6 mϵ, but failure for the threaded joints will likely occur at a lower strain than the material itself. Because there is not a readily established strain value to use to determine the onset of steel casing failure, an absolute limit of 1.6 mϵ for any location along the borehole during a single workover has been used to determine the maximum duration of workover activities.

Figures 6 and 7 show the predicted vertical strain on the casings for WH-6, 8, and 9, accumulated since January 24, 2009, at specific points along the casing; Figure 6 displays six years from 2009-2014, while Figure 7 is a zoom of the period April 2013 – June 2014. For WH-6 in Figure 6, two monitoring points are selected, one at the cavern roof (3230 feet depth) and one at the maximum strain location (2884 feet depth – about 340' above the roof). For WH-8 and WH-9, the maximum strain location is at the roof. The plotted time period in Figure 6 includes the late-2010 and mid-2012 workovers on WH-6, the 5-month workover on WH-8 in 2013, and the scheduled workovers on 2014 for WH-6 and 9. Figure 8 shows the strain as a function of distance from the roof of WH-9, at different points in time.

For the 2014 workover for WH-9, Figures 6 and 7 indicate that the strain rate in the casing decreases over time during a workover: a total accumulation of 0.44 mϵ during the initial 5-day depressurization period, ending with a strain rate of 0.14 mϵ/day; an additional 0.31 mϵ after ten days of zero wellhead pressure, closing with a strain rate of 0.02 mϵ/day; an additional 0.77 mϵ, 0.005 mϵ/day at the end of 90 days; and finally another 0.11 mϵ, 0.005 mϵ/day during the last 20 days, totaling 1.63 mϵ over the 100 days. After the cavern is repressurized, a small amount of strain, 0.14 mϵ, is predicted to be recovered. These strains are predicted to occur near the cavern roof; the amount of strain is predicted to decrease as a function of distance above the cavern, as shown in Figure 7. The calculations predict that the 110-day workover on WH-9 will add an additional 1.6 mϵ to the bottom of the borehole, and at least 1 mϵ to the bottom 140' of borehole. The results from the earlier JAS3D calculations predicted a very similar strain rate for WH-9 when under workover.

Several observations can be made from the predictions in Figures 6-8:

- The three-week workover on WH-6 scheduled in February 2014 at the same time as the workover on WH-9 (and also while WH-8 is fully pressurized) appears to increase the strain rate for WH-9 from 0.010 mϵ/day to 0.015 mϵ/day. For the three-week duration of the planned WH-6 workover, this is not a significant increase.

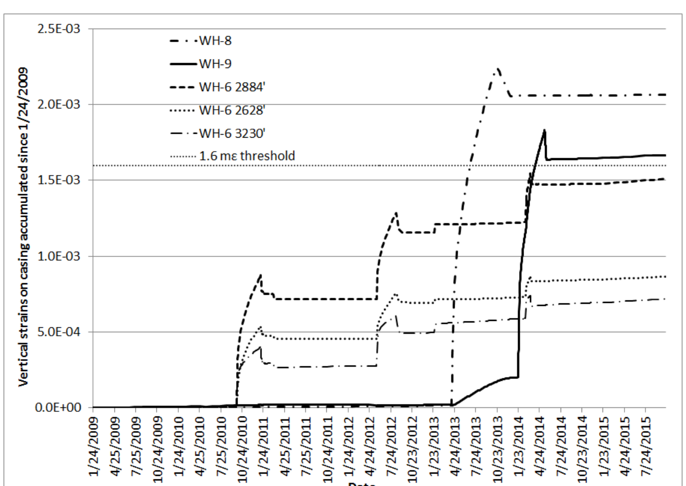

Figure 6. Predicted vertical casing strain for WH Caverns 6, 8, and 9 during scheduled workovers (2009-2014).

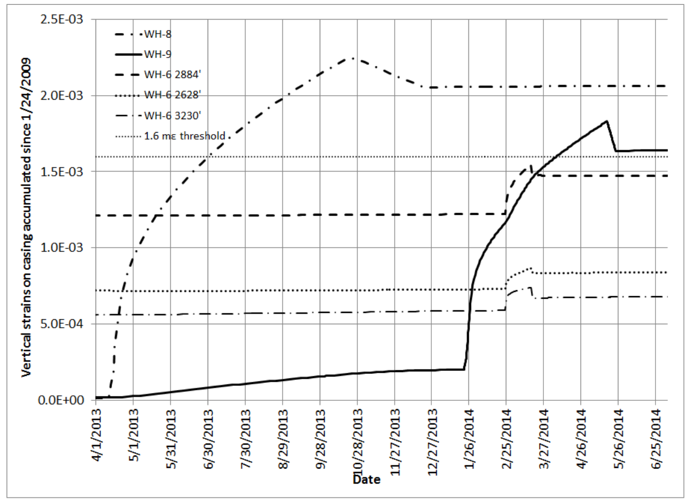

Figure 7. Predicted vertical casing strain for WH Caverns 6, 8, and 9 during scheduled 2014 workovers.

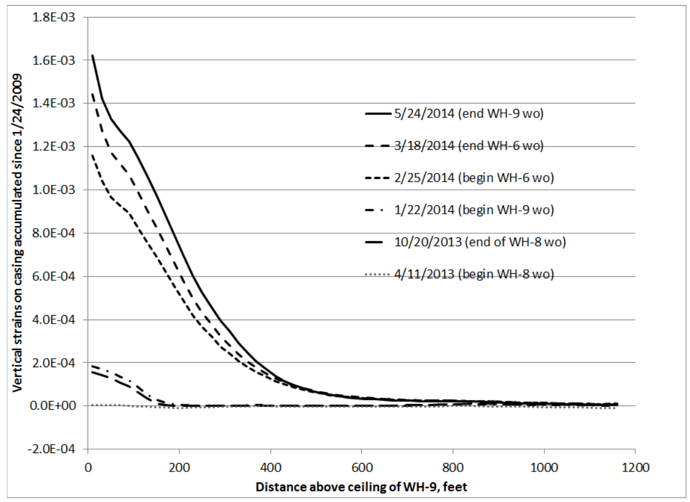

Figure 8. Predicted casing strain for WH-9 as a function of distance above the cavern roof.

- However, when WH-8 and WH-6 were at reduced pressure at the same time (April-September 2013), there is a noticeable effect on the casing for WH-9. The five-month workover on WH-8 added about 0.2 mϵ to the WH-9 casing.
- The five-month workover on WH-8 might have induced as much as 2 mϵ on the bottom of the borehole.
- The maximum strains for WH-8 and WH-9 occur at the bottom of the boreholes, whereas for WH-6 the maximum strain occurs roughly midway between the top of salt and top of cavern. This discrepancy in the location of maximum strain might be explained by cavern roof geometries used in the models (flat vs. domal), and requires further evaluation.

Based on these results, Sandia made the following recommendations:

- The maximum total workover length (i.e., duration of zero wellhead pressure) for WH Caverns 6, 8, and 9, should be 90 days, to keep the accumulated strain during a single workover to less than 1.6 mϵ.

- Because individual workovers for WH-6, 8, and 9 can apply excessive strains to their casings, it is recommended that cavern pressure monitoring during and immediately after a workover should be intensified to detect the potential development of any leaks.
- WH-6 and 8 should not be depressurized at the same time, as the combination induces additional strain on the casings for WH-9.
- For WH-6, the recommended minimum duration for depressurization to zero wellhead pressure is 5 days (or maximum rate of 52 kPa/hr); for repressurization, a minimum of 3 days at 67 kPa/hr to raise the wellhead oil pressure, followed by a minimum period of 14 days at 2.7 kPa/hr to the minimum normal operating pressure of 5.8 MPa (or wellhead brine pressure to 2.5 MPa).
- For WH-9, the recommended minimum duration for depressurization and repressurization is 5 days (52 kPa/hr).
- From a cavern integrity standpoint, there is no need to specify a maximum wellhead (or cavern roof) pressure differential between WH-6 and WH-9, so long as pressure change operations are performed slowly, and there is no indication of communication or fluid loss between the caverns (i.e. WH-6 and 9 can be depressurized either separately or together, given appropriately slow depressurization and repressurization processes).

The sonars proposed for WH-6 are meant to help answer two basic questions: 1) How much oil is left in WH-6? 2) What is the location of the oil, so that plans can be made to remove it? In order for the sonars to be useful, they must help verify two predictions from the geomechanical analyses: the geometry of the roof sag, and the amount of oil trapped by the roof sag.

Regarding the first geomechanical prediction – what is the geometry of the roof sag – Figure 9 plots the predicted roof subsidence at several dates. The simulations predict as much as 11 feet of roof subsidence near the center of the cavern. The roof depression is nearly axisymmetric, but slightly biased in the direction of nearby WH-9. The location of wellbore WH-6B where it intersects the roof is shown in the figure. The difference in elevation between the 6B entry point and the point of maximum sag is about 0.25 feet (76 mm). If the assumption is that the oil/brine interface (OBI) is at the point where WH-6B intersects the cavern roof, this means that only 70 to 80 mm of roof should be visible beneath the OBI. It is unknown if the sonar can detect that small difference accurately; if so, it would provide a means to estimate the shape of the roof above the OBI. If the sonar detects a much larger "bump" than 80 mm, it may indicate a steeper inclination of the roof than what is predicted, thus implying a larger amount of trapped oil than predicted.

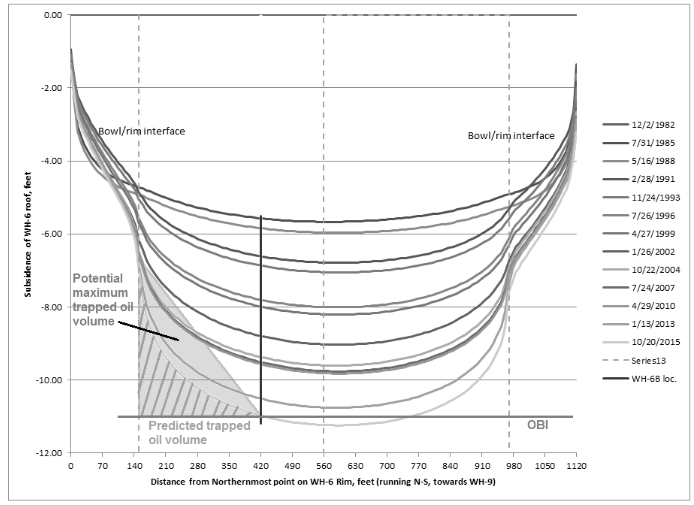

Figure 9. Predicted roof geometry of WH-6 from geomechanical calculations.

Regarding the second prediction – the amount of oil trapped by the roof sag – Sobolik & Ehgartner (2009a) calculated that the rim section of WH-6 contained approximately 1.0 MMB in 1980, and the geomechanical calculations predicted that the rim should have closed within 15-20 years. In addition, Sobolik & Ehgartner (2009a) presented data logs of Cavern 6 taken in the years 1983 to 1992. These logs were used to determine they might confirm the "lost oil" scenario regarding continued existence of the rim around the cavern. Figure 10 shows the measured changes in oil volume and interface depth beginning in 1983. From Cavern 6 data logs, oil volume starts out constant then it reduces by 1 MMB. During this volume reduction, caused by the inward deformation of the cavern by the creeping salt, one would expect the depth to the OBI to start out constant and then move upward. In fact, the interface drops this entire time period between 10 and 20 feet (3-6 m). This phenomenon seems to verify that the rim of WH-6 closed during this time period. After 1992, the cavern exhibits expected or typical behavior, with a continued decrease in oil volume (0.5 MMB) accompanied by a rising interface.

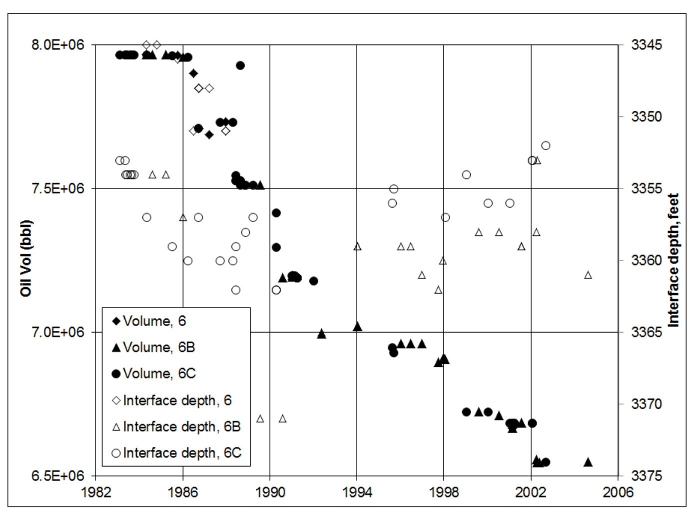

Figure 10. Measured oil volume and interface depth in Cavern 6 (Sobolik & Ehgartner, 2009a).

Based on the assumption that the rim has closed, and the predicted roof sag shown in Figure 9, estimates of the trapped oil volume in Cavern 6 have been calculated. Figure 9 also shows the areas on which these estimates are based. The hatched area is the cross-sectional area of oil-filled volume predicted to be in the cavern. When this area is integrated around the cavern (using an axisymmetric integration), the predicted volume of oil is 103,000 barrels. This volume is based on the assumption that the OBI interface is at the point where WH-6B intersects the cavern roof, and that the flat roof geometry as shown by the 1980 sonar is the true original geometry on the cavern. Because of the uncertain knowledge of the actual roof geometry, a potential maximum oil volume has been calculated based on area formed by a straight line between the maximum sag point and the top of the outer perimeter of the cavern (the gray region in Figure 9). This volume is estimated to be 170,000 barrels. Based on the current knowledge of the conditions of Cavern 6, the estimated amount of oil still contained in the cavern is between 103 and 170 thousand barrels.

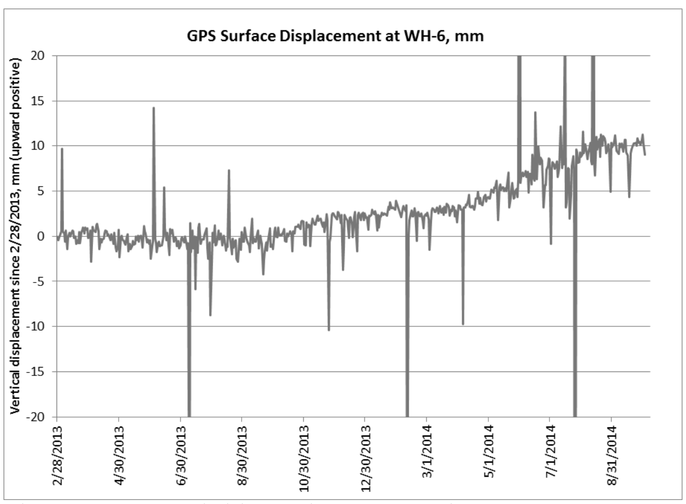

Figure 11. GPS subsidence data measured over WH-6.

In addition to pressure monitoring and wellbore inspections of WH-6, in 2013 a GPS and tiltmeter system was installed at the WH-6 wellhead to continuously monitor ground elevation, well head tilt and surface tilt over the cavern. The unit has been set to a predetermined alarm threshold and is set to alarm if ground movement/tilt exceeds those thresholds, notifying the site to investigate. Currently the system is set to issue a warning if ground displacement exceeds 76 mm or if tilt exceeds 0.1°. An alarm will sound if ground displacement exceeds190 mm or if tilt exceeds 0.3°. The warning/alarm is based on the calculated difference between measurements taken every hour, every 24 hours, and once a week. Figure 11 displays the measured elevation change since 2/28/2013. A distinct trend of upward movement begins around October 2013, totaling about 10 mm at the present date. Annual monument survey measurements typically show a downward subsidence of about 15-20 mm/year, so the cause of this apparent surface rise is currently unknown.

3 BRYAN MOUND CAVERNS 2, 3, AND 5

3.1 *Description of Bryan Mound site*

The Bryan Mound salt dome, located approximately 60 miles south of Houston, Texas, near the city of Freeport, is the largest of the SPR sites in terms of oil-storage capacity (20 caverns currently holding 43×10^6 m^3, or 226 MMB), and has operated since 1980. The geological characteristics related to the Bryan Mound site have been progressively described with greater detail (Hogan 1980; Preece & Foley, 1984; Neal et al., 1994; Stein & Rautman, 2005; Lord, 2007), and the Bryan Mound caverns have been extensively characterized and mapped (Rautman & Lord, 2007).

Figures 12 and 13 show plan views of the Bryan Mound site with the caverns' approximate locations within the salt dome, and the interface of the salt dome with the caprock and surrounding sandstone. Caverns 1 through 5 (also referred to as the Phase 1 caverns) were initially developed by Dow in 1942 for brine production in the period 1942 to 1957. These five caverns have very irregular shapes. Four of these caverns (Caverns 1, 2, 4 and 5) were purchased for the SPR in 1977 and certified as suitable for oil storage. Cavern 3 was shut down in 1957 due to its large roof span. Caverns 101-116 (Phase 2 caverns) were constructed by solution mining between 1981 and 1984 for oil storage, and have the more typical tapered cylindrical shape, with similar dimensions and spacings as the West Hackberry Phase 2 caverns. Figure 14 shows the oil storage cavern geometries based on sonar measurements obtained through 2007 (Rautman & Lord, 2007). Salt properties and anhydrite seams result in unpredictable cavern shapes as the insoluble content or dissolution rates of salt can spatially vary. This explains some of the asymmetries found in the cavern shapes.

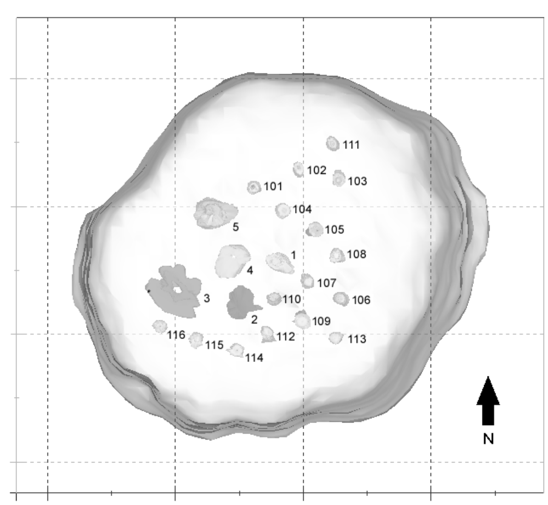

Figure 12. Top view of the Bryan Mound salt dome and oil storage cavern model (610 m grid spacing).

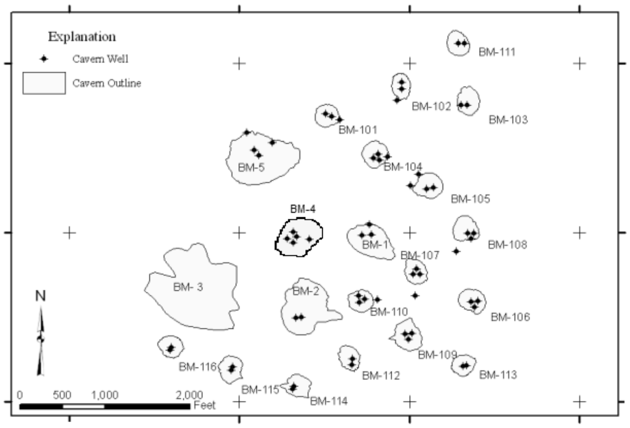

Figure 13. Schematic of the Location of the SPR Caverns at Bryan Mound.

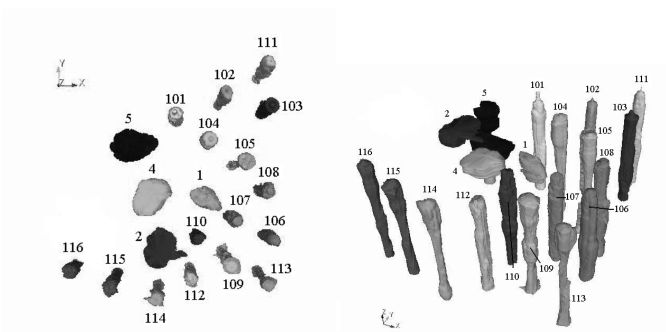

Figure 14. Visualization of the caverns at Bryan Mound SPR site.

The geomechanical behavior of the Bryan Mound site is characterized by three distinguishing features that affect site operations and the structural integrity of surface and underground structures. The features include heterogeneous salt creep properties, due to faulting, boundary shear zones, and varying levels of anhydrite impurities throughout the salt dome; a caprock was mined for sulfur in the early 20th century, resulting in significant regions of caprock that are structurally compromised and a residual high temperature environment; and potential pressure loss in the abandoned brine storage Cavern 3.

There are three caverns at the Bryan Mound site whose unusual shapes and dimensions have caused concerns about cavern collapse, sinkhole formation, and loss of accessibility to stored oil: abandoned brine storage cavern BM-3, large-diameter oil storage cavern BM-2, and very large oil storage cavern BM-5. Each of these caverns will be discussed separately.

3.2 *Description of Bryan Mound model*

Several mechanical analyses of the Bryan Mound site have been published (Sobolik & Ehgartner 2009b, 2012b, 2012c; Sobolik & Lord, 2014). These analyses utilized first JAS3D, Version 2.0.F (Blanford et al. 2001), and then Adagio (SIERRA Team, 2010, 2011; Arguello et al., 2012), both three-dimensional finite element programs developed by Sandia National Laboratories, and designed to solve large quasi-static nonlinear mechanics problems.

The salt creep at the Bryan Mound site was described in Munson (1998) as having secondary steady creep rates as one order of magnitude lower than for West Hackberry. However, field data show that the range of creep rates at BM extends over more than two orders of magnitude (Sobolik & Ehgartner, 2009b). Furthermore, because of heterogeneous nature of the Bryan Mound salt, it has to date only been modeled using the power law creep model, which is merely the secondary steady-state creep component of the M-D model. The power law creep model has been used for Waste Isolation Pilot Plan (WIPP) and SPR simulations for many years. The steady state creep strain rate is determined from the effective stress as follows:

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

where, $\dot{\varepsilon} =$ creep strain rate,
σ = effective or von Mises stress,
T = absolute temperature,
A, n = constants determined from fitting the model to creep data,
Q = effective activation energy,
R = universal gas constant.

Figure 15 shows a plan view of the meshed caverns used for the calculational model showing their placement within the salt dome. The overburden and caprock thicknesses are reasonably constant over the entire salt dome, so for meshing purposes they have been given constant values; the overburden layer is 232 m thick, and the caprock 85 m thick.

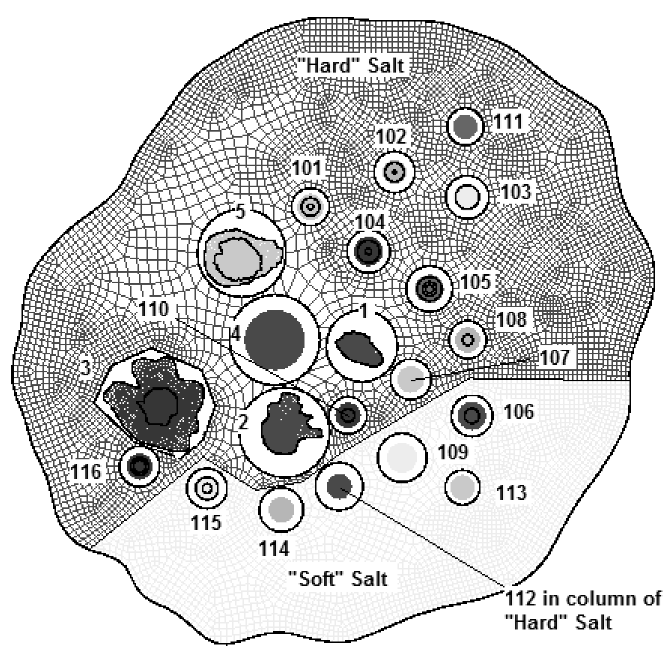

Figure 15. Bryan Mound caverns in the computational mesh.

3.3 *Concerns, action plan for BM Cavern 3*

The abandoned cavern BM-3 is a 410-m diameter cavern which was constructed for brine production and storage in the 1940s and plugged and abandoned in 1980. Cavern BM-3 is located in close proximity to several significant features of the Bryan Mound site, including four large oil and brine storage tanks, two storage caverns, and the primary access road for the site. Prior to its final closure, BM-3 had a significant documented history of fluid loss through its boreholes into the overlying caprock voids (Sobolik & Lord, 2014). Surface subsidence measurements have historically shown an unexpectedly larger subsidence rate over BM-3 than the rest of the site, typically 14 mm/yr (0.07 ft/yr) over BM-3 versus the site-average 6 mm/yr (0.02 ft/yr). Figure 16 shows a particularly egregious example of this difference between BM-3 and the rest of the site. Geomechanical calculations (Sobolik & Ehgartner, 2009b, 2012b, 2012c) that simulated a loss of fluid in BM-3 and predicted s similar surface subsidence pattern (Figure 17). The data and analyses indicate that BM-3 has and continues to lose fluid, resulting in an enhanced subsidence that may eventually affect surface facilities and boreholes for nearby storage caverns. Unfortunately, until recently these survey-based surface subsidence measurements have been very sporadic, occurring biennially until very recently, and then only quarterly. Also, there are no available cavern pressure data for BM-3, nor any other data indicating the current condition of the cavern or its associated infrastructure.

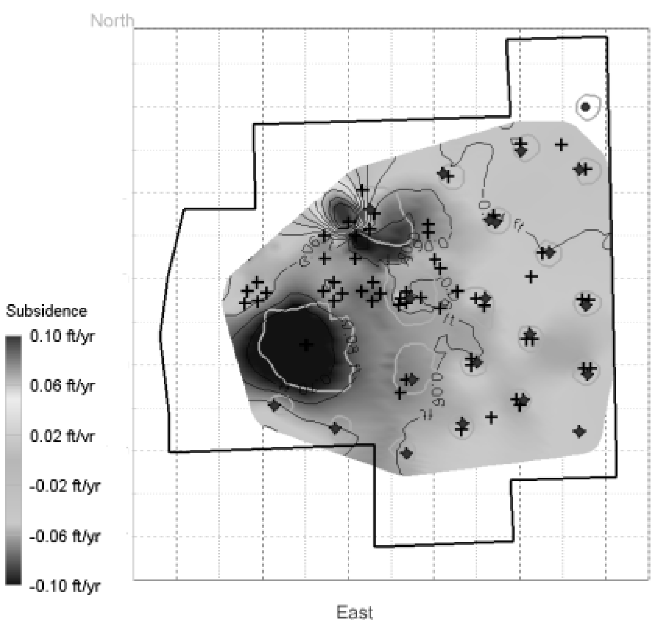

Figure 16. Contour plot of Bryan Mound subsidence rates (ft/yr) from January 2007 to April 2009.

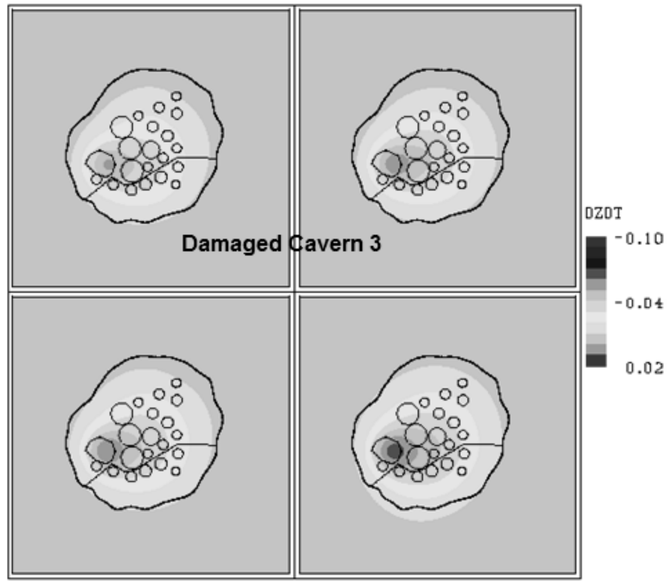

Figure 17. Predicted subsidence rates (ft/yr), damaged Cavern 3 (times August of 2010, 2011, 2012, 2013).

Additionally, the cavern's depth is at about 450 meters, only about 90 meters beneath the overlying caprock, conditions that raise concerns about cavern collapse extending to the surface. Several recent studies (Karimi-Jafari et al., 2008; NMEMNRD, 2011) identified the following parameters as high indicators of potential cavern collapse and sinkhole formation: caverns with large diameter-to-height ratios (>1); caverns with large diameter-to-depth ratios (>2/3); and caverns in close proximity (100 m) to the top or side of the salt dome. BM-3 exceeds all three conditions.

To provide better real-time monitoring, in 2013 a GPS and tiltmeter system was installed over BM-3 to continuously monitor ground elevation, well head tilt and surface tilt over and around the perimeter of the cavern. A combination GPS/tiltmeter unit was installed at the Cavern 3 wellhead, and two additional tiltmeters were installed in boreholes near the north and south extents of the cavern footprint. The warning and alarm thresholds are the same as for the GPS system installed over WH-6. Figure 18 displays vertical displacement. Over the last 18 months the GPS is averaging 8 mm/yr. This value matches that from the most current survey data (Sobolik & Lord, 2014), and also shows subsidence over BM-3 to still be higher than the surrounding site. Figures 19 and 20 display data output from the three tiltmeters over the cavern. Both in-ground tiltmeters in Figure 19 are tilting towards the south, whereas the wellhead tiltmeter is essentially stable with little or no tilt. The large spike noted around June 14^{th}, 2013 was the cause of placing the wellhead tiltmeter within a weather proof enclosure. Figure 20 displays the tiltmeter data from the Easting direction. All three tiltmeters are trending towards the east. However, it is curious that the southern tiltmeter trend resembles a seasonal cyclic pattern, whereas the northern tiltmeter does not. In general, looking at the data from both plots suggest the borehole tiltmeters, placed around the perimeter of the cavern, are tilting towards the southeast, where as the well head tiltmeter is essentially stable displaying little or no tilt. None of the values illustrated in Figures 18 through 20 exceed the established warning thresholds, nor do they give any indication of imminent stability problems for BM-3. However, it is interesting to note that the highest subsidence rate over Cavern 3 is measured at a monument located in the southeast region of the cavern.

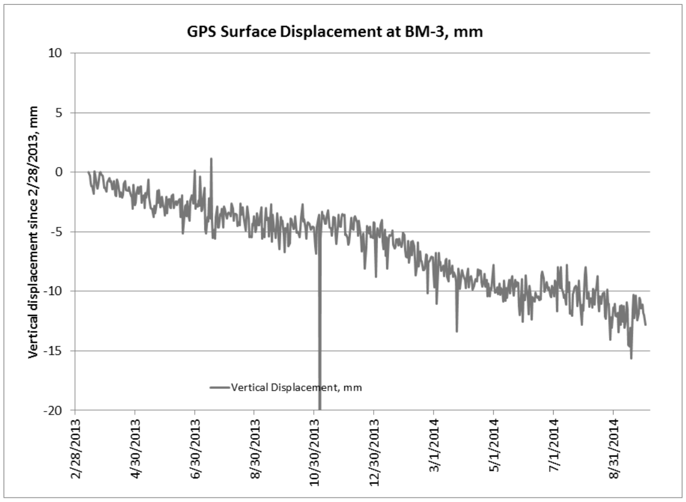

Figure 18. GPS subsidence data measured over BM-3.

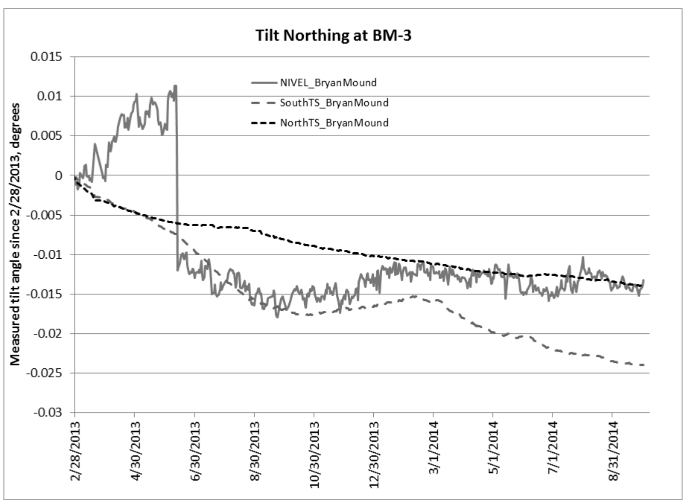

Figure 19. Northing tilt data measured over BM-3.

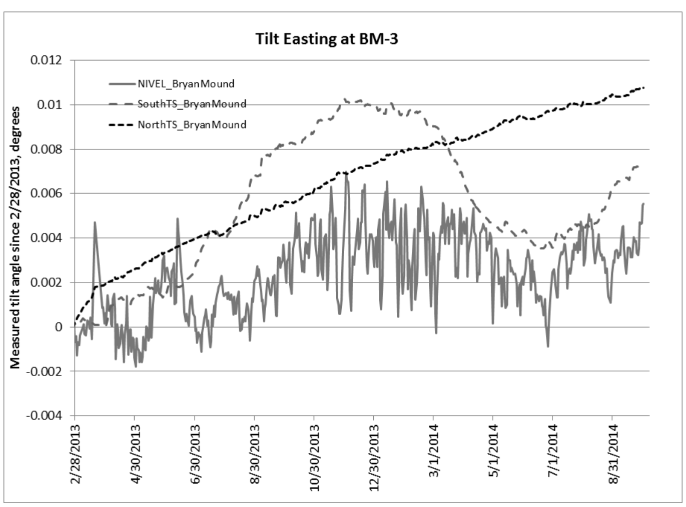

Figure 20. Easting tilt data measured over BM-3.

3.4 *Concerns, action plan for BM Cavern 2*

Bryan Mound Cavern 2 (BM-2) is a shallow, flat cavern with a diameter of about 200m, a height of about 67 m, and currently holds 7.2 MMB of oil (see Figure 21). The cavern was certified for storage in July 1985. BM-2 is a two-well cavern entered by Wells 2 and 2A; neither well has had any modifications to their original completion in 1979 (Wynn, 2014). Its location high in the salt dome (like BM-3 at about 450 m depth, only about 90 m beneath the overlying caprock) raises concerns of long-term cavern stability; however, because it is continually pressurized and monitored, those concerns are significantly mitigated.

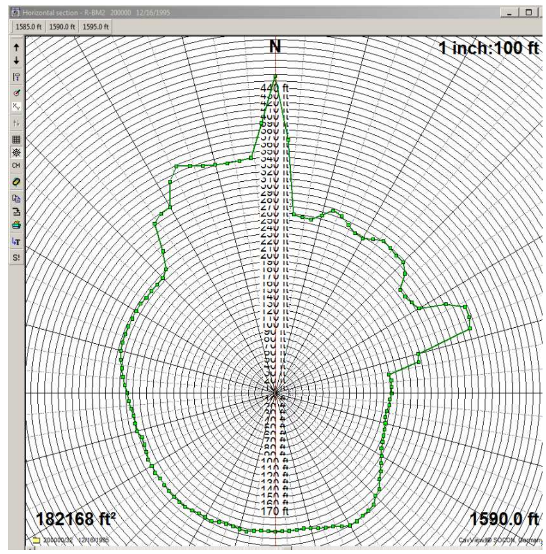

Figure 21. Plan view of BM-2, from 1995 sonar (Wynn, 2014).

There are three ongoing concerns regarding cavern BM-2:

- Much like cavern WH-6, the roof appears to have experienced significant sag, and there may be oil trapped above the OBI inaccessible for brine replacement recovery;
- The two wells have experienced significant damage and must be remediated. Such damage to the wellbore casings had been predicted by previous geomechanical analyses (Sobolik & Ehgartner, 2009b, 2012b). The drawdown (i.e. oil removal) capability of these wells is currently 91,000 barrels/day; the remediation options being considered will change that rate to between 20 to 97×10^3 barrels/day, with the larger rates incurring higher expenditures;
- There is evidence that BM-2 has been venting gas for many years. The gas flow has been continuous, resulting in a relatively predictable gas stream that is vented off on a regular basis. This situation implies that a path exists that conducts gas from outside the cavern into it. The further implication is that the current wellbores may be damaged extensively enough that they cannot be properly sealed.

To evaluate these concerns and the long-term disposition of BM-2, a plan has been developed for emptying the cavern of oil, mapping the cavern with new sonar measurements, and remediating and leak-testing the wellbores (Wynn, 2014).

3.5 *Concerns, action plan for BM Cavern 5*

Cavern 5 is a giant cavern characterized by upper and lower lobes separated by a small neck. Figure 22 shows the geometry of the cavern and the locations of the wells. This erratic geometry is highly related to the level of anhydrite encountered along at each depth; for example, the large ledge and transition zone from upper to lower lobe at about 2750 feet depth corresponds to a sudden in anhydrite content from ~10% to nearly 100%. The cavern was drilled in 1957 by Dow Chemical for brine production, and then converted to oil storage by DOE around 1980. BM-5 currently holds about 36.8 MMB of sour oil. Four wells were drilled into BM-5 prior to DOE ownership, though only two are active. Well 5A penetrates into the upper lobe, and has hanging string that extends well into the lower lobe to 3226 feet. Well 5C intersect the upper lobe, then proceeds through salt into the lower lobe near 2700 Feet. However, well 5C has a 273-mm hanging string broken off in the upper lobe at 2031 feet with oil in the brine string.

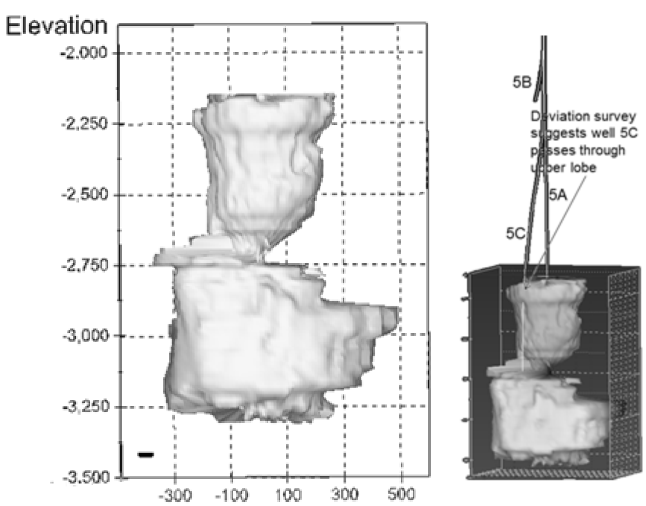

Figure 22. Geometry of BM-5 (dimensions in feet).

The geometry of the cavern creates difficulties in using fresh water to draw down the cavern for oil removal, as the possibility of a salt fall damaging the hanging string. The area of concern is in the region of the neck, at the bottom of the top lobe and top of the bottom lobe (Sobolik & Ehgartner, 2009b). Dilatant damage in this section of the cavern may cause salt falls which would potentially strike casing strings passing through the neck; this may explain this cavern's history of casing failures. These same locations are also prone to tensile stresses. Furthermore, the oil stored in BM-5 is sour oil that is known to have a propensity for emulsion problems when mixed with fresh water. This situation requires careful analysis of any process using fresh water for drawdown or cavern expansion, so as not to damage the quality of the oil. These two problems, hanging string damage and emulsion, can both be accentuated by salt falls from the neck region. The DOE is currently evaluating plans for full drawdown of BM-5 that take these problems into consideration.

4 CONCLUSIONS

Large-diameter caverns, both operational and abandoned, present long-term implications for oil storage facilities in domal salt. For operational caverns, the large diameters can affect wellbore integrity induced by significant roof sag, and also may isolate some oil above the oil/brine interface from easy accessibility. These caverns can also affect cavern and wellbore integrity of nearby caverns, and surface facilities above or adjacent to their footprints. Even when these caverns are decommissioned for oil storage purposes, they must be monitored and, if possible, pressurized to maintain their integrity throughout the life of the storage facility. The examples in this paper show how the use of a combination of cavern monitoring data (cavern pressure, sonars, surface subsidence, multi-arm calipers), wellbore remediation, and geomechanical analyses, can be integrated into the facility management process to provide direction to manage large-diameter caverns and to monitor their physical status.

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