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2013 Strategic Petroleum Reserve Big Hill Well Integrity Grading Report

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Abstract

This report summarizes the work performed in developing a framework for the prioritization of cavern access wells for remediation and monitoring at the Big Hill Strategic Petroleum Reserve site. This framework was then applied to all 28 wells at the Big Hill site with each well receiving a grade for remediation and monitoring. Numerous factors affecting well integrity were incorporated into the grading framework including casing survey results, cavern pressure history, results from geomechanical simulations, and site geologic factors. The framework was developed in a way as to be applicable to all four of the Strategic Petroleum Reserve sites.

Acknowledgments

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NOMENCLATURE

BBL	Barrel (42 US gallons)
BC	Bayou Choctaw SPR Site
BH	Big Hill SPR Site
BM	Bryan Mound SPR site
DM	DM Petroleum Operations Company
DOE	U.S. Department of Energy
MB	Thousand barrels (volume)
MIT	Mechanical Integrity Test
MMB	Million barrels (volume)
MAC	Multi-Arm Caliper
OBI	Oil-brine interface
OD	Outer Diameter
SNL	Sandia National Laboratories
SPR	Strategic Petroleum Reserve
WH	West Hackberry SPR site

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, DM Petroleum Operations (DM), 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 DM convened a working group meeting at the SPR project office in New Orleans in January, 2013 in order to discuss and develop a common grading system for prioritizing SPR wells. The 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.

This report documents the objectives, technical background materials, and grading process developed during the January 2013 Big Hill well integrity grading meeting. All 28 BH wells were evaluated and 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 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. 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.

After development of the framework, each Big Hill 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 Big Hill 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. In this graph, remediation and monitoring priorities increase from the lower-left to the upper-right portions of the graph.

This report, and the work behind it, represents the first step in the prioritization grading of all the SPR cavern access wells. The intent is to generate a similar report with well grades for each of the remaining 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 Big Hill remediation and monitoring well grades.

Well ID	Remediation Grade	Monitoring Grade
BH104B	5	1.26
BH106B	5	1.49
BH103B	4.5	1.88
BH107B	4.5	1.66
BH113A	4.5	1.97
BH103A	4	1.88
BH111A	4	1.59
BH112A	4	2.42
BH112B	4	2.38
BH113B	4	1.89
BH108B	3.5	1.13
BH111B	3.5	1.50
BH101B	3	1.26
BH102A	3	2.10
BH102B	3	2.06
BH108A	3	1.18
BH109A	3	2.04
BH101A	2.5	1.30
BH104A	2.5	1.34
BH105A	2.5	2.01
BH107A	2.5	1.75
BH106A	2	1.58
BH110A	1.5	1.52
BH110B	1.5	1.48
BH105B	1	1.96
BH109B	1	1.96
BH114A	1	1.83
BH114B	1	1.87

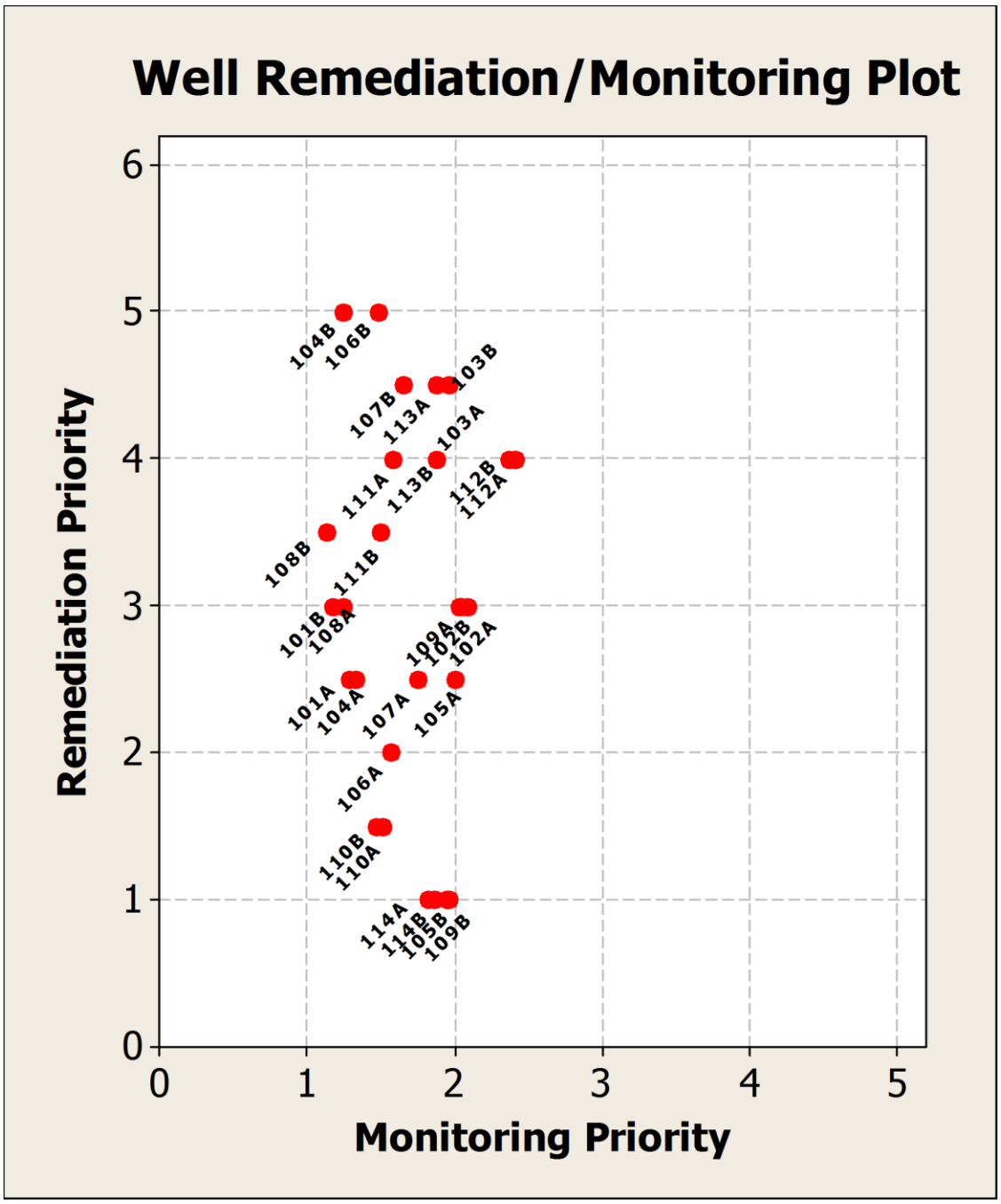


Figure 1-1. Plot of current Big Hill well grades for remediation and monitoring.

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.

Combined wellhead pressure monitoring and multi-arm caliper (MAC) surveys have returned 27 red well grade designations requiring remediation since 2008 (see Figure 2-1, reproduced from Erskine (2013)). These designations were developed by DM and rank a hydraulic failure, MIT failure, or deformation of the casing greater than the original wall thickness as red requiring remediation. Sandia National Laboratories (SNL), geotechnical advisor to SPR, developed a separate well grading color systems based on (i) review of MAC data at Big Hill (Sattler and Ehgartner 2011), and (ii) geomechanical simulations of likely operations futures for the cavern fields (Sobolik 2010; Park and Ehgartner 2012).

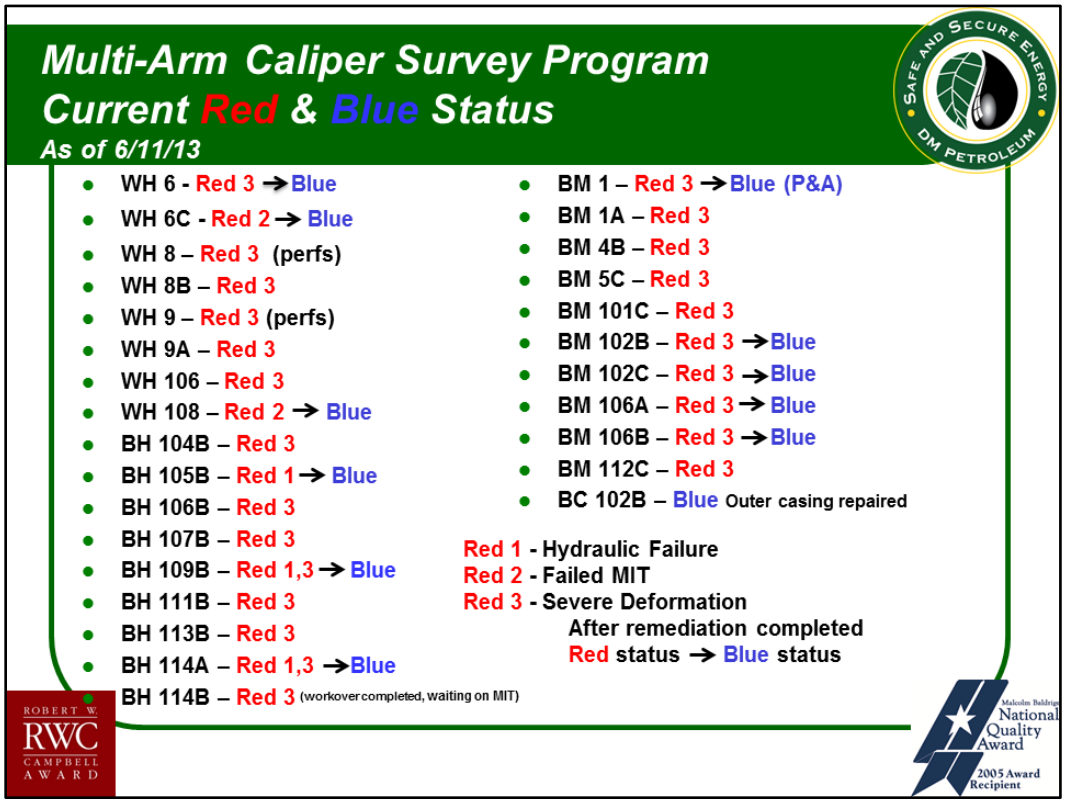


Figure 2-1. Listing of caverns designated red or mandatory for remediation, as determined by multi-arm caliper survey or wellhead fluid pressure monitoring since 2008, reproduced from Erskine (2013).

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, DM Petroleum Operations (DM), 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 DM 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. The 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.

2.1 Scope of Report

This report documents the objectives, technical background materials, and grading process developed during the January 2013 Big Hill (BH) well integrity grading meeting. All 28 BH wells were evaluated and 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 ranking 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

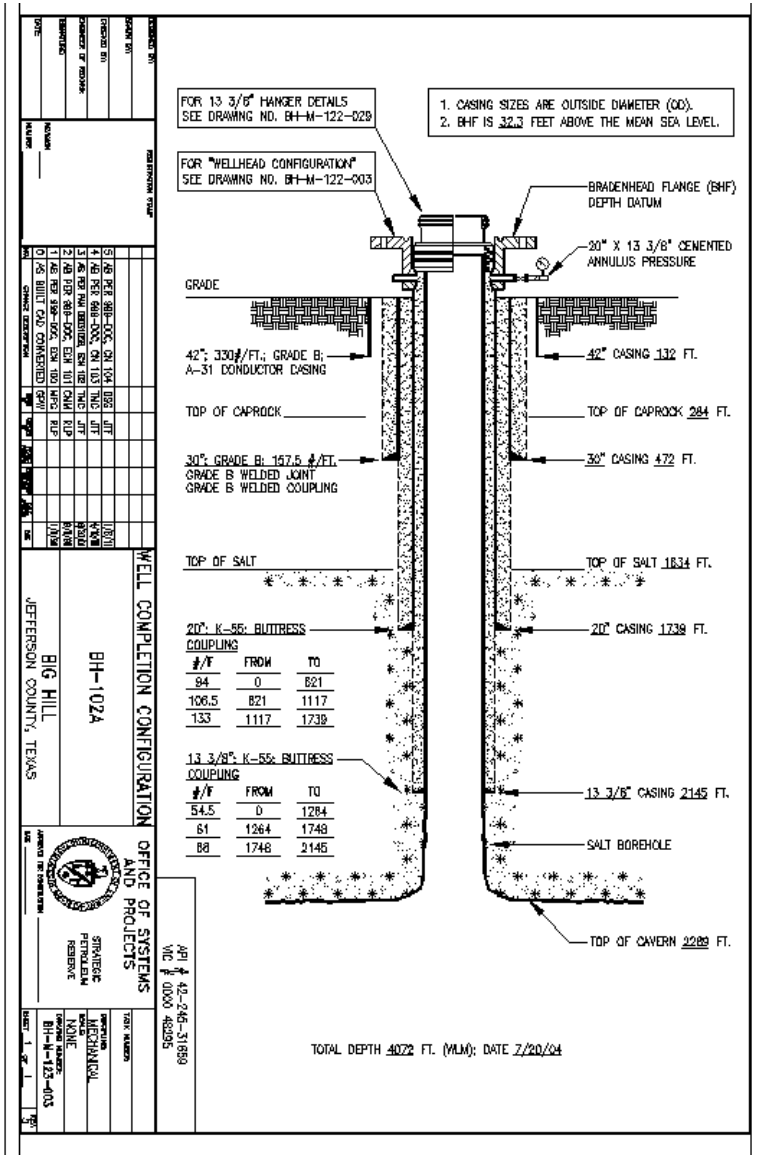
The cavern well systems are complex and dynamic. Many factors must be considered when determining the drivers for monitoring and remediation. SNL and DM subject-matter experts came together to present and discuss what they believe to be a necessary set of factors for resource planning and risk mitigation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

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

Excerpts from the introductory presentations under each area are documented below.

3.1 General Description of BH Wells

Big Hill has a relatively uniform configuration compared to other SPR sites, with fourteen caverns and two cased wells per cavern. All 28 wells were completed with two cemented casings into the salt. The original configuration utilized 13-3/8" OD for the final production casing extending about 500 feet into salt at the casing shoe. Current configurations for remediated wells have changed somewhat. Example well completion configurations for the original installation are shown for the BH102A and BH102B in Figure 3-1. The primary difference between Big Hill A- and B- wells is that the A-well is a "slick" hole carrying only oil, while the B-well contains a hanging string that extends to the brine pool at the bottom of the cavern. The annular space between the B-well cemented casing and the brine hanging string contains oil.



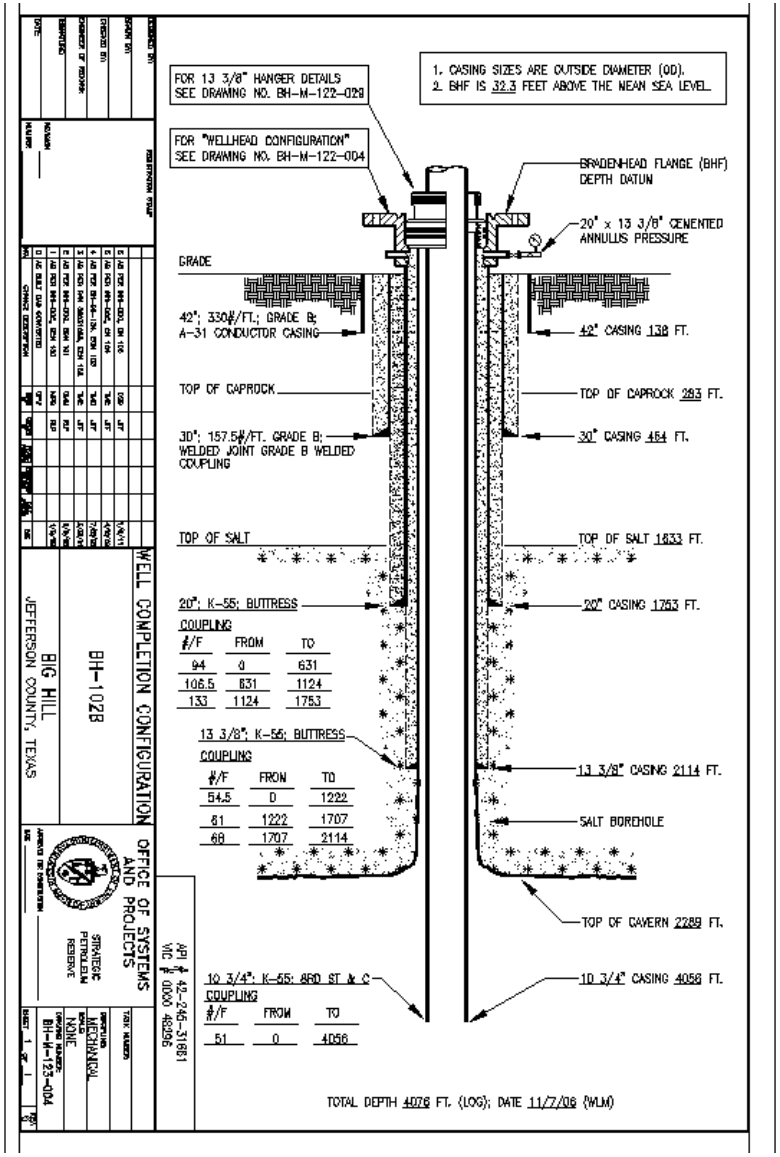


Figure 3-1. Well completion diagrams for BH102A and BH102B, typical for BH during initial completion in the 1980's.

3.2 Big Hill Site Geology

3.2.1 Geology

Understanding the Big Hill geology will aid in interpretation of the processes affecting cavern well integrity. Big Hill is one of a multitude of salt domes located along the U.S. Gulf Coast. Salt exhibits a plastic property and salt domes are a result of upward movement of deeply buried salt where flow is initiated by the weight of denser overlying sediments.

Many salt domes are overlain by a caprock, which is the product of accumulation of insolubles, such as anhydrite, from the dissolution of the domal salt at groundwater level. At Big Hill the caprock is comprised of lower anhydrite zone overlain by a limestone and gypsum zone, both of which are diagenetic alterations of anhydrite. The top of caprock is approximately 300 ft. below surface. The caprock thickness ranges between 850-1300 ft. and is one of the thickest caprocks known. The caprock structure exhibits vugs, faults, and fractures, all of which are caused by dissolution of the underlying salt during dome growth and hence the collapse of the salt-caprock interface, resulting in a highly permeable caprock.

The salt is composed of rather pure halite. Insolubles comprise 1.7% anhydrite, with sylvite concentrated around the edge of the dome. The top of salt is at a depth between 1300-1800 ft. The dome is generally cylindrical in shape and leans towards the south. The flanks are not smooth, but rather exhibit a crenulated fabric. The salt overhangs largely to the south with less prominent overhangs present along both the western and eastern sides of the salt flanks. Figure 3-2 displays the most recent remapping of both the top-of-caprock and top-of-salt structure contour maps by Rautman et al. (2005).

Magorian and Neal (1988) mapped anhydrite bands within the dome between cavern well bores using density logs. Two salt spines were identified and are separated by a shear zone trending north/northeast. The mapped salt shear zone correlates to a large fault mapped at the surface of caprock. Figure 3-3 presents the location of the interpreted spines from Magorian and Neal (1988).

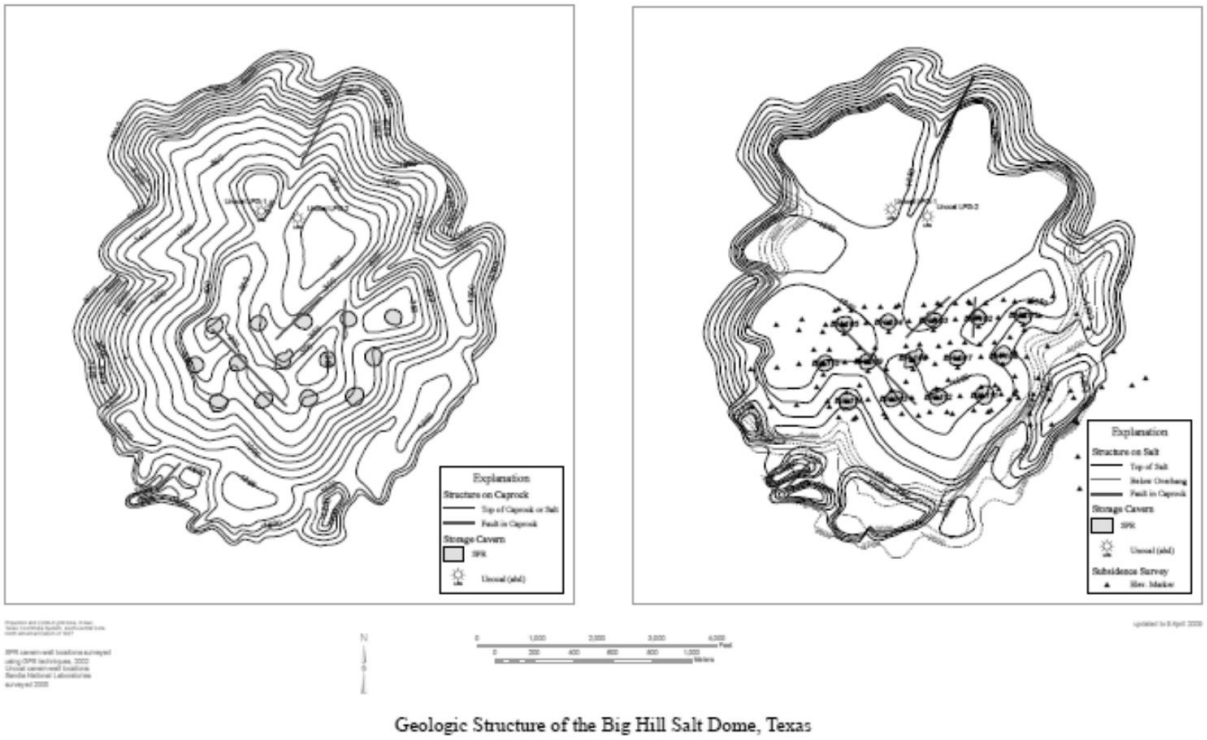


Figure 3-2. Big Hill structure contour maps for top-of-caprock (left) and top-of-salt (right).

Neal, Magorian et al. (1993) studied the leaching history of the Big Hill caverns and discovered additional evidence to support the inferred shear zone. During leach of Cavern 114 150 bbl of hydrocarbons were encountered. The hydrocarbons were thought to come from an isolated pocket within the salt. Cavern 114 is near the edge of the dome, adjacent to the south overhang were oil production had occurred. The hydrocarbons were most likely encapsulated within the salt during upward movement of salt along the shear zone. During sump development Cavern 103 experienced excessive corrosion caused by highly alkaline brine. High alkaline brines have been associated with anomalous zones. During leaching of Cavern 109 high pressure buildup occurred due to higher than normal gas production, this could be the result from the cavern's close proximity to the shear zone. No other major occurrences were noted during leaching of the other 11 caverns.

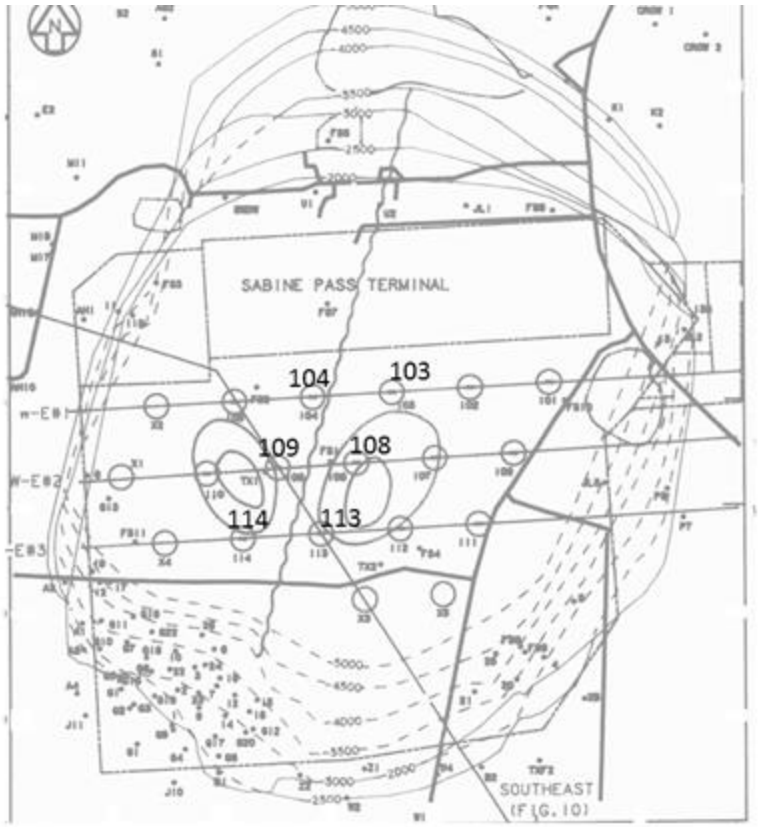


Figure 3-3. Big Hill top-of-salt structure map displaying location of interpreted spines and corresponding shear zone, reproduced from Magorian and Neal (1988).

Other salt spines and corresponding boundary shear zones have been inferred from mapping the top of caprock structure. Rautman et al. (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 presents the locations of possible boundary shear zones inferred from caprock structure.

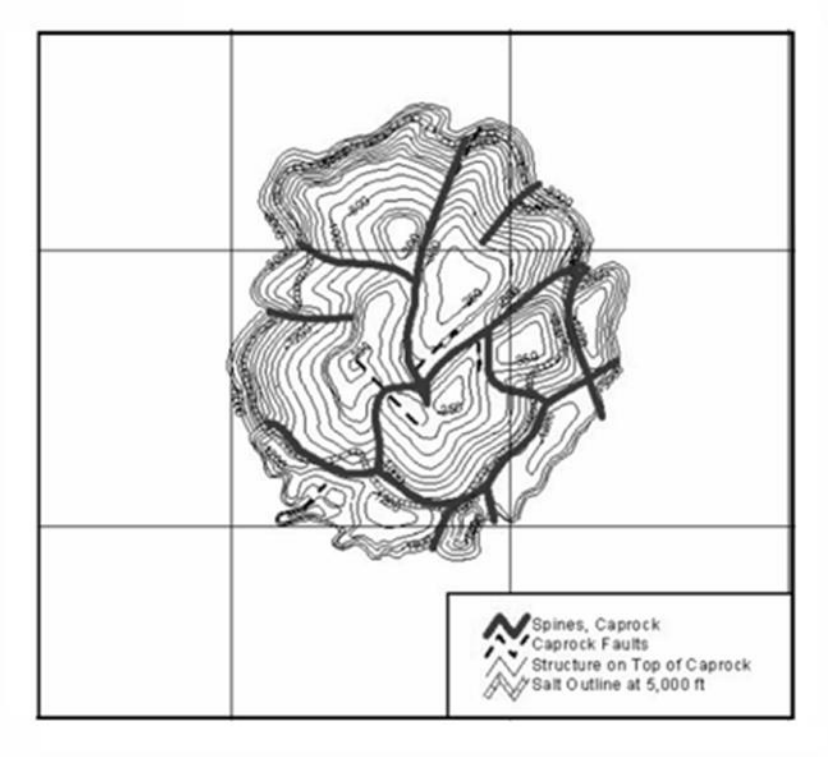


Figure 3-4. Big Hill top-of-caprock structure contour map showing inferred subdivision into a number of spines (Figure 4 from Rautman and others (2005)).

3.2.2 Subsidence

Monitoring subsidence rates is one tool to monitor cavern integrity. Typically, cavern closure manifests itself at the surface as subsidence. However, at Big Hill cavern closure rates are occurring at a greater rate than represented by the subsequent surface subsidence (see Figure 3-5). The discrepancy is due to the very thick caprock. Subsidence effects are most likely distributed over a greater surface area. A large discrepancy between surface and underground displacement can have an adverse impact on the integrity of the cavern wells. Rapid underground closure coupled with small surface subsidence suggests the possibility of significant vertical ground and casing strains between cavern and surface.

Subsidence surveys have been conducted annually or biennially since 1989 over the Big Hill site. Since 2002, with the addition of 135 new monuments, elevation measurements have indicated continuous surface uplift over the eastern edge of the site. Figure 3-6 displays the latest subsidence rates calculated between March 2011 and May 2012. Note the warm colors (i.e. yellow, orange, and red) indicate uplift. A definitive reason for the uplift has yet to be determined, but continued rise in elevation will eventually, if not already, impact well integrity. One possible contributor to the uplift phenomena is the injection of waste fluid into the caprock by a neighboring injection facility.

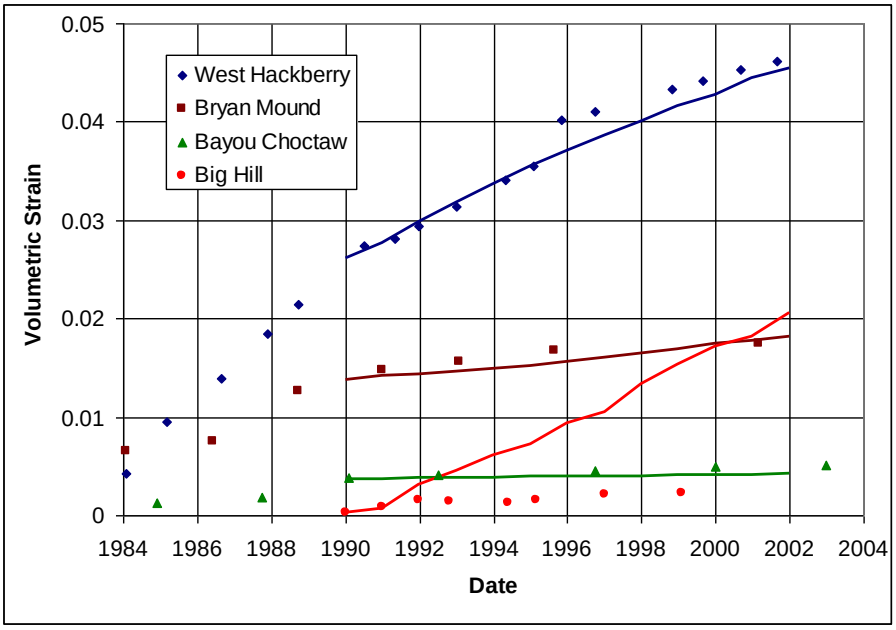


Figure 3-5. Volumetric strain versus time based on subsidence measurements (symbols) and CAVEMAN cavern analyses (solid lines), reproduced from Ehgartner and Bauer (2004).

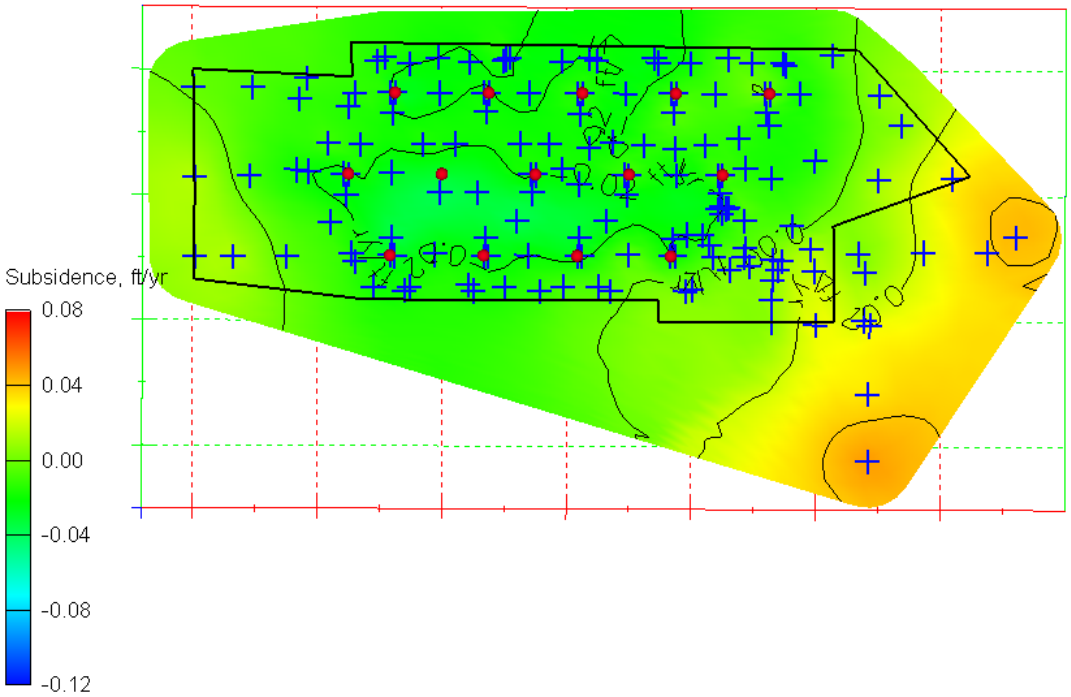


Figure 3-6. Contour plot of subsidence rates (ft/yr) from March 2011 to May 2012. Monument locations are noted by crosses.

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 and thus cavern closure increase, 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 Big Hill analyses.

3.3.1 Simulations of Well Casing Damage

A three dimensional finite element model, which allows each cavern to be configured individually, was recently constructed to investigate shear and vertical displacements across each interface (Park and Ehgartner 2012). The model contained interfaces between each lithologic unit and a shear zone to examine the interface behavior in a realistic manner. The modeling simulated the cavern responses forward in time from the initial cavern creation. The results from this analysis indicated that the casings of BH105 and BH109 failed, respectively, from shear stress that exceeded shear strength of steel 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.

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 interface between

the caprock and salt dome are calculated right above the center of each cavern. The movement rate of the salt dome top is larger than that of the stiff thick caprock.

3.3.1.1 Geomechanical model

Figure 3-3, shown previously, presents a plan view of the BH site with contour lines defining the approximate location of the salt dome top. The locations for the 14 SPR currently in-use caverns (101-114) and five potential expansion caverns (X1-5) are shown. The figure also indicates the undeveloped area north of the DOE property line (Sabine Pass Terminal). The horizontal shape of the dome is approximately elliptical. The major and minor ellipse axes are measured as 7000 ft. and 5800 ft., respectively.

The west-east cross-section #1 through the northern-most row of caverns (Cavern 101-105) provides a geologic representation near the middle of the dome (Figure 3-7). The site has a thin overburden layer consisting of sand and soil and an exceptionally thick caprock sequence comprised of two layers. The upper caprock is comprised mainly of gypsum and limestone, whereas the lower caprock is mostly anhydrite. A major fault extends approximately north-south along the entire length of the caprock for an unknown depth into the salt. This fault zone has a pronounced effect on the subsidence measured above the site and is a consideration for future cavern placement (Ehgartner and Bauer 2004).

For analysis purposes, the top layer of overburden is modeled as having a thickness of 300 ft., the upper caprock 900 ft. thick, and the lower caprock 430 ft. thick. The salt thickness over the caverns is approximately 660 ft. The bottom boundary of the present analysis model is set at 6000 ft. below the surface.

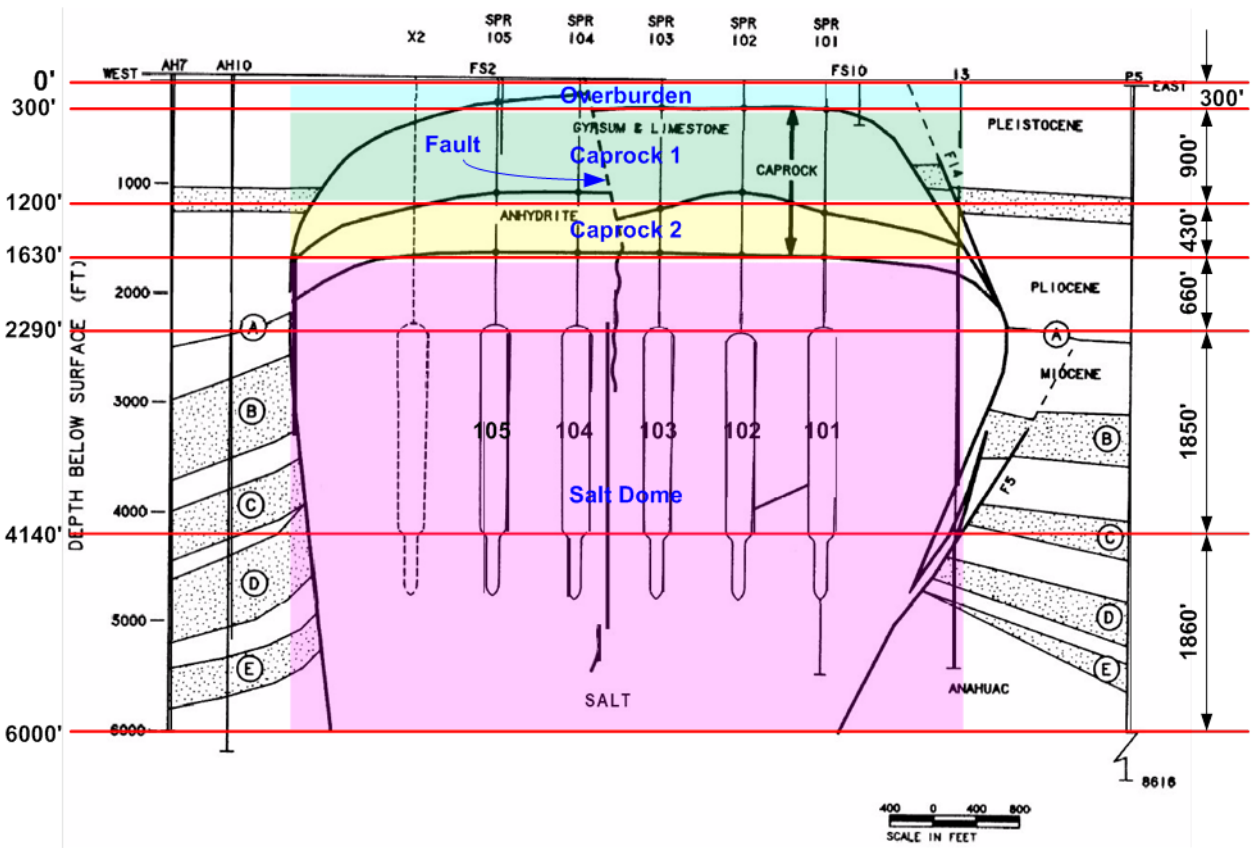


Figure 3-7. Cross-section (W-E #1 in Figure 3-3) near middle of dome, from Magorian and Neal (1988).

3.3.1.2 Interfaces and Fault Model

To investigate causes of well casing damage between the salt dome and the caprock, horizontal shear displacements and vertical strains at the interface need to be examined. Thus, interface blocks, special purpose analysis tools, are used to represent the interfaces between overburden and caprock 1; caprock 1 and caprock 2; caprock 2 and salt dome; surrounding rock and dome. The material behavior away from the interfaces is represented by the material properties of caprock 1, caprock 2, and salt. The fault, which was ignored for simplification in previous analyses (Park et al., 2005), is included in this model to better represent the large scale deformation considered in this study.

There is no interface geometry and material property data available from the field. The interfaces and fault are assumed to mechanically behave like sandy soil, thus the overburden material properties are used in the analysis for the interfaces and fault. In this study, the thicknesses of the interface materials are assumed to be a uniform 14 ft. (4.3 m) based on the measured largest thickness of the salt/caprock interface from Weatherford Multi Arm Caliper survey data (Sattler and Ehgartner, 2011). The thickness of fault varies from a millimeter to a hundred meters with fault displacement (Figure 3-8). These model attributes were incorporated into the finite element method (FEM) mesh which will be described in Section 3.3.1.4.

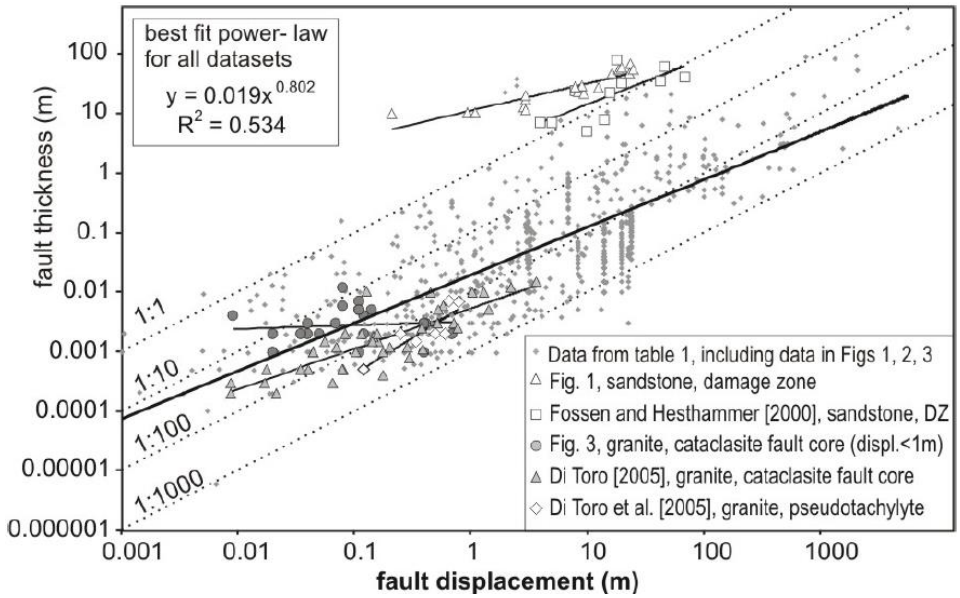


Figure 3-8. Log-log plot of a compilation of 16 fault thickness datasets reported in the literature including the data used by Hull (1988) and three datasets in Shipton, Soden et al. (2006)

3.3.1.3 Cavern model

3.3.1.3.1 Cavern geometry and layout

The cavern shapes are approximately cylindrical and the cavern array is regular as shown in Figure 3-9. The cavern dimensions used in the model are simplified and are listed in Table 3-1 based on the sonar data. The completion date for the initial leach of each cavern is also listed. The X- and Y-coordinates for the center of each cavern were calculated by subtracting the Universal Transverse Mercator (UTM) coordinates of the center of the dome from UTM coordinates of each cavern. That is, the origin for the coordinate system of the model is the center of the dome.

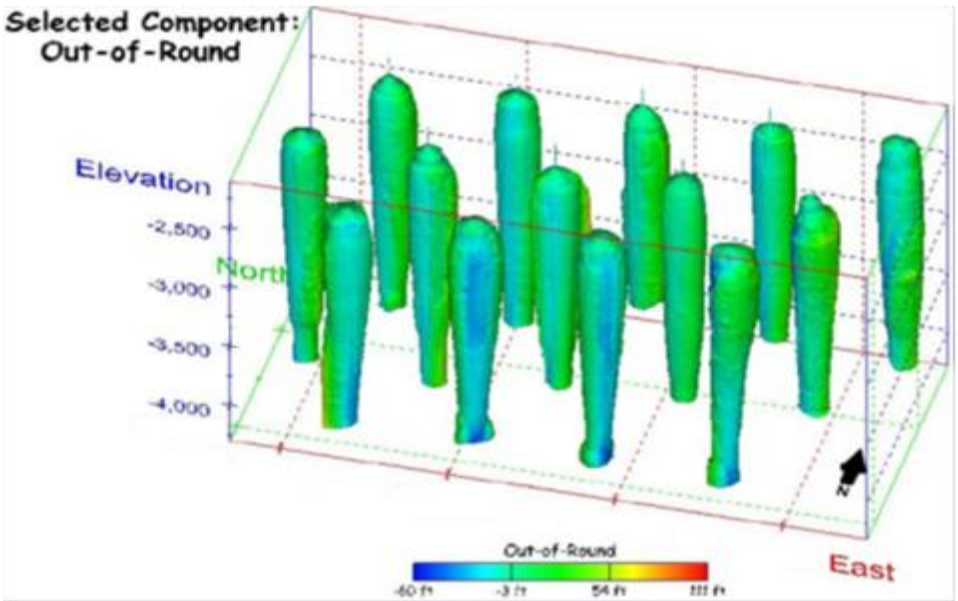


Figure 3-9. Perspective view of the entire cavern field at the Big Hill SPR site from the southeast, reproduce from Rautman and Lord (2007).

Table 3-1. Geometric parameters and initial leach completion dates for the fourteen extant caverns.

Cavern ID	X (East)	Y (North)	Z (Vertical Center)	Diameter	Radius	Cavern Top	Cavern Bottom	Cavern Height	Leach Completion Date
	ft	ft	ft	ft	ft	ft	ft	ft	mm/dd/yyyy
101	1875	-551	-3215	220	110	-2290	-4140	1850	9/18/1990
102	1125	-551	-3215	220	110	-2290	-4140	1850	10/21/1990
103	375	-551	-3215	220	110	-2290	-4140	1850	11/28/1990
104	-375	-551	-3215	220	110	-2290	-4140	1850	10/21/1990
105	-1125	-551	-3215	220	110	-2290	-4140	1850	11/11/1990
106	1500	-1200	-3215	220	110	-2290	-4140	1850	10/16/1990
107	750	-1200	-3215	220	110	-2290	-4140	1850	4/24/1990
108	0	-1200	-3215	220	110	-2290	-4140	1850	6/14/1990
109	-750	-1200	-3215	220	110	-2290	-4140	1850	7/24/1990
110	-1500	-1200	-3215	220	110	-2290	-4140	1850	4/19/1990
111	1124	-1849	-3215	220	110	-2290	-4140	1850	7/15/1991
112	374	-1850	-3215	220	110	-2290	-4140	1850	6/19/1991
113	-376	-1849	-3215	220	110	-2290	-4140	1850	5/1/1991
114	-1126	-1849	-3215	220	110	-2290	-4140	1850	8/29/1991

3.3.1.3.2 Model history

The Big Hill caverns were leached from April 1990 through August 1991 as listed in Table 3-1. To simplify the model history for the purposes of the present simulation, it is assumed that all existing caverns were initially leached in 1990, which is considered time t = 1 year in the simulation. The analysis simulates caverns that were leached to full size over a one year period by means of gradually switching from salt to fresh water in the caverns. It was assumed that the SPR caverns were filled with petroleum one year after their initial leaches start. The caverns are simulated as creeping for thirty years. The simulation then performs oil drawdowns in the SPR caverns.

Every five years after the 31st year from the beginning of the simulation, every SPR cavern is modeled as being instantaneously leached. Modeling of the drawdown process of the caverns is performed by deleting elements along the walls of the caverns so that the volume is increased by 16% over the current volume. Leaching is assumed to occur uniformly along the entire height of the cavern. However, leaching is not permitted in the floor or roof of the caverns. The 5-year period between each drawdown allows the stress state in the salt to return to a steady-state condition, as will be evidenced in the predicted closure rates. The simulation will continue until the 5th drawdown is completed to examine the evolution of the shear displacement and vertical strain in the interfaces for a total of 56 years. Creep closure is allowed to occur in all caverns during the simulation period.

To investigate the cause of oil leaks and evaluate the other casings at the site, the slick well casing above the caverns were recently inspected with multi arm caliper. The time frame for the multi arm caliper (present day) corresponds to approximately 21 years of simulation time and corresponding analysis results will be compared to the field inspection data. Figure 3-10 shows the time sequence for this study of the BH site, including the initial cavern leaching and the five drawdown leaches modeled in the simulation.

The pressure condition applied to each cavern is based on an average wellhead pressure of 905 psi which occurs when the wells are operated at normal or static conditions. An analysis of cavern pressures at BH between the years 1990 to 2010 indicates a cavern is pressurized within its normal operating range 74.3% of the time (1351 days during each five year period between drawdown leaches). Other operations, such as fluid transfers and workovers, require lower cavern pressures for 20.8% of the time (380 days during each five year period). Recently, operations have been improved to minimize low cavern pressures to assist in reducing volumetric losses due to creep (Ehgartner, 2010). Therefore, pressure drops are periodically included to simulate times during workover conditions. For simulation purposes, the pressure drop to 0 psi within each cavern lasts for 3 months which is about 4.9% of the time (89 days) during each 5-year period.

Rather than complicating the analyses, the following assumptions were made for the workover scenario. To simulate normal field conditions, no two caverns are in simulated workover mode at the same time. (At the time of the completion of this document, Big Hill caverns 107 and 108 are in workover mode simultaneously; the effects of multiple, adjacent caverns in simultaneous workover on other adjacent caverns will be addressed in future analyses). Figure 3-11 shows the wellhead pressure histories for each cavern.

Workover scenario:

- A constant pressure (905 psi) indicating a normal condition is applied for the majority of the time (Figure 3-11).
- For workover conditions, the wellhead pressure is dropped to zero.
- Workover of Cavern 101 begins one year after the initial leach is completed. After that, workovers are performed on Caverns 102 through 114 in numerical order. Workovers begin as soon as the workover of the prior cavern is completed.
- Workover durations are 3 month for all caverns.
- This workover cycle is repeated every 5 years.
- For both normal and workover conditions, the caverns are assumed to be full of oil having a pressure gradient of 0.37 psi/ft. of depth.
- Pressure due to the oil head plus the wellhead is applied on the cavern boundary during the normal operation.

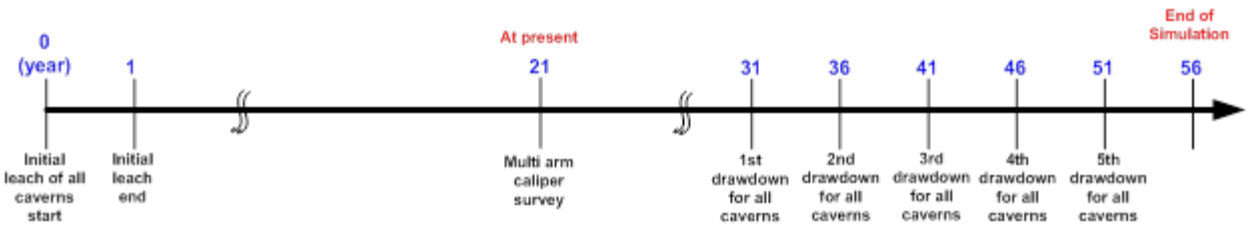


Figure 3-10. Time sequence for the simulation.

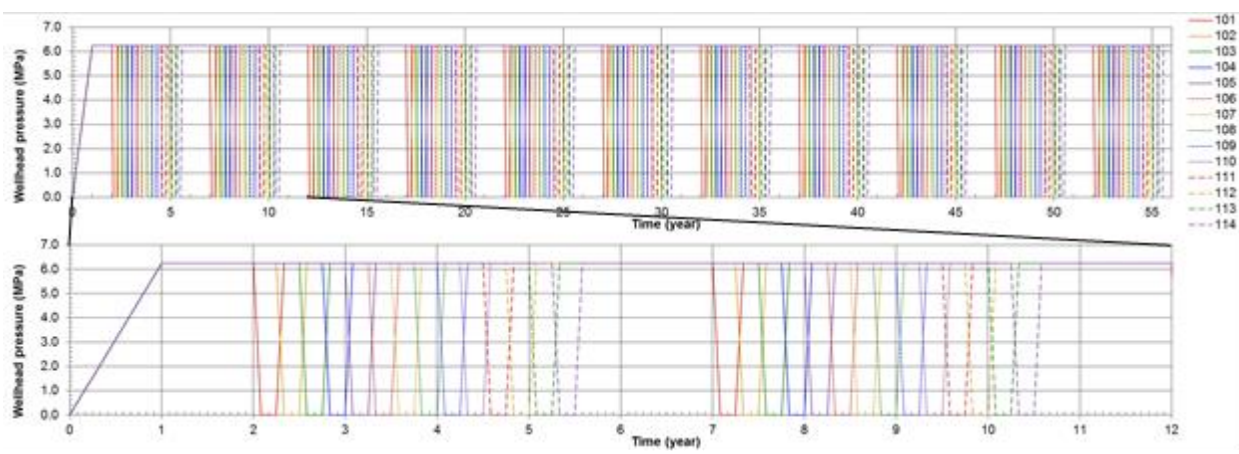


Figure 3-11. Wellhead pressure change in each cavern as a function of time.

3.3.1.4 Mesh

A three dimensional mesh, which allows each cavern to be configured individually, was constructed to investigate shear displacements and vertical strains in the interfaces. Figure 3-12 shows the overview of the finite element mesh of the stratigraphy and cavern field at BH. The mesh has been separated to show the individual material blocks. The X-axis of model is in the East direction, Y-axis is along the North direction, and Z-axis is the vertical direction, up being positive. The mesh consists of nineteen material blocks. Five blocks are used for Overburden, Caprock 1, Caprock 2, Salt Dome, and Surrounding Rock. Four blocks are used for the interfaces, and another four blocks are used for the fault. The other six blocks are used for the initial leach and five drawdown leaches for the fourteen caverns.

The Surrounding Rock block surrounds Caprock 1, Caprock 2, and Salt Dome. The interface block under Overburden is split off from the Overburden block. The thickness of every interface is 14 ft, thus the thickness of Overburden becomes 286 ft (= 300 ft – 14 ft). In the same manner, the interface under Caprock 1 is split off from the Caprock 1 block, thus the thickness of Caprock 1 becomes 886 ft. The interface under Caprock 2 is split off from the Caprock 2 block, thus the thickness of Caprock 2 becomes 416 ft. The interface surrounding Caprock 1, Caprock 2, and Salt dome is split off from the inside of the Surrounding Rock block, thus the radii of Caprock1, Caprock 2, and Salt Dome are not changed but the radius of the dome hole at the center of Surrounding Rock increases 14 ft.

The thickness of the fault (shear zone) is also assumed to be 14 ft. The strike direction and dip of the fault are 22º and 90º, respectively. The strike direction was approximated from Figure 3-2, and the dip was assumed to be vertical for simplification. The fault runs between Caverns 103 and 104, Caverns 108 and 109, and Caverns 113 and 114. The fault is assumed to extend down to the top of Salt Dome from the surface.

The dome consisting of Salt Dome, Caprock 1, and Caprock 2 is idealized to an elliptical cylinder with 7000 ft. major (N-S), 5800 ft. minor (E-W) diameters, and 5700 ft. height (4370 ft. salt dome height). Fourteen cavern blocks exist inside the Salt Dome block. All caverns are idealized to cylinders with 1850 ft. height and 220 ft. diameter. The cylinder blocks are surrounded by five onion ring blocks to idealize five drawdowns. The thickness of ring increases from inside to outside with 8.5, 9.1, 9.8, 10.6, and 11.4 ft. to idealize 16% volume increments. The top of caverns is 660 ft. down away from the top of salt (2290 ft. below the surface).

Figure 3-13 shows the assembled mesh and the boundary conditions. The salt dome is modeled as being subjected to regional far-field stresses acting from an infinite distance away. The lengths of the confining boundaries are 14,000 ft. (two times the dome's major diameter) in the N-S direction and 11,600 ft. (two times the dome's minor diameter) in the E-W direction. The mesh consists of 554,540 nodes and 545,580 elements with 19 element blocks, 6 node sets, and 84 side sets. The mesh was created using CUBIT[1] version 13.0.

[1] Mesh generation software copyrighted by Sandia Corporation.

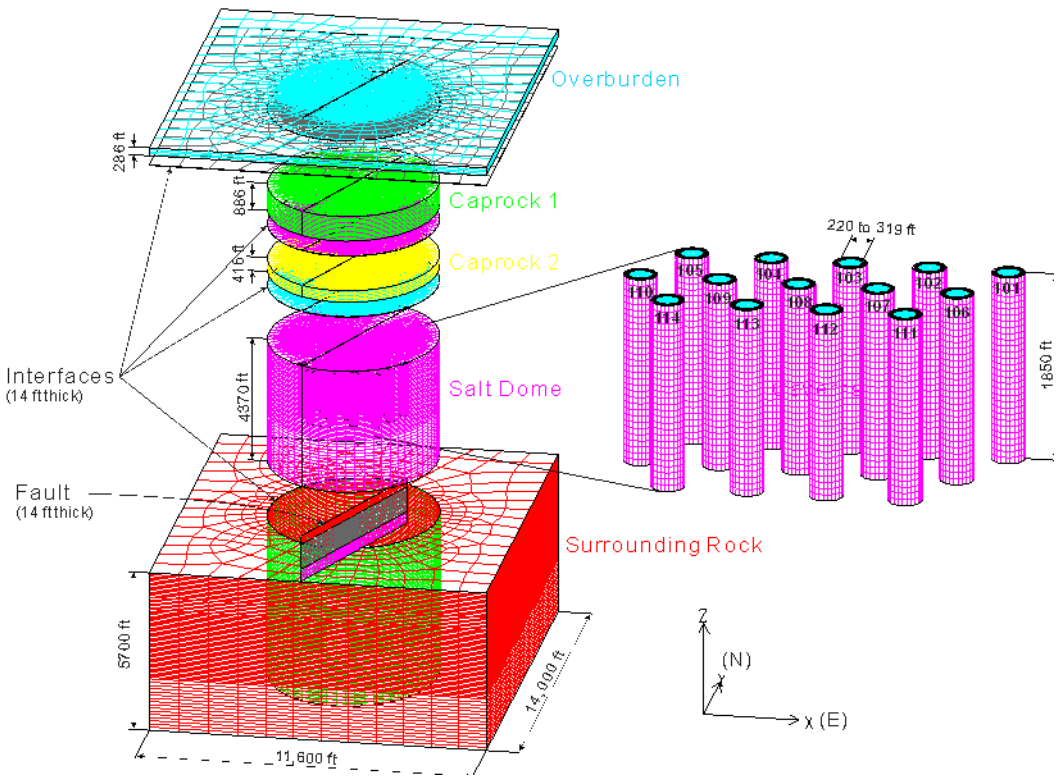


Figure 3-12. Overview of the finite element mesh of the stratigraphy and cavern field at Big Hill.

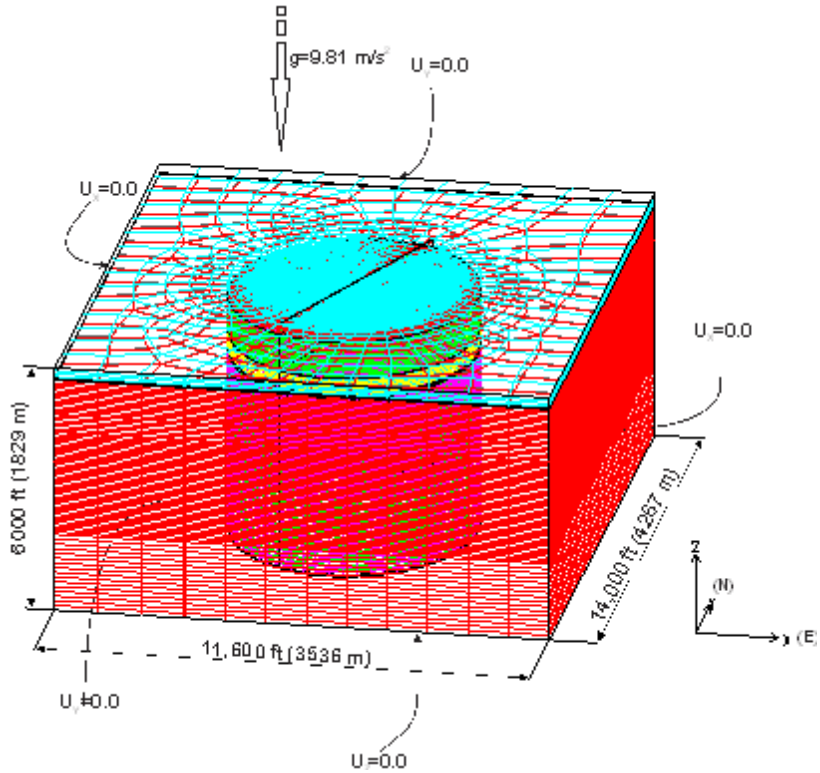


Figure 3-13. Finite mesh discretization and boundary conditions at Big Hill.

3.3.1.5 Model verification

Figure 3-14 shows the comparison of the simulated volumetric closure of 14 caverns normalized by the 14 initial cavern volumes (i.e. cavern volume strain) with the field data. The slopes of lines are close to each other, i.e. the modeled volume closure rates match to the field data well. There is some discrepancy between the analysis results and the field data, because the workover history for each cavern in the analysis is idealized with five year period. The predicted total volumetric closure normalized by total initial volume of fourteen caverns matches to the field data well. This model approximation is reasonable to use to investigate the interface behavior because it is judged to represent the gross volume closure (strain) rather well. It is hypothesized that well casing damage at the interface would be caused by large scale salt rock mass movements brought about by cavern volume closure.

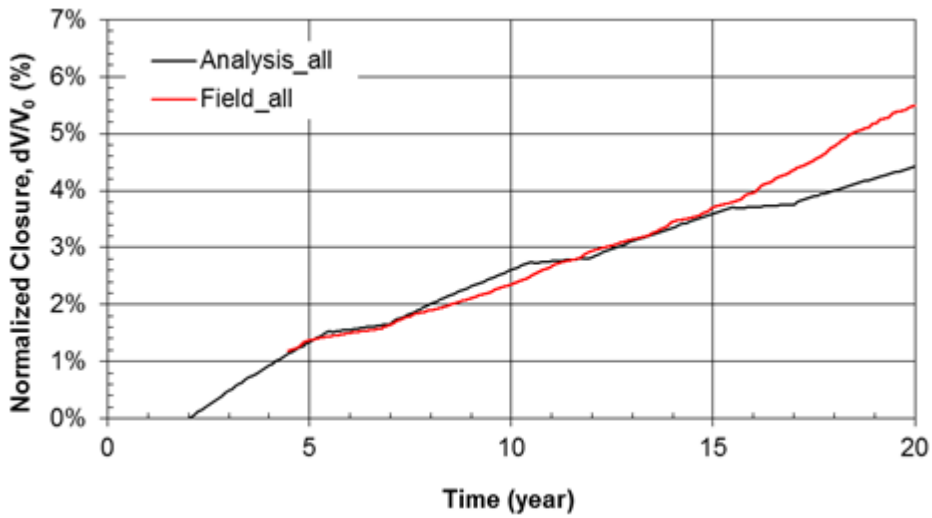


Figure 3-14. Comparison of predicted total volumetric closure normalized by total initial volume of the fourteen caverns with the field data, from Park and Ehgartner (2012)

3.3.1.6 Analysis Results

3.3.1.6.1 Horizontal displacement at salt-caprock interface

Horizontal strains in the interface between Caprock 2 and Salt Dome above the center of each cavern are calculated at year t = 21, which is twenty years after the initial leach is completed and represents calendar year 2010. The bottom of Caprock 2 and the top of Salt Dome move downward with cavern volume closure due to salt creep. The predicted direction and magnitude of relative horizontal movement on the salt top above the center of each cavern is shown in Figure 3-15. Every node above the center of fourteen caverns moves toward Cavern 108 over time. The horizontal node movement above Cavern 108 is predicted to be the least because Cavern 108 is located in the middle of fourteen caverns.

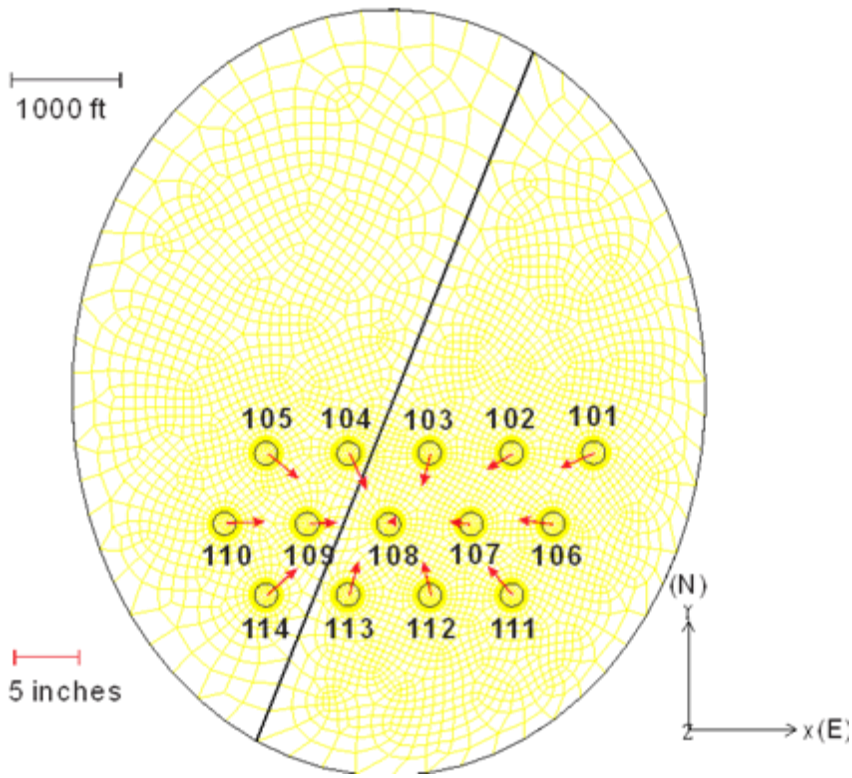


Figure 3-15. Predicted direction and magnitude of horizontal movement on the salt top above the center of each cavern at 2010 calendar year, from Park and Ehgartner (2012)

Figure 3-16 shows the horizontal strain (the ratio of horizontal displacement of the node on the top of Salt Dome to vertical distance between Caprock bottom and Salt dome top) above the center of each cavern. The strains above 101, 105, 110, 111, and 114 are larger than others. The well casings above them may fail by shear stress. Caverns 101, 105, 110, 111 and 114 make up a majority of the outermost caverns. The horizontal strain above Cavern 114 is predicted to be the most (0.0157), while the vertical strain is predicted to be relatively small (0.0053). The vertical strain above Cavern 101 is predicted to be least (0.0035), while the horizontal strain is predicted to be relatively large (0.0148). These results imply the well casings above the outermost caverns have a greater chance of undergoing horizontal shear failure, while being relatively safe from the vertical tensile failure.

Figure 3-17 shows the horizontal strain above the center of each cavern over time. The well casing of Cavern 105 failed due to shear displacement at 20 years after the initial leach (2010). The horizontal strain is calculated to be 0.0156 when the well casing failed. Therefore, the horizontal strain of 0.0156 can be used as for an approximate shear displacement failure limit (dash line in Figure 3-17). If this criterion is applicable to all the wells, the well casings of Caverns 101, 110, 111 and 114 are predicted to fail by shear strain in the near future, while the well casings of Caverns 103, 107, 108, and 109 are not predicted to fail due to shear displacement until 30 years after the initial leach (2020 calendar year).

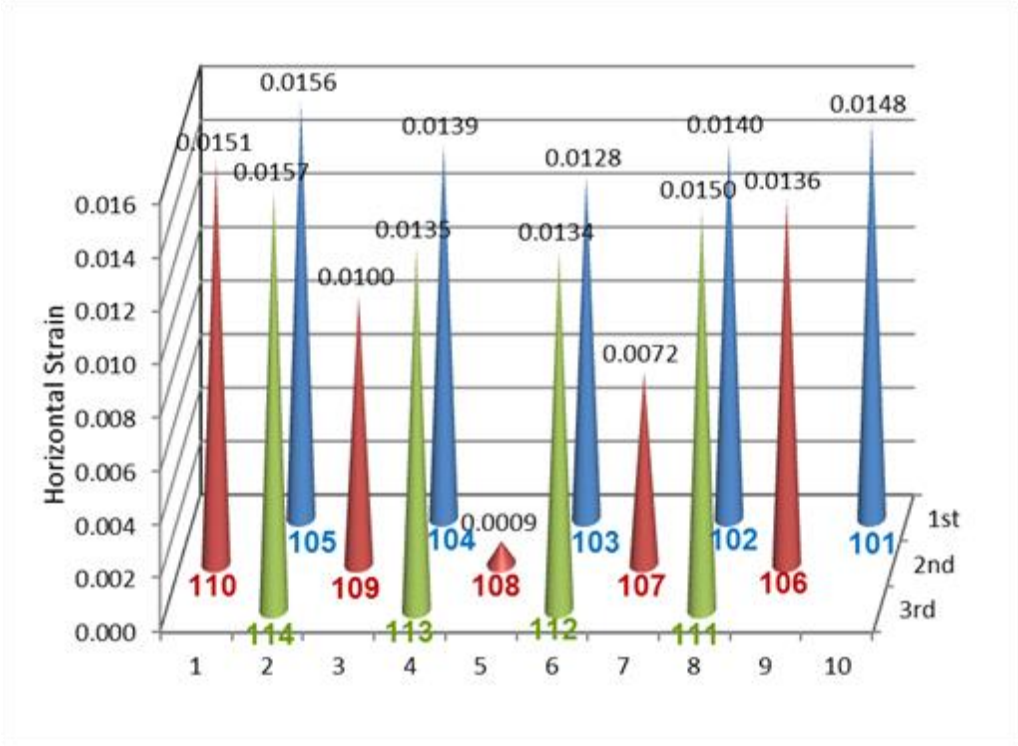


Figure 3-16. Horizontal strain between caprock bottom and salt dome top above the center of each cavern at 21 years simulation time, from Park and Ehgartner (2012).

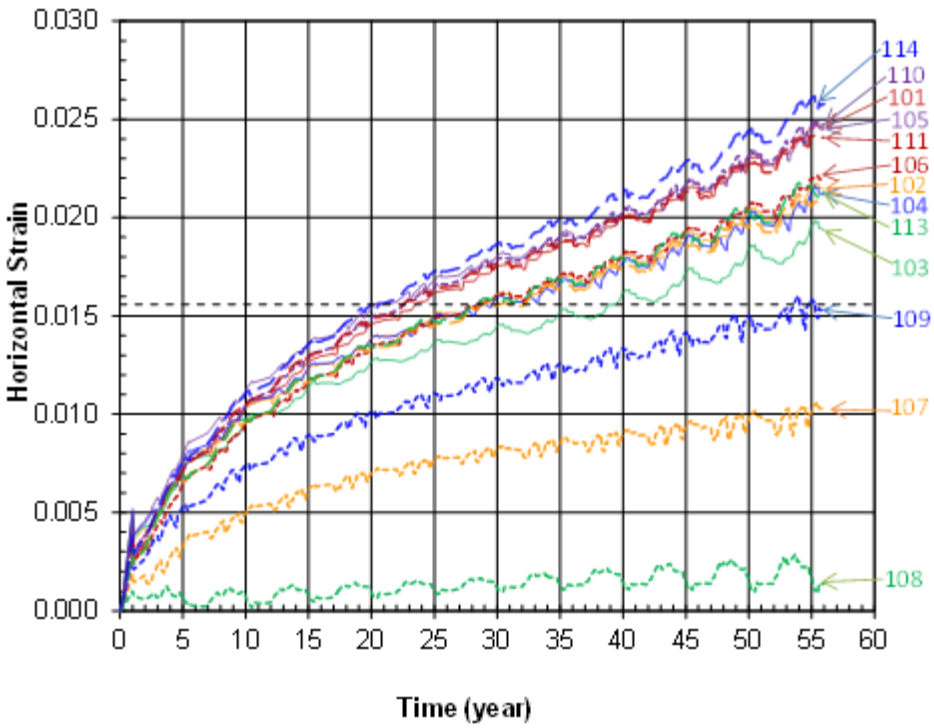


Figure 3-17. Horizontal strain between salt dome and caprock 1 bottom, from Park and Ehgartner (2012)

3.3.1.6.2 Vertical displacement at the salt-caprock interface

Figure 3-18 shows the vertical strain in the interface between Caprock 2 and Salt dome above the center of each cavern. The strains above Caverns 107, 108, and 109 are larger than others. The well casings above them could fail by tensile stress. The casing of BH Well 109B did fail at the joint (1630 ft depth) and oil leaked. The cause of failure could be a tensile stress created by the downward movement of salt dome top. Similar calculated vertical strain magnitudes suggest that the casings of BH Wells 107 and 108 may also fail by tensile stress in the near future.

Figure 3-19 shows the vertical strain as a function of time in the interface between Salt Dome and Caprock 2 above the center of each cavern. The well casing of Cavern 109 failed due to excessive vertical strain at 20 years after the initial leach done (2010 calendar year). The vertical strain was predicted to be 0.0081 when the well casing of Cavern 109 failed at the joint. Therefore, 0.0081 may be used as a vertical strain failure limit (dash line in Figure 3-24). If this criterion is applicable to all the wells, the well casings of Cavern 107 and 108 are predicted to fail in tension due to excess vertical strain in the near future while the well casings of Caverns 101, 102, 105, 106, 110, 111, 113, and 114 are not predicted to fail until 30 years after the initial leach (2020).

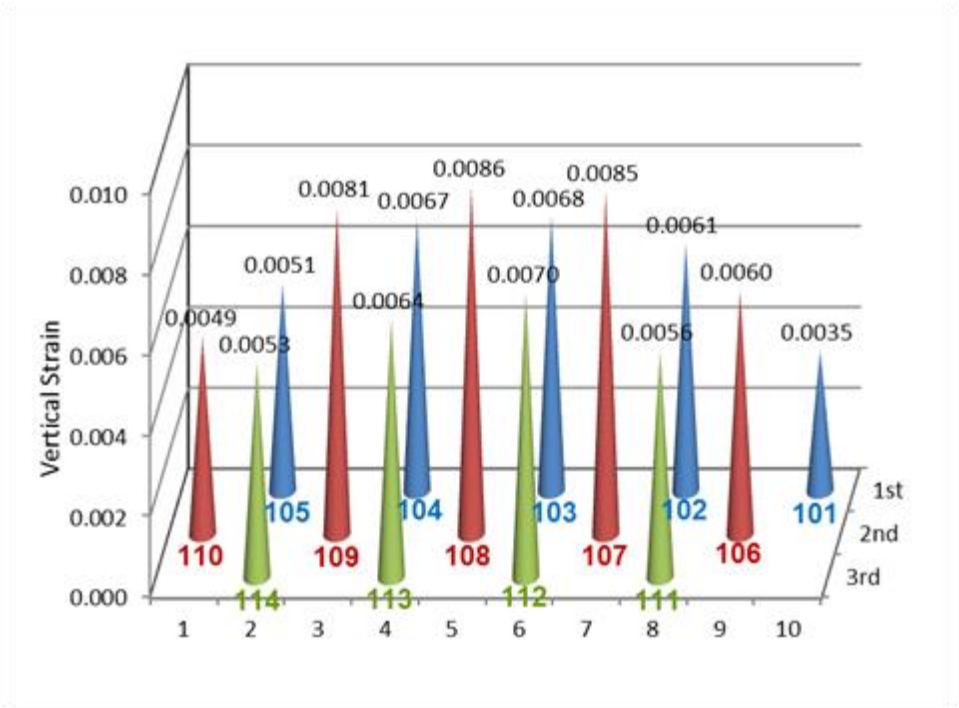


Figure 3-18. Vertical strain in the interface between caprock 2 and salt dome above the center of each cavern at 21 years simulation time, from Park and Ehgartner (2012).

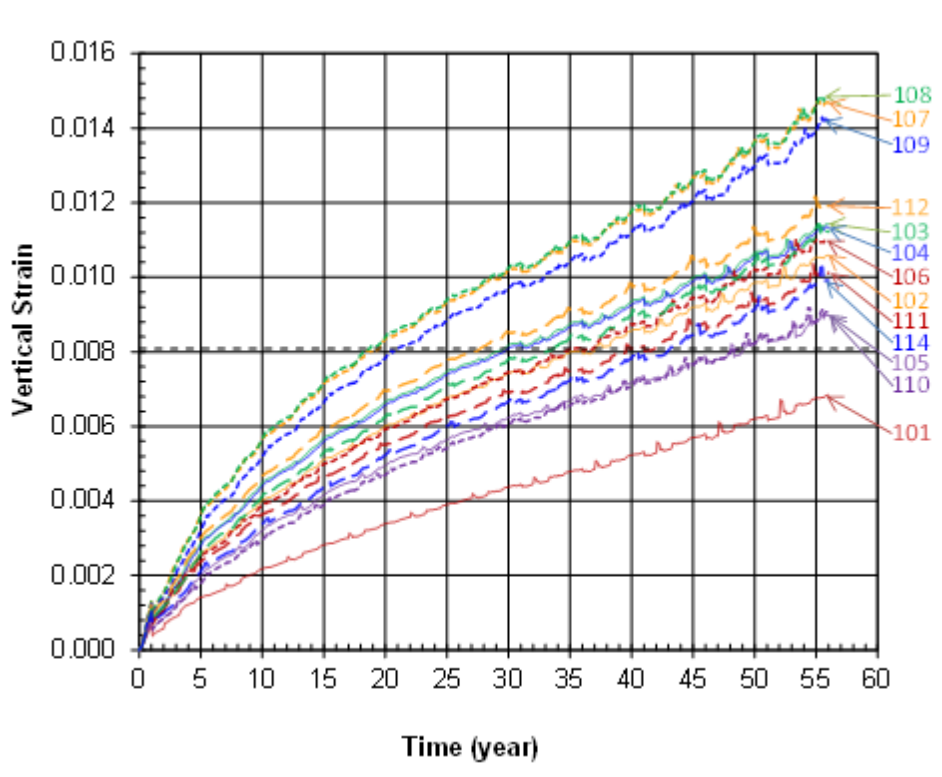


Figure 3-19. Vertical strain in the interface between caprock 2 and salt dome above the center of each cavern, from Park and Ehgartner (2012).

To evaluate the effects of these strains on wellbore casings, a smaller model was constructed that included an equivalent steel casing attached to sections of caprock and salt positioned 14 feet apart, like the large global model. The steel was modeled using the elastic plastic material model, and the relative displacements at the interface calculated by the global model were applied to the caprock and salt. Figure 3-20 shows the construction of this model, and the salt top movement relative to the caprock at 0 years and 31 years simulation time for the casings for Caverns 114 and 108. There are two steel casings in the wellbore for Caverns 114 and 108 at the interface. The horizontal and vertical displacements of salt top relative to the caprock bottom, which are calculated from this analysis, are applied. The deformation is magnified by 20. The directions of wellbore deformations of Caverns 114 and 108 in the plan view from top at 21 years are the same as shown previously in Figure 3-15. Caverns 114 and 108 illustrate the extremes for displacement: the salt top at the wellbore of Cavern 114 moves primarily horizontally and at Cavern 108 moves primarily vertically. The contour parameter, EQPS, means equivalent plastic strain, and is a combination of the vertical and horizontal strains. The red area indicates the damaged area, defined as when the value for equivalent plastic strain exceeds 0.0093 (see Section 5.3). The steel casing damage occurs near the caprock bottom and the salt top for Cavern 114, while the damage occurs longitudinally on the steel casings for Cavern 108. This implies the steel casings of Cavern 114 are failed by shear strain and at Cavern 108 are failed by tensile strain.

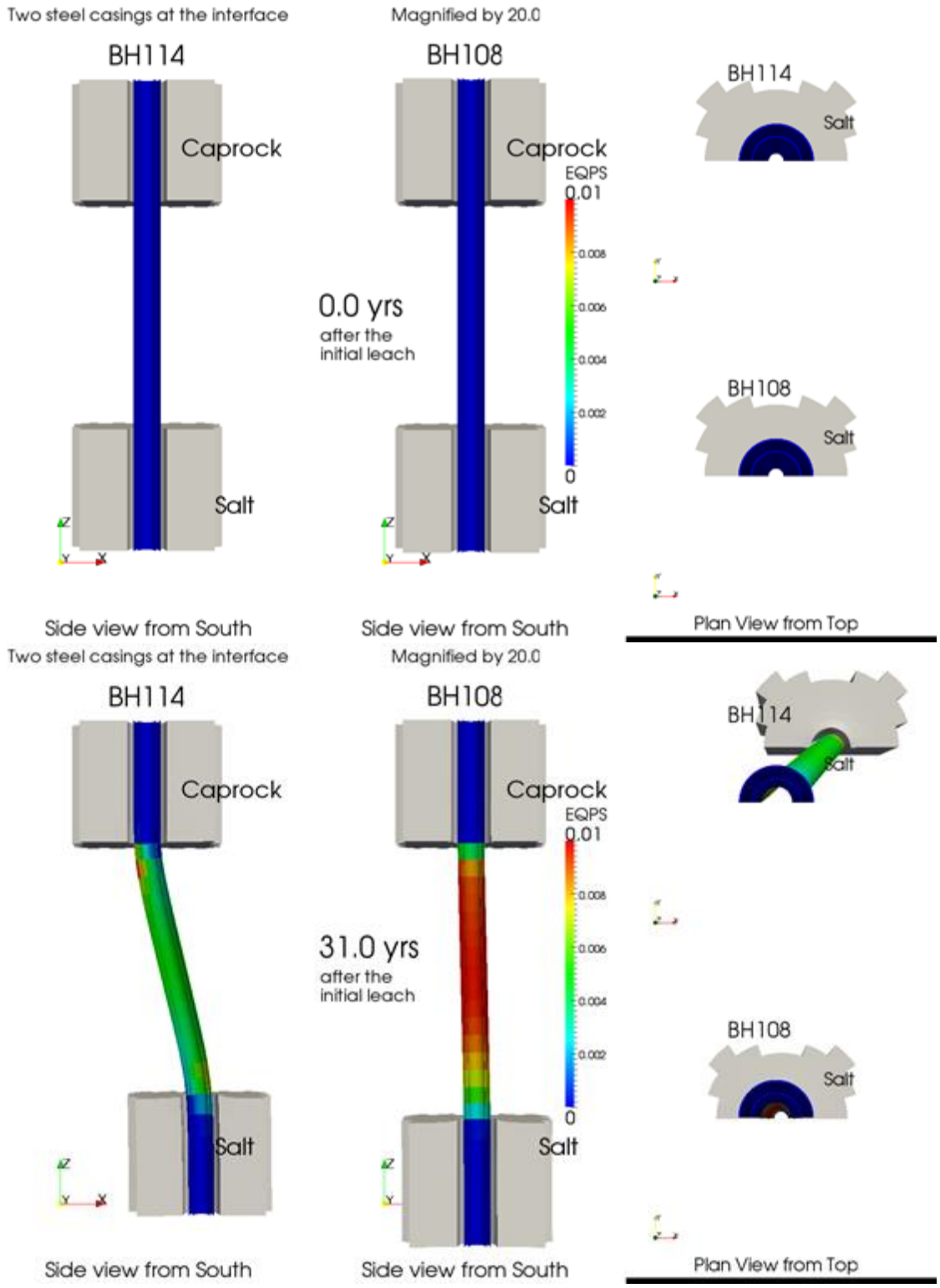


Figure 3-20. Salt top movement relative to the caprock at 0 year (top) and 31 years (bottom).

3.4 Regulatory Drivers

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.

As of September, 2013, SPR is proposing a change to its Level II Performance Criteria (DOE 1999) so that MIT test results must satisfy the following criteria:

- Minimum Detectable Leak Rate (MDLR) ≤ 750 bbl/yr
- Calculated leak rate < MDLR
- Test conditions (pressure, wellbore temperature and interface location) should have characteristics of a cavern that displays mechanical integrity

This report is written under the assumption that the above-mentioned proposed changes to the SPR Level II Criteria will be authorized in the near future and serve as the operating model for well performance at the SPR.

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.

3.5.1 Multi-arm caliper tools

Multi-arm caliper tools measure the inside diameter of the well casing by recording the radial movement of a series of feeler arms. These arms are extended outward by spring action so that they ride against the casing wall during measurement. The number of arms varies by manufacturer and intended use, but typically is in the range of 24 to 60. Figure 3-21 shows the configuration of the Weatherford 60-arm MAC tool; this tool was used for a majority of the MAC measurements made to-date at the Big Hill SPR site. Additional MAC logs were run at Big Hill using an E&P Wireline 56-arm MAC tool.

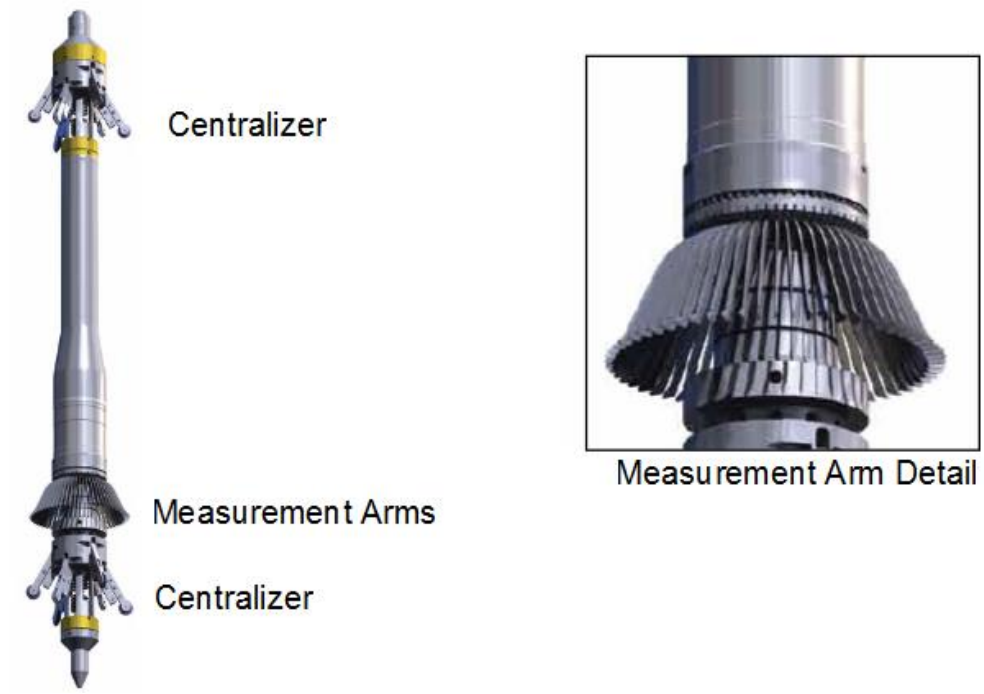


Figure 3-21 . Weatherford 60-arm multi-arm caliper tool

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 DM MAC Analysis

The current SPR Maintenance and Operations (DM) 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 identifying any problem areas they have identified.

Institutional knowledge of the storage caverns and wells are used by DM 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 DM MAC grading values obtained from DM and 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 M&O 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 BH114A were examined. BH114A was known to have severe casing deformation at the salt-cap rock interface and so was remediated by cementing an additional casing inside the existing configuration.

An examination of the C_v value distributions for BH114A shows that the post-remediation survey has a mean of 0.0015 and a standard deviation of 0.00056, while the pre-remediation survey had a mean of 0.0024 and a standard deviation of 0.00229. As expected, the pre-remediation survey C_v values have a larger mean and standard deviation, a result of the significant casing deformation which lead to the remediation of this well. These differences can be readily seen in Figure 3-22 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.

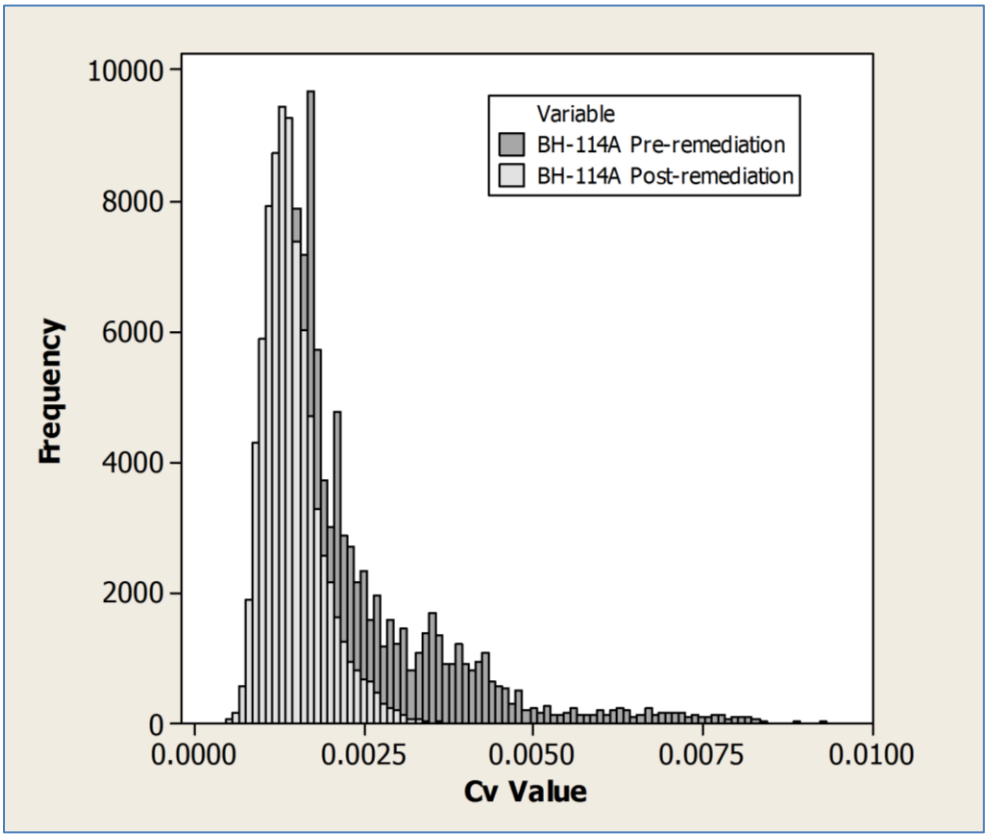


Figure 3-22. Overlaid histograms of C_v values for BH114A pre- and post-remediation MAC surveys.

The maximum C_v pre-remediation values occur at the salt-cap rock interface at a depth of approximately 1625 feet, where the C_v reaches a value of 0.1; the post–remediation value at this

same depth is on the order of 0.0008. This comparison clearly shows the sensitivity of the C_v to casing deformation.

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

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

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

$$Min_MID = \text{minimum measured internal diameter}$$
$$Max_MID = \text{maximum measured internal diameter}$$
$$EID = \text{expected internal diameter}$$
$$OD = \text{outer diameter}$$

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 may be provide information not represented in the C_v values.

Figure 3-23 is a plot of the C_v and RWD values for well BH113A for a depth interval encompassing the salt-cap rock interface. The C_v and RWD curves have the same general shape, but do differ significantly at various locations. This indicates that these two variables are providing different views of the radial arm data each of which can provide some insight into any casing deformation which is why both variables are included in the SNL well rankings presented here.

For the final ranking analysis, both the C_v and RWD values were used for the SNL ranking. The process used to combine these values into a single ranking value is discussed in Section 6 of this report.

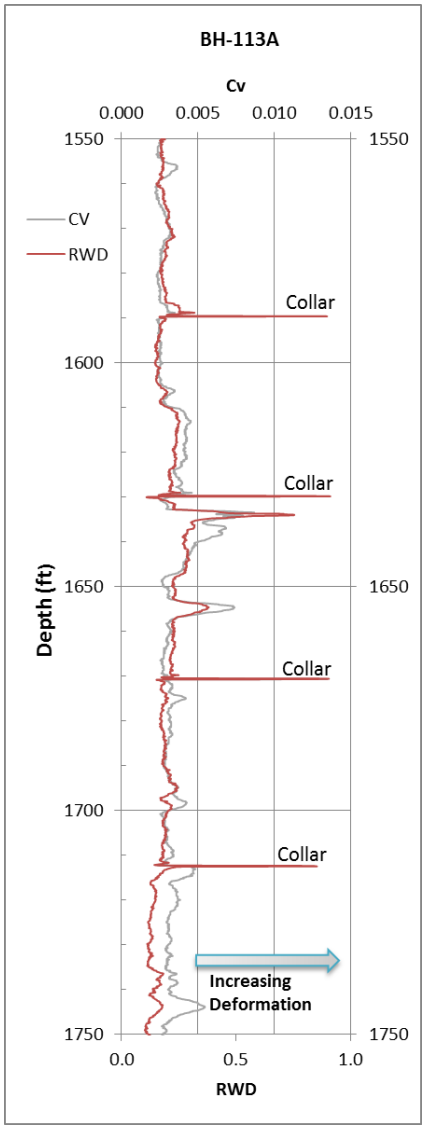


Figure 3-23. C_v and RWD values for BH113A over depth interval from 1550-1750 ft. Deformation is indicated in the salt-caprock interface region near 1630-1640 ft.

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 (typically B-well oil) 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 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 DM and SNL is ongoing in FY13 to upgrade CAVEMAN version 4 to a highly-automated enterprise application on the SPR network.

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 a deviation of about ~3×10 psi = ~30 psi at Big Hill.

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 graphical representation of CAVEMAN pressure monitoring for BH110 for a three-year period is shown for illustration in Figure 3-24. Measured pressure is shown in blue, while CAVEMAN predicted pressure is shown in pink. The difference between these is shown in yellow, which is scaled on the right-hand axis. The sawtooth features between 850 and 950 psia 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. Differences between predicted and measured are within the 3× historical RMS error (~30 psi) range so that CAVEMAN flag would not indicate a leak during this time frame. Certain upward deviations in measured from predicted may indicate neighbor cavern workovers, which are not considered in the CAVEMAN predictive model.

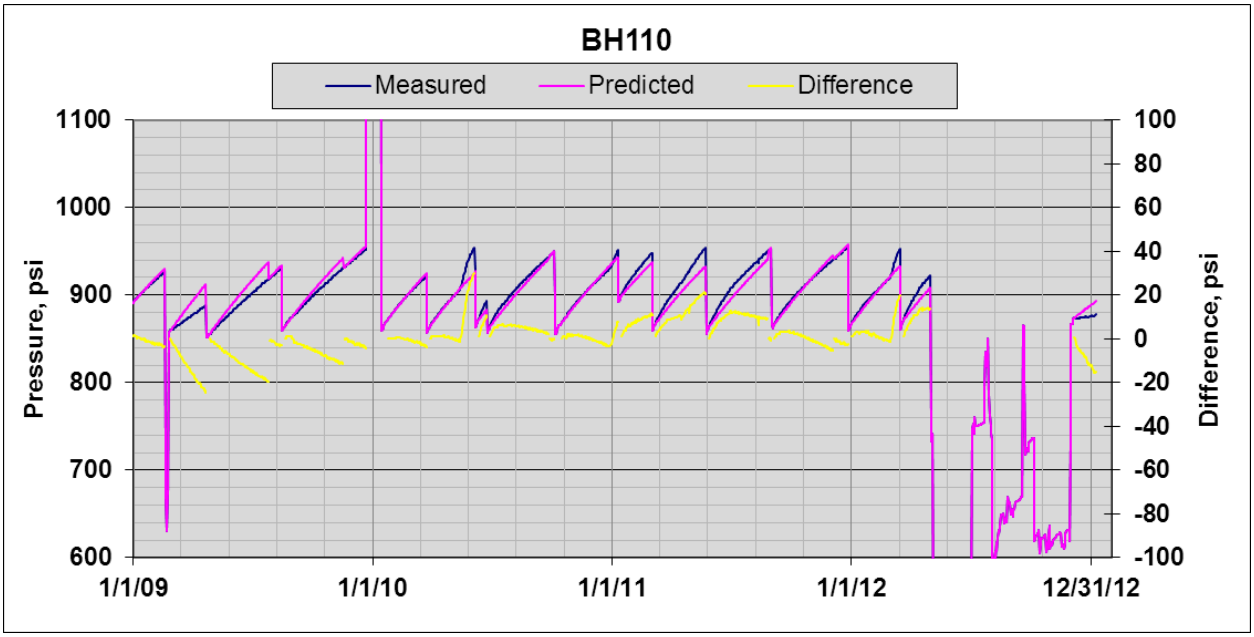


Figure 3-24. Graphical representation of measured vs. CAVEMAN-predicted oil wellhead pressure for BH110 over three-year period from January 2009 – December 2012.

A 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.

- 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 yr) 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

CAVEMAN fluid temperatures, both measured and predicted, are shown overlaid with oil volume in Figure 3-25.

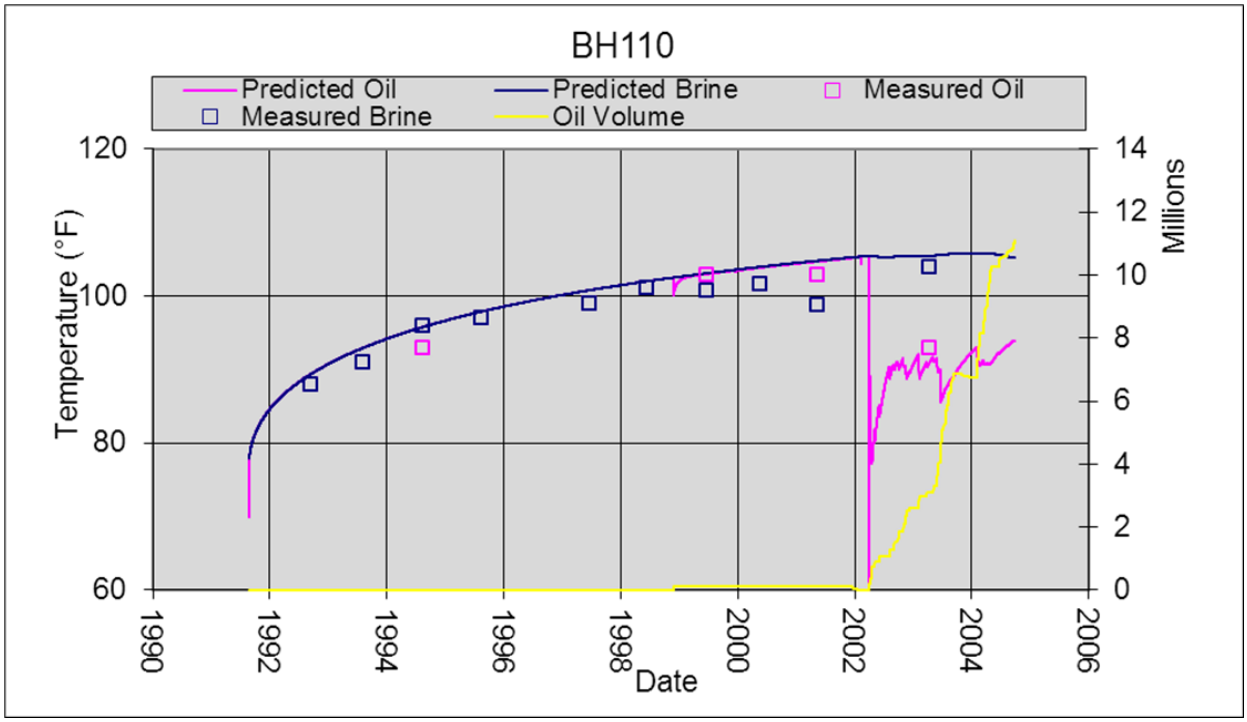


Figure 3-25. Comparison of CAVEMAN cavern-average fluid temperatures determined by measurement and modeling. Upward trending of temperature with time reflects geothermal heating.

3.6.2 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 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

A plan view of the Big Hill cavern field is shown in Figure 3-26. Cavern centers are generally separated by 750 feet. Annotations show the nearest neighbors in context to cavern 103.

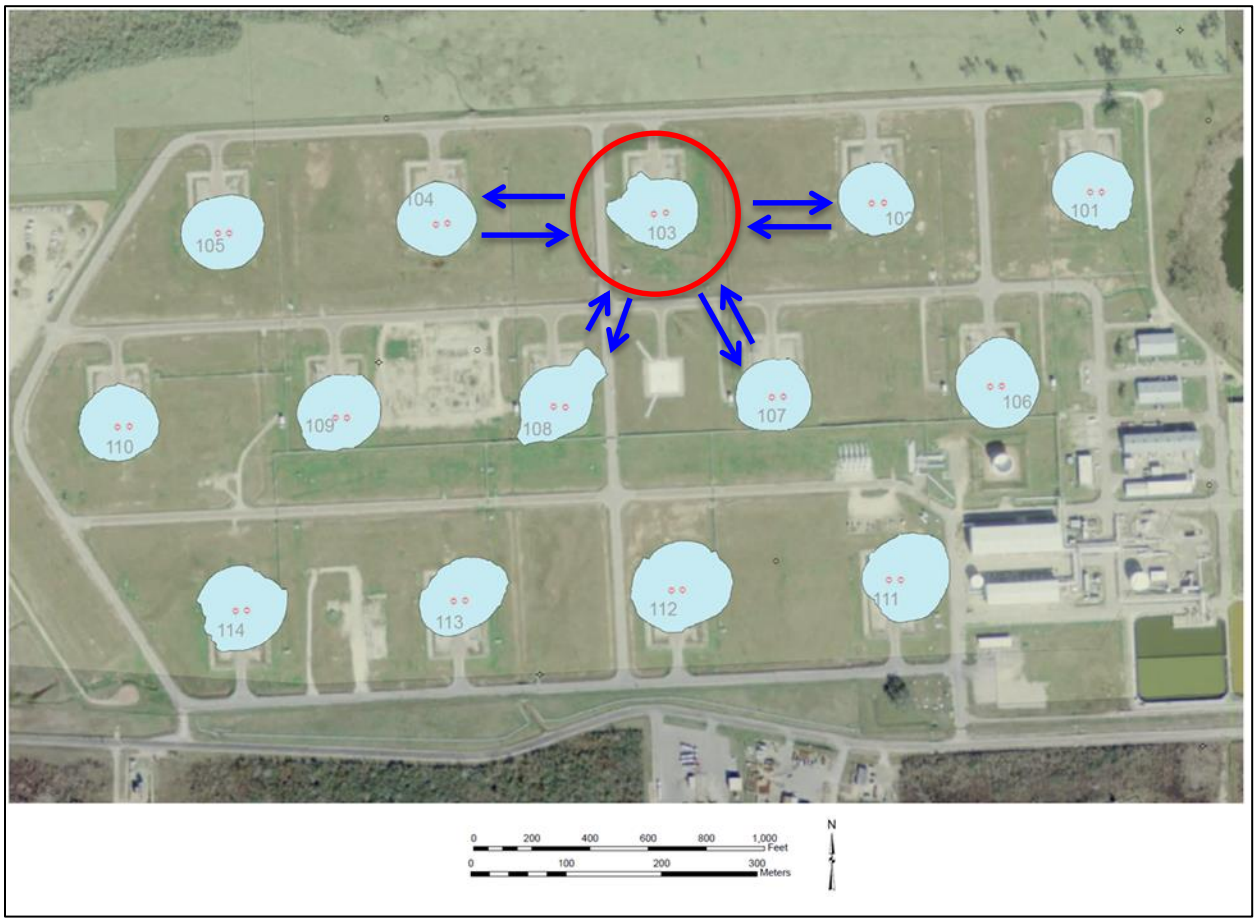


Figure 3-26. Plan view of Big Hill cavern field with annotation showing nearest neighbors to cavern 103.

3.6.2.1 One neighbor de-pressured

A typical example of nearest-neighbor effect from depressurization due to workover is shown in Figure 3-27. BH caverns 102 and 103 sit next to one another and are separated by about 750 feet at centerline. Both caverns were re-pressuring in parallel from mid-February to mid-March until BH103 was de-pressured for workover. Once BH103 B-well oil pressure was reduced to near zero in the last week of March, BH102 re-pressurization rate increased for a week or so until it was de-pressured for workover. This upturn in the re-pressurization curve is seen frequently when one cavern is de-pressured suddenly. The current hypothesis for why this happens is that the reduction in pressure in one cavern proportionally reduces its capacity to carry the load of overlying roof, caprock, and overburden. This load must be distributed out among pillars and neighboring caverns, at which point we see an increase in creep-driven pressurization rate in neighbors. Sandia is working on refining its geomechanical modeling capabilities to explore this

issue more closely and seeks to build a stronger basis for explaining this mechanism as more data and model results become available.

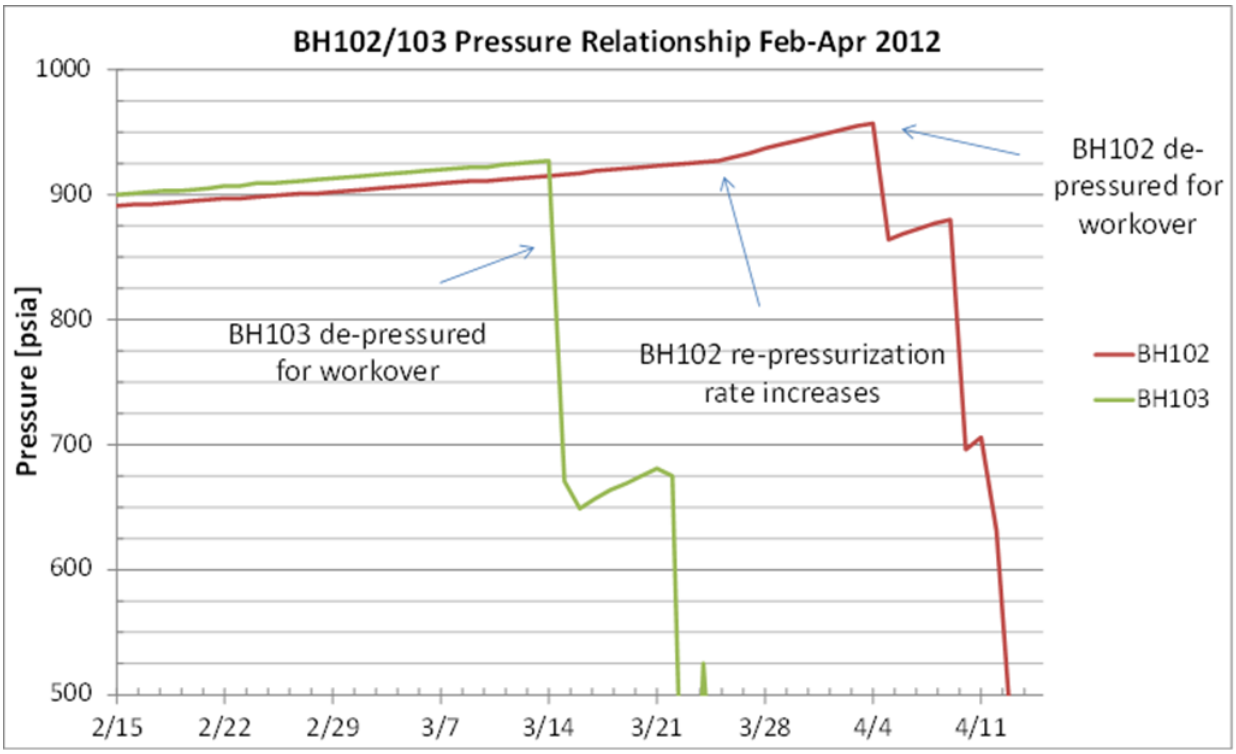


Figure 3-27. Oil wellhead pressure histories (tag number PIC30) for BH102 and 103 showing near-neighbor effects of depressurization due to workover.

3.6.2.2 Four nearest neighbors

Cavern interactions are not limited to binary pairs. Rather, they are affected by all caverns in the field to some degree. The authors assume that the greatest effects apply to the ring of nearest neighbors. If we focus on BH103, this means that the four nearest neighbors include 102, 104, 107, and 108 (refer to Figure 3-26). Daily reference oil wellhead pressures are shown for BH103 and these four nearest neighbors for the period 8/15/2012 – 11/30/2012 in Figure 3-28. BH103, shown in blue dashed line, steadily climbed to the top of its operating range (950 psi) from the period 8/15-9/26, and was then dropped to near the bottom of its operating range (~845 psi) to re-start its normal pressurization cycle. Starting about 10/24, BH103 pressure leveled and then dropped by several psi and then returned to its prior re-pressurization rate in early November. This anomalous behavior of concern is marked with a red circle. Site operations decided to put nitrogen on the BH103B oil wellhead in order to test for a leak, and this appears as a pressure spike that went off-scale around 11/14.

BH102, nearest neighbor to the east, underwent a long, steady re-pressurization over the entire time frame shown except during the first week of November when the pressure flattened, dipped about 2 psi, and then returned to re-pressurization by the week of 11/21. This feature is also marked on Figure 3-28 with a red circle. BH104, nearest neighbor to the west, was under leaching operations, so the reference pressure was up and down every day with fluid movements in and out of the cavern. Upon shut-in starting in early October, the rapid decline in pressure

may be attributed to fresh water leaching the salt walls. The leach rate declines over several weeks to a point where the pressure starts to flatten and increases starting the week of 11/7. About 11/21, BH104 was put under nitrogen for the state-mandated MIT.

BH107 and BH108, both neighbors to the south of BH103, were de-pressured for workover during the period shown in Figure 3-28. The BH107 workover started around 10/17 and ended around 11/24, while the BH108 workover started around 8/18, and ended around 11/15. The neighbor cavern pressurization rate increase that is often seen right at the start of workover is not seen in BH103 relative to the starts of BH107 and 108 workovers. BH107 might have responded to the BH108 workover around 8/29, as its pressurization rate did bump up temporarily.

Of greater concern here is that both BH103 and 102 experienced week-long dips in their re-pressurization rates with no obvious or well-understood cause from nearest neighbor operations. BH103 dipped while BH107 was being de-pressured, which is opposite of what was expected. BH102 dipped around the same time that BH108 was re-pressured, though these caverns are not nearest neighbors. The authors' interest in showing this plot is to illustrate that real site-level operations are complex and dynamic, and not easily reduced to simple cause-effect relationships. Moreover, these combinations of simultaneous workovers, much less next to caverns under leach, are not simulated in current geomechanics models. Sandia has committed to upgrading their models to be able to simulate some of these scenarios, though this is a work in progress and the results are not currently available to assist in interpretation of these particular data.

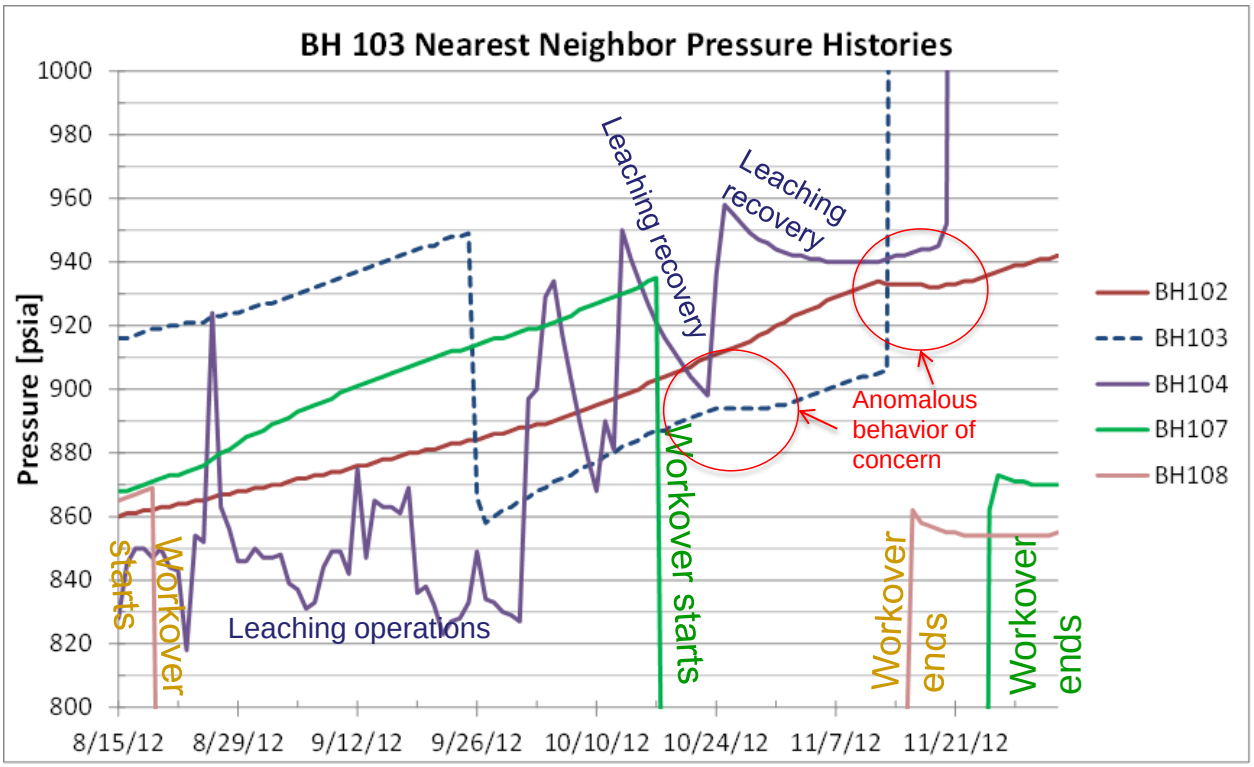


Figure 3-28. Daily reference oil wellhead pressures plotted for BH103 and four nearest neighbors for the period 8/15-11/30/2012. Color-coded annotations describe operations causing related features in pressure curves. Two red circles flag anomalous behaviors of concern that have, in other cavern wells, been early indicators of hydraulic failure of the cased well.

3.6.2.3 Unexplained Pressurization Anomalies

In addition to BH102 and 103 illustrated above in Figure 3-28, two other caverns BH112 and BH113 exhibited pressurization anomalies including flattening or even gradual pressure loss, followed by resumption of pressure increase due to creep. BH112 caused significant concern with a ~4 psi loss over 5 days in late in October 2012 (see Figure 3-29). Nitrogen was placed on the wellhead in order to isolate the crude oil from a possible leak path to the environment and is still in place as of February, 2014. Pressurization has resumed, though at a lower rate in the nitrogen-capped wells (~0.32 psi/day) than in the brine (~0.49 psi/day) (see Figure 3-30). This intensive monitoring is ongoing as of February, 2014, to include periodic logging for N_2-oil interface depths in order to locate any leak locations.

BH113 pressurization flattened for about a week in late August, 2013, and has since resumed apparently normal pressurization (see Figure 3-31). The cavern was de-piped in order to isolate the wells from any potential leak paths in the surface piping and nitrogen manifolds were installed in case nitrogen injection is deemed necessary.

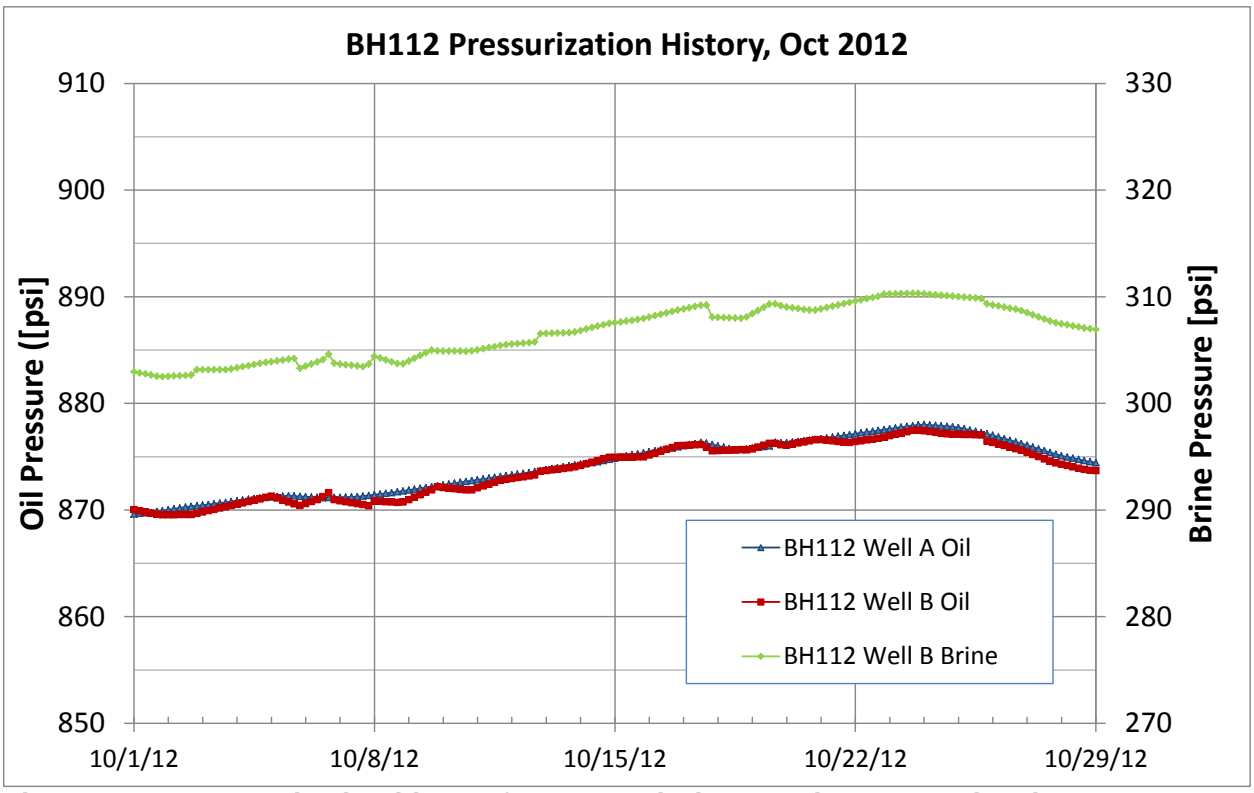


Figure 3-29. Pressurization history for BH112 during October, 2012, showing an unexplained flattening of the oil and brine wellhead pressures. Nitrogen was placed on the oil wells starting on November 1, 2012 in order to isolate oil from a potential leak path.

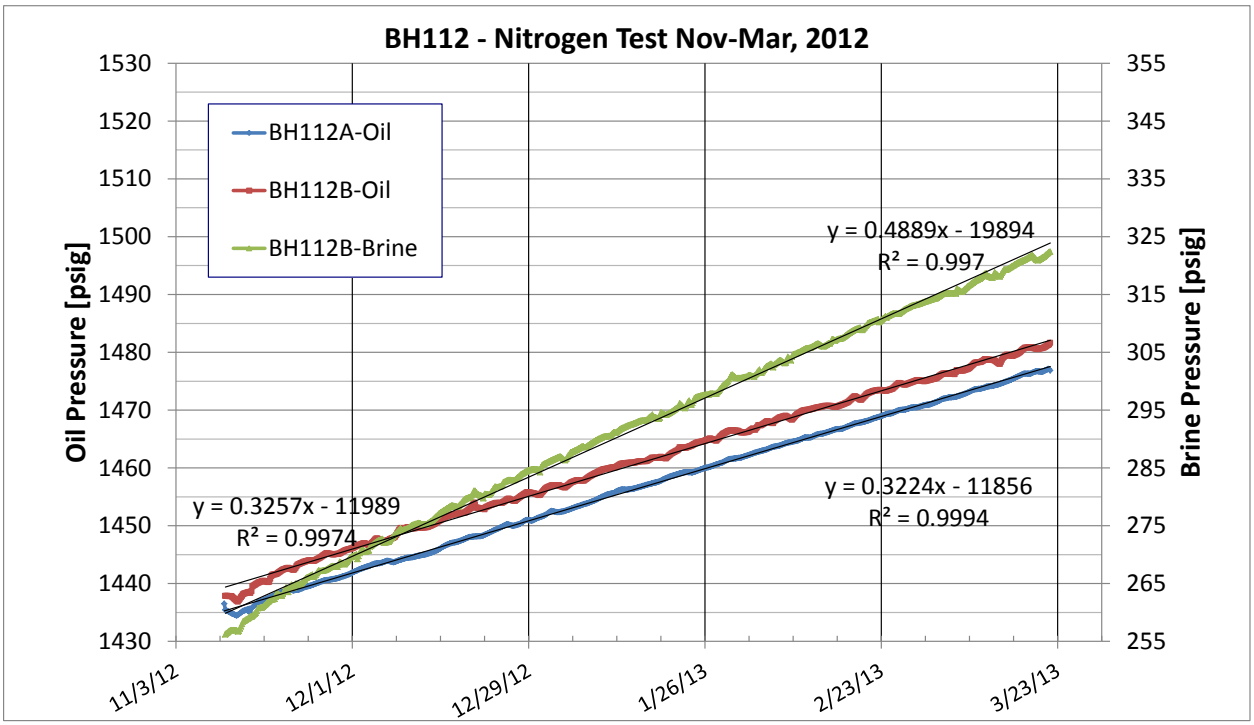


Figure 3-30. Pressurization history for BH112 from Nov 2012 – Mar 2013, showing differential pressurization rates between the N_2-capped oil wells and the brine well. Linear fits to each curve indicate approximate pressurization rates in psi/day.

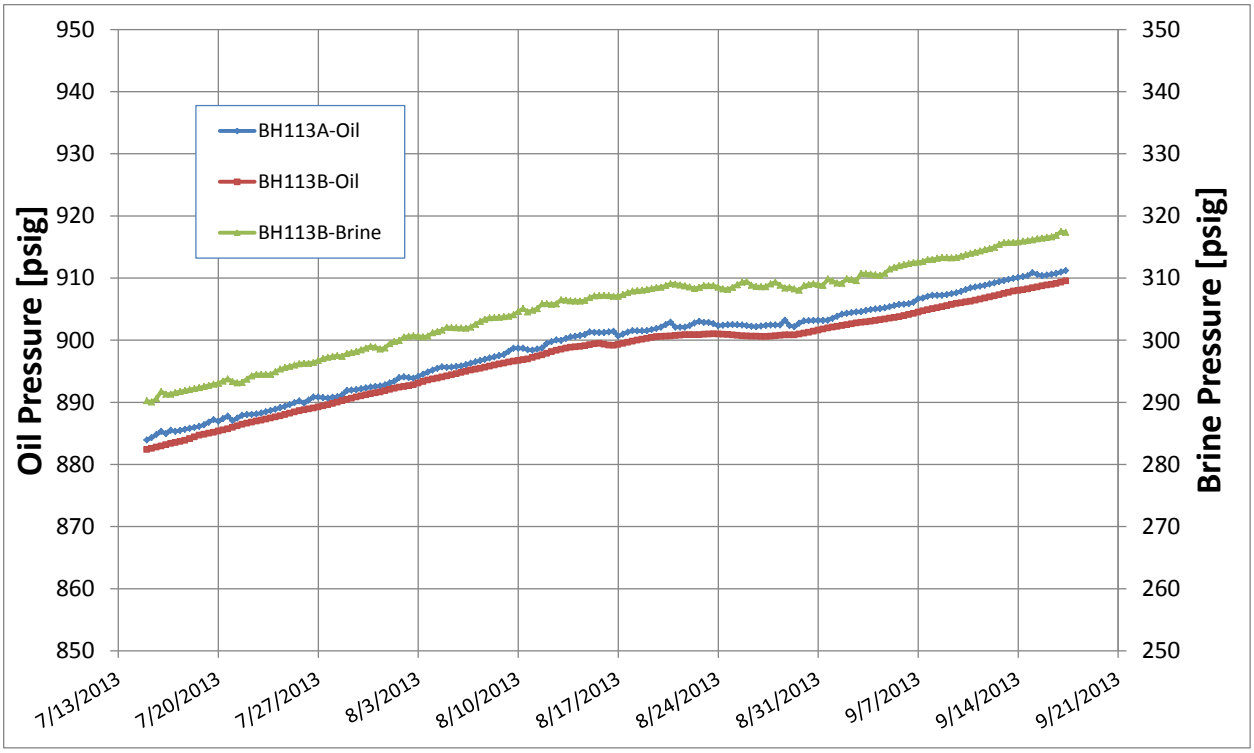


Figure 3-31. Pressurization history for BH113 from mid-July to mid-September 2013, showing an unexplained flattening of the oil and brine wellhead pressures.

3.6.3 Hydraulic Failure Indicated by Daily Pressure History

Complete hydraulic failure of a well is sometimes conspicuous from daily wellhead pressure monitoring. A case in point is BH114 from summer 2012. Wellhead pressure monitoring showed a departure from normal behavior in August, 2012. Re- pressurization histories were obtained from CAVEMAN, illustrated here in Figure 3-32, and represent (annular) oil pressure measurements at the wellhead for BH114B, which has a hanging string suspended into the brine layer. Several outliers in Figure 3-32 with higher than normal re-pressurization rates are identified as correlating with the de-pressurization of neighboring cavern BH109. A significant decrease in pressurization rate is associated with loss of cavern fluid volume likely due to a leak in one of the well casings.

In response to the marked downward deflection in the oil pressure in late August (bold blue curve), site personnel performed a wellhead analyses and found the surface infrastructure to be sound. They followed with special nitrogen injection tests in both cavern wells on September 5, 2012 in order to identify the problem well and depth of the leak zone. The tests found that the A-well lost 43 psi in one hour, while the B-well lost no pressure. The leak zone was determined to be around 1630 ft. in the A-well, which corresponds to the salt-caprock interface marked on current SPR well completion diagrams. SPR put forward a plan (French and Moore 2012) to place a temporary plug below the leak in well A to isolate it from pressurized cavern oil, and then performed remedial workovers by placing liners in both wells to provide a permanent fix (Guillory 2013).

A detailed analysis of the BH114 leak is available in Lord, Roberts et al. (2013).

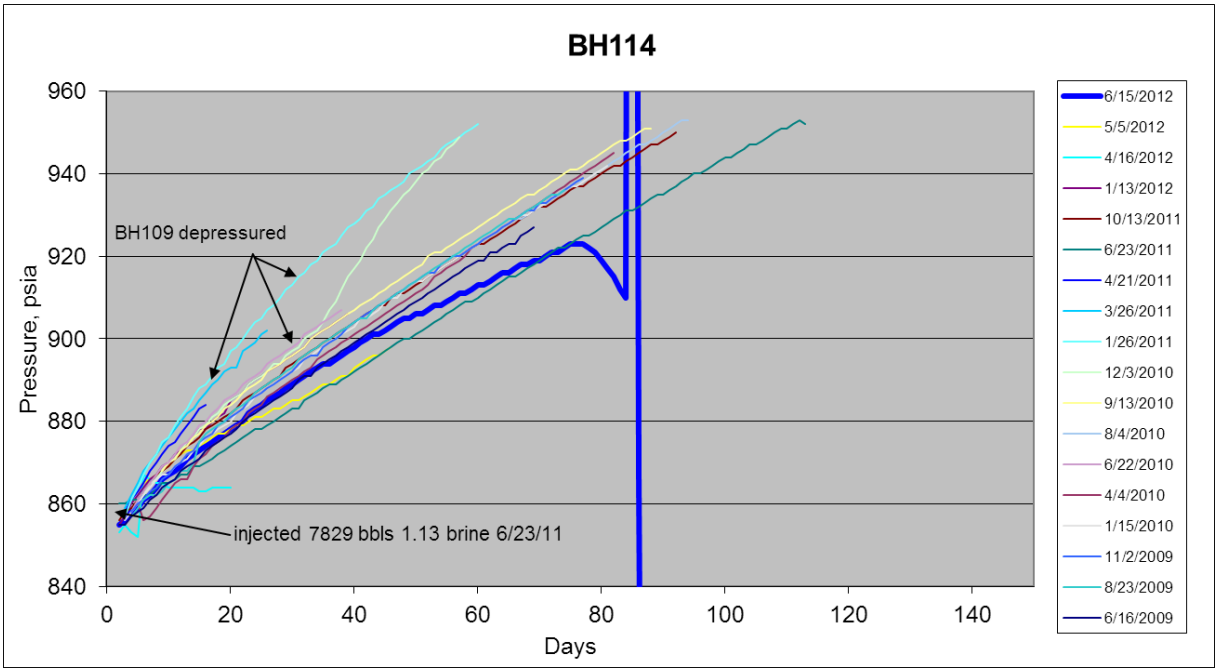


Figure 3-32. BH114B pressurization histories overlaid for several cycles. Bold blue line is summer 2012 showing significant deviation from historical that eventually proved to result from a hydraulic failure.

3.6.4 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 3-33 (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

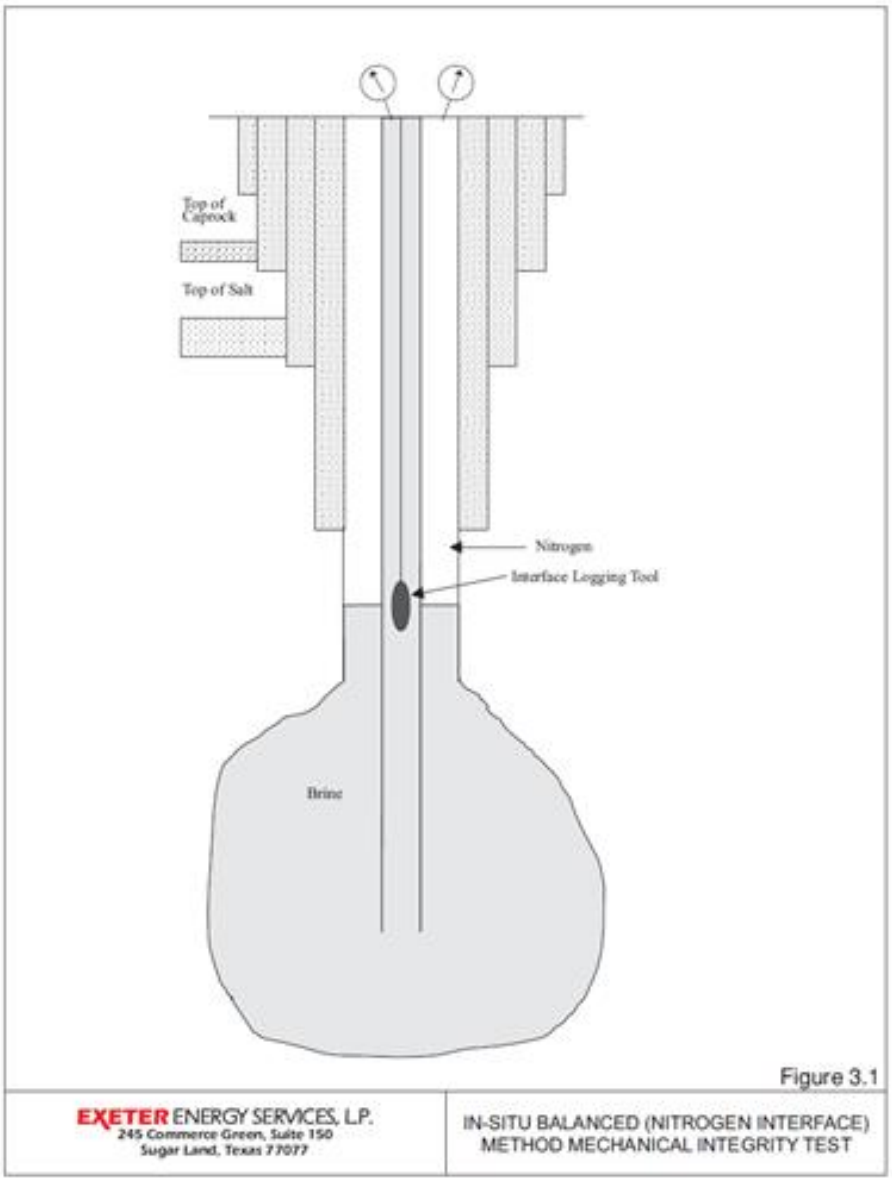


Figure 3-33. Schematic of typical nitrogen interface test, reproduced from Exeter-Energy-Services (2003)

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.

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 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.

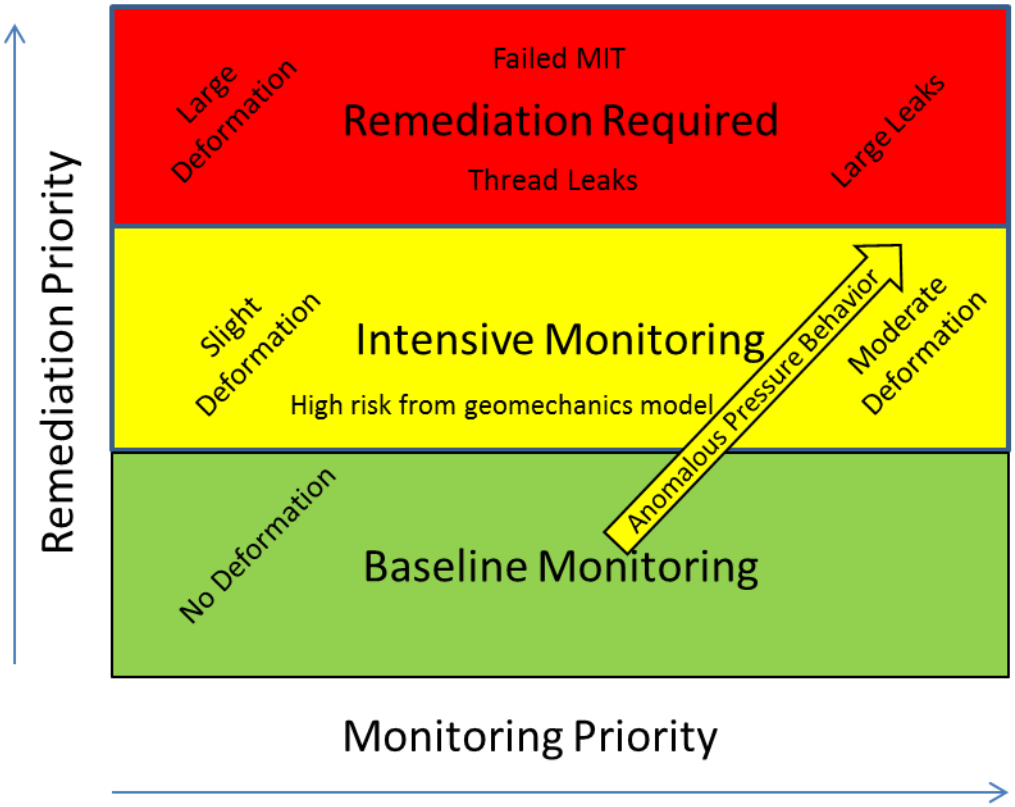


Figure 4-1. Illustration of well monitoring and remediation risk diagram.

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 DM, 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 and they are compared 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 DM MAC Grading

The DM 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 DM well grading system are listed in Table 5-1 below. The DM 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.

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

Grade	Conditions	DM 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.

The SNL procedure also resulted 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 manual inspection of the data. Each variable was then normalized by this maximum value resulting in a data range from 0 to 1. The normalized C_v and RWD values were then averaged for each well. The resulting average values were then binned into 5 categories and assigned a 1 through 5 final ranking value. The binning was based on the thresholds listed in Table 5-2.

Table 5-2. SNL Multi-arm Caliper Grading System

Grade	Average Normalized Cv + RWD Value
5	Average value >= 0.65
4	0.65 > Average value >= 0.5
3	0.5 > Average value >= 0.35
2	0.35 > Average value >= 0.2
1	Average value < 0.2

5.1.3 Comparison of DM and SNL Ranking Values

The availability of two different MAC grading from the same data set provides the opportunity to compare these two systems and review their similarities and any differences. An exact match between the two grading's is not expected. Even though both systems use the same numeric range, one through five, the criteria for binning wells into these values are not the same. Regardless of this, a comparison is useful in providing confidence in these grading systems and can assist in identifying potential anomalies in them.

Figure 5-1 provides a direct comparison between the DM (x-axis) and SNL (y-axis) well grades based on MAC survey results. The diagonal line shows where the two grades were equal. Points above this line have SNL grades higher than DM grades; points below the line have higher DM than SNL grades. Higher grade values indicate a higher level of concern based on the MAC data.

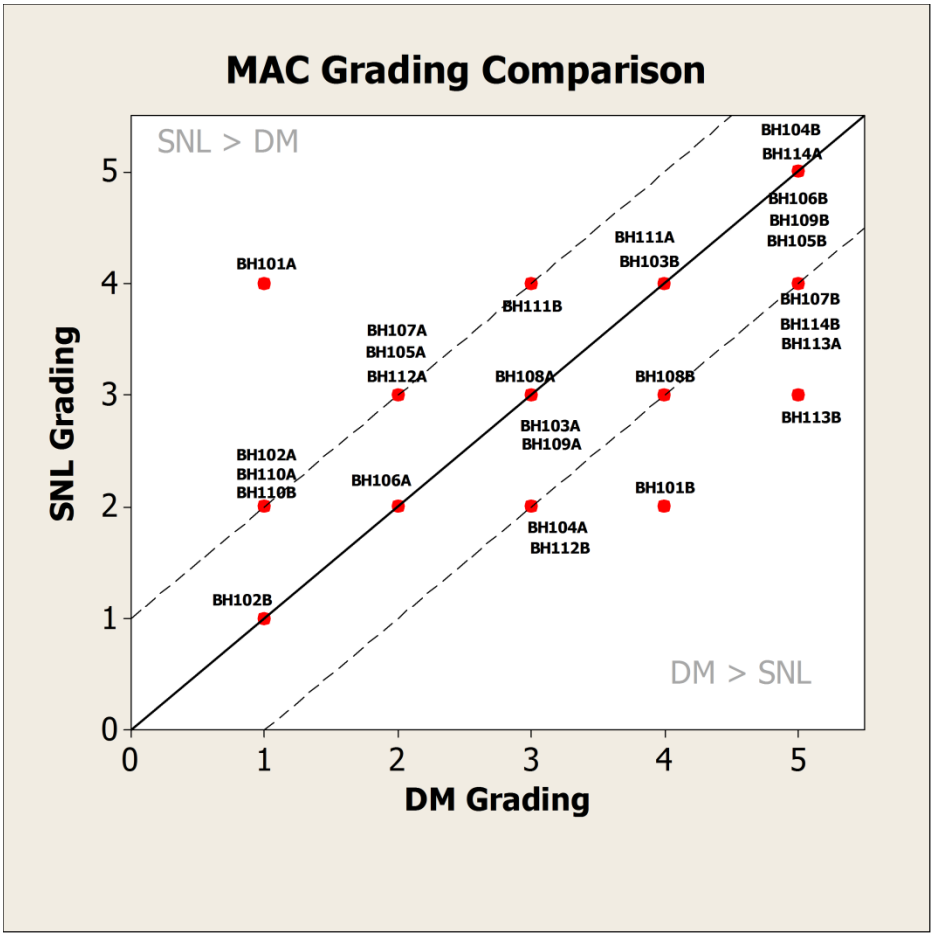


Figure 5-1. comparison between the DM and SNL well grades based on MAC survey results

There are twelve wells falling on the diagonal (SNL=DM), eight wells above the diagonal (SNL>DM), and eight wells below the diagonal (DM>SNL). The majority of wells falling off the diagonal line are within one grade levels for the two systems (area between the dashed lines). The three wells falling outside of one grade difference are BH101A, BH101B, and BH113B.

Examination of the data for these three wells leads to the conclusion that the differences in the grading values is due to differences in the interpretation of the MAC survey data. In one case, BH101A, the differences may also be due to a focus on different depth intervals. The SNL grading found a large amount of deformation for this well at a location just below the salt-cap rock interface region. Although the logging contractor's report does mention deformation in this same region, they indicate there is only minimal deformation at the salt cap-rock interface which may explain the differences in the SNL and DM grading.

In general, the comparison between the DM and SNL MAC grade values show relatively good agreement (25 out of 28 well grades are within one grade value). Only few discrepancies between the grades are evident, and these are likely due to differences in the depth range examined.

5.1.4 Survey Age Considerations

The collection of MAC surveys at the Big Hill site took place over a time period of approximately three years. The configuration of the "A" wells allows them to be surveyed more easily than the "B" wells and so they were surveyed first. The B wells were then surveyed at a later date as schedule and resources permitted. The A wells and B wells have identical original casing configurations (see Section 3.1) and are typically located about 40 feet from one another for a given cavern. Given these facts, one would not expect to see systematic differences between the MAC grade values between the A and B wells. But a comparison of the average MAC grade value (average of DM and SNL grades) shows a notable difference in these values between the A and B wells. Figure 5-2 shows a box plot of the average MAC grade values grouped by well identifier. In this figure, the box shows the 25 to 75 percentile range, with the mean and median being shown by the circles and horizontal lines respectively. As shown by this figure, there are notable differences in the distribution of grade values between the A and B wells. Since these differences are not attributable to actual differences between the A and B well configurations or geologic considerations, some other factor must be responsible for this variance.

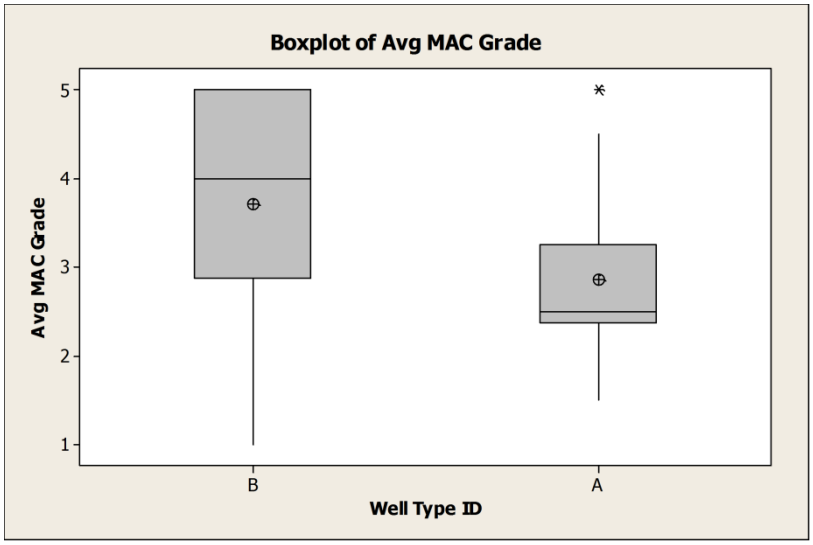


Figure 5-2. Box plot of the average MAC grade values grouped by well identifier.

Two wells at the Big Hill site, BH103A and BH114A had repeated MAC surveys run with several years in between, with no changes in casing configurations between the surveys. This allows an examination of the MAC radial arm data for the same well over time. The two plots in Figure 5-3 show the change in the coefficient of variation for BH103A and BH114A between two different survey dates. As shown in these plots, there is a significant increase in the C_v value between the two surveys which are separated by only a two to three year time period.

Because the timeframe over which the Big Hill MAC surveys were conducted spans a period of three years, and the A and B wells were surveyed at different ends of this time span, it is likely that the difference in grade values between the A and B wells is due to time of survey. That is, the more recently surveyed wells (B wells) have a higher average grade value because additional deformation had taken place since the earlier surveys (A wells). This can be seen in the scatter plot of survey age versus average MAC grade shown in Figure 5-4. In this figure the dashed lines show the average grade of the older and newer surveys.

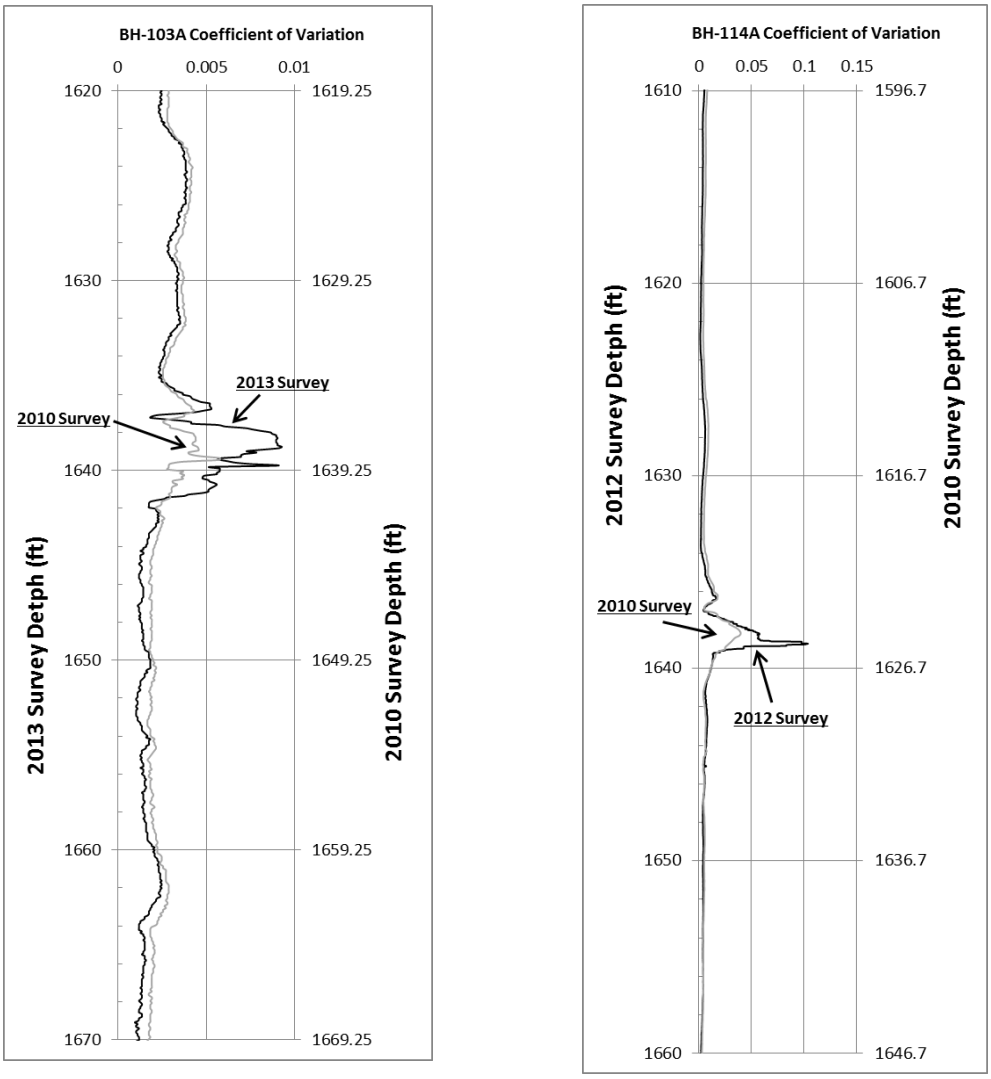


Figure 5-3. Change in the coefficient of variation for BH103A and BH114A between two different MAC survey dates.

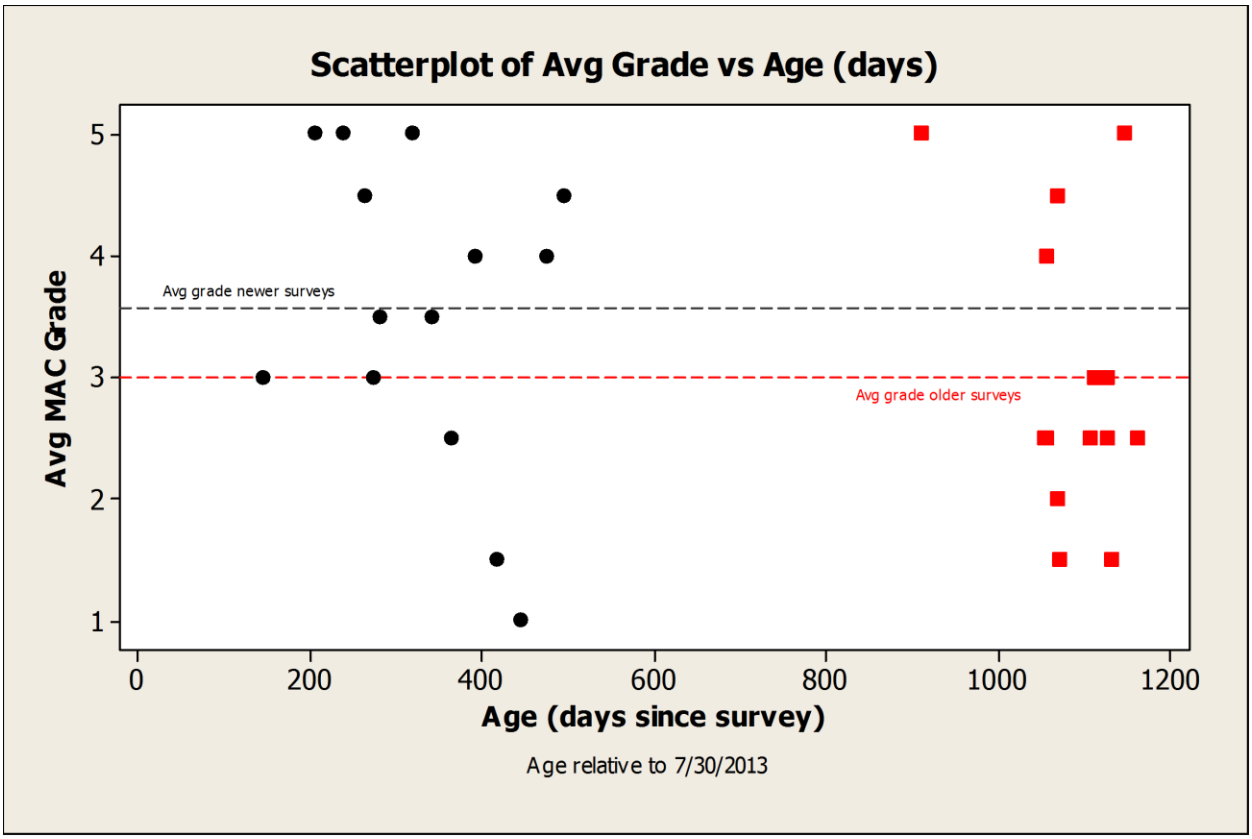


Figure 5-4. Scatter plot of survey age versus average MAC grade for Big Hill wells. Dashed lines show averages of newer (black) and older (red) surveys.

The patterns shown in Figure 5-3 and Figure 5-4 show that there is increasing deformation of the well casings as a function of time and that comparing MAC survey results for paired wells separated by as little as two or three years may not give an accurate comparison. This may lead to an inaccurate grading of the well system. Therefore, the age of the MAC surveys should be a consideration in the grading of wells for remediation and in the planning of the MAC survey schedule.

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 5-3.

Table 5-3. 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 3.6.2) 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 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 Geomechanics Grading

The Big Hill geomechanics model in Section 3.3 calculated large-scale displacements in the salt dome structure caused by the creep-induced closure of the storage caverns. The failure modes in this model are simplistic as each mode (shear and vertical strain) is considered separately. In reality both modes are need to be coupled to influence the strength of the casings. The coupling is necessary for the wellbore grading of each cavern.

The wellbore casings are not included in the model either. This omission led to questions about the effect of those casings on the interaction between the salt and caprock. To figure out how the wellbore impedes the movement of the salt dome top, the global model, which contains the wellbore blocks, was reconstructed to include wellbore casings, as shown in Figure 5-5 (Park and Ehgartner, 2012).

Figure 5-6 shows the maximum equivalent plastic strain (EQPS) histories in the steel casings of fourteen wellbores in the interface layer between the caprock bottom and the salt dome top. The number at each curve indicates the cavern ID. As described in Section 3.3, oil leaks were found in well casings of Caverns 105 and 109 at December 3rd, 2009 and October 8th, 2010, respectively. The oil leaks would occur when both double steel casings and double cement annuli fail. The failure point of the casing in Cavern 109 is used as the criterion for EQPS for all the boreholes. Therefore, when the steel casing of Cavern 109 failed 20 years after the initial leach (at 21 years simulation time), the calculated EQPS at that time is 0.0093. This value of 0.0093 could be used as the EQPS failure criterion for steel casing. The simulation time of 21 years corresponds to calendar year 2010, because this simulation assumed that all existing caverns

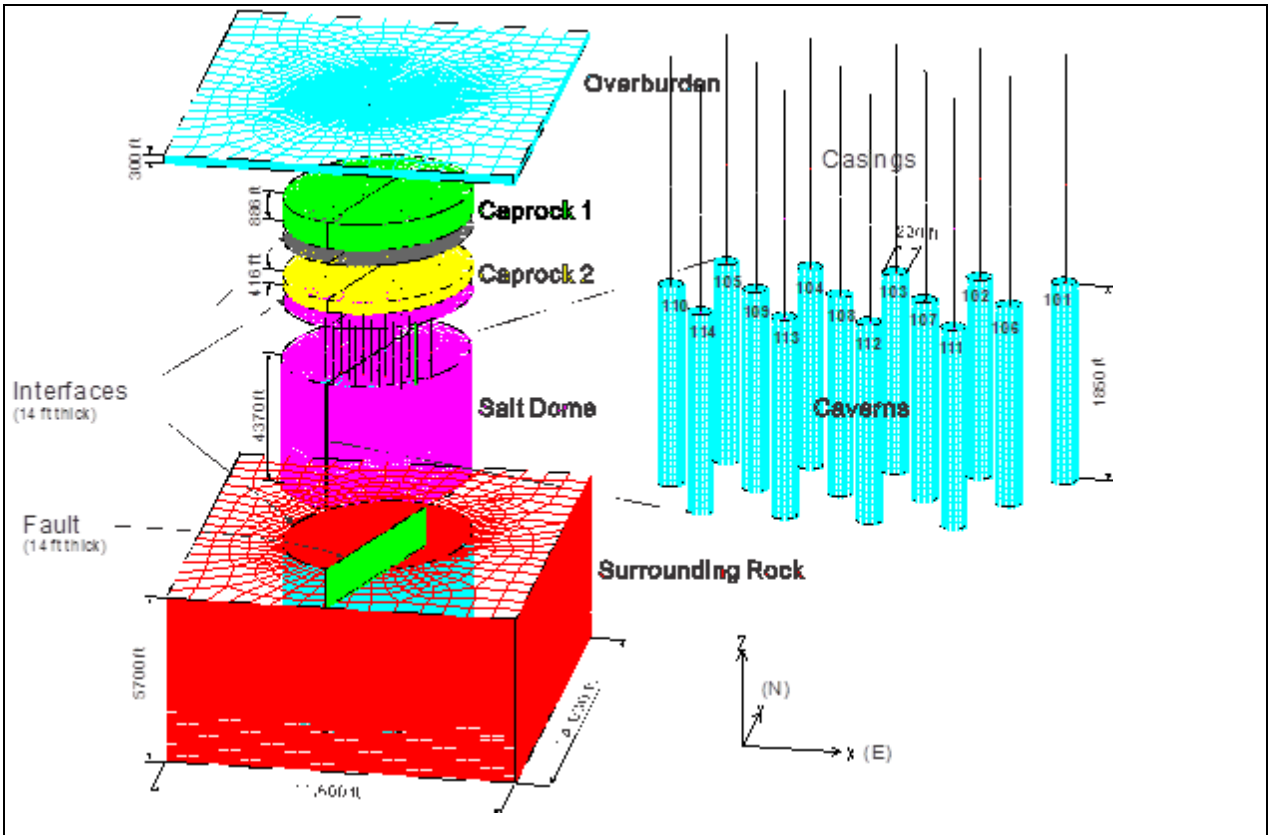


Figure 5-5. Global model including wellbore casings.

were initially leached in 1990. When the EQPS failure criterion for steel is applied to the curve for Cavern 105, the steel casing of Cavern 105 is predicted to occur at 19.7 years simulation time, i.e. the steel casing of Cavern 105 is predicted to fail at approximately one year earlier than Cavern 109. It is close to the field observations.

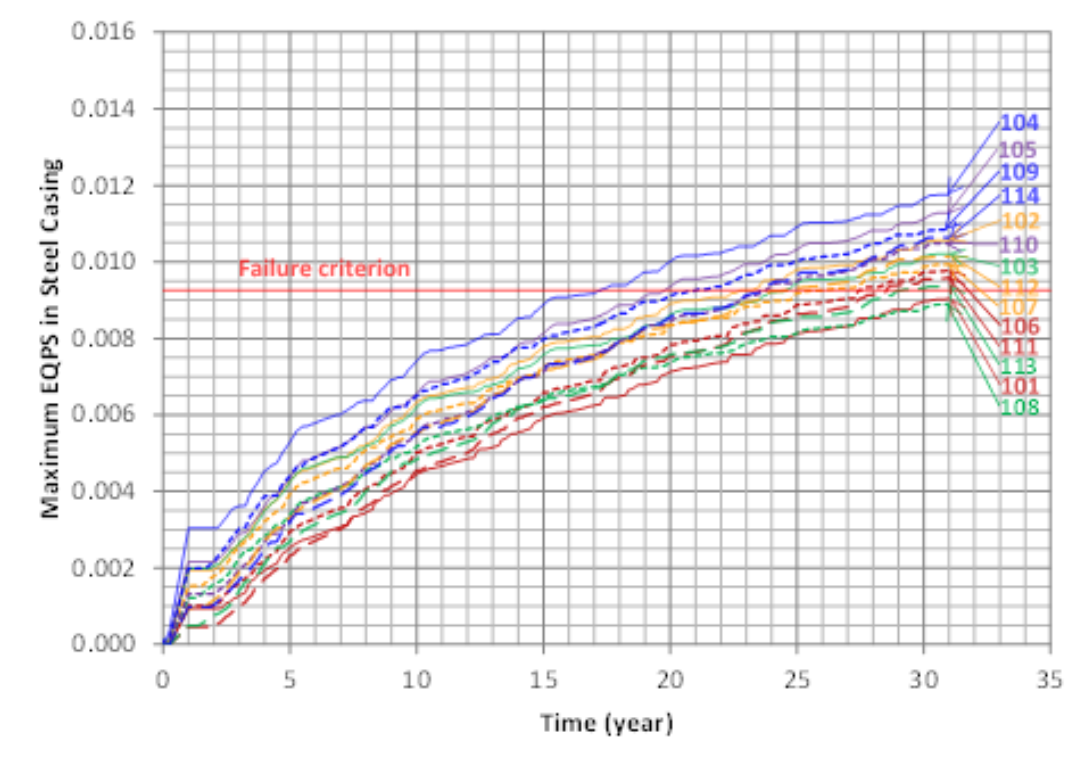


Figure 5-6. The predicted maximum EQPS histories in the steel casing.

To develop a separate well grading system based on the geomechanical simulations, the predicted leak dates obtained from Figure 5-6 were used for grading; wellbores that have already failed were given a score of 5, those predicted to fail in 2013 a score of 4, those predicted to fail in 2014 a score of 3, and so on. Table 5-4 lists the predicted leak date and the grade score for each cavern.

Table 5-4. Predicted leak date and grade for remediation.

Cavern ID	Predicted Leak Date Simulation Time (year)	Predicted Leak Date Calendar Time	Grade (1~5)	Remarks
101	No fail until 31	No fail until Oct-2020	1	
102	23.50	Apr-2013	4	
103	24.67	Jun-2014	3	
104	17.33	Feb-2007	5	
105	19.67	Jun-2009	5	Well B leaked, remediation
106	27.67	Jun-2017	2	
107	26.33	Feb-2016	2	
108	No fail until 31	No fail until Oct-2020	1	
109	21.00	Oct-2010	5	Well B leaked, remediation
110	23.83	Aug-2013	4	
111	28.58	May-2018	2	
112	24.83	Aug-2014	3	
113	29.83	Aug-2019	2	
114	23.67	Jun-2013	4	Well A and B deformed severely, Well A remediation

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

Table 5-5. 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 5-5 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 5-6. 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 5-6. 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 5-7.

Table 5-7. 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. As shown in Section 5.1.4 of this report, significant casing deformation can take place over a relatively short period of time; 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 5-8 lists the sub-components of this grading component; details regarding these sub-components are discussed below.

Table 5-8. 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 Big Hill caverns were designed and leached specifically for oil storage, and so their shape was controlled during leaching to meet optimal design criteria. 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 5-9. The pillar-to-diameter values were obtained from Eldredge, Checkai et al. (2013).

Table 5-9. 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. As discussed in Section 3.2.2 of this report, offsite injection of fluids is a concern at Big Hill. 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 BIG HILL 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 Big Hill 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.

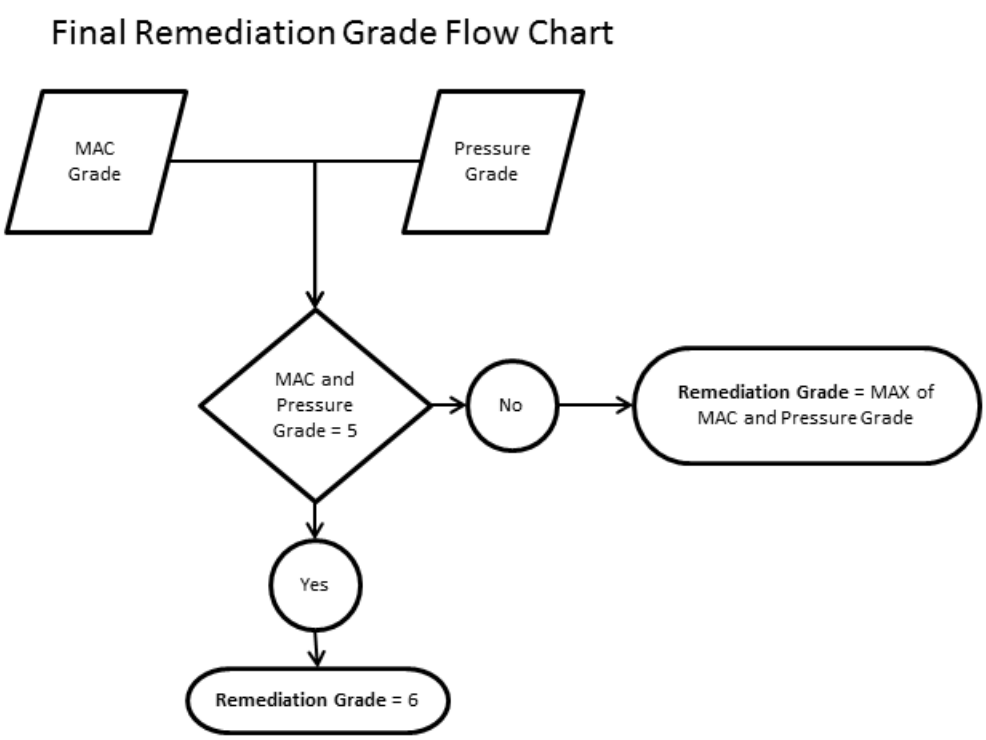


Figure 6-1. Remediation grade flow chart

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.

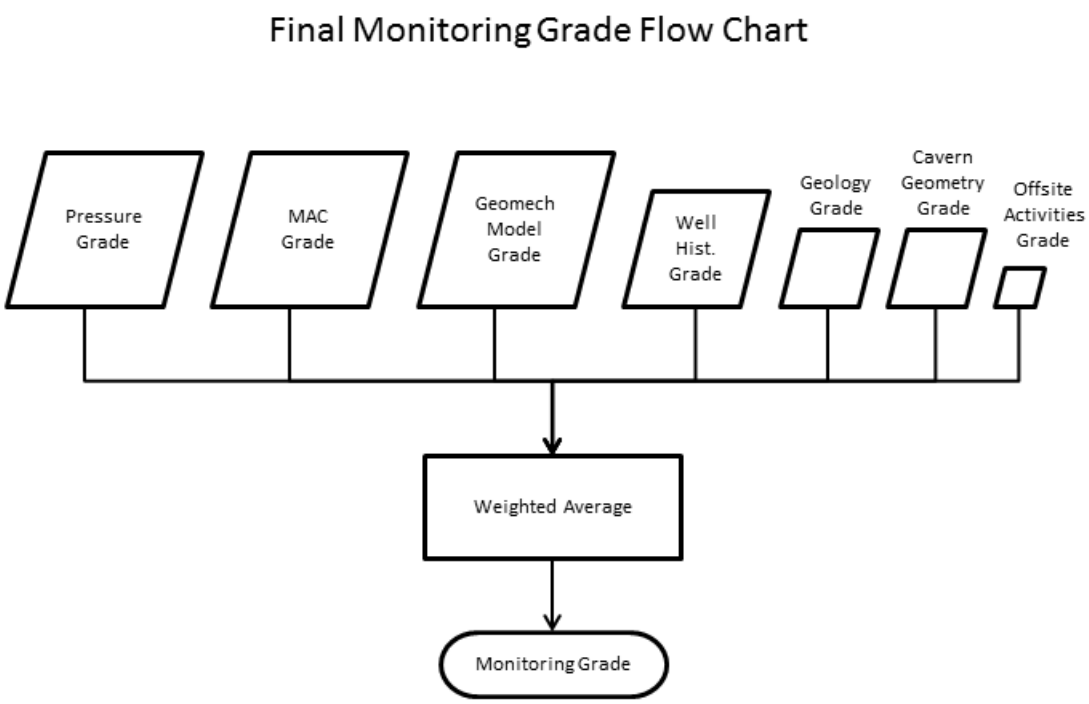


Figure 6-2. Monitoring grade flow chart. Individual grade component symbols sized according to their weight in the averaging process.

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.

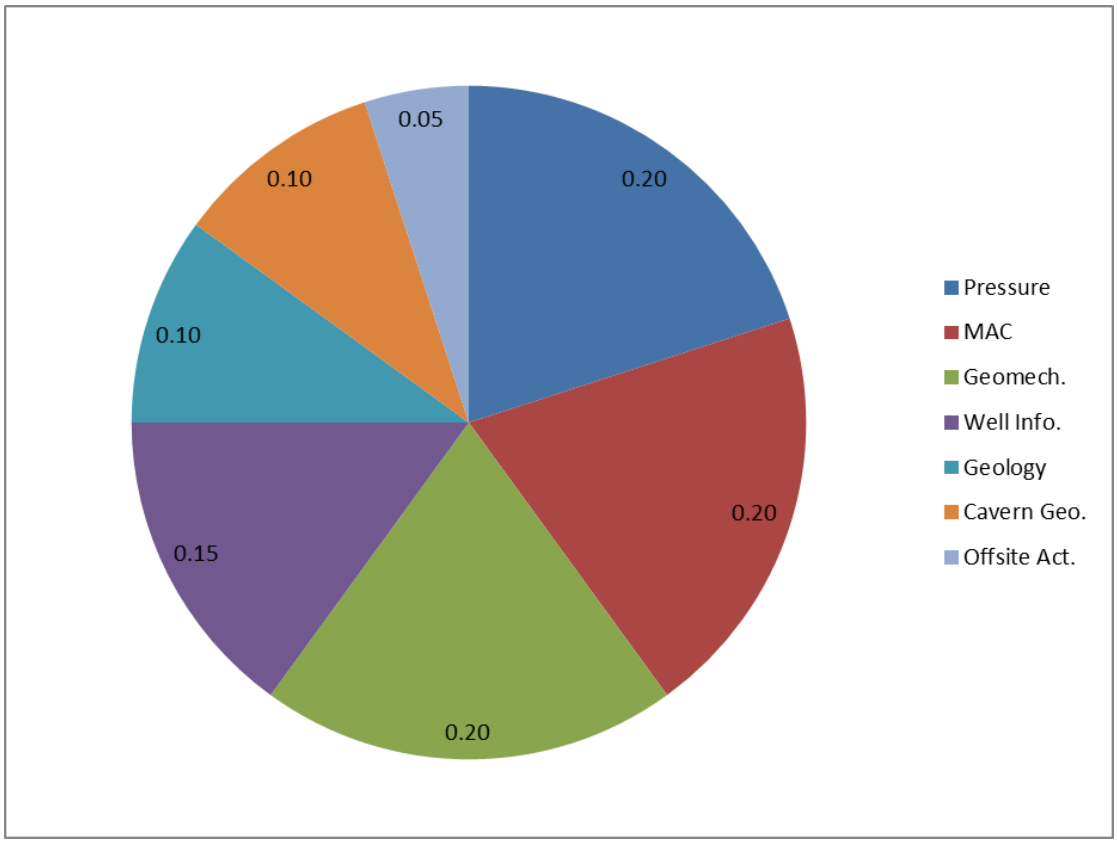


Figure 6-3. Relative weights of the individual grading components used in computing final monitoring grade.

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 C.

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 Big Hill grade values

The current Big Hill remediation and monitoring well grades are listed in Table 6-1sorted 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 Big Hill including any well remediation work.

Although Figure 6-4's Y-axis goes to a maximum value of six, there are no wells currently meeting the criteria to achieve a grade of six. Also note that those wells that have been remediated (BH105B, BH109B, BH114A, and BH114B) appear at the bottom of the graph. Prior to remediation, these wells all had a grade of five or six. This can be seen in Figure 6-5 which shows the remediation and monitoring grade values assigned using pre-remediation well information. This plot shows how wells with severe casing deformation and extreme pressure history concerns generate a "6" for remediation grade and are separated from the main body of well points in the plot.

Table 6-1. Current Big Hill remediation and monitoring well grades.

Well ID	Remediation Grade	Monitoring Grade
BH104B	5	1.26
BH106B	5	1.49
BH103B	4.5	1.88
BH107B	4.5	1.66
BH113A	4.5	1.97
BH103A	4	1.88
BH111A	4	1.59
BH112A	4	2.42
BH112B	4	2.38
BH113B	4	1.89
BH108B	3.5	1.13
BH111B	3.5	1.50
BH101B	3	1.26
BH102A	3	2.10
BH102B	3	2.06
BH108A	3	1.18
BH109A	3	2.04
BH101A	2.5	1.30
BH104A	2.5	1.34
BH105A	2.5	2.01
BH107A	2.5	1.75
BH106A	2	1.58
BH110A	1.5	1.52
BH110B	1.5	1.48
BH105B	1	1.96
BH109B	1	1.96
BH114A	1	1.83
BH114B	1	1.87

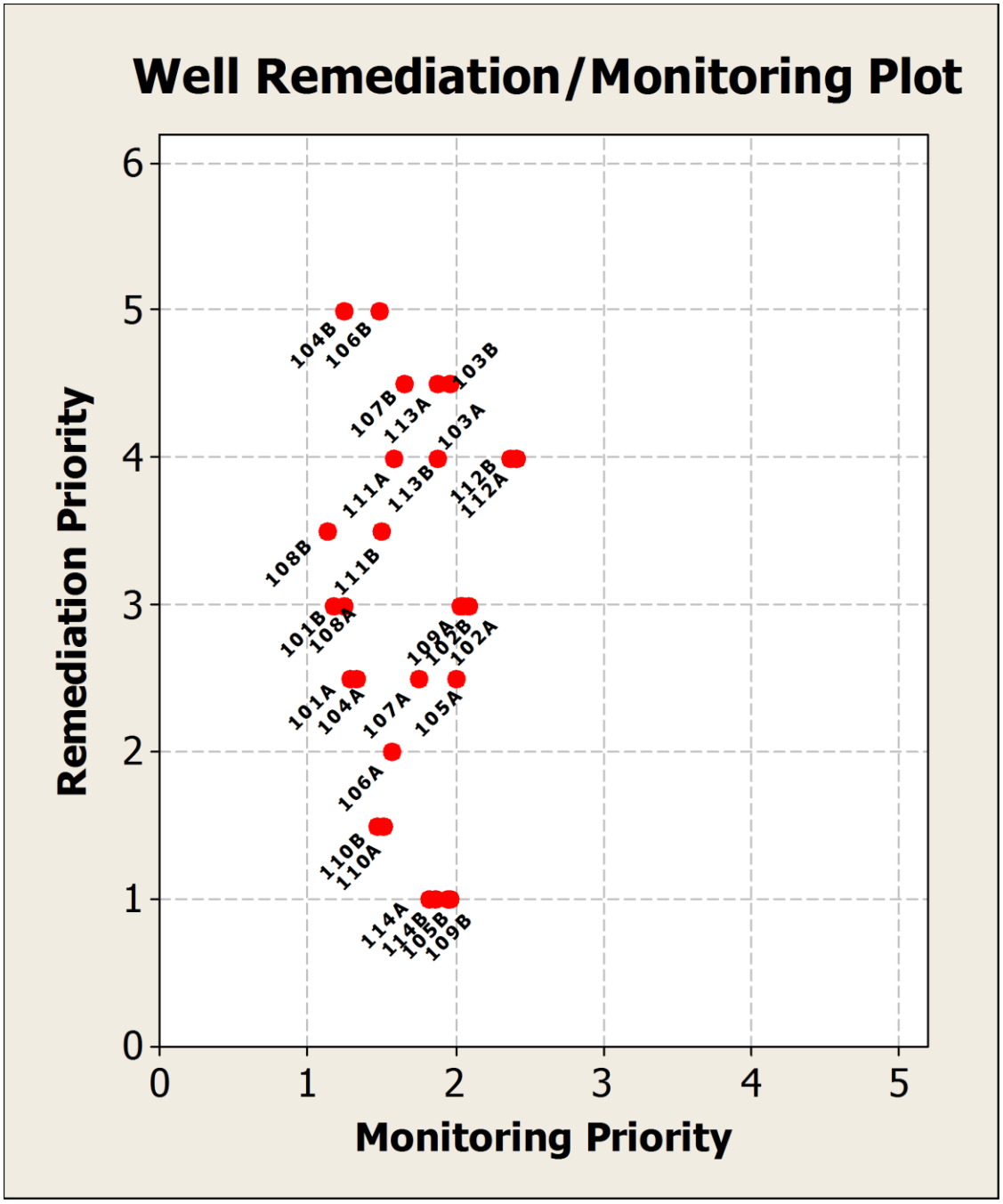


Figure 6-4. Plot of current Big Hill well grades for remediation and monitoring.

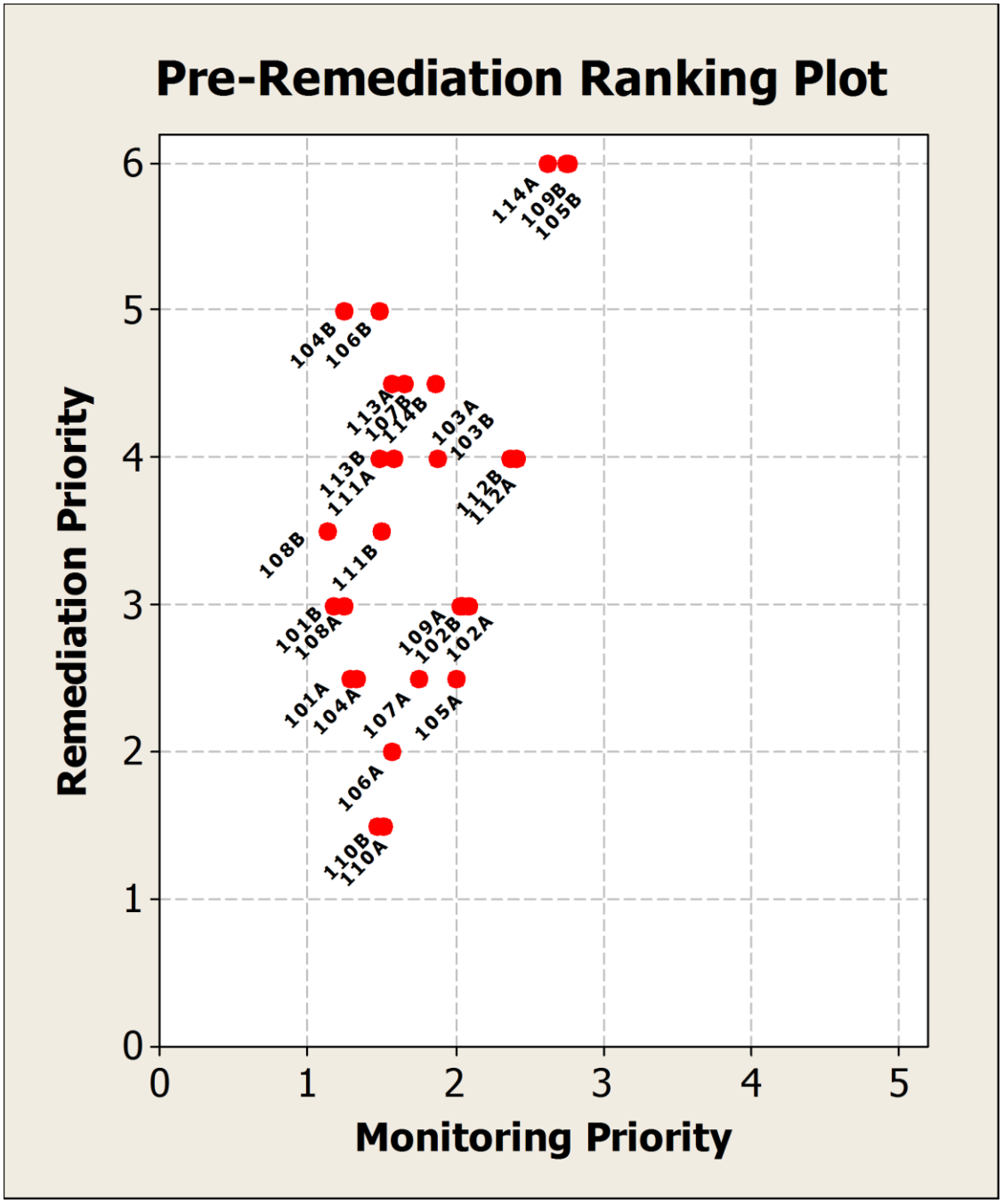


Figure 6-5. Plot of pre-remediation monitoring and remediation grade values; these values apply to pre-remediation conditions and <u>do not</u> reflect current conditions in the Big Hill wells.

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 DM 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, which has been on a frequency of about once a month in 2013.

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 Big Hill is the first 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 DM 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. The co-occurrence of several factors, including:

- 3 major hydraulic well failures at Big Hill in the last 4 years
- stricter State-level regulatory oversight on well integrity testing methods, and
- an internal shift toward aggressively resolving any known fluid leak, however small

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 Big Hill.

The intent is to receive feedback from DOE on the value of the approach applied for Big Hill, and then repeat the process for the remaining three sites. Right now, Bryan Mound has been identified as the next target site, with a tentative delivery date for the SAND report in April 2014. Similar reports for West Hackberry and Bayou Choctaw are planned at 6-month intervals.

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 the first Bryan Mound well grading, we will also provide updates for the Big Hill site. For deliverables, the working group would submit an executive summary for the combined BH and BM grading, and note any changes for BH in the

last 6 months. The supporting well grading workbook will be 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 Excel 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 DM Caverns to take custody of the Excel workbook. The workbook will be available as read-only to all SPR users through the DM 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. Assuming the well grading goes to Bryan Mound next, an executive summary will be presented concurrently with the roll-out of the Bryan Mound grading that includes any updates to the Big Hill grading.

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

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APPENDIX A: BIG HILL WELL RANKING MEETING AGENDA

OCC Room, 3rd Floor, 850 Building
Day 1 – Tuesday January 29th

Topic	Start-End Time	Discussion Lead / Presenter
Introductions	8:00 am – 8:15 am	Dave Lord
Meeting Goals and Agenda	8:15 am – 8:30 am	Dave Lord / Barry Roberts
Big Hill Geology Presentation	8:30 am – 9:00 am	Anna Lord
Geomechanics Presentation	9:00 am – 9:30 am	Byoung Park / Steve Sobolik
BREAK	9:30 am – 9:45 am	
Regulatory Drivers	9:45 am – 10:15 am	DM
DM Ranking Methodology Presentation	10:15 am – 10:45 am	DM
SNL Ranking Methodology Presentation	10:45 am – 11:15 am	Giorgia Bettin / Barry Roberts
Remedial Workover Presentation	11:15 am – 11:45 am	DM
LUNCH – Caliper Survey Data Presentation	11:45 am – 12:45 pm	Order In
Cavern Pressures Presentation	12:45 pm – 1:15 pm	David Lord / David Rudeen
Special Areas of Concern (cavern histories, etc.)	1:15 pm – 1:30 pm	ALL
Ranking Procedures for this Meeting	1:30 pm – 2:00 pm	Barry Roberts
BREAK	2:00 pm – 2:15 pm	
Well by Well Discussions / Ranking	2:15 pm – 5:00 pm	Barry Roberts

Day 2 – Wednesday January 30th

Topic	Start-End Time	Discussion Lead / Presenter
Well by Well Discussions / Ranking (cont.)	8:00 am – 10:00 am	Barry Roberts
BREAK	10:00 am – 10:15 am	
Well by Well Discussions / Ranking (cont.)	10:15 am – 12:00 am	Barry Roberts
LUNCH / Review of rankings so far	12:00 pm – 1:00 pm	Order in
Well by Well Discussions / Ranking (cont.)	1:00 pm -2:00 pm	Barry Roberts
Review of Final Rankings	2:00 pm -3:00 pm	Barry Roberts
Report Generation Planning*	3:00 pm -4:00 pm	Dave Lord
Discussion of Relevant Research Topics*	4:00 pm -5:00 pm	ALL

*these topics may get pushed to Thursday morning if necessary

Day 3 – Thursday January 31th

Topic	Start-End Time	Discussion Lead / Presenter
Overflow topics as necessary	8:00 am – 10:00 am	Barry Roberts

APPENDIX B: MEETING SIGN-IN SHEET 01/29/2013

Meeting Sign-In Sheet

Project: Sandia/DM/DOE Tech Mtg
Facilitator: Lisa Eldredge
Place/Room: MIC

Date: 1/29/2013
Time: 0800

PRINT NAME	ORGANIZATION	TITLE	PHONE	EMAIL
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APPENDIX C: 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-DM	Multi-arm caliper DM grade for zone of interest	NA
MAC-SNL	Multi-arm caliper SNL grade for zone of interest	NA
MAC-FINAL	AVG(MAC-DM, 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
FULLMAC-SNL	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

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	1/3
P2D	Pillar to diameter ratio	1/3
SLTBACK	Salt back (cavern to top of salt distance)	1/3

(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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