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2015 Strategic Petroleum Reserve Bayou Choctaw Well Integrity Grading Report

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Abstract

This report summarizes the work performed in the prioritization of cavern access wells for remediation and monitoring at the Bayou Choctaw Strategic Petroleum Reserve site. The grading included consideration of all 15 wells at the Bayou Choctaw site, with each active well receiving a separate grade for remediation and monitoring. Numerous factors affecting well integrity were incorporated into the grading including casing survey results, cavern pressure history, results from geomechanical simulations, and site geologic factors. The factors and grading framework used here are the same as those used in developing similar well remediation and monitoring priorities at the Big Hill, Bryan Mound, and West Hackberry Strategic Petroleum Reserve Sites.

Acknowledgments

We would like to thank Mr. James Quern for his review of this report. This work was funded by the Strategic Petroleum Reserve program administered by the Office of Fossil Energy of the U.S. Department of Energy.

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1 EXECUTIVE SUMMARY

The U.S. Strategic Petroleum Reserve (SPR) faces the challenge of operating and maintaining nearly 120 cased cavern wells across four sites in the storage complex over operational lifetimes spanning many decades. These cemented casings provide critical isolation of cavern fluids from the surface environment and groundwater. SPR well integrity monitoring shows that some of the wells require remediation because their casing has been compromised. Remediation is required for a variety of issues including deformation, parted casing and leaky casings threads.

The cost and regulatory implications of possible fluid loss and associated remediation are high. The U.S. Department of Energy (DOE), owner of the SPR, requested that the maintenance and operations contractor, Fluor Federal Petroleum Operations (FFPO), and the geotechnical support contractor, Sandia National Laboratories (SNL), devise a well integrity evaluation system that allows DOE to prioritize wells for remediation and monitoring.

An initial framework for well grading was developed for the Big Hill SPR site during a working group meeting at the SPR project office in New Orleans in January, 2013. The results from this meeting, subsequent framework, and Big Hill well grades are presented in Lord et al. (2014). This first meeting focused on the Big Hill site in order to address an area that had multiple failures, and perhaps the most complete monitoring data set to work with.

The intent of the SPR well grading initiative is to provide grading for all the SPR cavern wells. This is being done on a site-by-site basis. This report documents the objectives, technical background materials, and grading developed during an April 2015 Bayou Choctaw well integrity grading meeting. All 15 Bayou Choctaw wells were evaluated and currently active wells were graded for monitoring and remediation priority. Factors considered in the grading process are described in detail, and an overall ranking summary graphic is presented for use as a management tool. The grading was developed with the understanding that all four SPR sites would eventually be included, so the ultimate tool will consider well integrity on a program-wide basis.

The primary outcome of the initial Big Hill well integrity grading meeting was a framework summarizing what the assembled subject matter experts considered as the primary factors impacting well integrity at the SPR sites. These factors were then consolidated into a well grading framework that captures all the elements identified by the subject matter experts. These same factors were used in the Bayou Choctaw well grading presented here. The well grading framework consists of seven grading components. These seven components are:

1. MAC survey results
2. Cavern pressure history
3. Geomechanical simulation results
4. Geological considerations
5. Composite well information
6. Cavern geometry
7. Offsite activities

These seven components are then combined to generate two final grades; one for remediation priority and one for monitoring priority. Grading values range from 1 to 5 with 5 representing the highest priority.
Each Bayou Choctaw well was considered in turn and grading values assigned by the assembled subject matter experts for each of the factors listed above; in some cases, the individual grading components were complex enough as to require sub-components to fully consider their impact. The grading was, and is intended to be, an iterative process, with the grading component values being updated as new information comes to light.

The grading framework is realized in a spreadsheet format containing all the component grading values and associated formulas. This spreadsheet will be stored in a common location which will be available for examination by anyone actively involved in the SPR project. Editing of the spreadsheet values will be limited to a select group of subject matter experts. Any changes will be captured in accompanying metadata.

The current (as of the date of this report) remediation and monitoring grade values for the Bayou Choctaw wells are listed in the Table 1-1 which is sorted by remediation priority grade. A graph showing the grading values plotted in remediation and monitoring priority space is shown in Figure 1-1.

This report, and the work behind it, represents the final step in the prioritization grading of all the SPR cavern access wells. Similar reports with well grades have already been generated for the other SPR sites. Although this report is a static document, the well grades themselves are dynamic and will be updated as newer or additional information becomes available.

Table 1-1. Current Bayou Choctaw remediation and monitoring well grades.

Well ID	Remediation Grade	Monitoring Grade
19	4	2.29
15A	2.5	1.51
20	2	1.67
101A	2	1.89
15	1.75	1.55
17A	1.75	1.57
102A	1.75	1.47
18	1.25	1.58
19A	1.25	1.41
101B	1.25	1.90
17	1	1.42
18A	1	1.53
20A	1	1.60
102B	1	1.27
4**	-	3.22

*cavern 20 currently contains no directly accessible oil

**cavern 4 has never been used to store oil by the SPR

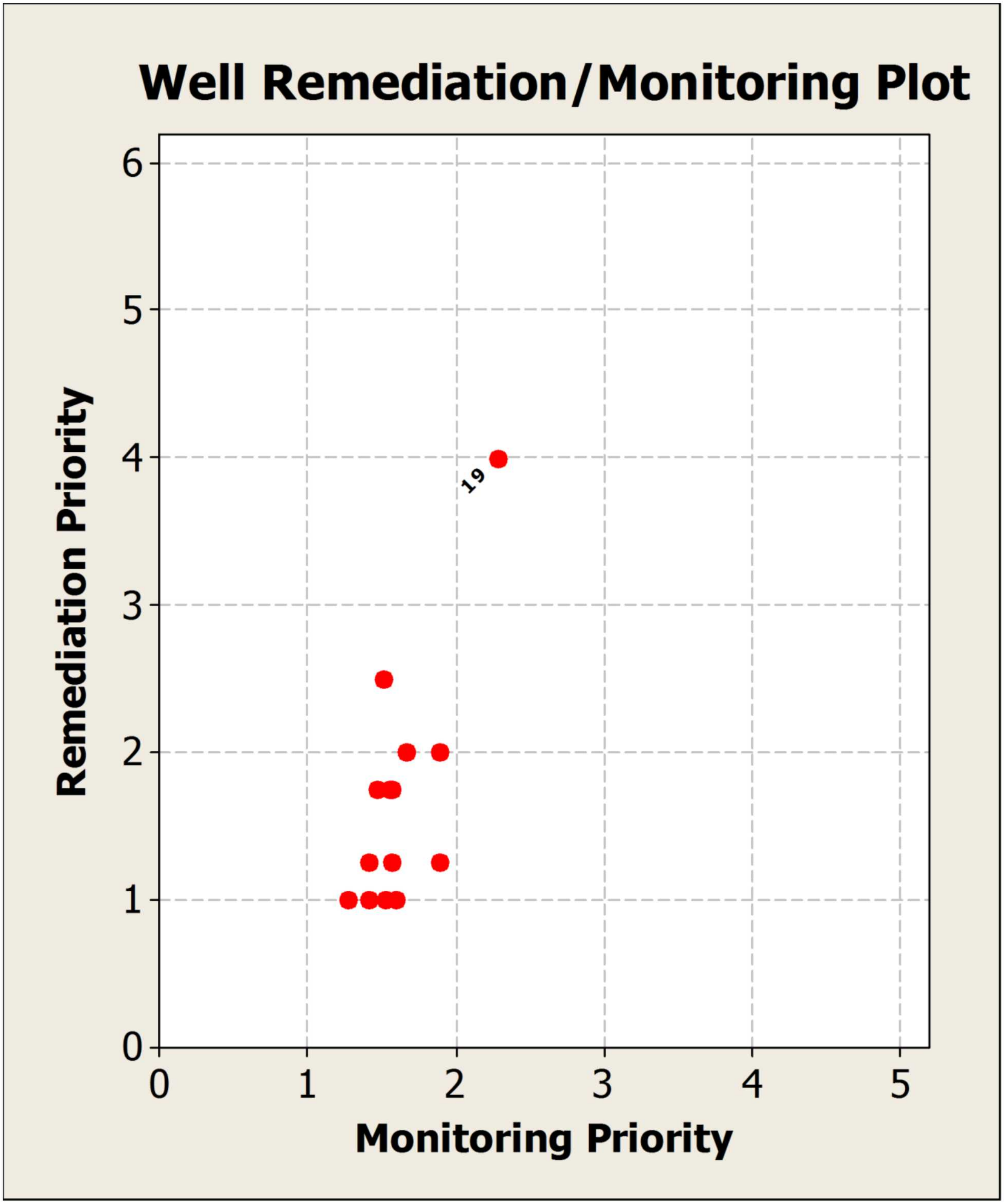

Figure 1-1. Plot of current Bayou Choctaw well grades for remediation and monitoring. Wells with remediation grades greater than 3 are labeled.

NOMENCLATURE

BBL	Barrel (42 US gallons)
BC	Bayou Choctaw
BM	Bryan Mound SPR site
DOE	U.S. Department of Energy
FFPO	Fluor Federal Petroleum Operations
MIT	Mechanical Integrity Test
MAC	Multi-Arm Caliper
SNL	Sandia National Laboratories
SPR	Strategic Petroleum Reserve

2 INTRODUCTION

The U.S. Strategic Petroleum Reserve (SPR) faces the challenge of operating and maintaining nearly 120 cased cavern wells across four sites in the storage complex over operational lifetimes spanning many decades. These cemented casings provide critical isolation of cavern fluids from the surface environment and groundwater. SPR well integrity monitoring shows that the wells require remediation for a variety of issues including: (i) deformation and/or parted casing at the salt-caprock interface, (ii) deformation at the historical sulfur production zone in the Bryan Mound caprock, and (iii) leaky threaded casings.

With increasing age, the SPR sites have seen an increase in well integrity concerns (Lord et al., 2014; Erskine, 2013). The cost and regulatory implications of possible fluid loss and associated remediation are high. The U.S. Department of Energy (DOE), owner of the SPR, requested that the maintenance and operations contractor, Fluor Federal Petroleum Operations (FFPO), and the geotechnical contractor, Sandia National Laboratories (SNL), devise a well integrity evaluation system that allows DOE to prioritize wells for remediation and monitoring. DOE, SNL, and FFPO convened a working group meeting at the SPR project office in New Orleans on January 29-31, 2013 in order to discuss and develop a common grading system for prioritizing SPR wells. This initial meeting focused on the Big Hill site in order to address an area that had multiple failures, and perhaps the most complete monitoring data set to work with. In this meeting, a framework and process for the grading of SPR wells was devised. This grading scheme prioritized wells according to remediation and monitoring needs. The framework was first applied to the Big Hill SPR site. This process and the associated grading are documented in Lord et al. (2014). This report presents the application of this process to the Bayou Choctaw SPR site.

2.1 Scope of Report

This report documents the objectives, technical background materials, and grading process developed during the April 2015 Bayou Choctaw (BC) well integrity grading meeting. All 15 currently accessible BC wells were evaluated and graded for monitoring and remediation priority. Well BC-4 was included in the analysis strictly for monitoring considerations; the BC-4 cavern has never contained oil for the SPR project. In addition, cavern BC-20 has been decommissioned, and no longer contains readily accessible oil; the wells for this cavern were included in the analysis to provide information for the long term stewardship of this cavern.

Factors considered in the grading process are described in detail below, and an overall grading summary graphic is presented for use as a management tool. The grading was developed with the understanding that all four SPR sites would eventually be included, so the ultimate tool will consider well integrity on a program-wide basis.

3 FACTORS CONSIDERED

The cavern well systems are complex and dynamic. Many factors must be considered when determining the drivers for monitoring and remediation. SNL and FFPO subject-matter experts came together to present and discuss what they believe to be a necessary set of factors for resource planning and risk mitigation purposes. These include

1. Site geology
2. Geomechanics
3. Regulatory drivers
4. MAC analysis and ranking
5. Pressure monitoring

A general discussion regarding each of these factors, along with a presentation of the general character of the Bayou Choctaw wells is given below.

3.1 General Description of BC Wells

The Bayou Choctaw site consists of a mixture of pre-existing caverns that were acquired by the SPR, and caverns that were developed by the SPR for petroleum storage. One of the pre-existing caverns, BC-4, was leached into the overlying caprock and hence, never used for oil storage by the SPR. As such, the well for this cavern is not considered here for remediation grading, but is given a monitoring grade for reference. In addition, cavern BC-20 is currently decommissioned and does not contain readily accessible storage oil. This cavern was decommissioned due to its close proximity to the margin of the salt dome.

The pre-existing caverns acquired by the SPR were typically single well caverns, with the SPR adding a second access well after taking ownership. Although there is some variety in the well completions at Bayou Choctaw, the typical well consists of multiple nested cemented casings, with the inner-most casing having an outer diameter of 13 3/8 inches.

All the active caverns at Bayou Choctaw have paired wells, with one of the wells having a hanging tubular string suspended within the inner most cemented casing. This hanging string extends to very near the cavern bottom and is used to move brine in and out of the cavern. Figure 3-1 shows example well completions for Cavern 15 at Bayou Choctaw. Table 3-1 lists the development history and number of wells per cavern for the Bayou Choctaw site.

Table 3-1. Well count for each Bayou Choctaw SPR Cavern

Cavern	Development History	Well Count
4	Pre-SPR	1
15	Pre-SPR	2
17	Pre-SPR	2
18	Pre-SPR	2
19	Pre-SPR	2
20	Pre-SPR	2
101	SPR Developed	2
102	SPR Developed	2

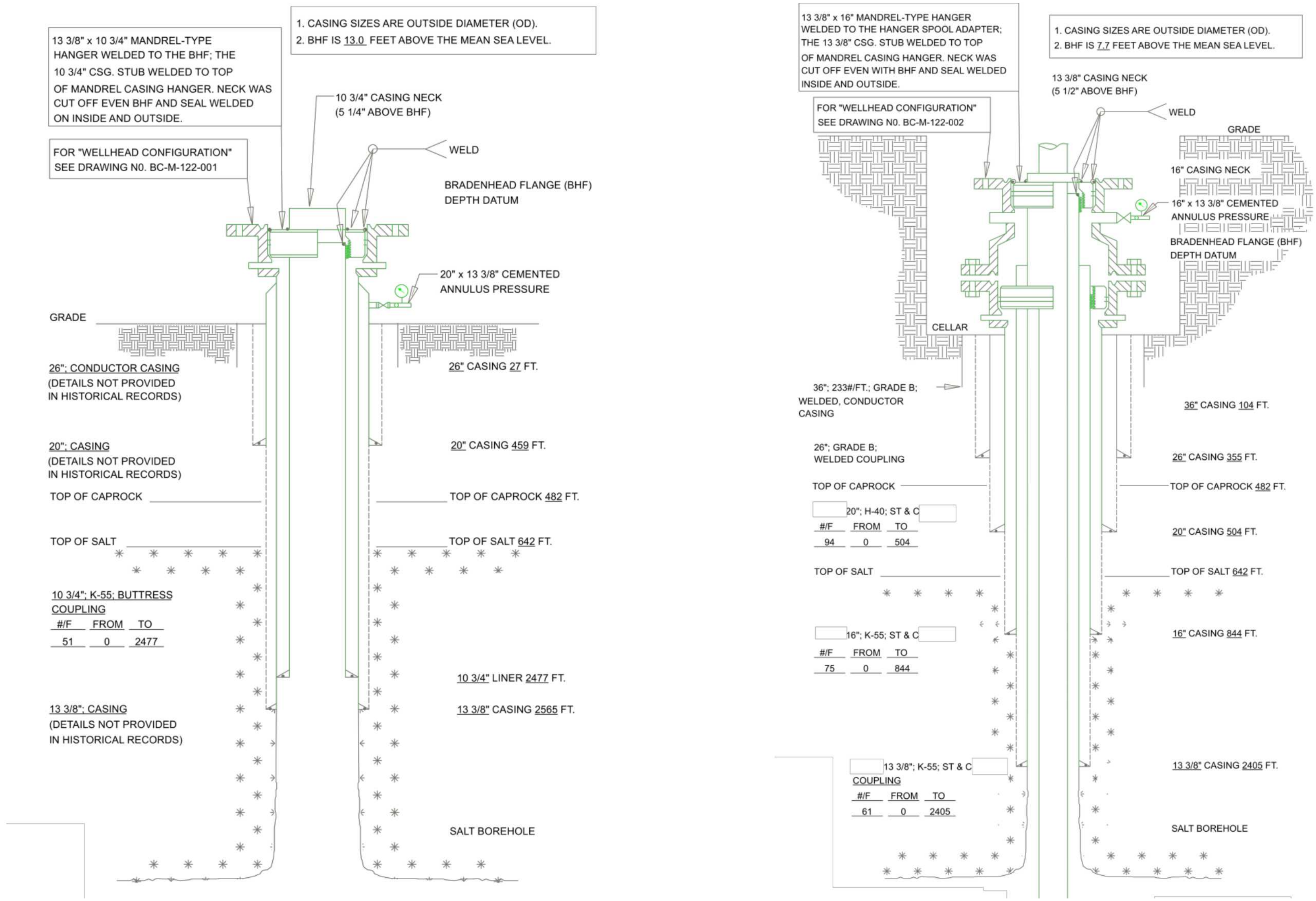

Figure 3-1. Example well completion diagrams for the Bayou Choctaw SPR site. Well BC-15 (left) demonstrates an original 13 3/8" inner casing which was subsequently lined with a 10 3/4" casing. Well BC-15A (right) shows an original 13 3/8" inner casing with a hanging string.

3.2 Bayou Choctaw Site Geology

3.2.1 Geology

Understanding the Bayou Choctaw geology will aid in interpretation of the processes affecting cavern well integrity. Bayou Choctaw is one of a multitude of salt domes located along the U.S. Gulf Coast. The Bayou Choctaw salt dome was discovered by seismic exploration and is relatively small, being only about one mile in diameter. The first oil well was drilled in 1931. Since 1931 over 300 wells have been drilled for gas and oil exploration. In 1934 brining operations began, resulting in 20 caverns. DOE purchased 11 of the leached caverns and used five of those for crude oil storage.

<u>Caprock</u>

The Bayou Choctaw salt dome is overlain by a caprock, which is the product of the accumulation of insolubles from the dissolution of the domal salt at groundwater level. At Bayou Choctaw the caprock is unusual because of the shale content. The caprock is comprised of granular gypsum interspersed with lenses of clay. One single massive section of gypsum and clay is recognized near the base of the caprock. The top of caprock is at approximately 400 to 500 feet below ground surface (Figure 3-2). The caprock is approximately 200 to 300 feet in thickness.

Two boreholes were drilled in 1978 through the caprock and into salt, Core Hole 1 was drilled directly south of Cavern Lake (i.e. collapsed Cavern 7) to a depth of 809 feet, and Core Hole 2 was drilled 100 feet north of Cavern 4 to a depth of 668 feet. Both core holes experienced loss of circulation and occurrence of gas, specifically ethane. The stratigraphy over both caverns is essentially the same; however, core recovery from Core Hole 1 was less than 50%, whereas recovery from Core Hole 2 was generally 100%. The core logging from the boreholes identified a single massive section of structurally stable gypsum and clay near the base of the caprock, which is thought to be maintaining the structural stability of the Cavern 4 roof. The section is 24 feet thick near Cavern 4 and approximately 10 feet thick in the vicinity of Cavern 7. Near Cavern 7 in Core Hole 1 two cavities were discovered within the salt. The first one was large enough to be sonar surveyed and was found to be 11 feet in extent. A cavity was also noted in Core Hole 2 at the salt-caprock interface (PB-KBB, 1978).

Lost circulation zones encountered during drilling provide information on the structural integrity of the caprock, generally inferring that a vuggy zone has been intercepted. At Bayou Choctaw there is no information on cavern wells, 102B, 15, 18, 19, and 20 within the Sandia SPR library. However, loss circulation zones were noted during the drilling of 101A (676'-1040') and 17A (682-1051').

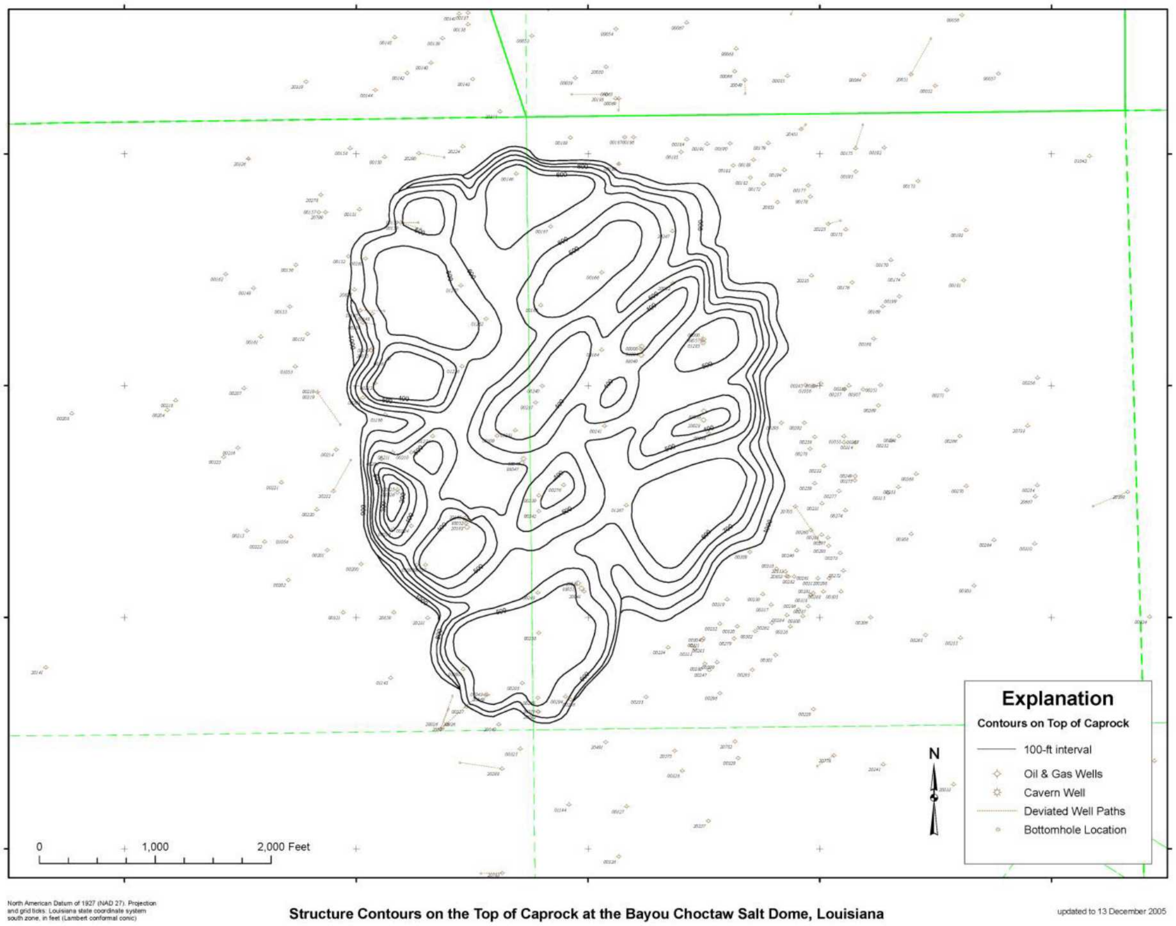

Figure 3-2. Map showing structure contours drawn on the top of caprock.

Salt

The Bayou Choctaw salt dome is generally cylindrical in shape and leans towards the west exhibiting a significant overhang (Figure 3-3). The top of salt is at a depth of approximately 700 feet. The dome is essentially flat across the top, but structural detail can be distinguished and those patterns mapped to infer the boundaries between separate salt spines.

The Bayou Choctaw salt dome is rather homogeneous in composition. Salt core was collected during the drilling of Cavern 101 and during the development of the second well for Cavern 102. The cores together span a depth within the salt from approximately 1060 feet to 4700 ft. In general the salt alternates between dark grey anhydrite bands and clear salt. Anhydrite impurities can be up to 5%.

Structurally, the overhang to the west may cause the greatest concern to caverns located within that region. The salt is most likely moving in a horizontal direction within that region.

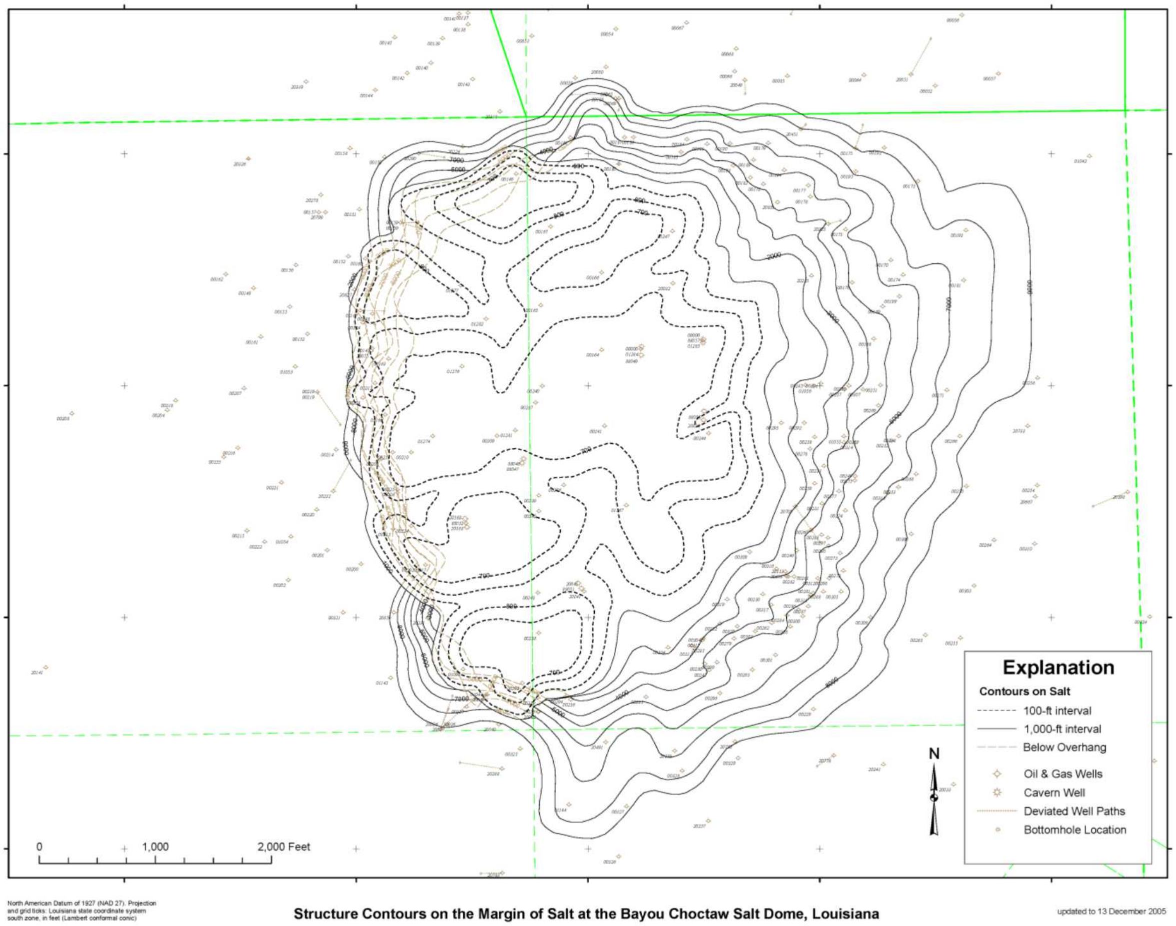

Figure 3-3. Map showing structure contours drawn on the margin of salt. Contours below the overhang are shown in brown.

Spines/shear zones

Salt domes in general are thought to consist of several spine complexes (Kupfer, 1976). Shear zones are regions separating salt spines, typically characterized by containing impurities, compositional change, physical property variation, and inclusions of hydrocarbons. Along with the mapped structure across the top of salt, salt spines and corresponding boundary shear zones have also been inferred from mapping the top of the caprock structure. Rautman and others (2005) suggest that caprock "records" cumulative salt movements. Generally, thick regions of caprock represent accumulation of large quantities of impurities; implying large quantities of salt were dissolved during active uplift. Whereas, thin caprock suggest relatively small quantities of salt has been dissolved implying a region of less uplift activity. Salt spines are inferred from identifying regions of thick caprock. Figure 3-4 displays the caprock isopach map displaying the thickness variations. The thickest regions correlate to the salt structural highs. The thickest caprock region is located over the western flank of the dome, which overlies the salt overhang. Figure 3-5 displays an interpretation of the possible boundary shear zone locations along with the location of the underlying caverns. Cavern wells near shear zone boundaries may be subjected to greater shear stress.

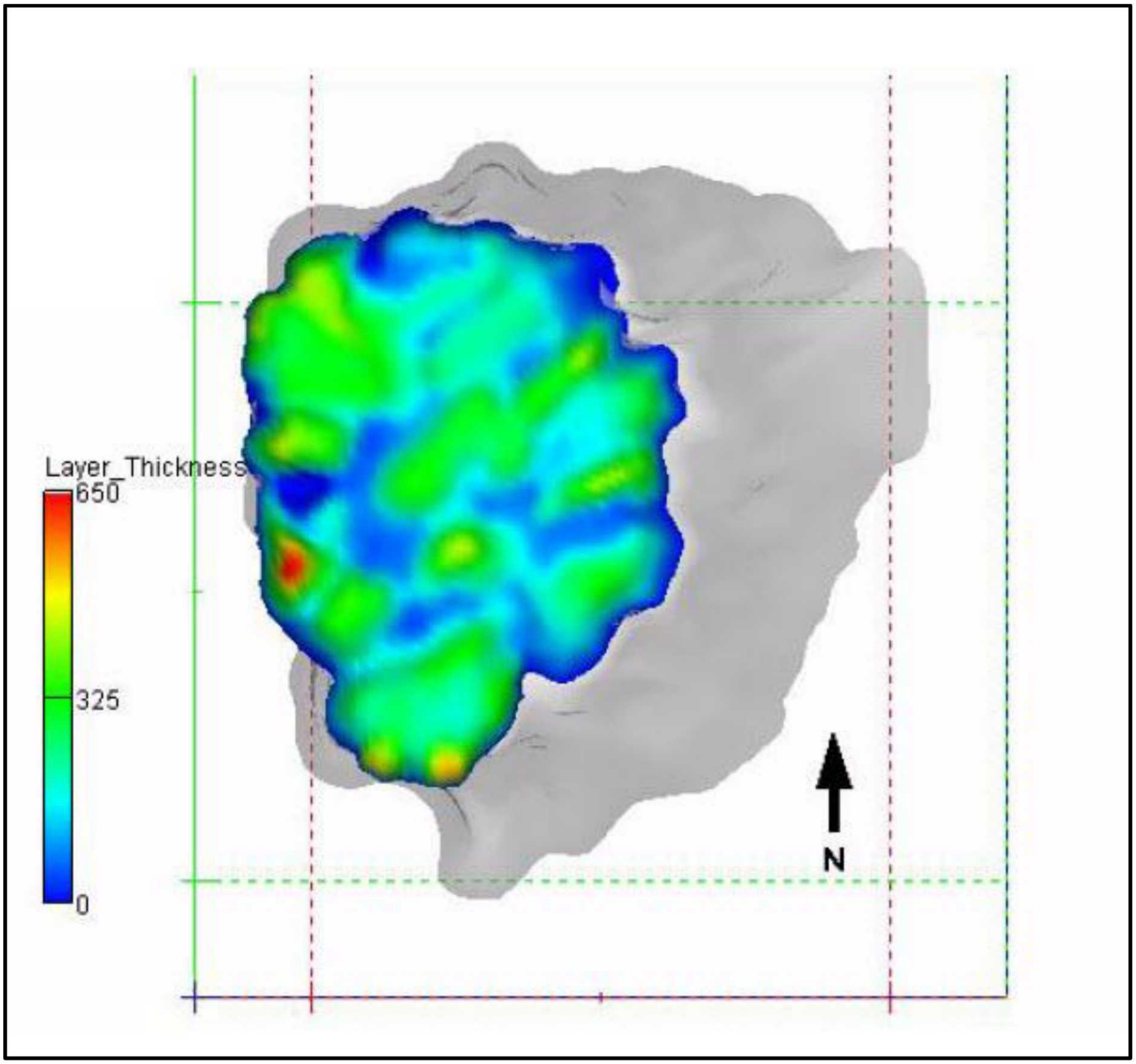

Figure 3-4. Top view of a model showing the color-coded thickness of the caprock overlying the Bayou Choctaw salt dome.

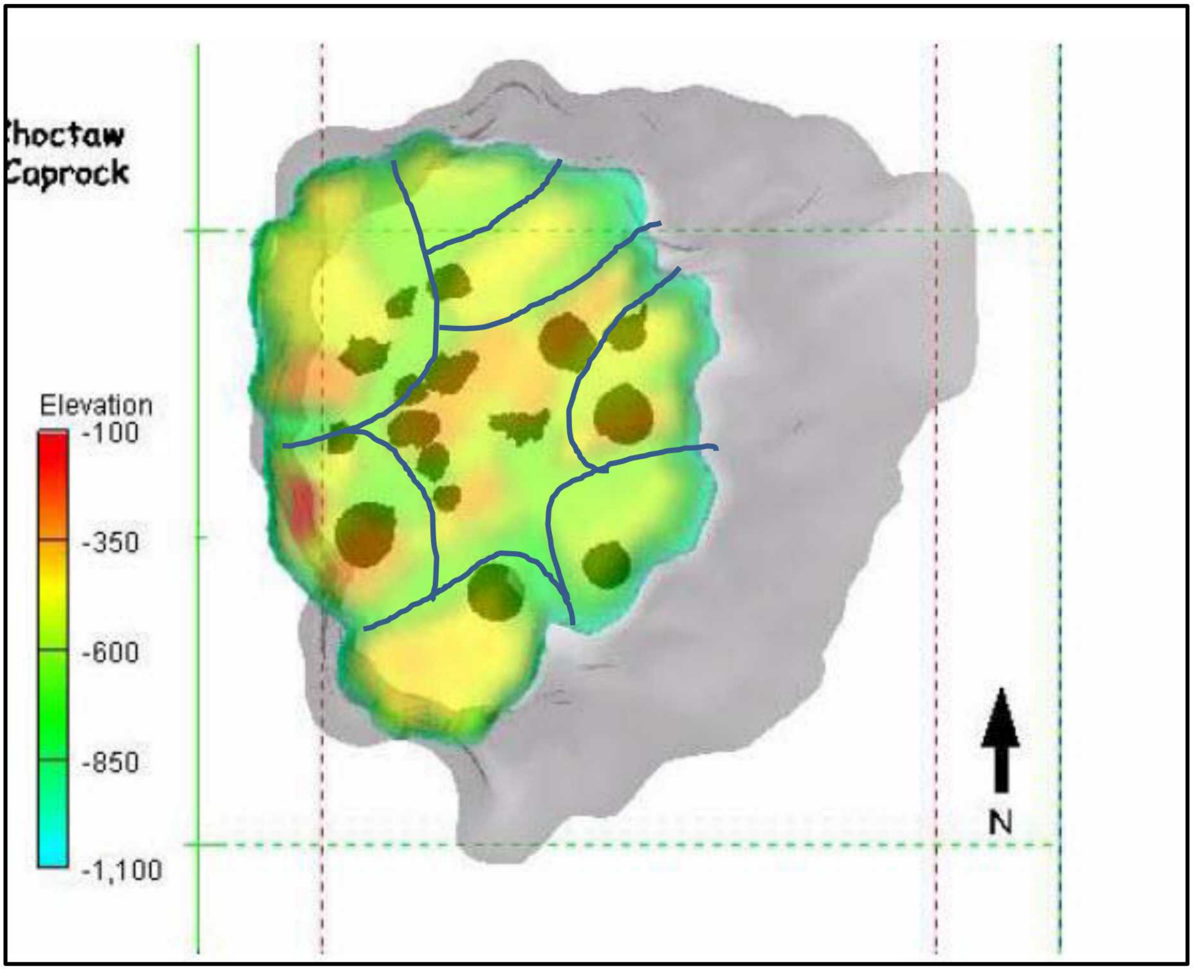

Figure 3-5. The Bayou Choctaw cavern field shown in relationship to the structural geometry of the top of caprock. Inferred boundary shear zones are designated as lines.

Boundary shear zones are also identified by regions of impurities, compositional changes, physical property variation, and inclusions of hydrocarbons. Table 3-2 lists the number of salt falls documented in each cavern. Salt falls may indicate regions of higher impurities, which further support the presence of a boundary shear zone. Wells near boundary shear zones may be subjected to additional stresses. Cavern 101 has experienced the greatest number of salt falls.

Table 3-2. Listing of Bayou Choctaw cavern salt falls.

Cavern	# Salt Falls
BC-4	0
BC-15	1
BC-17	1
BC-18	0
BC-19	0
BC-20	1
BC-101	4
BC-102	1

Cavern Communication

Several of the abandoned brining caverns at Bayou Choctaw have shown to be in communication with each other across the northwestern region of the site either through the caprock or salt (Figure 3-6). Most notable is the connection among caverns 3, 11, and 13. These three caverns are in pressure communication with each other and are connected at low pressures (<300 psi) through the salt and at high pressures through the caprock (>300; PB-KBB, 1978). These caverns are in close vicinity to both collapsed Cavern 7 and Cavern 4. There are a number of documented events that suggest Cavern 4 is in communication specifically with Cavern 1, 7, and 10. Allied Chemical's Cavern 7 well history (ACER, 1981; Appendix A) notes that when Cavern 7 lost circulation, in October 1942, Cavern 4 recorded a pressure increase. Several other instances of interaction between caverns are noted in a memo from Ney to Mazurkiewicz (Ney, 1980): (1) In 1953, the Cavern 7 well casing and brine string broke at the caprock-salt interface. The string was pulled out and an attempt was made to airlift brine samples out of the cavern. Operations were stopped when a pressure drop was noted at the Cavern 4 wellhead. (2) In 1954 the collapse of Cavern 7 caused a 1500 gpm outflow at Cavern Well 4. (3) When Cavern Well 1 lost flow there was a subsequent pressure increase seen at Cavern 4. And lastly (4) a pressure surge was noted at Cavern 4 when the casing in Well 10 ruptured. It is clear that the caprock is significantly fractured, specifically documented in the northwest quadrant of the dome, allowing for communication between caverns. A crumbled caprock in general has the propensity to cause a host of problems with well integrity.

DOE SPR Bayou Choctaw Site

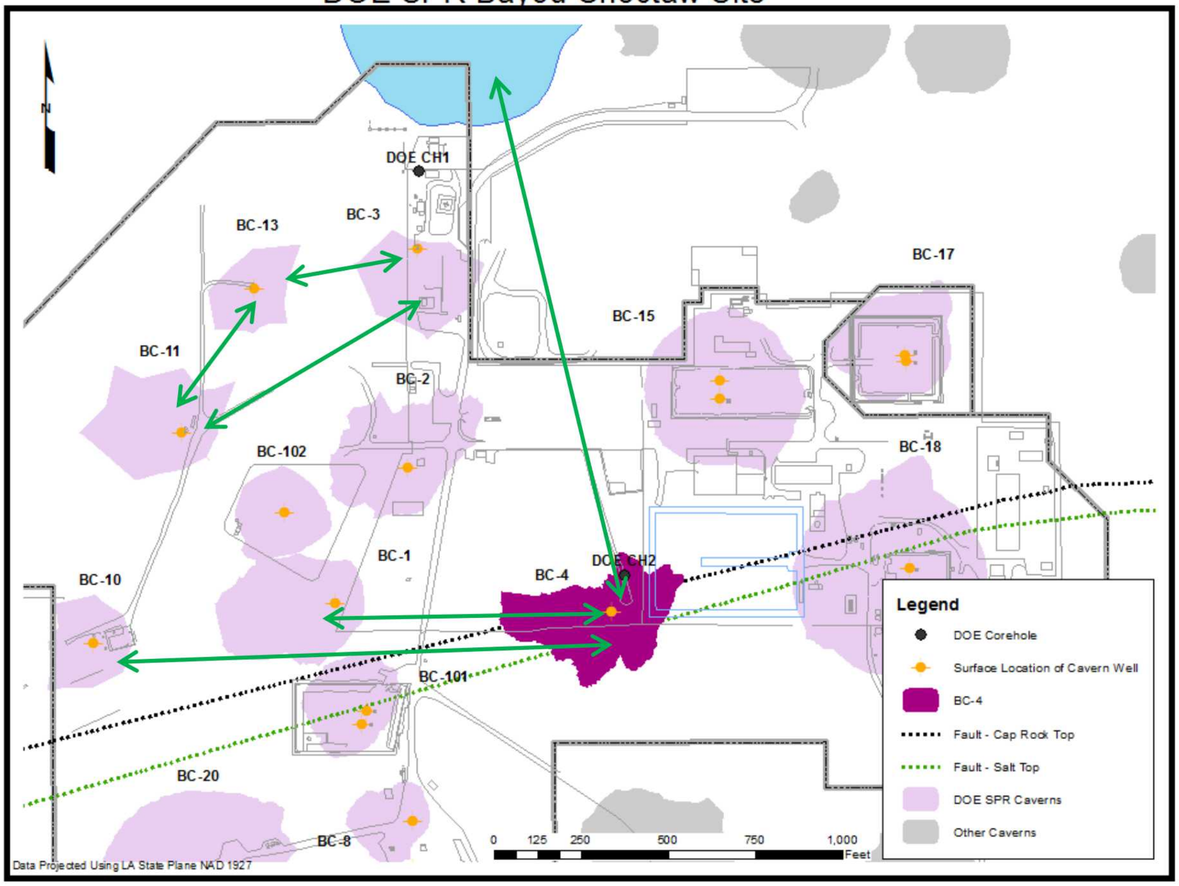

Figure 3-6. Map displays communication between the shallow abandoned caverns. Cavern footprints in pink and abandoned Cavern 4 in purple. Green arrows show path of communication between caverns.

3.2.2 Subsidence

Typically, cavern closure manifests itself at the surface as subsidence. Monitoring subsidence rates is one tool to monitor cavern integrity and geologic processes that may affect well integrity. The Bayou Choctaw subsidence program was initiated specifically to monitor for potential flooding and the stability of Cavern 4. Subsidence surveys have been conducted either annually or biennially at the site since 1982. In general the average subsidence rates calculated for the Bayou Choctaw site has been negligible. Historically, SPR subsidence rates are calculated by subtracting historic data from the current elevations. This method produces a negative rate indicating subsidence, or a positive rate indicating uplift. Figure 3-7 displays the latest rates calculated over the site in 2014 with the average subsidence at -0.01 ft/yr. Shown are the monument and markers, cavern well locations and the DOE boundary. The display shows that the rates are pretty uniform site wide. Over the history of site monitoring program there has never been any indication that the ground above Cavern 4 is subsiding at a faster rate than rest of the site.

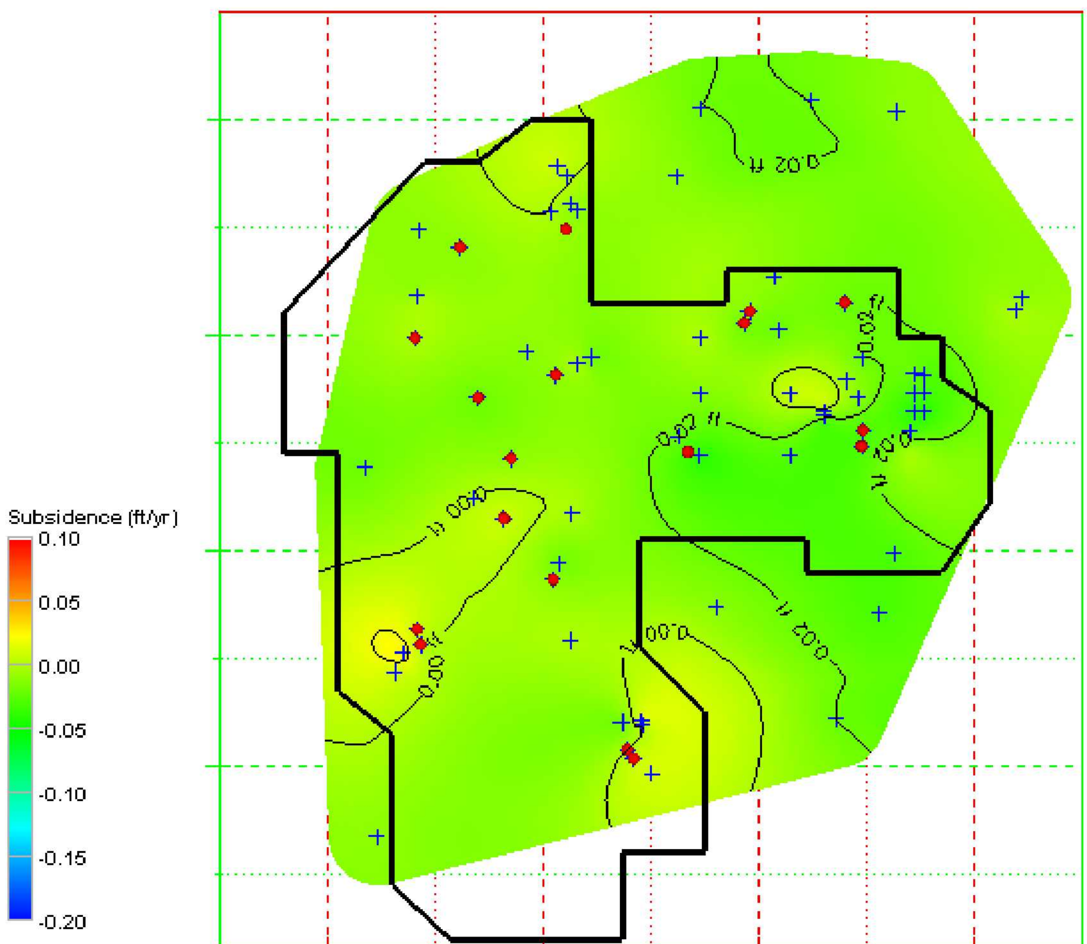

Figure 3-7. Contour plot of subsidence rates (ft/yr) using both markers and monuments from April 2013 to April 2014. Monument and marker locations are noted by blue crosses while SPR caverns are identified as red circles.

GPS and Tiltmeter Monitoring
A GPS and tiltmeter system was installed over Cavern 4 in 2013 to replace the existing system that had been in place since 1988. The GPS unit continuously monitors changes in ground elevation and the tiltmeter monitors well head tilt. Each 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 0.25" or if tilt exceeds 0.05°. An alarm will sound if ground displacement exceeds 0.625" or if tilt exceeds 0.09°. The warning/alarm is based on the calculated difference between measurements taken every hour, every 24 hours, and once a week. The system was installed in the month of March, 2013.

The GPS data is displayed as a plot in Figure 3-8 presenting vertical displacement. The GPS unit was physically removed from the wellhead July 28, 2013 for sonar and wireline surveys to be run. The data presented is from August 15 to present, after the GPS system was re-established on the wellhead and the system reset. The measured surface displacement appears to be cyclical and quite likely related to temperature (Figure 3-9). The results are not concerning.

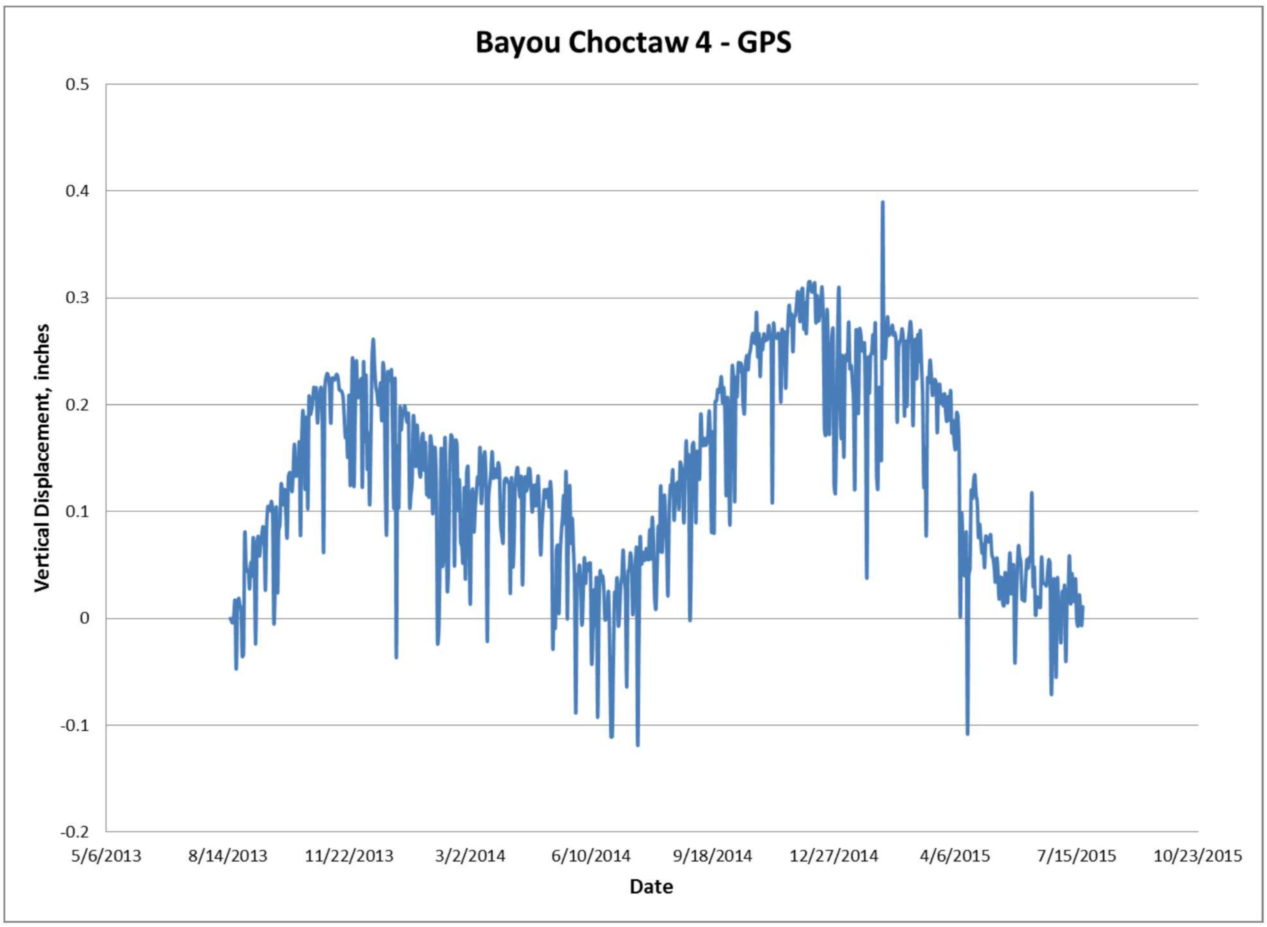

Figure 3-8. Plot of GPS measured vertical displacement.

Figure 3-10 and Figure 3-11 display tiltmeter data recorded from both the Northing and Easting directions, respectively. The data presented was recorded after the GPS and tiltmeters were reinstalled after being removed for well logging July 28, 2013. The tiltmeter data also appears to be cyclic and follow temperature variations. Overall the tilt is trending towards the north – northwest. The degree of tilt seen is not of concern.

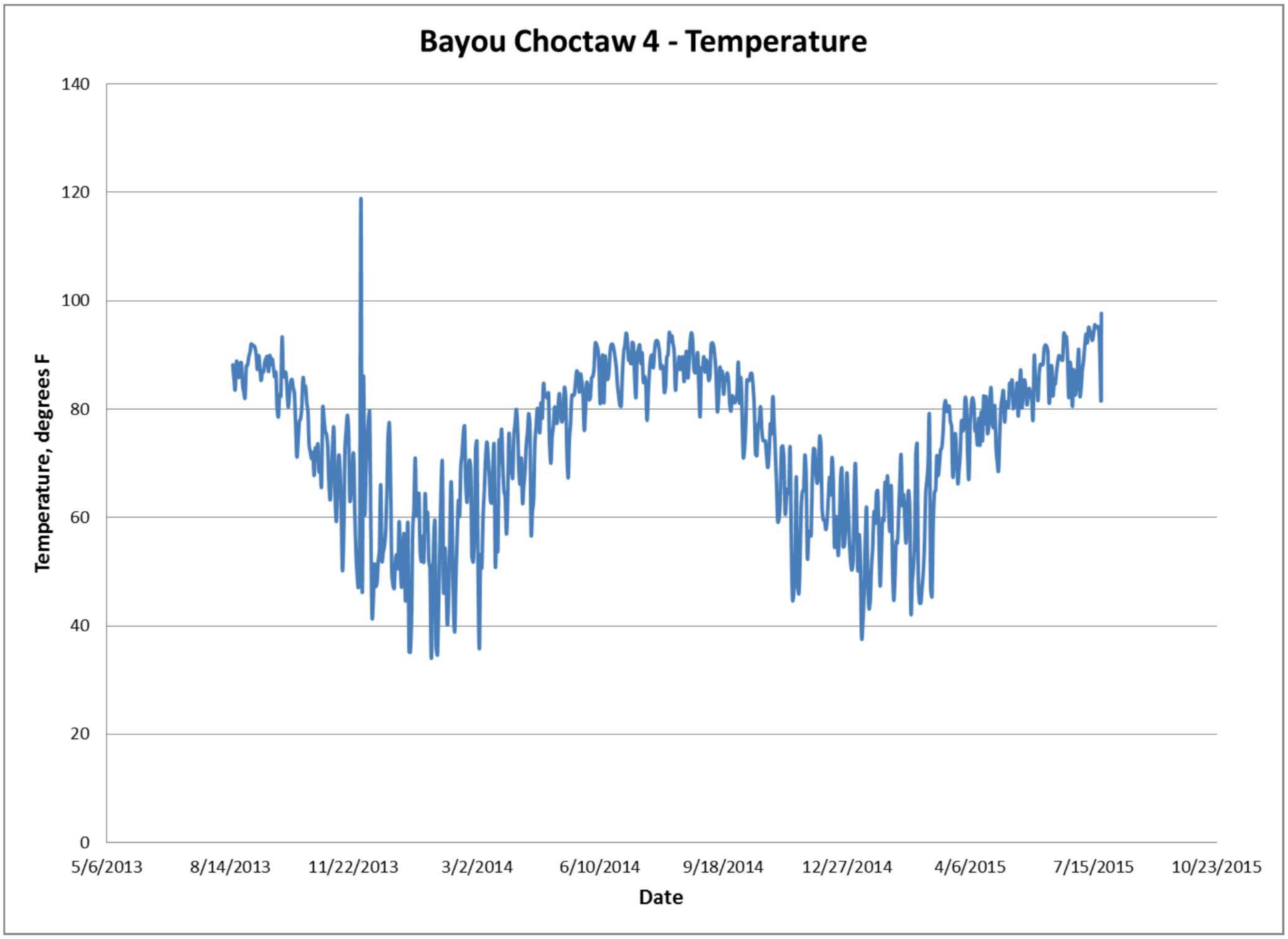

Figure 3-9. Plot of temperature at Bayou Choctaw.

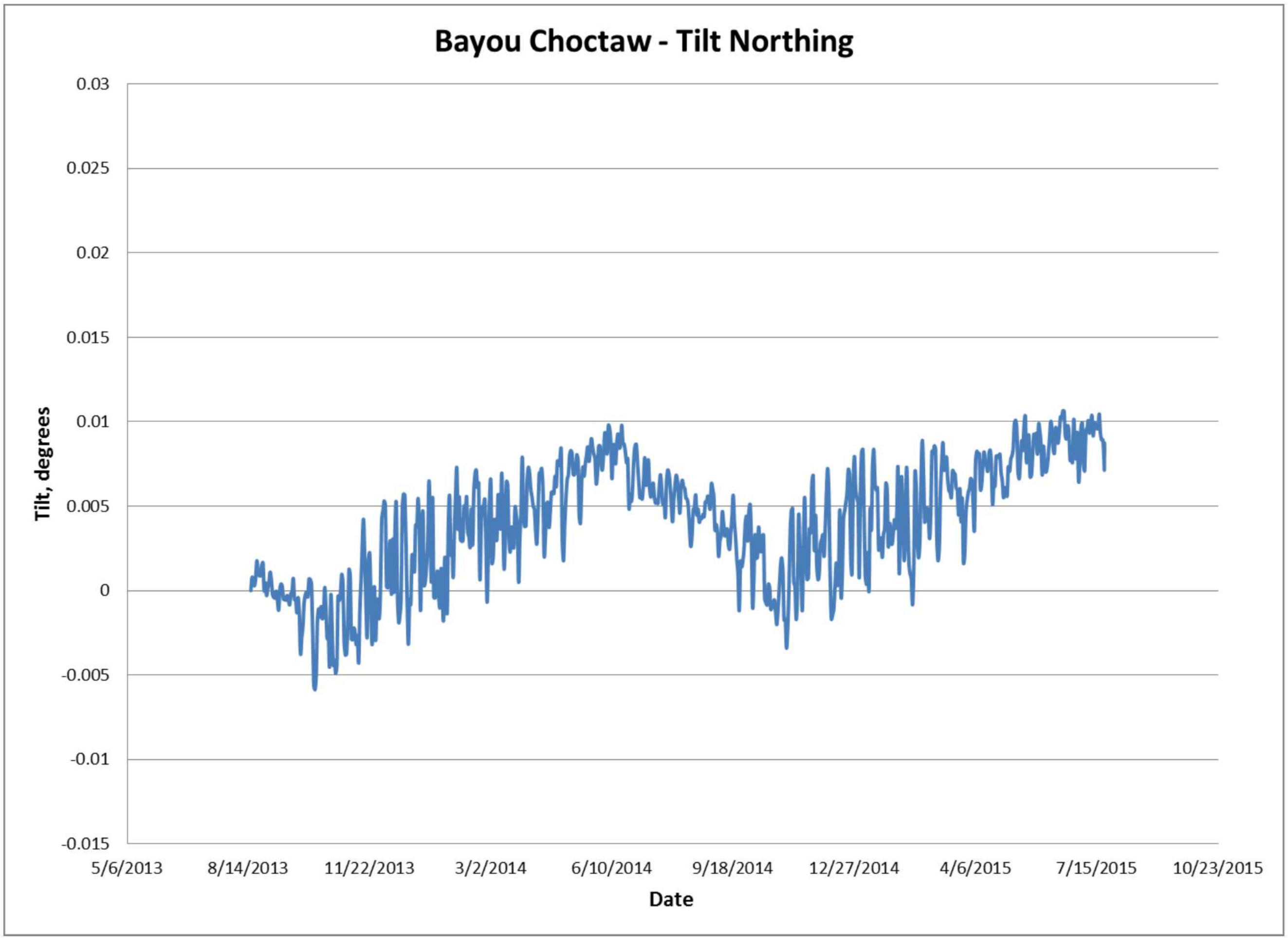

Figure 3-10. Tiltmeter plot, displaying tilt from the Northing direction.

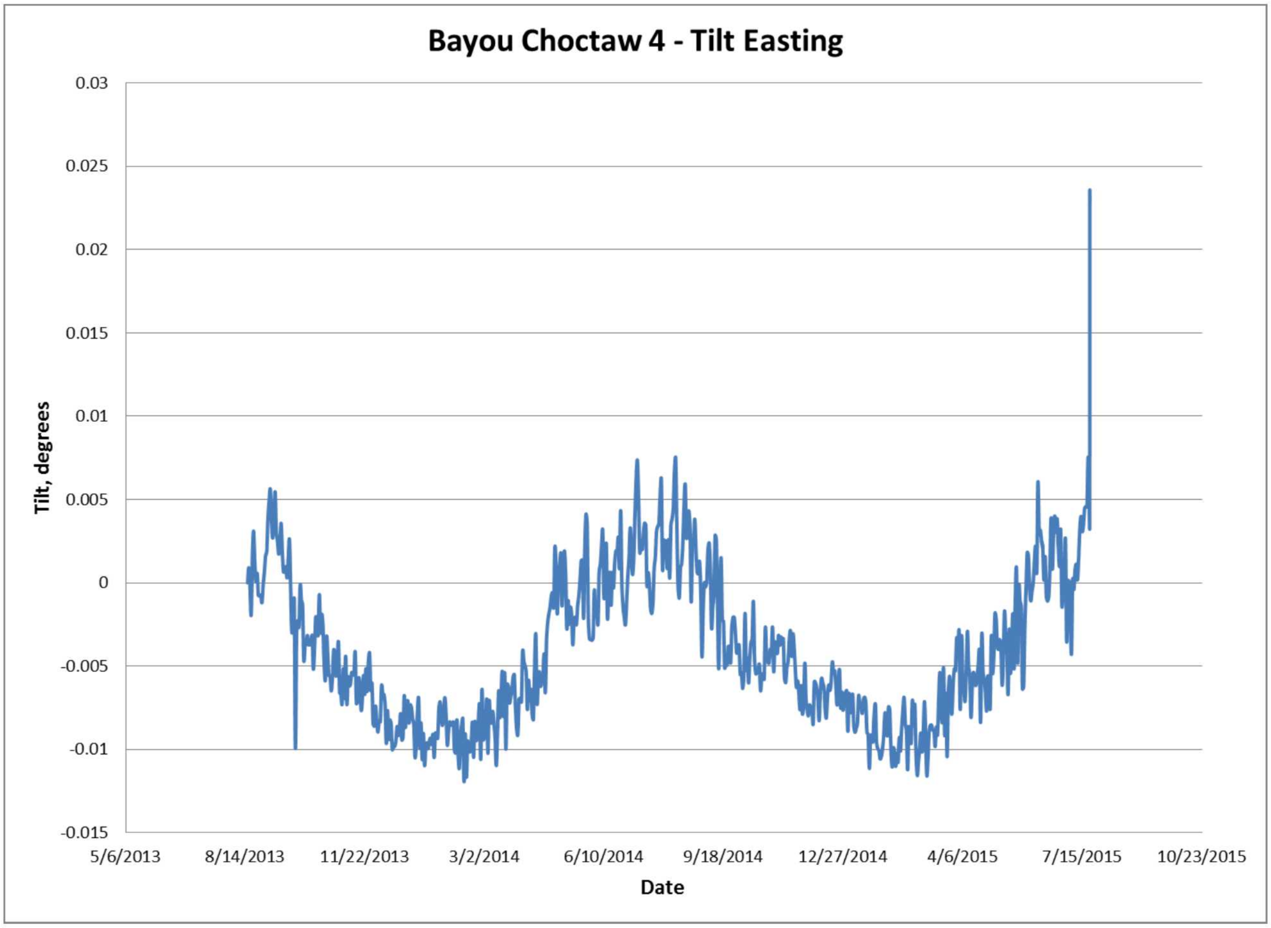

Figure 3-11. Tiltmeter plot, displaying tilt from the Easting direction.

3.3 Geomechanics

As a matter of normal operation of storage caverns in a salt dome, the continuous mechanical creep of salt, along with the change in internal cavern and casing pressure due to cavern closure and fluid exchanges, impose several mechanical conditions on the skin, well, and casing of a cavern that could potentially create damage. For a geomechanical analysis of a cavern, the scenarios of interest include the following:

- Does the pressure change in the cavern create stress changes in the surrounding salt that would cause either tensile cracking or dilatant damage to the salt? Potential consequences of such conditions include salt falls that could impact the hanging string, loss of salt around the casing shoe, and tensile cracking of the salt (especially important if such a crack could intersect a nearby cavern).
- How much additional axial strain is imparted to the well casings during a workover or similar low-pressure operation? Normal cavern closure imparts tensile strain to the well

casings, particularly in the section in the salt dome. When the cavern pressure is lowered during a workover, salt creep rate increases; and thus cavern closure increases, which also increases the tensile strain on the casings.

- What other stress conditions are imparted to the casing during workovers, due to external sources such as damaged caprock, sliding along the salt/caprock interface, or operations on nearby caverns?
- What effect does the cavern shape (i.e., a "normal" tall, vertical cylindrical/teardrop shape vs. a large-diameter "pancake" shape) play in these scenarios?

To address these questions, Sandia has recently performed large-scale geomechanical analyses for all four SPR sites. The following sections summarize the Bayou Choctaw analyses.

3.3.1 Simulations of Well Casing Damage

3.3.1.1 Finite element model

A three dimensional finite element (FE) model capturing realistic geometries of Bayou Choctaw site has been constructed using the sonar and seismic survey data obtained from the field (Park and Roberts, 2015-Draft). The model contains the interbed between the caprock and salt top; and the interface between the dome and surrounding in situ rock stratigraphy to examine the interbed behavior in a realistic manner. Figure 3-12 shows the overview of the hexahedral finite element mesh of the stratigraphy and cavern field at Bayou Choctaw. The caverns in gray, blue, and green indicate abandoned, SPR, and commercial caverns, respectively. The element blocks in Figure 3-12 are combined into an entire FE mesh as shown in Figure 3-13. The boundary conditions for numerical analysis are also shown. The salt dome is modeled as being subject to a regional far-field stresses acting from an infinite distance away. The Surrounding Rock block encircles the Caprock and Salt Dome blocks. The lengths of the confining boundaries are 11,000 ft in the N-S direction and 9,100 ft in the E-W direction. The sizes of the caverns are much smaller than the dome size. The model boundary distances (Surrounding Rock) are enough to be regarded as infinite distance away from the caverns (i.e. fixed boundaries are applied).

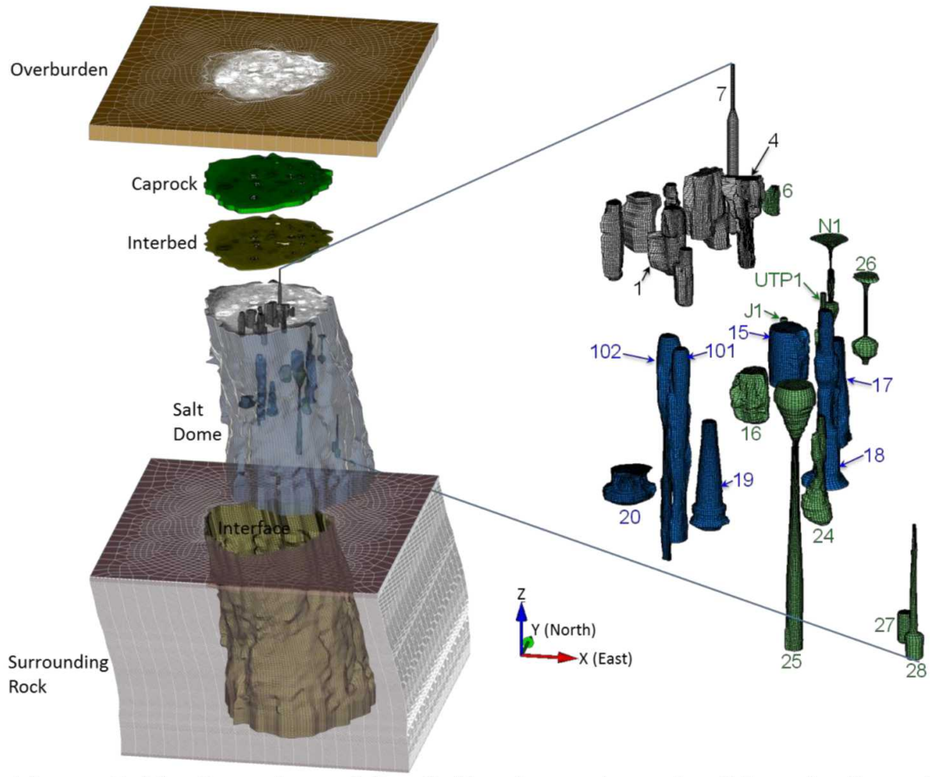

Figure 3-12. Overview of the finite element mesh of the stratigraphy and cavern field at Bayou Choctaw.

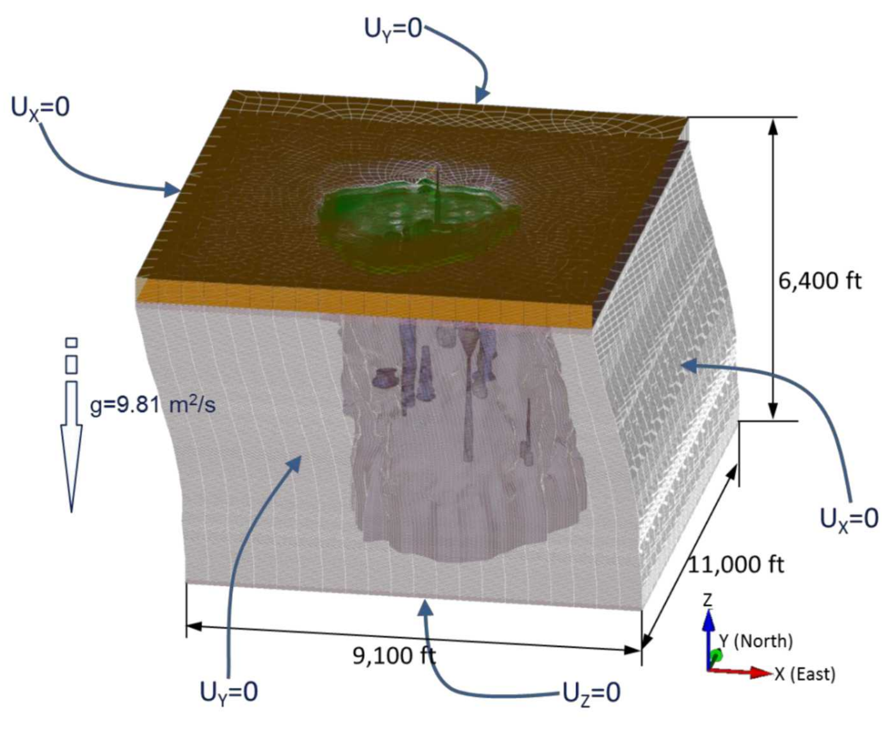

Figure 3-13 Entire finite element model and boundary conditions at Bayou Choctaw.

3.3.1.2 Model history

The modeling simulated the cavern responses forward in time from the initial cavern creation. For the purposes of the present simulation, it is assumed that all caverns were drilled twenty-one years ago to simplify the model history. The analysis simulates caverns that were leached to full size over a one year period by means of gradually switching from salt to fresh water in the caverns. It was assumed that the SPR caverns were filled with petroleum and non-SPR caverns were filled with brine at year one, and then permitted to creep for twenty years to reach the preset twenty-one year age for the caverns to be simulated. Subsequently, every 5 years after year twenty-one, the BC-15, 17, 18, 19, and 101 caverns were instantaneously leached to simulate drawdowns. The wall of BC-20 is very near the edge of the dome at about 4000 ft below the surface, so no drawdown leaching is considered for this cavern. BC-15 and 17 are close to each other, so only three onion skins for leaching were included in the mesh; this limits these caverns to three drawdowns in the simulation. Modeling of the leaching process of the caverns is performed by deleting elements along the walls of the cavern so that the cavern volume is increased by 15 percent per a drawdown. Leaching is assumed to occur uniformly along the entire height of the cavern. However, leaching is not permitted in the floor or roof of the caverns. The 5-year period between each drawdown allows the stress state in the salt to return to a steady-state condition, as will be evidenced in the predicted closure rates. The simulation was run till just before 6th leach to investigate the structural behavior of the dome for 46 years, during which creep closure occurs in all caverns.

Figure 3-14 shows the time sequence for this simulation.

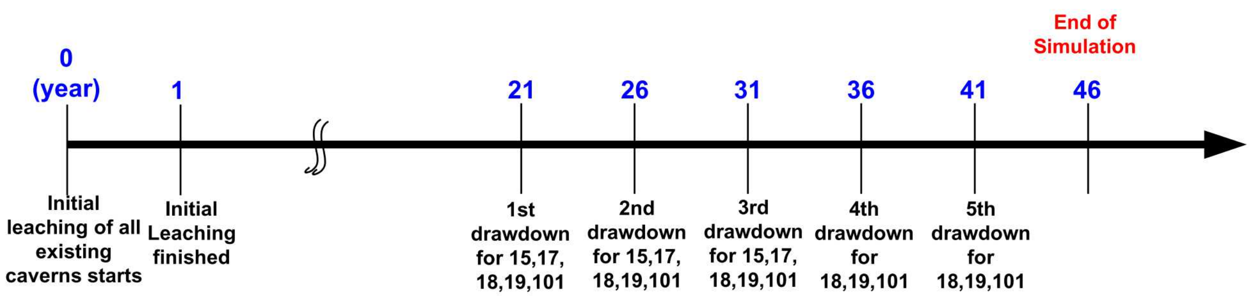

Figure 3-14 Time sequence for the simulation.

The pressure conditions applied to the caverns were based on the average wellhead pressures listed in Table 3-3. For cavern BC-15, which operates over a range of pressures from 815 to 990 psi under normal conditions, the pressure starts at 815 psi, then, due to creep and thermal expansion of fluids, the pressure gradually rises to 990 psi. At that time some brine is removed from the cavern to reduce the pressure down to 815 psi again. Thus, on average, a pressure of 903 psi is used for Cavern 15 wellhead pressure operating under normal conditions. In the same manner, the pressures of 903, 715, 925, 850, and 913 psi are used for the normal operating wellhead pressures of BC-17, 18, 19, 20, and 101, respectively. BC-102 has been owned and operated as a SPR storage cavern since November 2012. It was owned by UTP before that. Therefore, BC-102 is regarded as a non-SPR cavern in this preliminary simulation.

Figure 3-15 shows the well head histories of each SPR cavern. To consider the effect of the workover process, the following order and durations of workovers are used:

- A constant pressure is applied for the majority of the time, with pressure drops periodically included.
- For workover conditions, zero wellhead pressure is used.
- BC-15 and 17 have a workover at one year after switching from brine to oil. BC-19 workover is at year 2; BC-18 and 20 at year 3; and BC-101 at year 4. This cycle is repeated every 5 year until the end of the simulation.
- All workover durations are 3 months.
- For both normal and workover conditions, the caverns are assumed to be full of oil with a pressure gradient of 0.37 psi/ft of depth.

Table 3-3. Range of operating pressures measured at the wellhead for SPR caverns at BC.

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

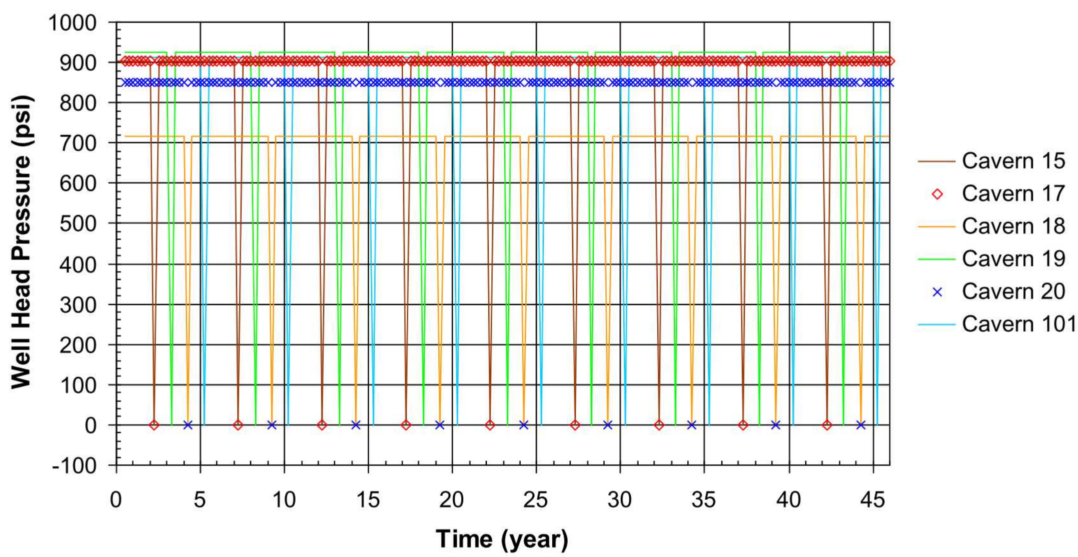

Figure 3-15 Well head history of each SPR cavern.

3.3.1.3 Analysis result

Creep closure in the caverns induces bulk movement of the salt dome that is simulated with the geomechanics models. The bottom of caprock and top of salt both move downward with cavern creep closure. In turn, horizontal displacements and vertical distances in the interbed between the caprock and salt dome are calculated right above the center of each cavern (Figure 3-16).

The salt top subsides because the volume of caverns decreases with time due to salt creep closure, while the caprock subsides at a slower rate because the caprock is thick and stiffer. This discrepancy leads to vertical and horizontal deformation of the well casing at the depth of the interbed. The deformation increases with time so the well will eventually fail and an oil leak will occur (Park, 2014).

Figure 3-17 shows the predicted horizontal strain history at the intersection of each wellbore and the interbed between salt dome top and caprock bottom (squares in yellow in Figure 3-16). The black solid curve in Figure 3-17 indicates the predicted horizontal strain history of a single simulated well above Big Hill cavern 105. Big Hill well 105B is believed to have failed due to shear displacement. The horizontal strain was calculated to be 1.46% when the well casing failed at 20.42 simulation years (Park, 2014). Therefore, the ratio of 1.46% could be used as a shear displacement failure limit (horizontal dashed line). This criterion could be applied to the BC wellbores because the as-built geometry of wellbores of SPR in BH and BC are similar. All the predicted horizontal strains (colorful curves) for the BC caverns are much less than the failure limit for the entire simulation period. Therefore, the BC SPR wellbores are not predicted to fail due to shear strain for at least 45 years after the initial leach.

Figure 3-18 shows the predicted vertical strain history at the intersection of each wellbore and the interbed between salt dome top and caprock bottom. The black solid curve in Figure 3-18 indicates the predicted vertical strain history of BH-109. The vertical strain was calculated to be 0.81% when the well casing of BH-109 failed at 21.25 simulation years (Park, 2014). Therefore, the ratio of 0.81% could be used as a tensile displacement failure limit (horizontal dashed line). All the predicted vertical strains (colorful curves) for the BC caverns are much less than the failure limit for the entire simulation period. Therefore, the BC SPR wellbores are not predicted to fail due to tensile strain for at least 45 years after the initial leach.

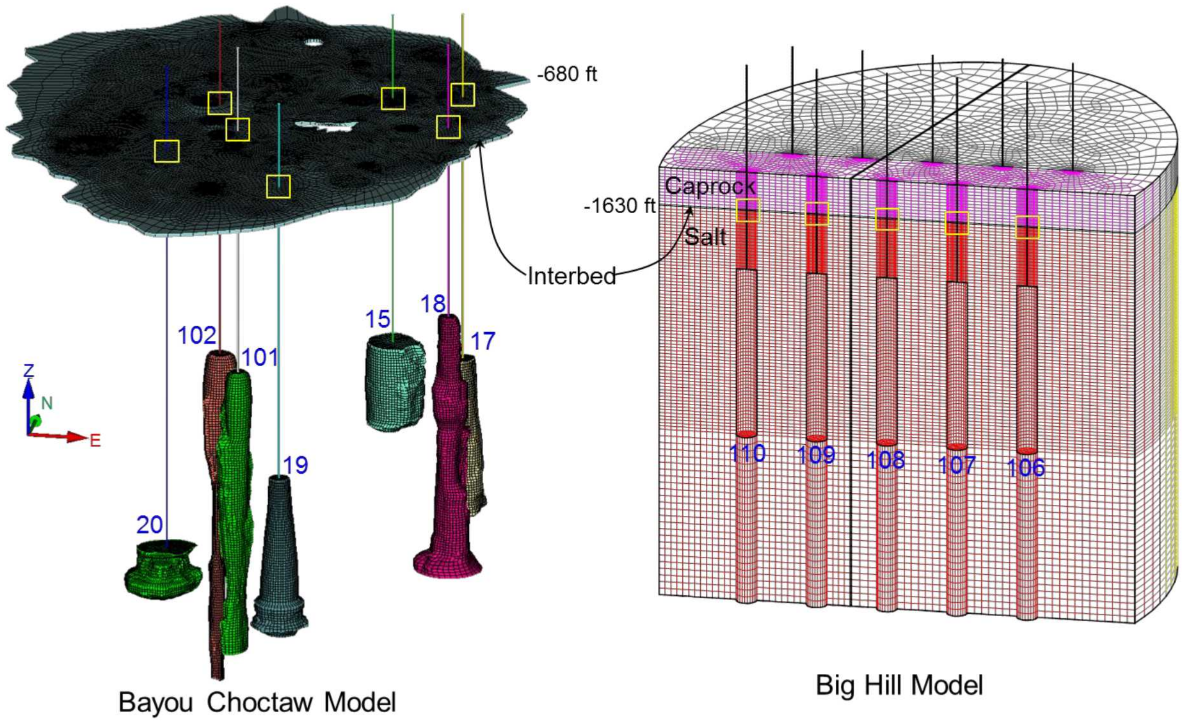

Figure 3-16 Wellbore locations at the interbeds of Bayou Choctaw and Big Hill models

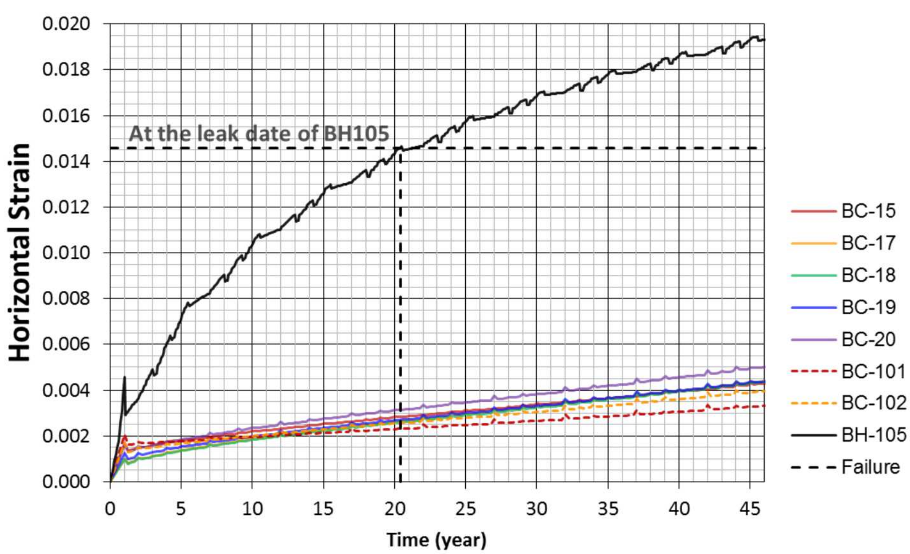

Figure 3-17 Predicted horizontal strain histories at the interbed between Caprock and Salt dome right above the center of each cavern

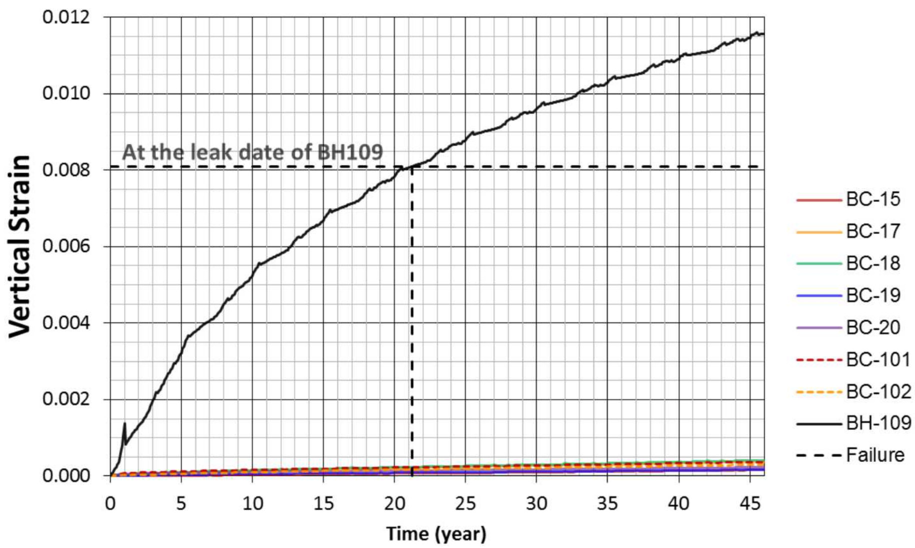

Figure 3-18 Predicted vertical strain histories at the interbed between Caprock and Salt dome right above the center of each cavern.

3.3.1.4 Conclusions

The possibility of failure/collapse of the wellbores of BC SPR was checked at the interbed between caprock and salt. The results from this analysis indicate that the wellbores of all SPR caverns at Bayou Choctaw are not predicted to fail from shear stress that exceeds shear strength of the steel casing due to the horizontal movement of the top of salt relative to the caprock, and tensile stress due to the downward movement of the top of salt from the caprock. Therefore, *all of BC SPR wellbores are given a score of 1* as a well grading from the geomechanical simulation.

Even though a FE mesh capturing the real geometries of BC site was used, this preliminary result is based on the simplified model history as mentioned in Section 3.3.1.2. Thus, the results are somewhat rough. In the future, the real internal pressure change of each cavern will be applied to the model. Then, more realistic results will be obtained.

3.4 Regulatory Drivers

The SPR is subject to a number of state laws (TXRRC, 1994; LADNR, 2007) pertaining to the integrity of salt dome cavity and hydrocarbon storage well operations in Texas and Louisiana. In the event that the laws differ between states, SPR applies the more stringent rule to all of its operations. All active storage wells must be tested with the nitrogen-brine interface method or equivalent every five years, which drives the 5-year cycle on what is known as the mechanical integrity test (MIT). The intent is to demonstrate that the system can maintain brine-nitrogen (or at SPR, oil-nitrogen) interface levels according to standards applied in the salt cavern storage industry. A written test procedure is submitted to the state for approval at least 10 days prior to starting the test. A complete record of the test is filed with the state within 30 days after testing is completed. Each well must also be inspected at least once every 10 years for corrosion, cracks, deformations, or other conditions that may compromise integrity and may not be detected by the five-year test. SPR complies with this requirement by running a multi-arm caliper in the cased section of every well at least every 10 years.

3.5 Multi-Arm Caliper Analysis

Multi-arm caliper (MAC) well logs are used within the SPR complex to determine if the casings in the cavern access wells are being deformed. Deformation of this type is typically the result of rock mass movements from the surrounding geology. Deformations seen from these surveys can be indicative of potential future casing failures.

Not all wells at the Bayou Choctaw site have had MAC surveys performed on them as of the writing of this report. Table 3-4 lists the availability of MAC survey for each Bayou Choctaw well at the time this report was generated.

Table 3-4. MAC survey status.

Well ID	MAC Status
BC-4	No MAC, Cavern not used for oil storage
BC-15	Completed 9/23/2015
BC-15A	Completed 6/27/2013
BC-17	Completed 8/4/2010
BC-17A	Completed 6/5/2013
BC-18	Completed 9/20/2010
BC-18A	Completed 8/5/2013
BC-19	Completed 3/13/2013
BC-19A	Completed 9/23/2010
BC-20	No MAC due to cavern stability concerns
BC-20A	Completed 9/22/2010
BC-101A	Completed 4/24/2013
BC-101B	Completed 9/21/2010
BC-102A	Completed 2/7/2012
BC-102B	Completed – waiting for data

3.5.1 Multi-arm caliper tools

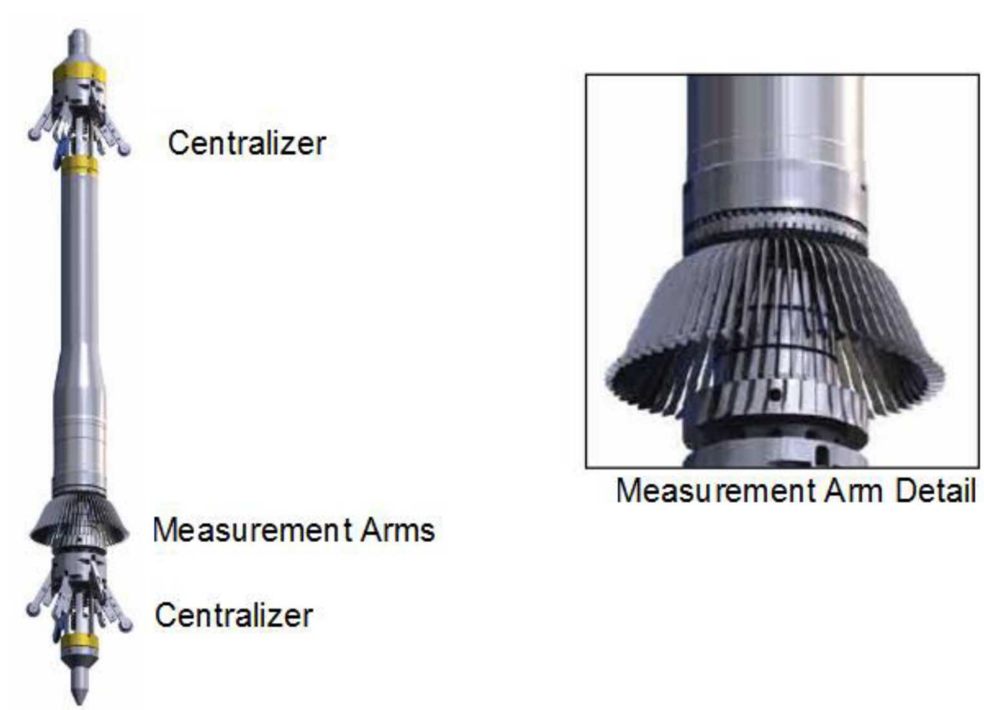

Figure 3-19 . Weatherford 60-arm multi-arm caliper tool

In general, logging using a MAC tool is relatively uncomplicated. The tool is raised through the casing and the radial displacement of the feeler arms is measured as a function of depth. Typically the tool also contains a mechanism to record the general tool attitude. In wells with significant deviation from true vertical, this can be used to identify the "high arm" which can provide some general orientation information; in vertical or near-vertical wells, the high arm is not defined and is typically set to a constant value.

The data produced from the MAC logging tool consists primarily of the radial measurements of the feeler arms and the attitude of the tool in space. For vertical or near-vertical wells the attitude information is not useful, so the remaining useful information is solely contained in the radial measurements. The radial arm data, and their change as a function of depth, are often used to calculate a series of values quantifying the shape of the casing and the amount of distortion from the casings original geometry.

3.5.2 FFPO MAC Analysis

The current SPR Maintenance and Operations (FFPO) contractor uses information contained in the logging contractor's report along with an understanding of the sites and specific well history to interpret the MAC survey data as part of the information used in prioritizing remediation activities.

The information contained in the logging contractor's report typically includes a well log image file showing the response curves of the feeler arms and curves for various parameters computed from the radial arm data as a function of depth. In addition to these static image files, most logging contractors also supply software which allows interactive viewing and investigation of the radial arm data in a three-dimensional view within their own proprietary software system. With this software one can interactively investigate any problem areas and get a detailed three-dimensional view of any casing deformation, and plots of various casing parameters. Finally, the logging contractor typically provides a summary report giving their overall interpretation of the condition of the casing, and listing any problem areas they have identified.

Institutional knowledge of the storage caverns and wells are used by FFPO to interpret the information in the logging contractor's report and gauge the relative importance of any deformation noted in the logging report. It is this determination of relative importance which is reflected in the FFPO MAC grading values presented in this report.

3.5.3 SNL MAC Analysis

The SNL MAC survey grading system uses a different technique than that employed by the Maintenance and Operations contractor. To allow direct control of the calculations, the SNL MAC survey grades are based on the raw measured radial arm data directly. The radial arm measurements were taken from Log ASCII Standard (LAS) files supplied by the survey contractors. The radial arm measurement data were extracted directly from the LAS files and then processed to generate analysis variables as a function of depth. The radial arm radius values were converted to diameters by adding the values of opposing arms. These diameter values then form the basis for the analysis variables.

During initial investigations of the MAC survey data, a series of different analysis variables were explored. From this, it was determined that the coefficient of variation of the measured casing diameters was an effective summary measure of casing deformation. The coefficient of variation (C_v), is the standard deviation normalized by the mean (μ). It scales the standard deviation (σ) so that values from populations with different means are comparable. The applicability here is that it removes the overall casing diameter from influencing the standard deviation and will allow for comparisons between differing casing sizes if necessary.

$$C_v = \frac{\sigma}{\mu}$$

For a perfectly circular object, the population of measured diameters would all have the same exact value; therefore the standard deviation would be zero. This would lead to a C_v of zero as well. In reality, no casing section is perfectly circular, even prior to installation, therefore virtually all diameter C_v values computed from radial arm measurements will be greater than zero; it is only relatively large C_v values that indicate casing deformation.

One caveat to this is that radial measurements where the survey tool is not centered in the casing will also lead to C_v values greater than zero, even in perfectly circular casing. This is because the radial values are not measured from the center of the casing and so do not represent true diameter measurements. Conversely, significant de-centralization of the tool is usually caused by some type of casing distortion and therefore, still indicative of casing issues.

As a comparison of the distribution of C_v values that are observed in newly installed casing and in casing known to have significant deformation, pre and post-remediation C_v values for a well at the Bryan Mound site were examined. Bryan Mound well BM-4B was known to have notable casing deformation within the cap rock and so was remediated by cementing an additional casing inside the existing configuration. For this well, pre and post remediation MAC surveys were preformed providing an opportunity to compare C_v values for deformed and newly installed casing.

An examination of the C_v value distributions for BM-4B shows that the post-remediation survey has a mean of 0.0015 and a standard deviation of 0.00028, while the pre-remediation survey had a mean of 0.0018 and a standard deviation of 0.00069. As expected, the pre-remediation survey C_v values have a larger mean and standard deviation, a result of the casing deformation which lead to the remediation of this well. These differences can be readily seen in Figure 3-20 which shows a comparison of the C_v values between the pre and post-remediation MAC surveys. As seen in this figure, there are significant differences in the distribution of C_v values between the two surveys; most notable is the shift in the pre-remediation values to higher C_v values.

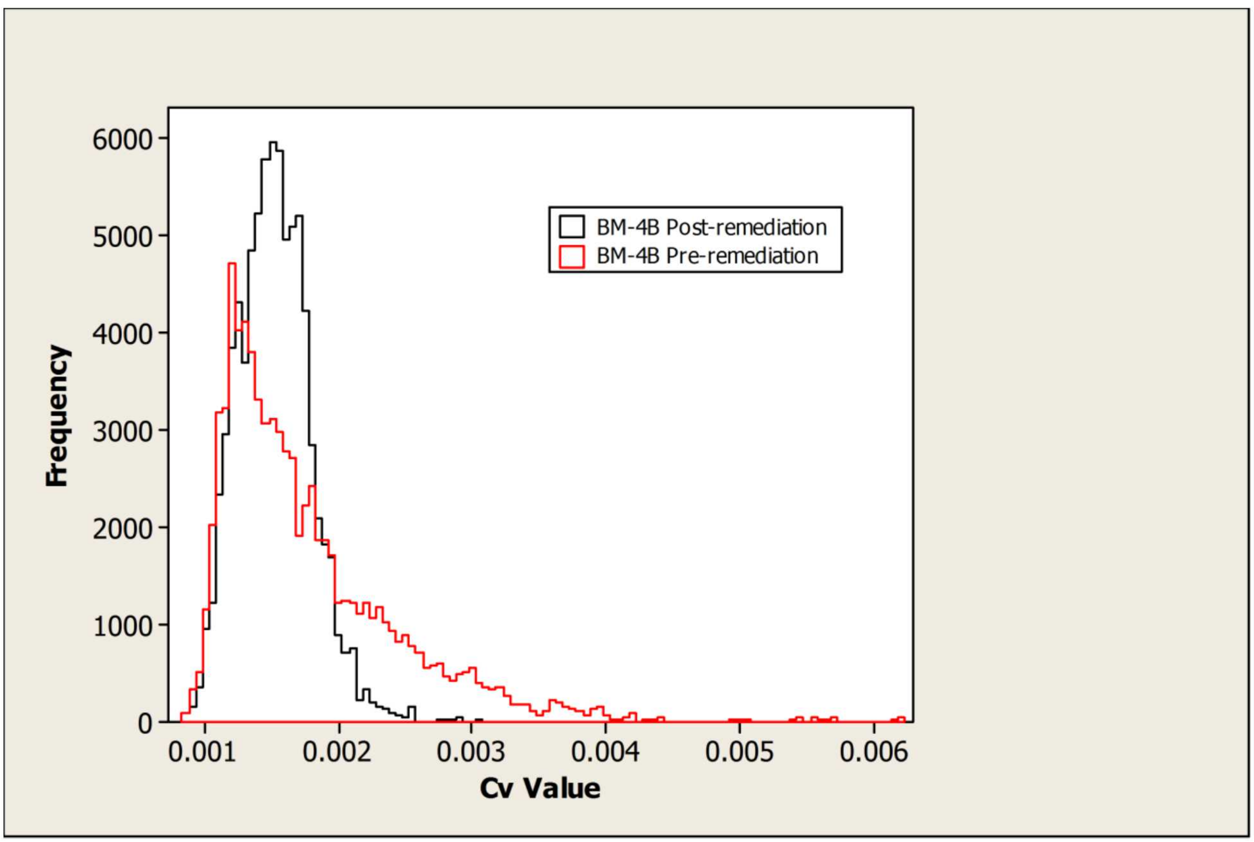

Figure 3-20. Overlaid histogram outlines of C_v values for BM4B from pre- and post-remediation MAC surveys.

In addition to C_v values, an additional variable, Relative Wall Displacement (RWD) was also used in the Bayou Choctaw well grading. Like C_v, RWD was computed directly from the radial arm values contained in the LAS files for each Bayou Choctaw well.

RWD presents an indication of the maximum displacement of the casing wall as a function of depth. This is computed by determining the maximum difference between the measured internal casing diameters and the expected internal diameters which is a function of the casing weight. This difference is then normalized by dividing by the expected casing wall thickness. This results in a value that represents casing wall displacement scaled to the wall thickness; a value of one represents displacement of the equivalent of one casing wall thickness at that depth. RWD is computed as shown below:

$$RWD = \frac{(Max\ ID\ Delta) * 0.5}{Expected\ Casing\ Wall\ Thickness}$$

Where:

$$Max\ ID\ Delta = \mathrm{MAX}(|(Min\_MID) - (EID)|\ ,\ |(Max\_MID) - (EID)|)$$

$$Expected\ Casing\ Wall\ Thickness = OD - EID$$

$Min\_MID =$ minimum measured internal diameter
$Max\_MID =$ maximum measured internal diameter
$EID =$ expected internal diameter
$OD =$ outer diameter

The RWD variable was added to the ranking procedure because it gives a better indication of the actual maximum displacement of the casing wall than C_v values do. Although C_v and RWD values are highly correlated for a single well, in some cases they do not directly track one-another in which case RWD can provide information not represented in the C_v values.

For the final analysis, both the C_v and RWD values were used for the SNL grading. A simple averaging was used for the combination of these two component grades.

Example plots showing diameter C_v and RWD values for well BC-101A are shown in Figure 3-21. Each of these plots show values for two different depth ranges. The red line (right axis) shows values for the depth interval where deformation is most expected to occur, namely, the caprock and salt-caprock interface region. The black line (left axis) shows values for a section of the casing much deeper in the well bore. Interestingly, the deeper casing segment shows greater deformation than the shallower salt-caprock interface region. This pattern of relatively greater deformation lower in the well casing is seen for many of the wells at Bayou Choctaw; fortunately, for most of these wells, the magnitude of the deformation is not great.

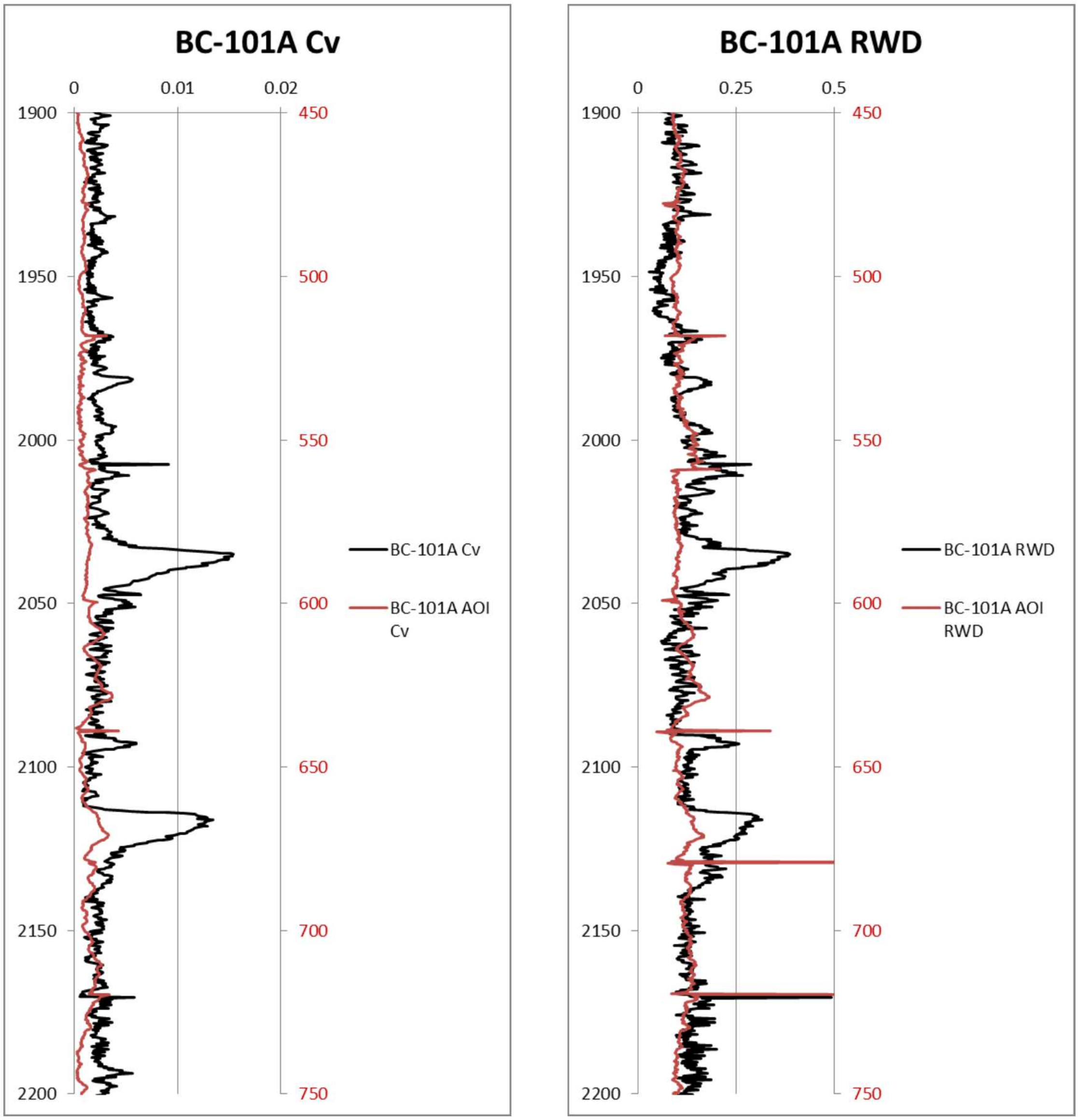

Figure 3-21. Plots of Cv and RWD for well BC-101A comparing values within the caprock depth range (red line, right axis) to those deeper in the well casing (black line, left axis). Major short interval spikes represent casing collars.

3.6 Pressure Monitoring

Wellhead pressure monitoring is a useful technique for evaluating cavern integrity when properly placed into context with current and historical cavern operations. SPR uses two basic types of pressure monitoring. One covers long periods of time, following the natural creep cycles and geothermal heating, looking for anomalies from established patterns. This technique employs both manual examination as well as a cavern physics model CAVEMAN, developed by SNL (Ballard and Ehgartner, 2000), that compares predicted pressures with measured pressures at a reference oil wellhead for each cavern. A second type of monitoring uses nitrogen for short-term well testing ranging in duration from hours to months depending on application. Nitrogen is particularly useful for isolating a well and depth interval where a possible leak exists. Examples are discussed below to illustrate these principles.

3.6.1 CAVEMAN

CAVEMAN is a software tool that predicts an expected pressure at a cavern wellhead with time and compares this with wellhead pressure measurements on a daily basis. Divergence between measured and predicted pressures could indicate a leak, a need for model calibration, or an operational scenario that CAVEMAN is not configured to simulate. The tool evolved from observational methods in the 1980's to a desktop computer model and production code in the mid-1990's. CAVEMAN Version 3 was released in 2000 (Ballard and Ehgartner 2000), while version 4 was released in 2004. CAVEMAN version 4 utilizes four Excel workbooks, one for each SPR site with visual basic coding running most of the data processing. A joint effort between FFPO and SNL is ongoing to upgrade CAVEMAN version 4 to a highly-automated enterprise application on the SPR network. The initial version of the application, which reproduces the predictive capability of CAVEMAN version 4, has been developed by FFPO and verified by SNL. As of this writing, however, the application has not been released for general use.

CAVEMAN monitors and predicts oil wellhead pressures during shut-in on a daily basis. It flags abnormal behavior based on a 3× historical root-mean squared (RMS) error, which is about ~11 psi for Bayou Choctaw, implying that the CAVEMAN creep model parameters may be in need of recalibration.

The CAVEMAN model estimates oil, brine and cavern volumes, average fluid temperatures, and cavern closure from salt creep. CAVEMAN cannot model certain transients or anomalous events, including pressures during fluid movements, impacts from neighboring caverns, leaking wells, or hanging string breaks. A leaking well may appear as a divergence between predicted and measured pressure, but leaks are not explicitly modeled. CAVEMAN can provide predictions of cavern pressure recovery after workover, though this requires special calibration that is not as robust as the normal pressurization cycling.

A wellhead pressure history under normal operating conditions that is representative of Bayou Choctaw is shown in Figure 3-22 for BC-17. Measured pressure is shown in blue, while CAVEMAN predicted pressure is shown in pink. The difference between these is shown in green, which is scaled on the right-hand axis. Also, shown in red is the recommended operating pressure range. The saw tooth features between 825 and 875 psig are typical pressure cycles as monitored at the oil wellhead. Creep closure and thermal regain increase the pressure gradually with time. Site operations, in turn, releases fluid as necessary every few months to reduce the pressure to the bottom of the normal operating range. The large drop in pressure between May and July 2013 was due to a workover of wells at BC-17. The extra, smaller "teeth" in the pink curves are corrections to the CAVEMAN predicted pressures. For this case, which shows better agreement than most at Bayou Choctaw, differences between predicted and measured are well within the 3× historical RMS error (~8 psi) range for this cavern, so that the CAVEMAN flag would indicate no leaks during this time frame. Certain upward deviations in measured pressure may indicate neighbor cavern workovers, which are not considered in the CAVEMAN predictive model. These upward deviations are not as prevalent at Bayou Choctaw as they are at Big Hill, thus the reader is referred to the discussion in the Big Hill well-grading report (Lord et al., 2014) for examples.

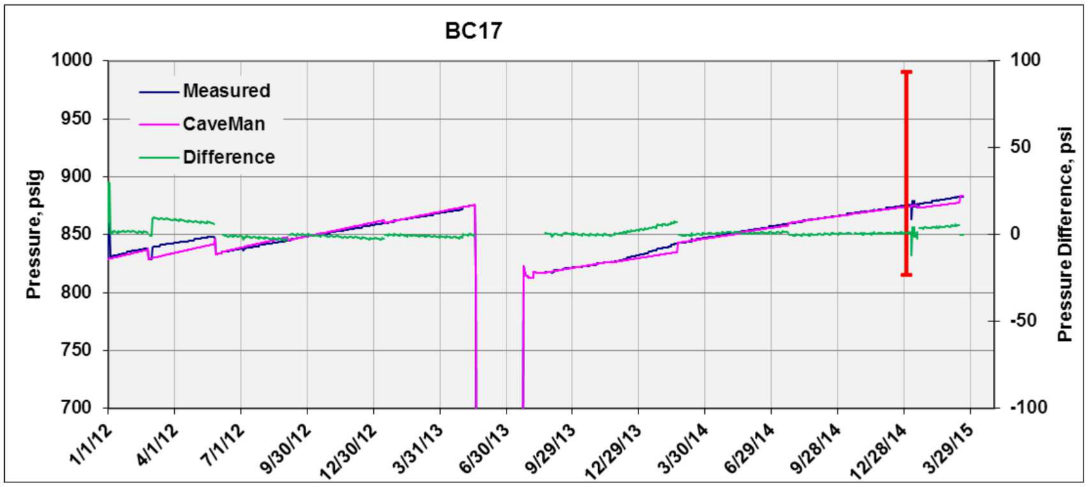

Figure 3-22. Measured vs. CAVEMAN-predicted oil wellhead pressure for BC17 over 2.5 year period from January 2012 – March 2015.

Another important utility of the CAVEMAN model is that it established protocols for data collection and now serves as a data repository for many important parameters. CAVEMAN saves a single measured value per day for each parameter as shown below.

- For A-well oil, B-well hanging string brine, and B-well oil annular wellhead pressures
  - Long-term oil pressure for primary well
  - Short-term (1 year) for all wellheads
- For fluid transfers
  - Transfer volumes
  - Incoming fluid temperatures
  - Incoming brine specific gravity

CAVEMAN runs a quasi-static pressure simulation based on the definition of compressibility, which relates changes in pressure with changes in volume. Four fundamental processes are included:

- Thermal expansion of oil and brine
- Elastic response of cavern
- Cavern closure due to salt creep
- Salt dissolution

3.6.2 Nitrogen Testing

Nitrogen testing is used to satisfy state regulatory requirements for verifying well integrity every five years, formally called the mechanical integrity test (MIT). Special nitrogen testing may also be implemented as-needed by site personnel in order to diagnose possible well leaks between the 5-year MIT cycles.

The principle of nitrogen testing is shown schematically in Figure 3-23 (figure reproduced from Exeter-Energy-Services, 2003)). The wellhead is typically isolated from surface piping with blind flanges and nitrogen is pumped in with metered pressure and mass in order to push the nitrogen-oil interface down below a selected reference depth. For a MIT, the reference depth is the last cemented casing seat. For a special nitrogen test, the reference depth is in the likely leak region. For many SPR wells, this is the salt-caprock interface. Nitrogen gas exposed to a leak region will typically escape quickly and lead to an initial transient in wellhead pressure coupled with upward movement of the nitrogen-oil interface depth that comes to an equilibrium point right at the leak depth as the more viscous oil slows the leak rate.

For the 5-year MIT, an initialization wireline log is run after a 2-7 day equilibration period following injection to establish well fluid temperature with depth and locate the nitrogen–oil interface. After a MIT test duration of 5-14 days, a finalization wireline log is run to establish how much the temperature and nitrogen-oil interface position have changed. These data combined with well geometry are used to calculate an estimated nitrogen leak rate in bbl/yr. The current position of state regulators is that an MIT passes if the calculated nitrogen leak rate is less than the MIT uncertainty level, or minimum detectable leak rate (MDLR). The MDLR is specific to each well and each test, and is calculated by the cavern operator along with the results of the MIT. MDLR values must not exceed 750 bbl/year. The MIT fails if the calculated nitrogen leak rate exceeds the MDLR. The site cavern engineer writes a cavern integrity test report that is submitted to the state within 30 days of the test. If the test passes, no further action is required. If the test fails, further examination follows which may lead to well remediation.

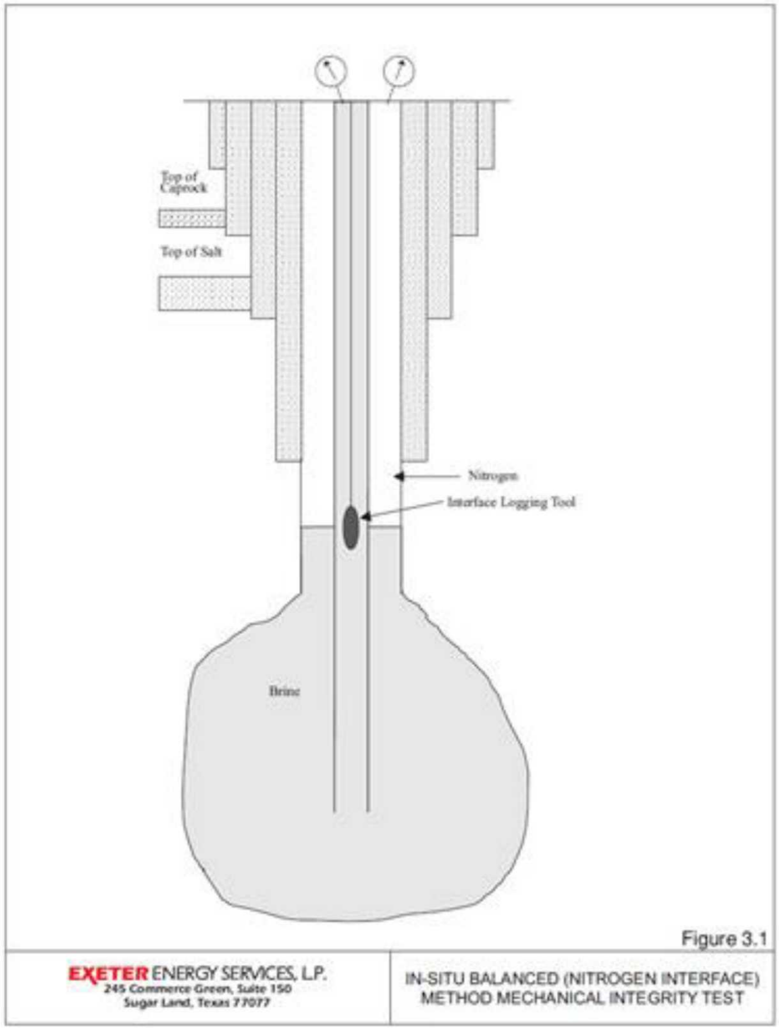

Figure 3-23. Schematic of typical nitrogen interface test, reproduced from Exeter-Energy-Services (2003).

3.6.3 Neighboring Cavern Effects

All of the caverns in a given dome are at some level geomechanically coupled. This implies that changes in one cavern's physical operating environment, such as changes in fluid pressure or stress in the solid matrix, will affect neighboring caverns. More visible effects are expected for caverns in close proximity to those subjected to large transients in stress states (i.e., closest neighbor to a cavern that was de-pressured for workover). Historical geomechanical modeling at SPR has typically simulated generalized operating futures at larger temporal and spatial scales than required to evaluate the selected phenomena we are seeing in individual caverns. Hence, the geomechanical models are currently configured to provide useful dome-scale resolution over decades, but not necessarily cavern-level resolution over several months of atypical operations activity.

Close observation of cavern pressure histories reveals that there are a number of operating scenarios that lead to deviations in pressurization behavior of nearest neighbors. The models we currently use on SPR are not built to simulate these conditions. Examples include:

1. Effects of workover on neighboring cavern pressure
2. Effects of workover on neighboring cavern well integrity
3. Effects of simultaneous workovers (multiple nearest neighbors de-pressured) on subject cavern
4. Effects of extended workovers (> 3 months) on subject and neighbor well integrity

3.6.4 Unexplained Pressurization Anomalies

At the SPR Big Hill site several caverns exhibited pressurization anomalies including flattening or even gradual pressure loss, followed by resumption of pressure increase due to creep. For these wells, nitrogen was placed on the wellhead or wellheads, and they were de-piped in order to isolate the crude oil from a possible leak path to the environment. In one case pressurization has resumed normally, and in another, pressurization has resumed at a lower rate in the nitrogen-capped well than in the brine well. This intensive monitoring continued for an extended period and included periodic logging for N_2-oil interface depths in order to locate any leak locations. Recent, relevant unexplained pressurization anomalies have not been identified at Bayou Choctow during normal operations. More specific details on pressurization anomalies and illustrative examples can be found in the Big Hill well grading report (Lord et al., 2014).

3.6.5 Cemented Annulus Pressure

A useful tool for monitoring the structural integrity of a well is the behavior of the fluid pressure in the cemented annulus. The presence of a positive fluid pressure in the annulus is a possible indicator of a leak which may be too small to be seen from the wellhead pressure monitoring tools. Two separate indicators were used to gauge the relation between wellbore and annulus pressure: recent historical pressure measurements, and pressure data from the latest MIT. The historical data from the last 6 months for each of the BC wells was analyzed and the relation between wellbore and annulus pressure described. The wells at BC have shown very few problems with leaky cemented annuli with 13 of its 14 wells having a grade of 1 or 2. Examples of BC cemented annulus pressure behavior are shown in Figure 3-24 and Figure 3-25.

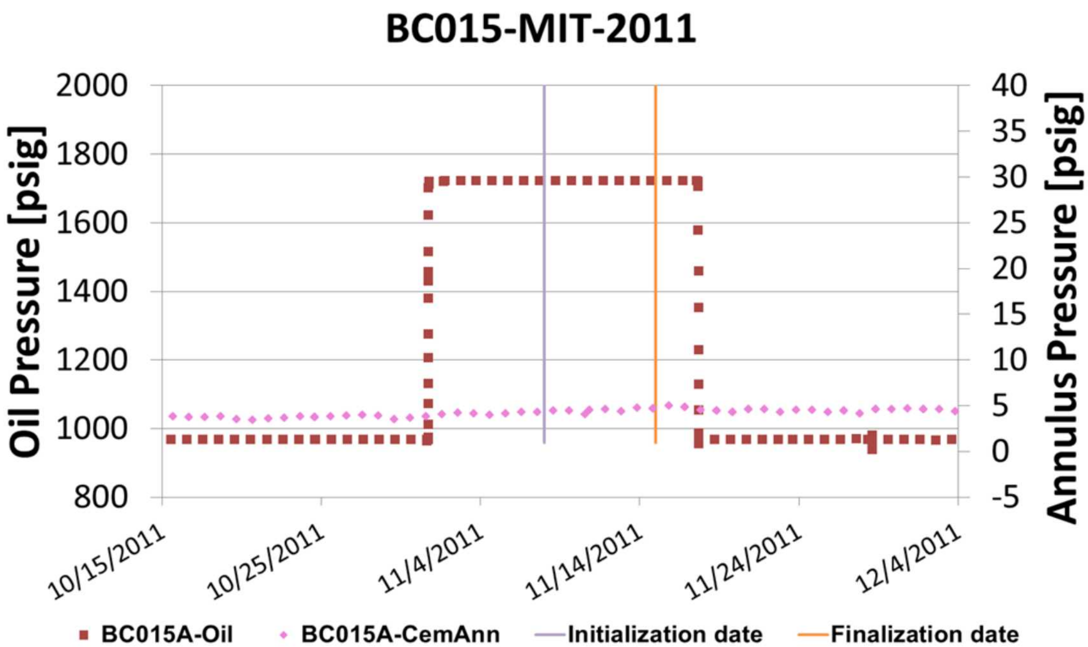

Figure 3-24: BC015 cemented annulus pressure behavior during the 2011 MIT. A very small positive cemented annulus pressure is recorded, but no response to changes in the borehole pressures is found.

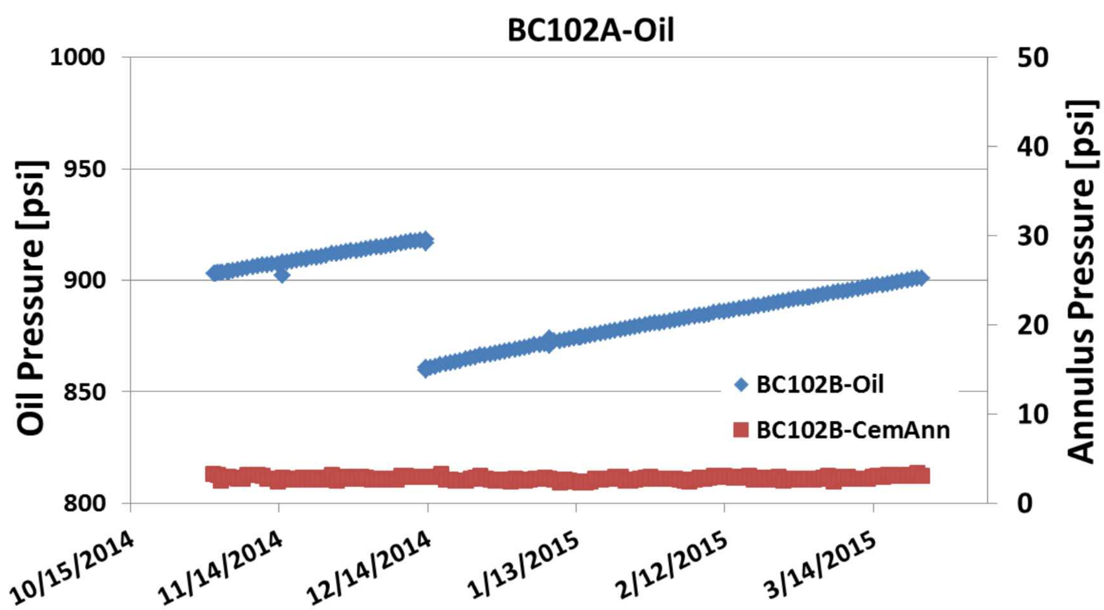

Figure 3-25: BC102 cemented annulus pressure behavior during normal operating conditions. No response to changes in the borehole pressures is found.

The one exception at the BC site is well BC-19, where complete hydraulic connection is shown both during MIT (under nitrogen) and normal operating conditions (in oil), see Figure 3-26. This well is the only annular pressure grade 5 at BC.

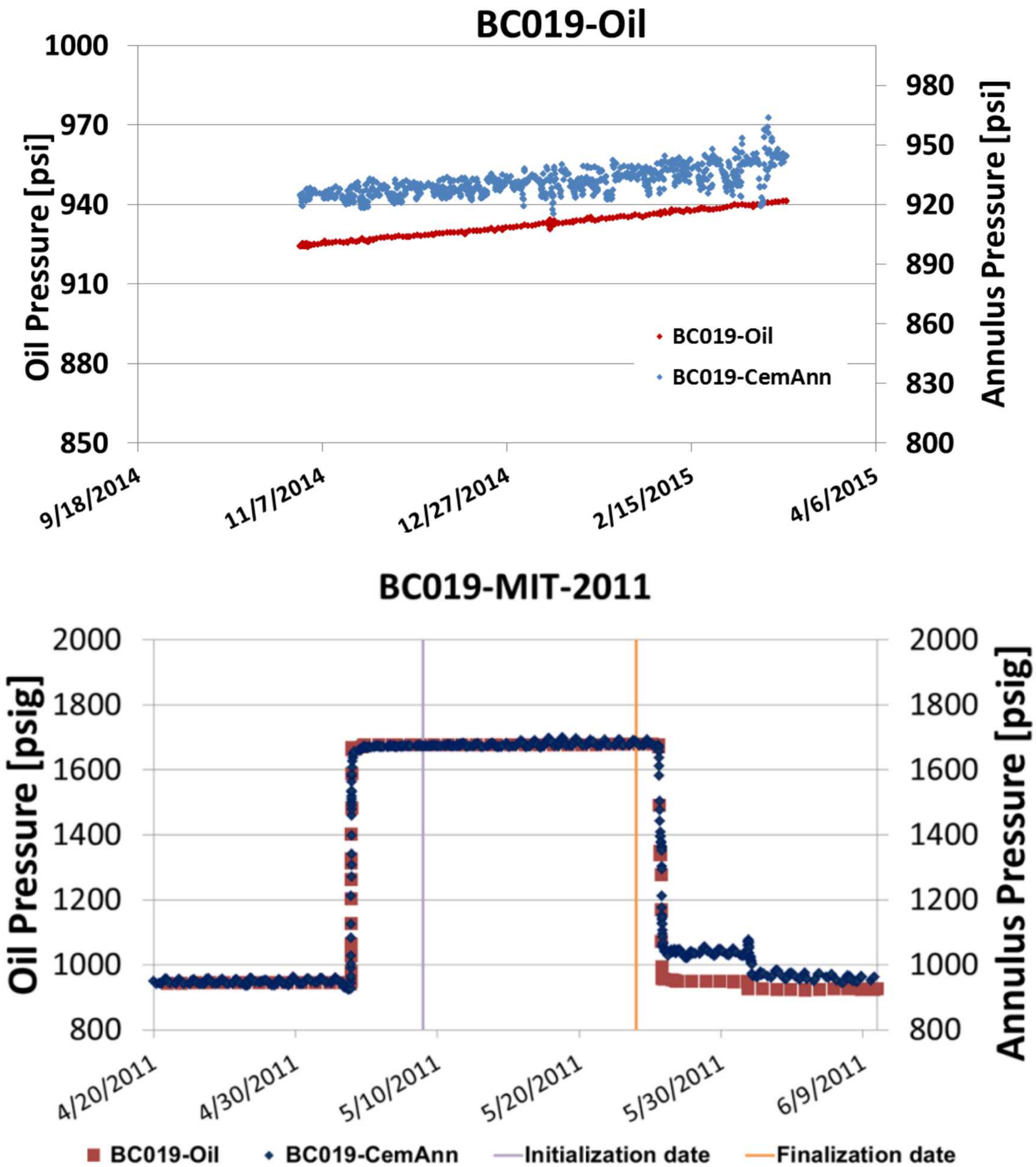

Figure 3-26: (Top) BC019 cemented annulus pressure behavior during normal operating conditions. (Bottom) BC019 cemented annulus pressure behavior during the 2011 MIT. In both cases the annulus pressure follows the borehole pressure very closely.

4 METHODS FOR GRADING

A grading scheme was developed in order to set priorities for well monitoring and remediation based on the principles presented in Section 3 of this report. The Well Integrity Working Group determined that a two dimensional space was required to convey the key information. Highest priority was ranking according to need for remediation. Second priority was ranking for monitoring intensity. An example sketch showing this principle is given in Figure 4-1.

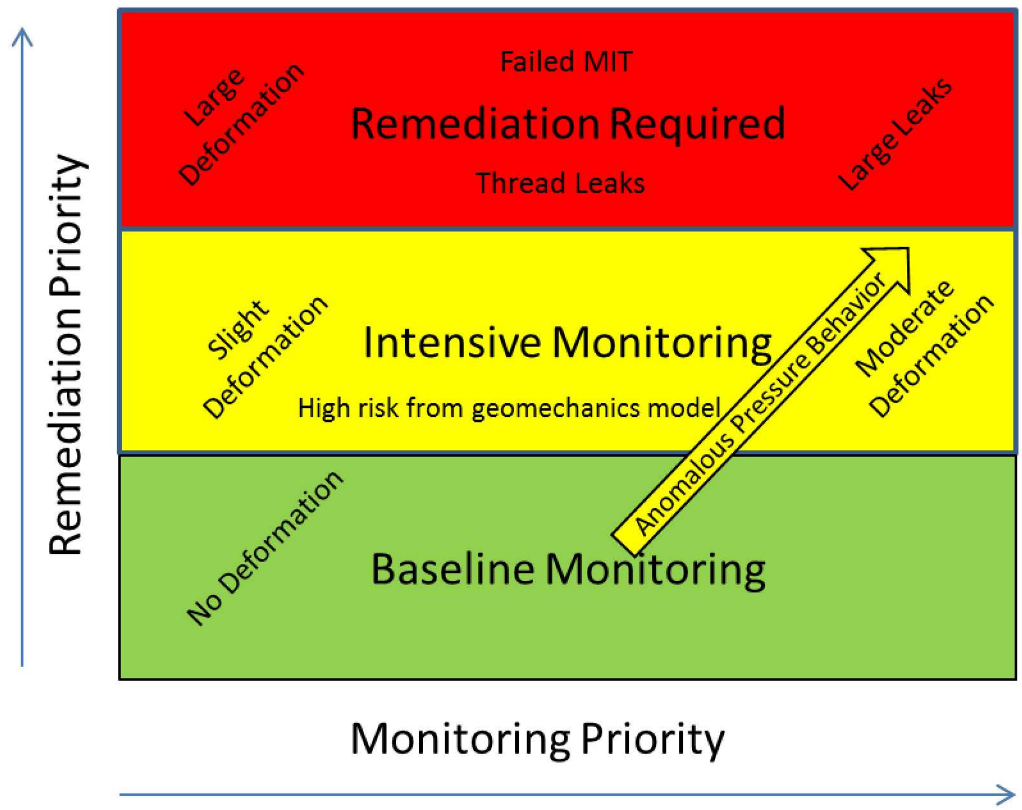

Figure 4-1. Illustration of well monitoring and remediation risk diagram.

Any cavern that exhibited technically defensible evidence of fluid loss or showed significant casing deformation would be categorized as high priority (red zone), requiring remediation. Larger leaks would generally take priority over smaller leaks in remediation planning. Caverns that were not yet leaking, but showed elevated risk due to moderate casing deformation, anomalous pressure behavior, or were identified in geomechanics modeling as high risk, would be categorized as medium priority (yellow zone) and placed under intensive monitoring. Caverns showing no specific problems would be categorized as low priority (green zone) and set to a baseline monitoring schedule.

The well integrity working group developed a well grading framework consisting of seven grading components. These seven components were:

1. MAC survey results
2. Cavern pressure history
3. Geomechanical simulation results
4. Geological considerations
5. Composite well information
6. Cavern geometry
7. Offsite activities

These seven components were then combined to generate two final grades; one for remediation priority and one for monitoring priority (see Figure 4-1). Grading values ranged from 1 to 5 with 5 normally representing the highest priority; in extreme cases, where several factors indicated a very high remediation priority, grading values of 6 were assigned to the remediation grade. Details of how grading values were developed for each of these components are provided below.

5 DEVELOPMENT OF GRADE VALUES

This section presents the methodology of assigning well grade values for the various components listed in Section 4. These individual grade values are then combined to derive single values for remediation and monitoring priorities. The process for combining the grade values from these individual components and the weighting values used in this process are presented in Section 6.

5.1 MAC Grading

The well ranking component based on the results of the multi-arm caliper surveys is unique in that it encompasses grading values from two different sources, but based on common information. The history of analysis of the MAC survey data has resulted in a grading value determined by the M&O contractor FFPO, and a separate value determined by SNL. These two independent looks at the same data provides an opportunity to check these grades against each other to identify potential anomalies in the ranking values.

Each ranking technique is discussed below. How these values are combined and used is presented at the end of this section. Similar to the other ranking criteria, the final ranking values span a range of numeric values from 1 to 5, with higher values indicating wells most in need of remediation.

5.1.1 FFPO MAC Grading

The FFPO MAC grading procedure takes a holistic approach in looking at the MAC data. The logging contractor's report and associated log data are used to determine the basic magnitude of any casing deformation, and then other related factors are considered. These other factors include length of time since the MAC survey was completed, behavior of the paired well and general cavern history. The general guidelines of the FFPO well grading system are listed in Table 5-1 below. The FFPO grading system uses a color grade consisting of red for highest priority, yellow for intermediate priority, and green for lowest priority wells. The yellow grade is then further subdivided into high, medium, and low priority ratings. The mapping of this color code system into the 1 to 5 grading used in this report is also shown in in Table 5-1. In cases where no FFPO color code was available (e.g. no MAC data for well), then a value was assigned based on the expert opinion of the workgroup. These values will be updated once a color code is available.

Table 5-1. FFPO Multi-arm caliper grading system.

Grade	Conditions	FFPO Color Code
5	Casing deformation exceeds casing wall thickness	Red
4	Significant casing deformation but no indication of casing failure	Yellow - High
3	Moderate casing deformation	Yellow – Medium
2	Minor casing deformation	Yellow – Low
1	Overall casing condition is good; no significant deformation	Green

5.1.2 SNL MAC Grading

As discussed in Section 3.5.3, the SNL ranking technique relies on the direct processing of the raw radial arm measurement data. This data is currently summarized into variables, C_v and RWD, that vary as a function of depth in the well casing. These two variables represent the extent and magnitude of any casing deformation.

5.1.2.1 MAC Baseline Values

With the Bayou Choctaw site being the last of the four SPR sites to be examined with this well grading process, C_v and RWD values for all the other sites were available for comparison. This provides the opportunity to establish a baseline value for comparison against all the SPR sites.

The baseline values were developed by looking at the range and distribution of C_v and RWD values, which wells had known casing failures, and the maximum values for wells without casing failures. Based on these analyses, it was determined that a value of 0.012 should be used as a baseline to normalize the C_v data and that no normalization of the RWD data is necessary.

The baseline C_v value represents the level at which the well is exhibiting significant deformation. Using a baseline value to normalize the data first allows updating of the baseline value, if needed, without changing the final grade mapping procedure.

The RWD data were not normalized because this value reflects apparent casing movement relative to the casing wall thickness; deformation greater than one casing thickness has been seen to be associated with casing failure. A value of one for RWD is considered here to be an indication of significant casing deformation.

This procedure to compare C_v and RWD values across the SPR complex represents a new process which differs from the process previously used in assigning well grades at the other SPR sites. This new process is now possible since an analysis of the MAC data for the other sites has been performed. The grading values for the other SPR sites will be updated to use the baseline process described here.

5.1.2.2 Final Grade Mapping

The SNL MAC grading procedure also results in a ranking value ranging from 1 to 5 for each well. The general procedure was as follows. The maximum value of each variable (C_v and RWD), not associated with a casing joint, was determined by automated and manual inspection of the data. The C_v maximum was then normalized by the baseline value discussed above; the RWD maximum value was used directly. The normalized C_v and RWD values were then mapped to a 1 to 5 grading scheme based on the binning thresholds shown in Table 5-2 and Table 5-3 respectively; separate thresholds were developed for the C_v and RWD values. The 1 to 5 grade values for C_v and RWD were then averaged to obtain a final MAC grade.

Table 5-2. C_v grade binning

Grade	Maximum Normalized Cv Value
5	Value >= 1.0
4	1.0 > Value >= 0.75
3	0.75 > Value >= 0.55
2	0.55 > Value >= 0.35
1	Value < 0.35

Table 5-3. RWD grade binning

Grade	Maximum RWD Value
5	Value >= 1.0
4	1.0 > Value >= 0.75
3	0.75 > Value >= 0.55
2	0.55 > Value >= 0.35
1	Value < 0.35

5.1.3 Combination of FFPO and SNL Ranking Values

The grade values determined from the MAC surveys are used both for the remediation and monitoring grades (see Section 4). The SNL grade value for the *entire length* of the MAC survey is used for the monitoring grade. This considers potential issues regardless of the depth of the deformation. This is useful for planning monitoring priorities.

For the remediation grade, the FFPO and SNL grade values for a particular depth zone of interest are both considered. For this, a zone of interest has been identified for each well. This is a depth region where the greatest amount of casing deformation is expected to occur. This zone is typically identified based on historic casing deformation and is tied to geologic phenomenon at that depth. For the Bayou Choctaw Site, the zone of interest is the entire thickness of the caprock. This includes regions within the caprock as well as the critical salt-caprock interface.

To obtain a final 1-5 remediation grade value based on the MAC surveys, the SNL and FFPO MAC grade values are combined. The two MAC grades are simply averaged to obtain the final MAC grade. In this averaging, each term is equally weighted. This only applies to the remediation grade value.

5.2 Pressure Grading

Pressure monitoring information was considered from both long-term CAVEMAN-style monitoring as well as short-term nitrogen testing. A numerical system was developed in order to communicate the degree of risk associated with recent behavior and observations, summarized in Table 5-4.

Table 5-4. Pressure grading system.

Grade	Conditions
5	Confirmed hydraulic leak through cemented casing or around shoe in excess of what can be offset by nitrogen injection. Failed MIT.
4	Pressure trending anomalies such as flattening or loss of pressure. Apparent nitrogen leak yet leak zone may or may not be identified. Cemented annulus pressure tracks with oil pressure. Leak can be contained with nitrogen.
3	Pressure trending anomalies such as flattening or loss of pressure. No problems under last MIT or nitrogen test with detailed pressure trending analysis.
2	Some discrepancy in the pressure history curves.
1	No known problems with CAVEMAN and/or pressure trending analysis, or under nitrogen/MIT.

The lowest level of concern (grade 1) is no known problems with any of the pressure monitoring data. Some attention is required (grade 2) for caverns that show a mismatch between historical pressure trending and current. There are many possible causes for this such as neighbor depressurization (see discussion in section 3.6.3) or slow recovery from workover, which are not immediate risks for well integrity, though the disparities should be noted.

When a pressure curve flattens or trends downward during normal operations, there is cause for immediate concern and this should elevate the cavern to focused monitoring (grade 3). Pressure loss indicates likely fluid loss, and preventing current and future oil loss to the environment is a high priority. Actions such as hourly pressure monitoring via direct e-mails from the Distributed Control System (DCS) to selected technical staff, nitrogen testing, and accelerated caliper surveys may be in order. The well can remain at grade 3 if no further leak is identified. When a cavern exhibits a known slow leak that can be contained by a nitrogen cap, a grade 4 is given. Evidence of cemented annulus pressure tracking with oil pressure indicates that primary containment has failed. Grade 5 is given to any well that will not contain pressure and is actively leaking fluid to the environment at a rate that cannot be controlled with nitrogen. This designation includes failed MIT's.

5.3 Cemented Annulus Pressure Grading

As described in section 3.6.5 the recent pressure data, as well as the data from the latest MIT were considered. Each well was given an assigned grade 1-5 according to Table 5-5. The lowest grade (1) corresponds to no pressure in the cemented annulus, and we associate that to no *known* hydraulic connection to the inside of the well. A grade (2) corresponds to a small positive pressure. This implies that the integrity of the cement has been compromised and fluid, either from a very small leak from the well or from the formation is infiltrating into the annulus. Consequently, grade (3) is similar to (2) but a larger pressure might correspond to a greater leak. If the pressure in the annulus responds to changes in the wellbore pressure, the hydraulic connection between the two is confirmed. A grade of (4) is given if the magnitude of the annulus pressure is smaller than the wellbore and (5) is the magnitude is the same. The reasoning is that a smaller leak would produce a smaller pressure, while a large one would allow the pressure to equilibrate to the same value.

Table 5-5: Annular pressure grading system.

Grade	Condition
5	Annulus pressure similar in magnitude and time response to the wellbore pressure.
4	Annulus pressure less than the wellbore pressure. The annulus pressure responds 'similarly' to changes in the wellbore pressure.
3	A large pressure (100's of psi) is present in the annulus but it does not respond to changes in the wellbore pressure.
2	A small positive pressure (smaller than 100 psi) is present in the annulus but it does not respond to changes in the wellbore pressure.
1	No positive pressure in the cemented annulus

5.4 Geomechanics Grading

The possibility of failure/collapse of the wellbores of BC SPR was checked at the interbed between caprock and salt. The results from this analysis indicate that the wellbores of all SPR caverns at Bayou Choctaw are not predicted to fail from shear stress that exceeds shear strength of the steel casing due to the horizontal movement of the top of salt relative to the caprock, and tensile stress due to the downward movement of the top of salt from the caprock. Therefore, *all of BC SPR wellbores are given a score of 1* as a well grading from the geomechanical simulation.

5.5 Geology Grading

The geology component of the well grading criteria encompasses those aspects of the site geology which may affect cavern well integrity. This well grading component is composed of several sub-components. These include aspects discussed in Section 3.2 of this report such as subsidence, salt spines, and caprock concerns. Because the geologic concerns related to well integrity at the SPR sites are diverse and complex, a set of fixed grade-mapping rules was not developed. Instead, the expert opinion of SPR project geologists was used to assign a 1 – 5 grade to the geology grade sub-components. These sub-components were then equally weighted to obtain the final geology grade which was incorporated into the final site grade for each well.

Table 5-6 lists the sub-components of the geology grading component and a brief explanation of its inclusion.

Table 5-6. Sub-components of geology grading component

Sub-Component	Explanation
Salt Fall Count	Relative number of salt falls in the associated cavern
Spine/Fault Distance	Relative distance to nearest fault or salt spine boundary
Uplift/Subsidence	Relative amount of uplift or subsidence in area of well
Salt Overhang	Relative proximity to overhanging salt margin
Caprock Issues	Relative significance of any caprock issues impacting well integrity

The items listed in Table 5-6 are designed to capture the majority of geologic factors which may impact well integrity while trying to minimize overlap with other grading components. Below is an explanation for the inclusion of each of these factors.

Salt fall count represents the relative amount of cavern-wall spalling known to have taken place over the history of the cavern. This can be an indication of stresses or weaknesses in the salt which may affect the integrity of the well casing; it is assumed that an increased number of salt falls is associated with an increase in the potential for well integrity issues.

The relative distance to the nearest fault or salt spine boundary captures the relative location of the well with respect to structurally anomalous zones within the salt dome. It is assumed that proximity to these features is associated with increasing potential for well integrity concerns.

The uplift/subsidence component considers if the well is in an area of vertical displacement of the surrounding geologic media. This could have a direct impact on the integrity of the well casing by imparting tensile or compressive stresses to the casing string; grading values for this component are increased for greater magnitudes of subsidence or uplift.

An overhang in the salt dome margin is indicative of change in the direction of salt flow within the dome, and any change in salt flow direction may generate differential stresses within the salt which may impact the integrity of any nearby wells. This is the basis for including proximity to salt overhangs into the geologic component of the well grading system. This grading component increases for those caverns closest to salt dome margin overhangs.

The caprock component captures concerns such as fractured or vuggy caprock. Additional issues such as extreme thickness or historic injection or extraction from the caprock should also be considered.

5.6 Composite Well Information Grading

The composite well information component of the well grading system is composed of the seven sub-components listed in Table 5-7. These sub-components are combined using equal weighting averaging into the final composite well information component. These sub-components use relative or deterministic grading criteria as described below.

Table 5-7. Sub-components of composite well information component.

Sub-Component	Explanation
Age	Time since initial well installation or well remediation
Gas Regain	Relative rate of gas accumulation in the well casing
Fluid in Cement Annulus	Relative amount of fluid in the cemented annulus
Well Deviation	Relative deviation of the well bore from true vertical
Leak History	Any substantiated leak history
Well Pair History	Accounts for events or leaks for wells in close proximity
MAC Age	Time since last multi-arm caliper survey

The age sub-component is directly computed from the initial installation or most recent remediation date of the well. For this, well remediation is considered to be the installation of a well liner or other activity which results in a new layer of isolation material between the native geologic material and stored product. The absolute age is then compared to the maximum absolute age and then given a continuous grading value between one and five. This generates increasing grading values as the age of the well increases.

Gas regain in SPR caverns occurs when light hydrocarbon gases in the salt dome transfer into the oil, accumulating with time. The SPR Vapor Pressure Program monitors gas regain through bubblepoint pressure measurements of the oils in storage. An update for the gas regain rate for every SPR cavern is published annually by the SPR Vapor Pressure Committee, and these values are imported into the well grading algorithm. Currently, the regain rate is directly adapted to a numerical grade as shown in Table 5-8.

Table 5-8. Vapor Pressure Grading

Cavern Regain Rate (psi/yr)	Grade
0	1
$0 \leq rate < 0.1$	2
$0.1 \leq rate < 0.2$	3
$0.2 \leq rate < 0.3$	4
$rate \geq 0.3$	5

Any fluids (e.g. oil, nitrogen from testing, etc.) accumulating in the cemented annulus space is an indication of a compromised casing system. The fluid in cement annulus sub-component represents this condition. This is a relative grade term determined by expert opinion. Wells with no evidence of fluids in the cemented annulus would receive a grade of one, with increasingly higher fluid quantities receiving higher grades up to a maximum of five.

The well deviation sub-component represents the departure of the well bore from a true vertical orientation. Virtually all SPR cavern wells are drilled to have an absolute vertical orientation. Changes in the geology and other factors typically result in the actual well bore deviating from vertical to some degree. Wells with large deviations may reflect substantial heterogeneities in the subsurface which may impact casing integrity. In addition, the actual deviation of the well bore itself may, in extreme cases, be of concern for casing integrity. This sub-component is graded in a relative sense using expert opinion; low-deviation wells are given low grade values, and high-deviation wells are given high grade values.

Leak history is a sub-component that reflects any known prior leakage from the well casing. Even if a well has been remediated, the fact that it has had a leak at some point in its history is informative in assessing its potential for future leaks. Often leaks are associated with processes and characteristics associated with the surrounding geologic media. These conditions persist even after a well has been remediated and is no longer leaking, therefore, the leak history of the well can be indicative of conditions which may produce future leaks. This sub-component is graded using expert opinion and relative grade values. A well with no known historical leaks should be given a grade of one; wells with a history of severe or multiple leaks are given increasingly greater values up to a value of five.

The well pair history sub component provides a grade that reflects the status of adjacent wells. This term is intended to be used primarily for well groups accessing a common cavern. A well with known integrity issues can be considered an indicator that any other wells for that cavern should also be considered candidates for potential well integrity issues. This is a relative term based on expert opinion. The grading considers the condition of adjacent wells and their relative proximity.

The age of the MAC survey is of interest when considering well integrity as it reflects the uncertainty in our understanding of the current casing condition. This is represented by the MAC age sub-component. Significant casing deformation can take place over a relatively short period of time (Lord et al., 2014); therefore, the amount of time that has elapsed since the most recent MAC survey is important in setting the confidence in our understanding of the current casing condition. This grade is computed using the dates of the most recent MAC survey and a recent reference date. The grade represents the number of years since the last survey; if the number is greater than five, it is set to five, if it is less than one, it is set to one.

5.7 Cavern Geometry Grading

The cavern geometry well grading component relates those aspects of the cavern's shape, spatial location within the salt dome, and relative location to adjacent caverns which have an impact on cavern well integrity. The sub-components of the term are associated with cavern stability which has a direct impact on well integrity. Table 5-9 lists the sub-components of this grading component; details regarding these sub-components are discussed below.

Table 5-9. Sub-components of cavern geometry component

Sub-Component	Explanation
Shape	Relative term for cavern deviation from ideal shape
Pillar-to-Diameter	Term capturing proximity of adjacent caverns relative to cavern size
Salt Roof Thickness	Relative term relating thickness of salt above cavern roof

The shape sub-component reflects how the actual shape of the cavern (diameter, height, etc.) compares to what is considered an optimally shaped cavern. A cavern with a less than optimal shape may experience additional roof stress which can compromise casing integrity. This is sometimes the case with caverns which were originally used for brine generation. Often the leaching was not performed in a controlled manner resulting in large roof spans which may impart additional stresses on the casing string. The grade values for this sub-component reflect how far the cavern's shape deviates from an optimal shape based on expert opinion.

The pillar-to-diameter sub-component captures the relative stability of the cavern as related by the caverns diameter and its closest approach to any neighbor caverns. The pillar-to-diameter ratio is a common value used in evaluating salt dome caverns, and this value has been computed for all the SPR caverns. Caverns with small pillar-to-diameter ratios may be impacted by pressure changes in adjacent caverns which may result in cavern and casing integrity issues. The mapping of pillar-to-diameter values to casing integrity grading values was done as shown in Table 5-10. The pillar-to-diameter values were obtained from Eldredge, Checkai et al. (2013).

Table 5-10. Grade values for pillar-to-diameter sub-component

Grade	Pillar-to-Diameter Value
5	Value <= 0.5
4	0.5 < Value <= 1.0
3	1.0 < Value <= 1.5
2	1.5 < Value <= 2.0
1	Value > 2.0

The salt roof grading sub-component reflects the thickness of salt above the cavern roof. A thicker salt roof is generally associated with increased cavern stability while thinner roofs are less stable. In extreme cases, the salt roof may be completely missing and the cavern roof actually composed of overlying caprock. The grading values for this sub-component are an interpretation of the relative thickness of the salt roof and its impact on cavern stability.

5.8 Offsite Activities Grading

The offsite activities component of the well grading system captures any non-SPR activities which can affect SPR cavern well integrity. The most common offsite activity impacting SPR well integrity is the injection or extraction of subsurface fluids, but this component is not limited to only those concerns. This component is given a relative ranking ranging from 1 to 5 depending on the interpreted potential impact of the offsite activity based on best available information.

6 BAYOU CHOCTAW WELL GRADES

Previous sections of this report have presented the factors considered in establishing a well grading framework (Section 3), and how those factors were quantified in establishing well grading values (Section 5). This section presents the actual numeric grades for the Bayou Choctaw wells and discusses the formulation used in distilling the individual factors into a single well grade value. The values presented here are current as of the date of this report, but are not unchangeable; many of the factors considered here are dynamic so grading values are expected to be updated as newer information comes available.

6.1 Computation of combined grading components

As discussed in Section 4 of this report, the actual final well grading included two dimensions; a remediation priority dimension and a monitoring priority dimension. A schematic of this concept is presented in Figure 4-1. Computation of the final well grades is based on a spreadsheet framework. The spreadsheets contain the data and formulas which determine the final well grades. Each major component in the grading framework is represented as a separate spreadsheet which contains any sub-components for that component. A master spreadsheet tied to the component spreadsheets then merges all the component grades into a grade for remediation priority and an additional grade for monitoring priority. These merging processes are shown diagrammatically in Figure 6-1and Figure 6-2.

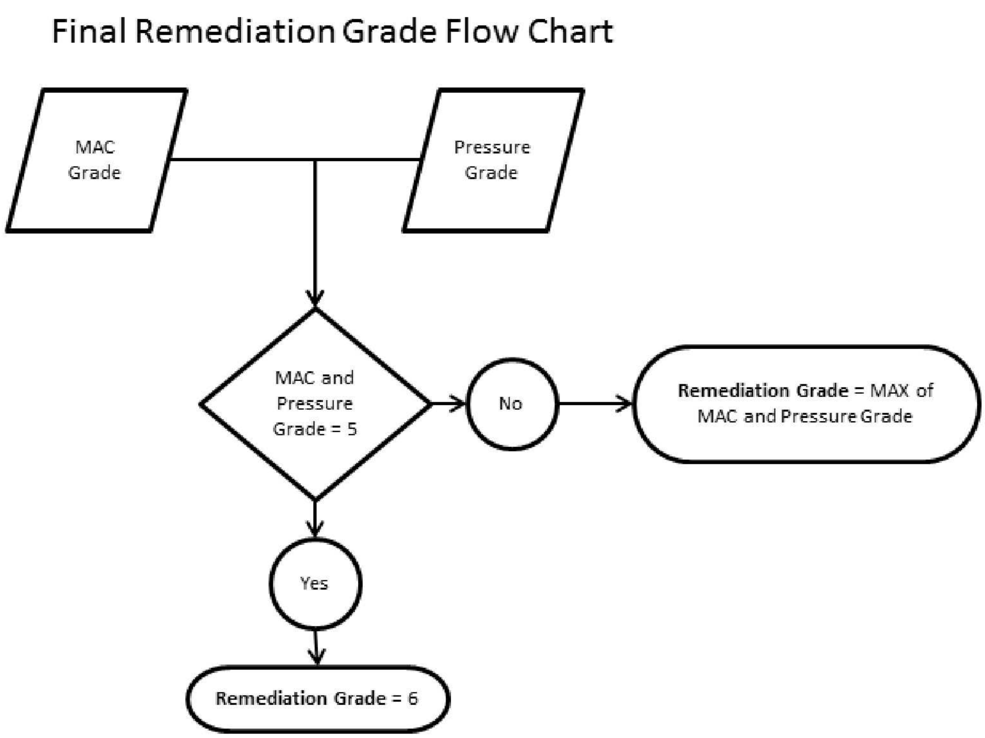

Figure 6-1. Remediation grade flow chart

The final remediation grade (Figure 6-1) represents the maximum grade value from the multi-arm caliper grade (Section 5.1) and the pressure monitoring grade (Section 5.2). These two grading components are used because they are the most useful in indicating remediation priorities. The maximum of these two values is used to assure that high priority wells are appropriately represented. In cases where both the MAC and pressure grade values are 5 (maximum grading value) the well requires immediate attention and the final remediation grade is given a flagging value of 6 to indicate that it has highest priority.

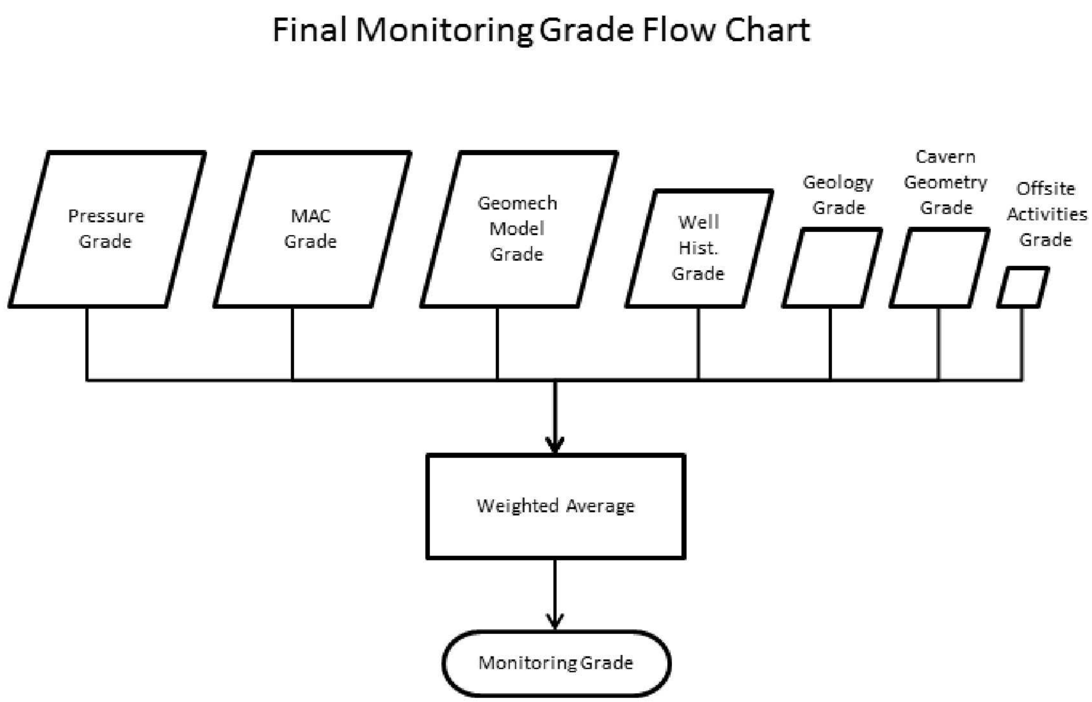

Figure 6-2. Monitoring grade flow chart. Individual grade component symbols sized according to their weight in the averaging process.

For the final monitoring grade (Figure 6-2), the grade is computed as a weighted average of the individual grading components discussed in Section 5. The relative weights of the individual components are shown in Figure 6-3.

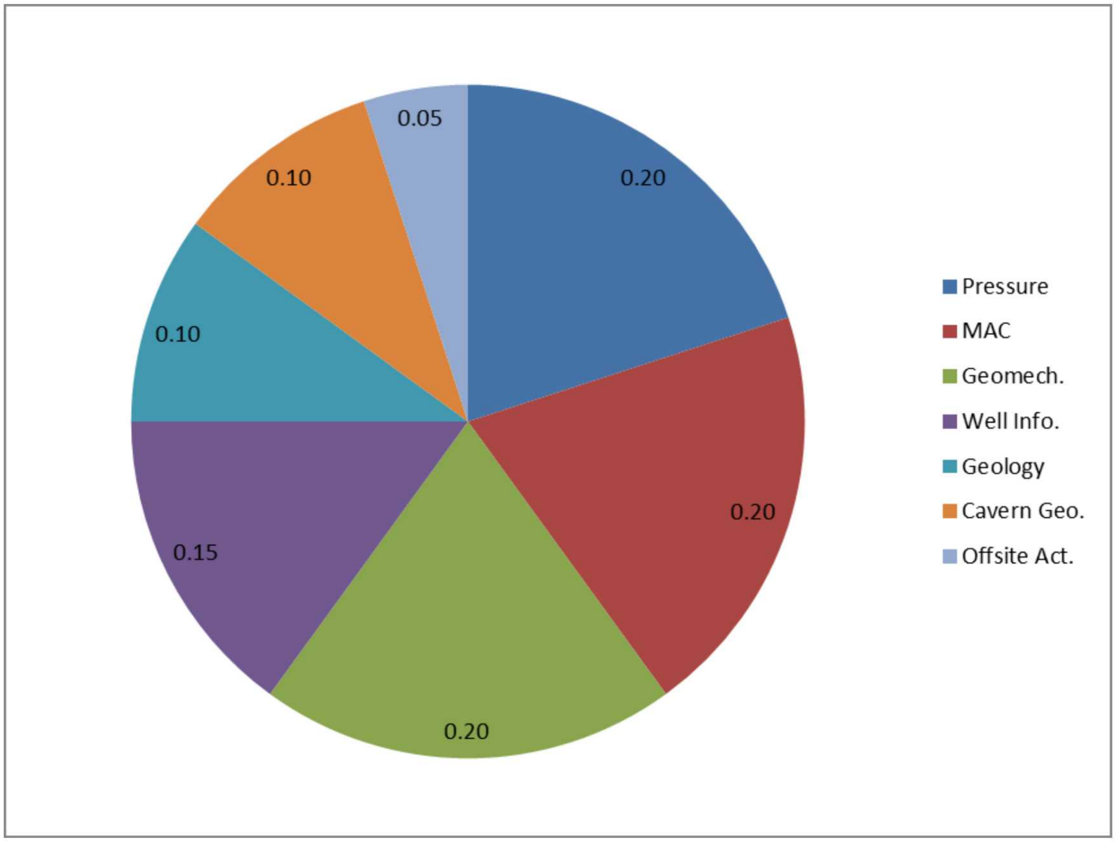

Figure 6-3. Relative weights of the individual grading components used in computing final monitoring grade.

The grade values for the major components (pressure history, multi-arm caliper, geology, etc.) may be computed using additional sub-components which provide additional detail in the grading process. The weights of the sub-components and additional computational details of computing the final remediation and monitoring grades are given in Appendix B.

The final numeric well grade values range from one (lowest priority) to five (highest priority). This applies to all the component and sub-component grade values as well. The one exception to this is for the final remediation well grade. This grade is computed from the MAC survey component and the pressure component. As discussed above, if both of these components have a value of five (5), then the computed remediation grade is set to six (6). This is done to set wells showing severe deformation and extreme pressure issues apart as needing immediate attention.

6.2 Final Bayou Choctaw grade values

The current Bayou Choctaw remediation and monitoring well grades are listed in Table 6-1 sorted by remediation priority; highest remediation priority wells (higher numeric values) appear at the top of the table. This same information is displayed graphically in Figure 6-4. In this figure, remediation and monitoring priorities increase diagonally from the lower-left to the upper-right corner. Note that these values represent the current conditions at Bayou Choctaw, including any well remediation work, at the time this report was produced.

Table 6-1. Current Bayou Choctaw remediation and monitoring well grades sorted by remediation priority.

Well ID	Remediation Grade	Monitoring Grade
19	4	2.29
15A	2.5	1.51
20	2	1.67
101A	2	1.89
15	1.75	1.55
17A	1.75	1.57
102A	1.75	1.47
18	1.25	1.58
19A	1.25	1.41
101B	1.25	1.90
17	1	1.42
18A	1	1.53
20A	1	1.60
102B	1	1.27
4**	-	3.22

*cavern 20 currently contains no directly accessible oil

**cavern 4 has never been used to store oil by the SPR

Although the Y-axis in Figure 6-4 goes to a maximum value of six, there are no wells currently meeting the criteria to achieve a grade of six. Also note that wells that have been remediated are re-evaluated based on their remediated status. This may result in wells moving from the top to the bottom of the remediation axis as their status changes and they are re-evaluated.

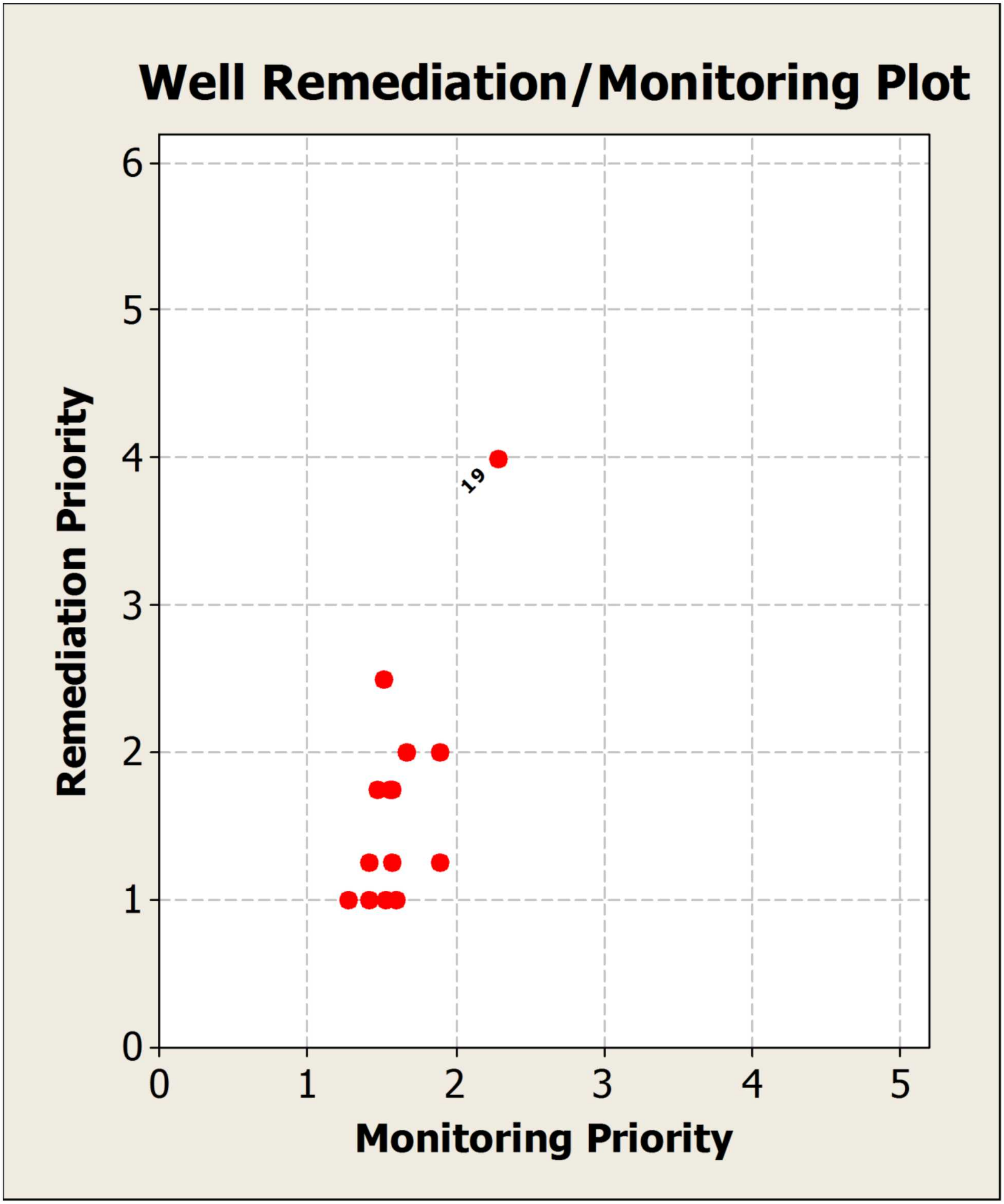

Figure 6-4. Plot of current Bayou Choctaw well grades for remediation and monitoring. Wells with remediation grades greater than 3 are labeled.

7 ADMINISTRATION

7.1 Well Integrity Working Group

The ah-hoc SPR well integrity working group provides technical support for the SPR well integrity program. Working group members include representation from FFPO Cavern Integrity, Sandia Geotechnology & Engineering, and DOE Maintenance & Operations. The lead members of the working group are co-authors on this SAND report. The well integrity working group meets on an as-needed basis to review well grade values and address immediate well integrity issues.

7.2 Reporting Requirements

- The working group intends to produce a Well Grading SAND report for each of the four SPR sites. This report, for Bayou Choctaw, is the fourth of the four.
- For each SAND report and any major update, a representative from the working group will request to give a presentation to the SPR project manager and assistant project managers
- For periodic working group meetings, SNL will inform the DOE assistant project manager for M&O of the location and agenda for the meeting
- The working group will give updates, written, verbal, or both, as requested by the FFPO Caverns Director, SNL Project manager, or DOE senior management

7.3 Update Schedule

The long-term objective of the well grading system is to provide management-level guidance on resource allocation toward maintaining SPR cavern well integrity. An increasing concern regarding well integrity issues at the SPR has created an urgency for establishing a prioritization system as soon as possible. The well integrity working group offers this SAND report and the accompanying Well Grading Workbook tool as the first iteration for the Bayou Choctaw Site. The same style or report and Well Grading Workbook are already available for the Big Hill, Bryan Mound, and West Hackberry Sites.

As a starting point, the working group proposes that the well grading is updated every six months, so that at the same time that we roll out next well grading, we will also provide updates for the previously graded sites. For deliverables, the working group would submit an executive summary for the previously graded sites, and note any changes made within the last 6 months. The supporting well grading workbook will be reviewed and updated at least once every six months as well.

7.4 Documentation Control

A formal SAND report will accompany the first of each well grading effort per SPR site. These are static documents that present a large volume of background material that will not change. There is no planned update schedule for the SAND reports. Conversely, the electronic spreadsheet workbooks (one for each SPR site) that contain the grading data are living documents that will require updates. The current plan is for Sandia to develop the first version of each, and when the working group agrees that the major development work is completed, for FFPO Caverns to take custody of the electronic workbook. The workbook will be available as read-only to all SPR users through the FFPO Caverns SharePoint interface. Edit privileges will be limited to selected members of the well integrity working group.

During the initial phase of the well grading project where the first round of grading is underway for each site, an executive summary will be produced concurrently with each new SAND report. The scope of the executive summary will include all of the sites graded to-date. The executive summary will be presented concurrently with the roll-out of the next site's grading that includes any updates to any previously developed grading.

All other working group deliverables (presentation files, technical reports, executive summaries) deemed appropriate for release to the SPR community will be managed by FFPO Caverns and made available to SPR staff through the FFPO Caverns SharePoint interface.

REFERENCES

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APPENDIX A: BAYOU CHOCTAW WELL RANKING MEETING AGENDA

- Bayou Choctaw Well Grading Meeting Agenda –
NOLA DOE Training Room 1st Floor
Day 1 – Tuesday April 14th

Topic	Start-End Time	Discussion Lead / Presenter
Introductions	8:00 am – 8:15 am	Barry Roberts
Meeting Goals and Agenda	8:15 am – 8:30 am	Barry Roberts
Review of BH, BM, & WH Well Grades	8:30 am – 9:30 am	Barry Roberts
Bayou Choctaw Geology Presentation	9:30 am – 10:00 am	Anna Lord
BREAK	10:00 am – 10:15 am	
Geomechanics Presentation	10:15 am – 10:45 am	Byoung Park
SNL Multi-arm Caliper Analysis Presentation	10:45 am -11:15 am	Barry Roberts
Cavern Pressures Presentation	11:15 am – 12:00 am	Giorgia Bettin / David Rudeen
LUNCH	12:00 am – 1:00 pm	
Review of Grading Procedures	1:00 pm – 1:30 pm	Barry Roberts
Well by Well Discussions	1:30 pm – 2:45 pm	Barry Roberts
BREAK	2:45 pm – 3:00 pm	
Well by Well Discussions (cont.)	3:00 pm – 5:00 pm	Barry Roberts

Day 2 – Wednesday April 15th

Topic	Start-End Time	Discussion Lead / Presenter
Well by Well Discussions (cont.)	8:00 am – 10:00 am	Barry Roberts
BREAK	10:00 am – 10:15 am	
Well Grade Assignments	10:15 am – 12:00 am	Barry Roberts
LUNCH	12:00 pm – 1:00 pm	
Well Grade Assignments (cont.)	1:00 pm -2:00 pm	Barry Roberts
Review of Final Grades	2:00 pm -3:00 pm	Barry Roberts
Report Generation Planning	3:00 pm -4:00 pm	Barry Roberts

APPENDIX B: DETAILS OF WELL GRADE FRAMEWORK

This appendix presents additional details of the computation of the well grading values. The actual computations and data values are contained in spreadsheet files. Presented here are tables, equations and descriptions of the computations held in those spreadsheets. The Main Grade Criteria table shown below lists the components used to directly compute the remediation priority grade value (rows highlighted in red), and the monitoring priority grade value (rows highlighted in green).

MAIN GRADE CRITERIA

Name	Meaning	WT
MAC-FFPO	Multi-arm caliper FFPO grade for zone of interest	NA
MAC-SNL	Multi-arm caliper SNL grade for zone of interest	NA
MAC-FINAL	AVG(MAC-FFPO, MAC-SNL)	NA
PRESS	Pressure history information grade	NA
REMED	IF (MAC-FINAL = 5 AND PRESS = 5 THEN 6, OTHERWISE (MAX (MAC-FINAL, PRESS))	NA
PRESS	Pressure history information grade*	0.20
MACMON	Multi-arm caliper SNL grade for entire survey length	0.20
GEOMCH	Geomechanical modeling based grade	0.20
WELLINFO	Well history considerations*	0.15
GEOL	Geological ranking*	0.10
CAVGEOM	Cavern geometry considerations*	0.10
OFFSITE	Offsite activities considerations*	0.05

*indicates that multiple sub-component factors are considered in this term

The above components are combined to create two separate variables. These two separate variables are then mapped on to two axes to produce a plot displaying the grade values. The two final variables are referred to as MONITORING PRORITY (x-axis), and REMEDIATION PRIORITY (y-axis).
The REMEDIATION PRIORITY (y-axis) is based solely on the REMED criteria as shown above; the MONITORING PRORITY (x-axis) is based on a weighting of several factors.

MONITORING PRORITY=
(PRESS*WT)+(MACMON*WT)+(GEOMCH*WT)+(GEOL*WT)+(WELLINFO*WT)+CAVGEOM*WT)
+(OFFSITE*WT)

The monitoring priority grade value is composed of many components, several of which have sub-components. A listing of these components and sub-components, and how they are combined is provided in the tables below. These components would each be represented by a separate spreadsheet in the master grading workbook.

COMPONENT RANKING FACTORS

Multi-arm caliper for monitoring grade (MACMON)

Name	Meaning	Wt
MACMON	SNL derived multi-arm caliper grade based on entire length of survey	1

Cavern pressure history grade (PRESS)

Name	Meaning	Wt
PRESS	Grade based on cavern pressure history	1
PRESS/ANNULAR	Grade considering cavern pressure and annular pressure	NA

Geomechanical simulation grade (GEOMCH)

Name	Meaning	Wt
GEOMCH	Grade based on geomechanical modeling results	1

Well History Information (WELLINFO)

Name	Meaning	Wt
AGE	Scaled age factor	1/7
GASREG	Gas regain factor	1/7
FLUIDANU	Fluid in cement annulus	1/7
WELLDEV	Well deviation	1/7
LEAKHIST	Leak history	1/7
PAIRHIST	History of any paired well	1/7
MACAGE	Time passed since last MAC survey	1/7

(Currently all these factors, with a non-zero weight, are equally weighted)

Geology (GEOL)

Name	Meaning	Wt
SALTFALL	Number of salt falls for cavern	1/5
SPINEDIST	Distance from any known (mapped) salt spines	1/5
UPLIFT	Uplift of subsidence issues at the site	1/5
SOVRHNG	Salt overhang	1/5
CAPTHCK	Caprock thickness (currently not used)	1/5

(Currently all these factors, with a non-zero weight, are equally weighted)

Cavern Geometry (CAVGEOM)

Name	Meaning	Wt
SHAPE	General cavern shape	1/4
P2D	Pillar to diameter ratio	1/4
SLTBACK	Salt back (cavern to top of salt distance)	1/4
SHOEDIA	Casing shoe depth and cavern diameter	1/4

(Currently all these factors, with a non-zero weight, are equally weighted)

Offsite Activities (OFFSITE)

Name	Meaning	Wt
OSPUMP	Offsite pumping (injection or extraction)	1

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