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U.S. Strategic Petroleum Reserve Big Hill 114 Leak Analysis 2012

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Abstract

This report addresses recent well integrity issues related to cavern 114 at the Big Hill Strategic Petroleum Reserve site. DM Petroleum Operations, M&O contractor for the U.S. Strategic Petroleum Reserve, recognized an apparent leak in Big Hill cavern well 114A in late summer, 2012, and provided written notice to the State of Texas as required by law. DM has since isolated the leak in well A with a temporary plug, and is planning on remediating both 114 A- and B-wells with liners. In this report Sandia provides an analysis of the apparent leak that includes: (i) estimated leak volume, (ii) recommendation for operating pressure to maintain in the cavern between temporary and permanent fixes for the well integrity issues, and (iii) identification of other caverns or wells at Big Hill that should be monitored closely in light of the sequence of failures there in the last several years.

ACKNOWLEDGEMENTS

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EXECUTIVE SUMMARY

This report addresses recent well integrity issues related to cavern 114 at the Big Hill Strategic Petroleum Reserve site. DM Petroleum Operations, M&O contractor for the U.S. Strategic Petroleum Reserve, recognized an apparent leak in Big Hill cavern well 114A in late summer, 2012, and provided written notice to the State of Texas (Erskine 2012) in a letter dated September 6, 2012. DM has since isolated the leak in well A with a temporary plug, and is planning on remediating both 114 A- and B-wells with liners.

DOE requested that Sandia provide an analysis of the apparent leak, to include: (i) estimated leak volume, (ii) recommendation for operating pressure to maintain in the cavern between temporary and permanent fixes for the well integrity issues, and (iii) identification of other caverns or wells at Big Hill that should be monitored closely in light of the sequence of failures there in the last several years.

This report provides the requested information on these three items and supplies additional information regarding the history and integrity testing of the access wells for cavern BH114.

Key findings of this analysis:

(i) The total leaked oil volume was estimated at 2,480 barrels using the differences between the measured and predicted pressure history of the cavern in conjunction with the overall compressibility of the cavern.

(ii) The Sandia geomechanics team recommends that SPR hold the BH114 cavern at normal operating pressure (versus zero wellhead pressure) during the projected 6-8 week period between the isolation and remediation workovers in order to minimize creep closure of the cavern and related effects such as subsidence and wellstrains that are exacerbated with low operating pressure.

(iii) Investigation into well and cavern monitoring priorities reveals numerous differences between Sandia and DM recommendations. Final recommendations will need to consider information and concerns from all parties.

In closing, Sandia recommends that the continued monitoring, analysis, modeling, and mitigation of the SPR cavern wells should be advised by a joint technical working group that includes expert technical representation from DOE, the M&O contractor (DM) and the geotechnical contractor (Sandia). The group should convene on a periodic basis, starting quarterly, to review new data, analyses, interpretations, and modeling results and pass formal advice up to management on recommended and required actions in presentations and reports as related to preserving well integrity. A concept for a working meeting to grade Big Hill caverns is presented.

NOMENCLATURE

BBL	Barrel (42 US gallons)
BH	Big Hill SPR site
BHF	Bradenhead flange
BM	Bryan Mound SPR site
CAVEMAN	Name of software used to monitor and predict well pressure
DM	DM Petroleum Operations
DOE	U.S. Department of Energy
M&O	Maintenance and operations
MB	Thousand barrels (volume)
MBD	Thousand barrels per day
MIT	Mechanical integrity test
MMB	Million barrels (volume)
MS	Microsoft
MW	Molecular weight
N_2	Nitrogen gas
NIT	Nitrogen injection test
SNL	Sandia National Laboratories
SPR	Strategic Petroleum Reserve
WH	West Hackberry SPR site

1 INTRODUCTION

The U.S. Strategic Petroleum Reserve, owned by the U.S Department of Energy (DOE), stores in excess of 700 million barrels (MMB) of crude oil in a collection of salt caverns along the U.S. Gulf Coast. These caverns are on average, between 2,000 and 4,500 feet below ground surface, and are connected to surface infrastructure by wells. A typical well is lined with several concentric steel casings (tubes) that are cemented into place. These wells provide isolation of cavern fluids (crude oil, brine) from the groundwater and surface environment. During operational lifetimes of many decades, problems may arise in which wells are physically deformed by geomechanical stresses, thermal stresses, or chemical attack, and lose hydraulic integrity. DOE is obligated under the state laws of Louisiana and Texas to monitor and remediate such instances, and Sandia frequently is consulted to work in conjunction with the Maintenance and Operations Contractor, DM Petroleum Operations (DM), to study and report on the well failure issues. The current report examines a well failure at the Big Hill storage site near Winnie, TX in summer, 2012.

1.1 Problem Statement

DM Petroleum Operations, M&O contractor for the U.S. Strategic Petroleum Reserve, recognized an apparent leak in Big Hill cavern well 114A in late summer, 2012, and provided written notice to the State of Texas (Erskine 2012) in a letter dated September 6, 2012. Wellhead pressure monitoring showed a departure from normal behavior in August, 2012. Re-pressurization histories were obtained from CAVEMAN, illustrated here in Figure 1-1, 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 1-1 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), DM performed wellhead analyses and found the surface facilities 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. DM 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 perform remedial workovers by placing liners in both wells to provide a more permanent fix.

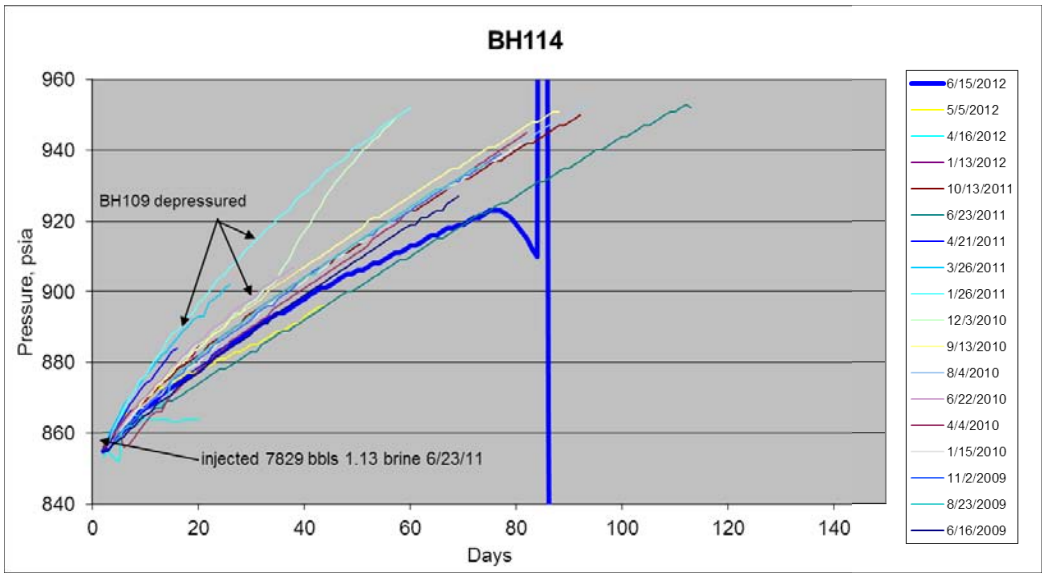

Figure 1-1. BH114 Cavern Re-Pressurization Histories. Bold Blue Line is Most Recent History from Summer 2012 Showing Significant Deviation from Historical.

1.2 Scope of Report

DOE requested that Sandia provide an analysis of the apparent leak, to include: (i) estimated leak volume, (ii) recommendation for operating pressure to maintain in the cavern between temporary and permanent fixes for the well integrity issues, and (iii) identification of other caverns or wells at Big Hill that should be monitored closely in light of the sequence of failures there in the last several years. Responses to these issues are addressed in this report.

2 BACKGROUND

2.1 BH114 A/B Well Histories

Well number 114B at Big Hill was drilled before 114A and was completed from January-April, 1985 (Walk 1985b) . Well number 114A was drilled and completed from April-August, 1985 (Walk 1985a). The majority of geophysical logs were run in well BH114B with a more limited set run in BH114A. It appears as though the geologic horizon picks were based from the BH114B data and the geology was assumed to be the same in well 114A.

2.1.1 BH114A

BH114A was drilled to a total depth of 4750 ft. below the Kelly Bushing. The Sea Level elevations of the drilling pad and Kelly Bushing are reported as 23.87 ft. and 45.07 ft. respectively (Walk 1985b).

Drilling mud circulation was lost several times during drilling. This occurred both during initial drilling and during subsequent reaming of the hole. Specifically, circulation was lost while drilling the pilot hole at a depth of 564 ft. (below Kelly Bushing) and partially lost between 427 ft. and 450 ft. while opening the hole to a larger diameter. There was complete loss of circulation from 641 ft. to 1780 ft. during drilling of the pilot hole. All of the lost circulation zones include some segment of the caprock sequence indicating void space in the caprock.

During drilling, well logs were collected at different levels of well completion. These included temperature logs, caliper logs, cement bond log, sonic logs, and density neutron and gamma ray logs. Not all logs were run over all depth intervals and some were run with differing levels of casing in place.

The geology horizons recorded in the drilling report for BH114A are as follows:

Formation Top	Depth in feet (BHF)
Overburden	2
Caprock	350
Salt	1630

2.1.2 BH114B

BH114B was drilled to a total depth of 5480 ft. below the Kelly Bushing. The Sea Level elevations of the drilling pad and Kelly Bushing are reported as 25.27 ft. and 45.13 ft. respectively (Walk 1985a).

Drilling mud circulation was lost several times during drilling. There were no fluid returns to the surface during drilling of the interval from 1036 ft. to 1407 ft. (below Kelly Bushing) and from the interval from 1556 ft. to 1768 ft. Both these lost circulation zones overlap the caprock interval again indicating void spaces in the caprock.

During drilling, numerous well logs were collected at different levels of well completion. These included dual induction logs, self-potential logs, caliper logs, cement bond log, sonic logs, and density neutron and gamma ray logs. Not all logs were run over all depth intervals and some were run with differing levels of casing in place.

The geology horizons recorded in the drilling report for BH114B are as follows:

Formation Top	Depth in feet (BHF)
Overburden	2
Caprock	350
Salt	1630

2.1.3 BH114A Well Completion

Images of the casing profile and depth reference chart from the original well history report (Walk 1985a) are shown for BH114A in Figure 2-1 and Figure 2-2, respectively. The top of salt was indicated at 1630 ft. below the Bradenhead flange (BHF). Both the 20" intermediate casing and 13-3/8" production casing were set in salt at 1730 ft. and 2130 ft., respectively (relative to BHF). Cement bond logs for the 13-3/8" production casing for the caprock-salt interface zone indicated a good cement bond although adjacent zones were listed as poor.

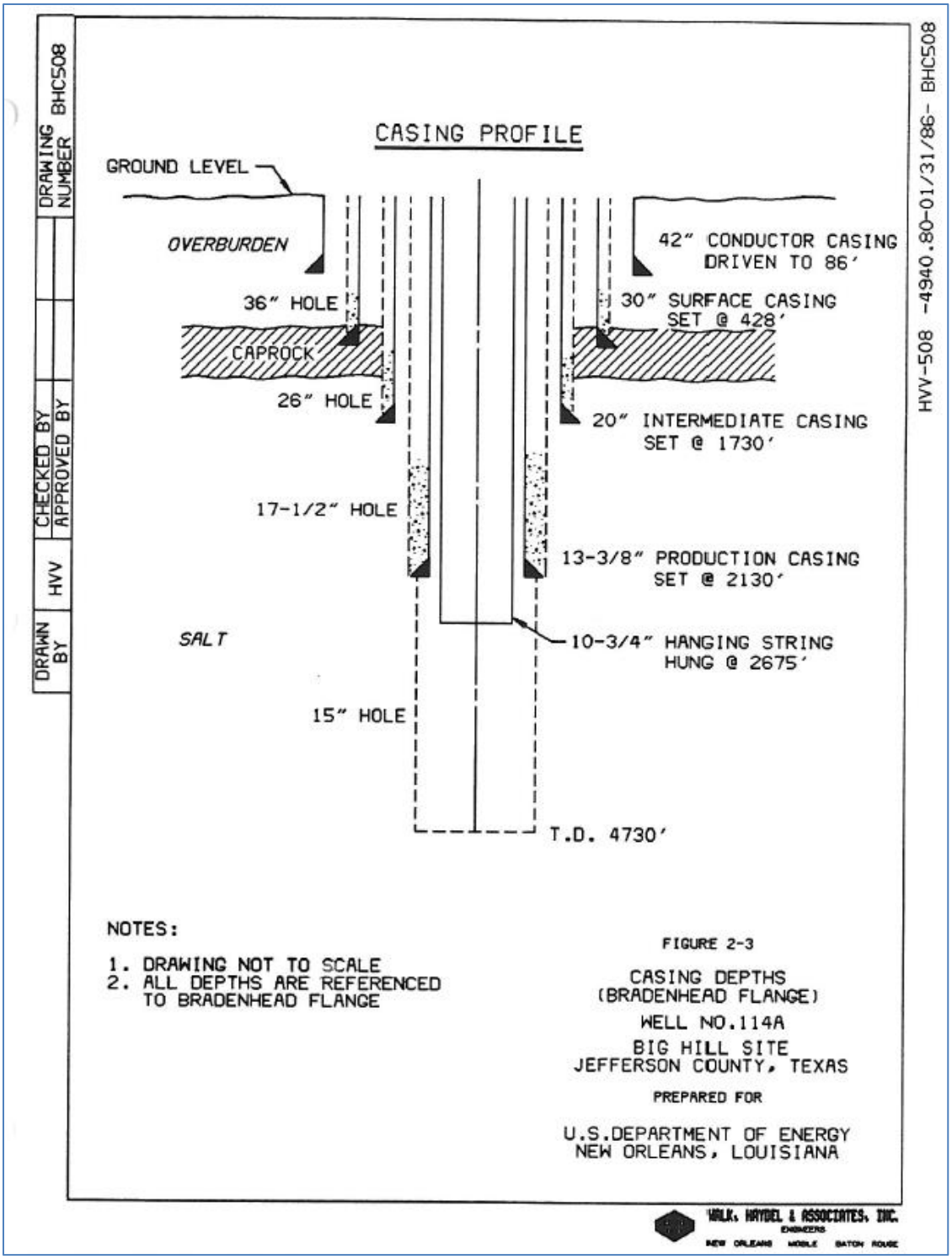

Figure 2-1. Casing Profile for BH114A at the Time of Completion in 1985, Reproduced from Walk (1985a).

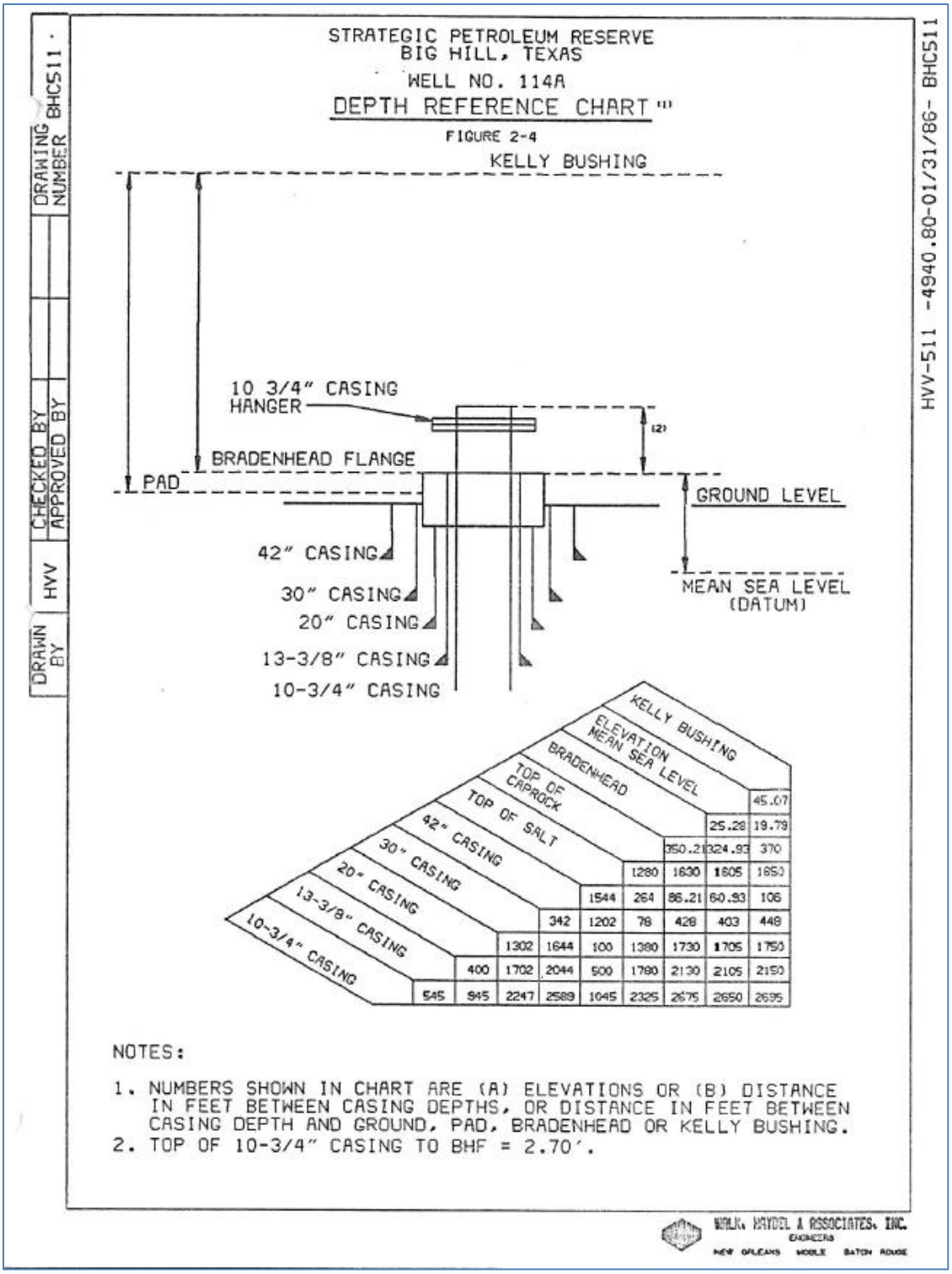

Figure 2-2. Depth Reference Chart for BH114A at the Time of Completion in 1985, Reproduced from Walk (1985a).

2.2 BH114 Cavern Integrity Tests

Cavern integrity tests are required by state regulatory authorities every five years in order to demonstrate that the cavern wells can hold pressure and prevent loss of fluids into the environment. The test procedure involves de-piping the wellhead to isolate the cavern from the surface piping, and then pumping nitrogen down into each the A- and B-wells while logging the nitrogen/oil interface over prescribed depths and monitoring wellhead pressure and interface location with time. A nitrogen leak rate in bbl/yr is calculated based on the pressure history and interface movement, and divided by 10 in order to approximate the equivalent oil leak rate. The maximum permissible oil leak rate is 100 bbl/yr (Exeter-Energy-Services 2003).

Sandia reviewed the last three BH114 cavern integrity test reports published in 1997, 2003, and 2007 by DM (Perry 1997; Perry 2003; Perry 2007) and concur with the general findings that there were no significant nitrogen leaks in the A- or B-wells as determined by the testing procedure. Well configuration diagrams circa 2001-2002 are shown here in Figure 2-3 and Figure 2-4 as reproduced from Perry (2007). Figure 2-5 presents the measured pressure history from February 2007 to October 2012, of BH114 as measured in well BH114B. In this figure, events that significantly affect the cavern pressure are annotated along the top margin.

2.2.1 Baseline Nitrogen Test Performance

In order to establish the baseline performance for the BH114 wells under nitrogen testing, wellhead pressures and oil-nitrogen interface depths recorded for the initial and final test days for each well in the 2002 and 2007 tests are summarized in Table 2-1. Note the wellhead pressure levels increased by about 10 psi and the interfaces moved up about 2-3 feet over the 14-20 day test durations. The steady upward trending in pressure was likely due to long-term creep closure of the cavern.

Table 2-1. Nitrogen Well Leak Test Data for BH114 Reported in Perry (2003) and Perry (2007).

Well	Date	Wellhead Pressure (psia)	Interface Depth (ft)
114A	12/9/2002	1631.6	2155.4
114A	12/23/2002	1641.8	2152.8
114B	12/9/2002	1633.1	2155.5
114B	12/23/2002	1642.6	2152.6
114A	10/16/2007	1634	2154.8
114A	11/5/2007	1644	2152.2
114B	10/16/2007	1635	2162.7
114B	11/5/2007	1645	2159.2

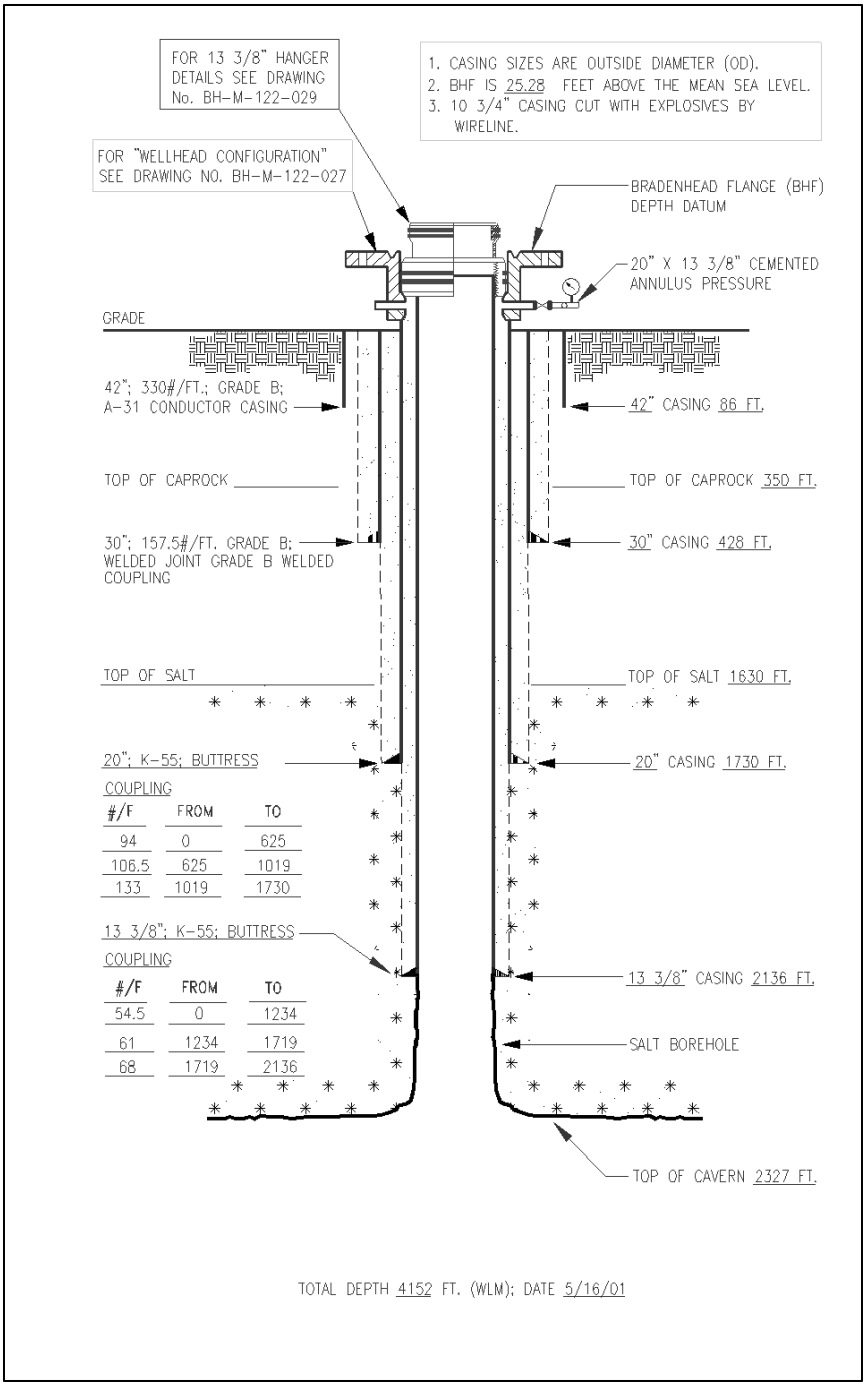

Figure 2-3. Well Configuration for BH114A, Dated 5/16/2001.

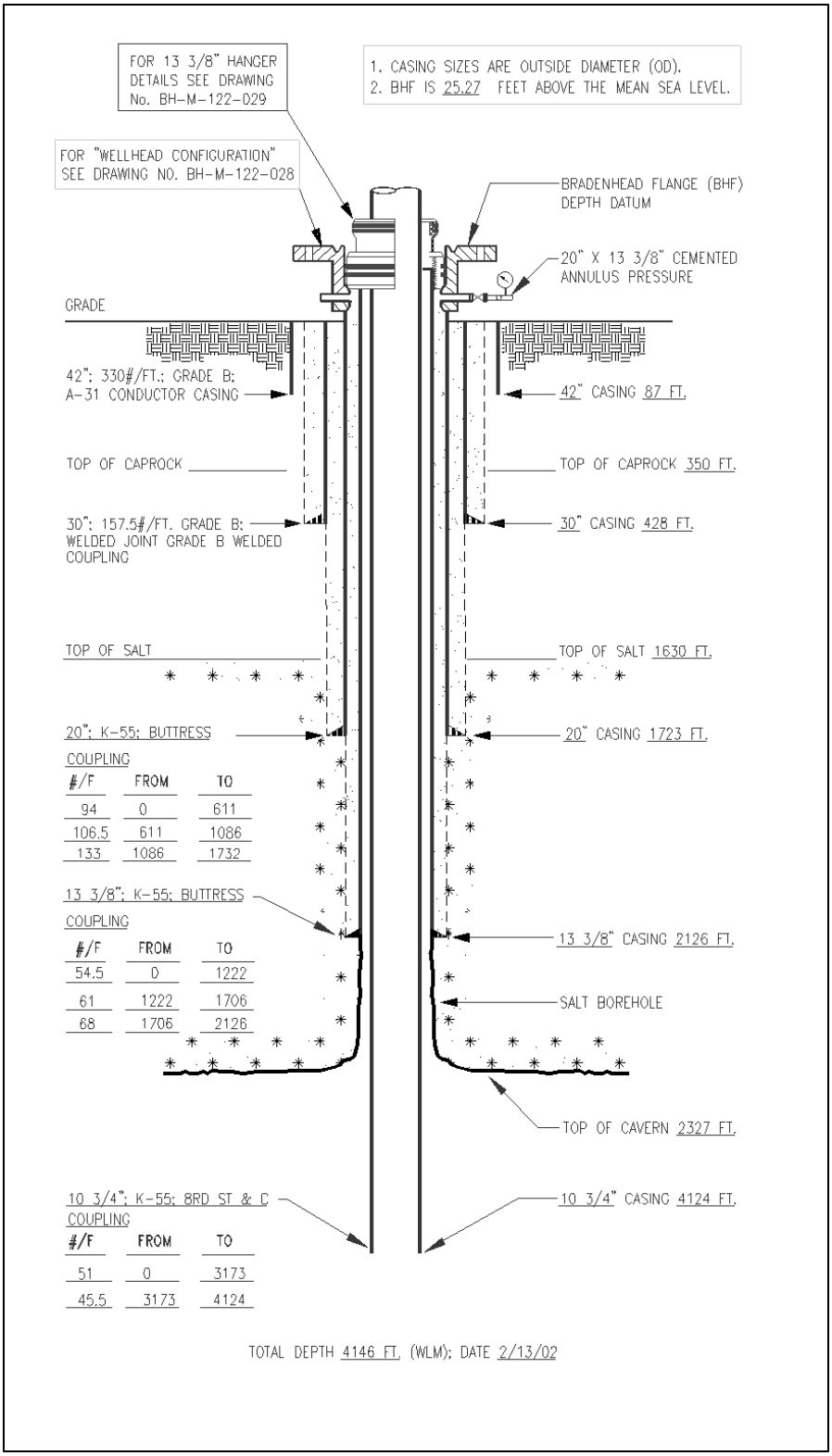

Figure 2-4. Well Configuration for BH114B, Dated 2/13/2002.

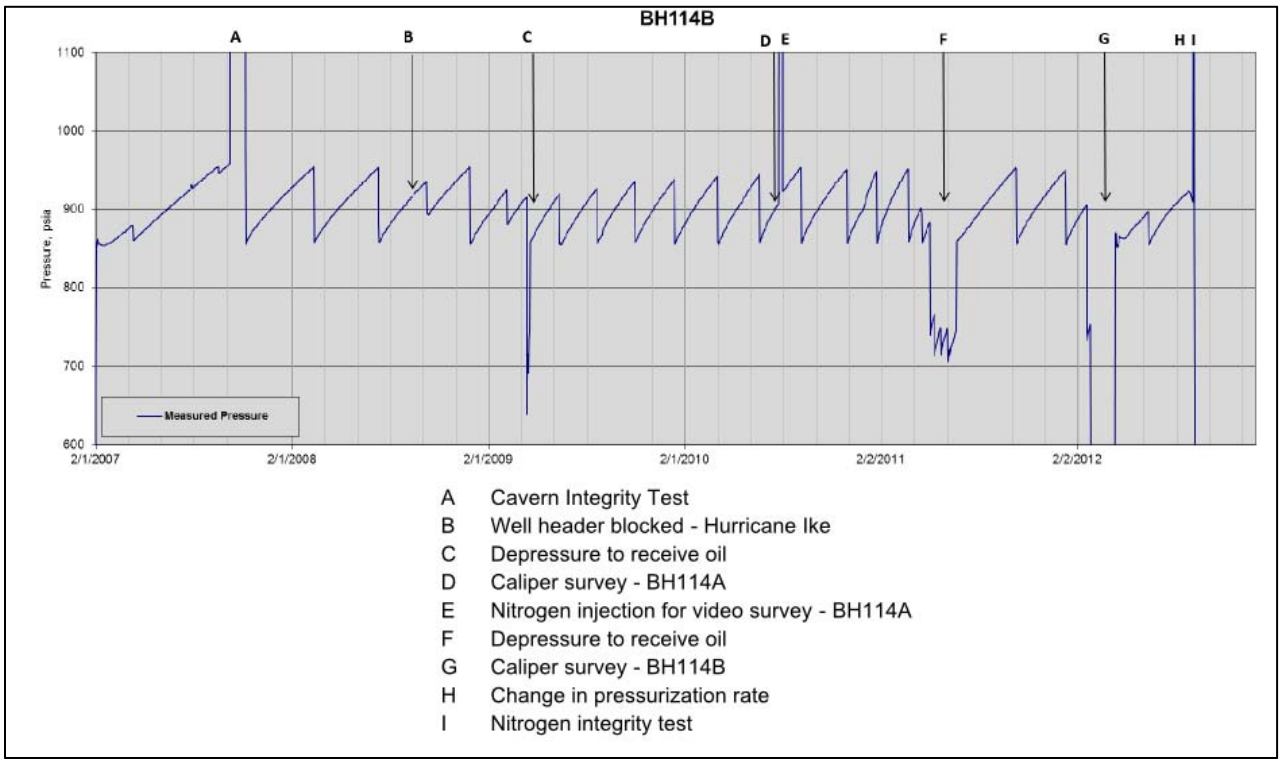

Figure 2-5. Recent Well Pressure History with Events for BH114B.

2.2.2 Nitrogen Injection Tests, September 5, 2012

Big Hill site personnel conducted a pair of special nitrogen injection tests on 9/5/2012 on the BH114A- and B-wells in order to confirm which well was leaking and also to approximate the leak depth. The wellheads were de-piped[1] and test manifolds[2] were installed. No wireline was used to measure interface depths; rather, they were approximated based on prior experience and calculations. Table 2-2 shows the test chronology for well BH114A with total metered N_2 injected (scf), measured wellhead pressure (psia), and estimated nitrogen-oil interface depth (ft). Nitrogen was injected incrementally over a 1 hour 50 minute period, pushing the interface down to about 1800 feet with pressure measured at P = 1467 psia. The well was shut in for an hour, and the pressure decreased by 43 psi to P = 1424 psia and remained stable for more than three hours when the test was concluded. The approximate depth associated with this pressure is between 1640 and 1660 ft. according to Table 2-2. Note the salt-caprock interface is listed in the 1985 depth reference chart (Figure 2-2) at 1630 ft.

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[1] De-piping entails isolating the wellhead from other surface piping by adding blind flanges. This assists the diagnostic process for isolating and identifying possible leak zones inside the well.

[2] Test manifolds allow the cavern engineer to connect the wellhead to a nitrogen source to facilitate nitrogen interface testing.

Table 2-2. Nitrogen Injection Data for BH114A on 9/5/2012, Showing Wellhead N_2 Pressure Stabilization at 1424 Psia, Which Indicates a Leak Region Around 1640-1660 ft. Deep.

NITROGEN INJECTION DATA

DATE 9/5/12 WELL NO. 114A

SITE BIG HILL NITROGEN QUANTITIES IN SCF

TIME	N2/OIL I/F	INCR N2	TOTAL N2	N2 PRESSURE	BRINE PRESSURE	REMARKS
950	0	0	0	904		BEGAN INJECTION (B WELL OIL @910 PSIG, B WELL BRINE @263 PSIG)
1000	100	3153	3153	923		SHUT-IN FOR 3 MINUTES TO MONITOR PRESSURE FOR STABILIZATION
1015		26347	29500	1060		FIFTEEN MINUTE READING
1030		27500	57000	1177		FIFTEEN MINUTE READING
1045	1200	30000	87000	1285		BEGAN TRACKING I/F USING PRESSURES
1050	1300	10000	97000	1316		
1055	1400	10000	107000	1346		SHUT-IN FOR 3 MINUTES TO MONITOR PRESSURE FOR STABILIZATION
1107	1500	10000	117000	1377		
1112	1600	10000	127000	1407		
1114	1620	2000	129000	1413		
1115	1640	2000	131000	1419		
1116	1660	2000	133000	1425		
1117	1680	2500	135500	1431		
1119	1700	3500	139000	1437		SHUT-IN FOR 10 MINUTES TO MONITOR PRESSURE
1132	1720	7500	146500	1443		
1136	1740	3500	150000	1449		
1137	1760	2500	152500	1455		
1139	1780	3000	155500	1461		
1140	1800	2700	158200	1467		FINAL READING; STOPPED INJECTION
1240				1424		LOST N2 PRESSURE WITHIN 1 HOUR AND STABILIZED
1600				1424		N2 PRESSURE STABLE; APPROXIMATION AT SALT/CAPROCK INTERFACE

The nitrogen injection procedure was repeated for BH114B, with data shown in Table 2-3. The pressure was raised to 1479 psia and remained stable, corresponding to an interface depth of approximately 1840 ft. The data imply that there is no leak in this well over the test interval.

As a whole, the special nitrogen injection test data indicate that the A-well will not hold pressure while the N_2-oil interface is below the top of salt. Note that prior published cavern integrity tests from 2002 and 2007 showed an ability to hold much higher pressures to over 1600 psia for several weeks (Table 2-1).

Table 2-3. Nitrogen Injection Data for BH114B on 9/5/2012. Wellhead N_2 Pressure Stabilized at 1479 Psia Indicating no Leak Above the N_2 – oil Interface Near 1840 ft.

NITROGEN INJECTION DATA

DATE 9/5/12 WELL NO. 114B

SITE BIG HILL NITROGEN QUANTITIES IN SCF

TIME	N2/OIL I/F	INCR N2	TOTAL N2	N2 PRESSURE	BRINE PRESSURE	REMARKS
1255	0	0	0	915	267	BEGAN INJECTION (A WELL OIL @1424 PSIG)
1257		1400	1400	940		SHUT-IN FOR 3 MINUTES TO MONITOR PRESSURE FOR STABILIZATION
1319	1200	21100	22500	1285		BEGAN TRACKING I/F USING PRESSURES
1321	1300	2500	25000	1316		
1323	1400	2500	27500	1346		SHUT-IN FOR 3 MINUTES TO MONITOR PRESSURE FOR STABILIZATION
1329	1500	2500	30000	1377		
1333	1600	2500	32500	1407		
1333	1620	750	33250	1413		
1334	1640	750	34000	1419		
1334	1660	400	34400	1425		
1335	1680	500	34900	1431		
1336	1700	600	35500	1437		SHUT-IN FOR 10 MINUTES TO MONITOR PRESSURE
1348	1720	600	36100	1443		
1348	1740	600	36700	1449		
1349	1760	600	37300	1455		
1349	1780	550	37850	1461		
1350	1800	450	38300	1467		
1352	1840	1100	39400	1479	268	FINAL READING; STOPPED INJECTION
1600				1479	268	N2 PRESSURE STABLE

2.3 Historical Perspective from BH105 Well Failure

In 2010 Ehgartner documented in a letter report (Ehgartner 2010b) and in a corresponding presentation (Ehgartner 2010a) an analysis of a similar re-pressurization discrepancy as discussed in Section 0. The focus of the Ehgartner report was a re-pressurization discrepancy that occurred with cavern BH105. Using the difference between measured and expected wellhead pressures and cavern compressibility (bbl/psi), Ehgartner (2010b) estimated the volume of oil lost due to the leak. Note that expected wellhead pressure and cavern compressibility were estimated by CAVEMAN.

2.3.1 CAVEMAN Analysis of BH105

Figure 2-6 presents histories of measured (blue) and CAVEMAN predicted (pink) wellhead pressures for BH105 from 2006 through 2010 showing many re-pressurization cycles with very good agreement as shown by the blue line underlying the pink line for a majority of the data range. During the last shown pressurization cycle in 2010, measured pressure departed significantly from the predicted pressure indicating a leak that was growing in time.

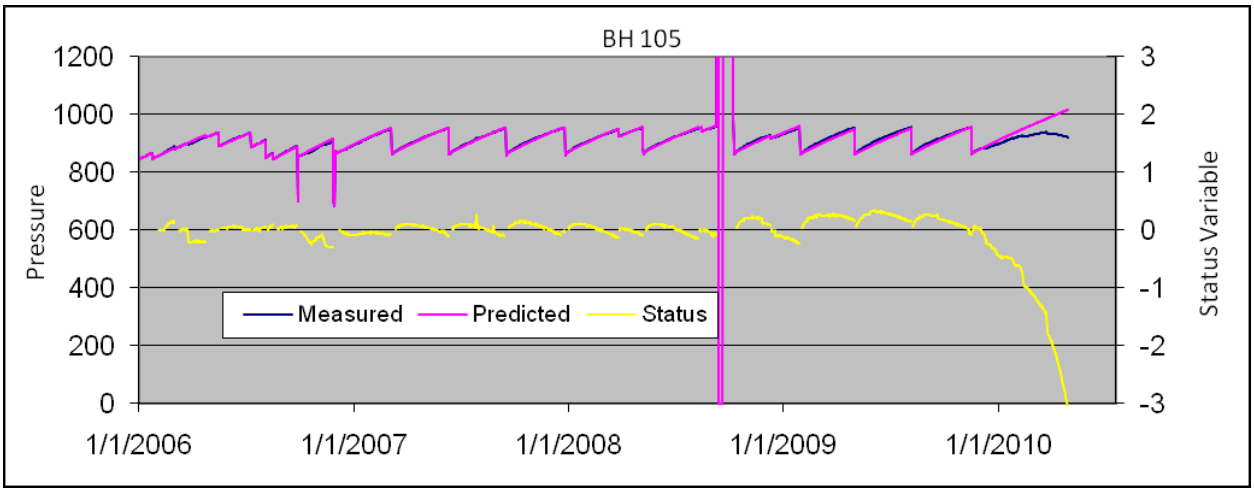


Figure 2-6. Measured and CAVEMAN-Predicted Pressure Histories for BH105, Reproduced from (Ehgartner 2010b).

Figure 2-7 displays the pressure difference (measured – predicted) for the last re-pressurization cycle in Figure 2-6. The leak appears to initiate in early December 2009, grows slowly until early February 2010, and accelerates through May 2012. Using a CAVEMAN estimated compressibility of 76 bbl/psi for BH105, a cumulative oil leak volume is estimated to be (113 psi) * (76 bbl/psi) ≈ 8600 bbls using the final pressure difference. Applying the compressibility to the pressure difference history yields the cumulative leak history shown in Figure 2-8. Differentiating the leak history with respect to time gives the leak rate history shown in Figure 2-9. Because of excessive noise in the calculated leak rate history, it is presented as a moving, 7-day average.

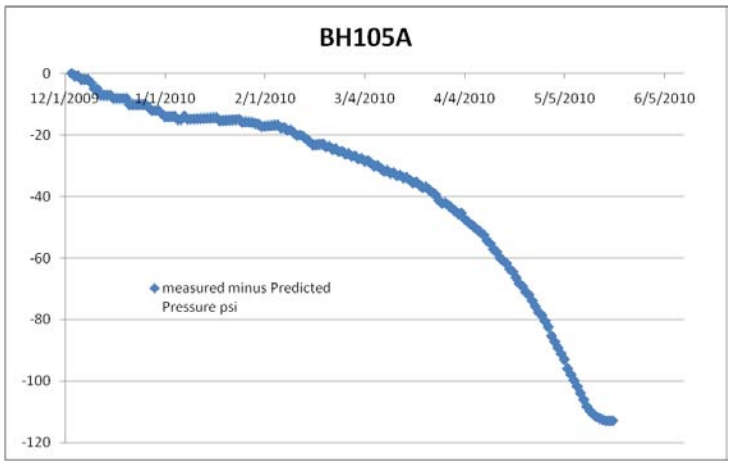


Figure 2-7. Difference Between Measured and Predicted Pressure for Last Re-Pressurization Cycle, Reproduced from Ehgartner (2010b).

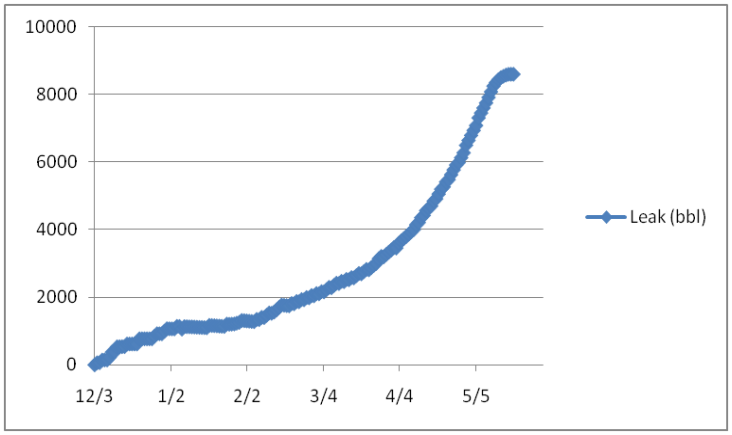


Figure 2-8. Cumulative Leak Volume History, Reproduced from Ehgartner (2010b).

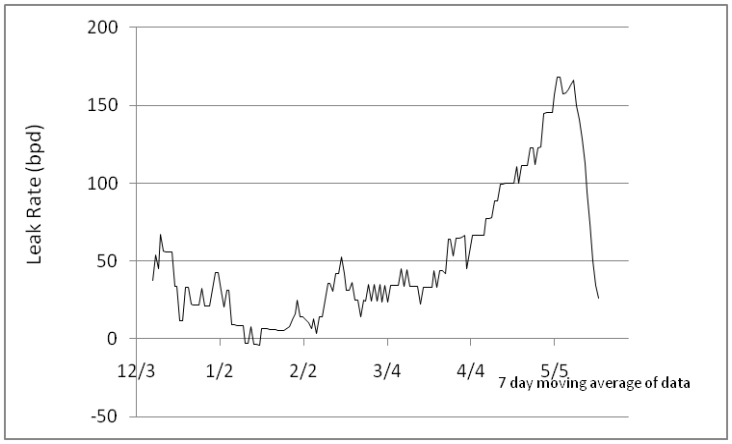


Figure 2-9. Estimated Leak Rate History, Reproduced from Ehgartner (2010b).

2.3.2 Analysis of BH105 Pressure Data Assuming Linear Repressurization History

Ehgartner presented a slightly modified analysis in a MS PowerPoint presentation summarized in Figure 2-10, copied from his presentation. In this analysis, instead of using the CAVEMAN predicted pressure for the last pressurization cycle, he apparently[3] used a regression fit to the early time data (red), projected it forward in time (gray) and reduced the cumulative leak volume by the size of any fluid withdrawals occurring during the analysis period. The fluid withdrawals show up as instantaneous drops in the measured pressure history as annotated in the figure. The blue dashed line is an approximation to the original CAVEMAN history added by the authors. The new analysis resulted in a cumulative leak volume of 4907 bbls (57% of earlier estimate of 8600 bbls).

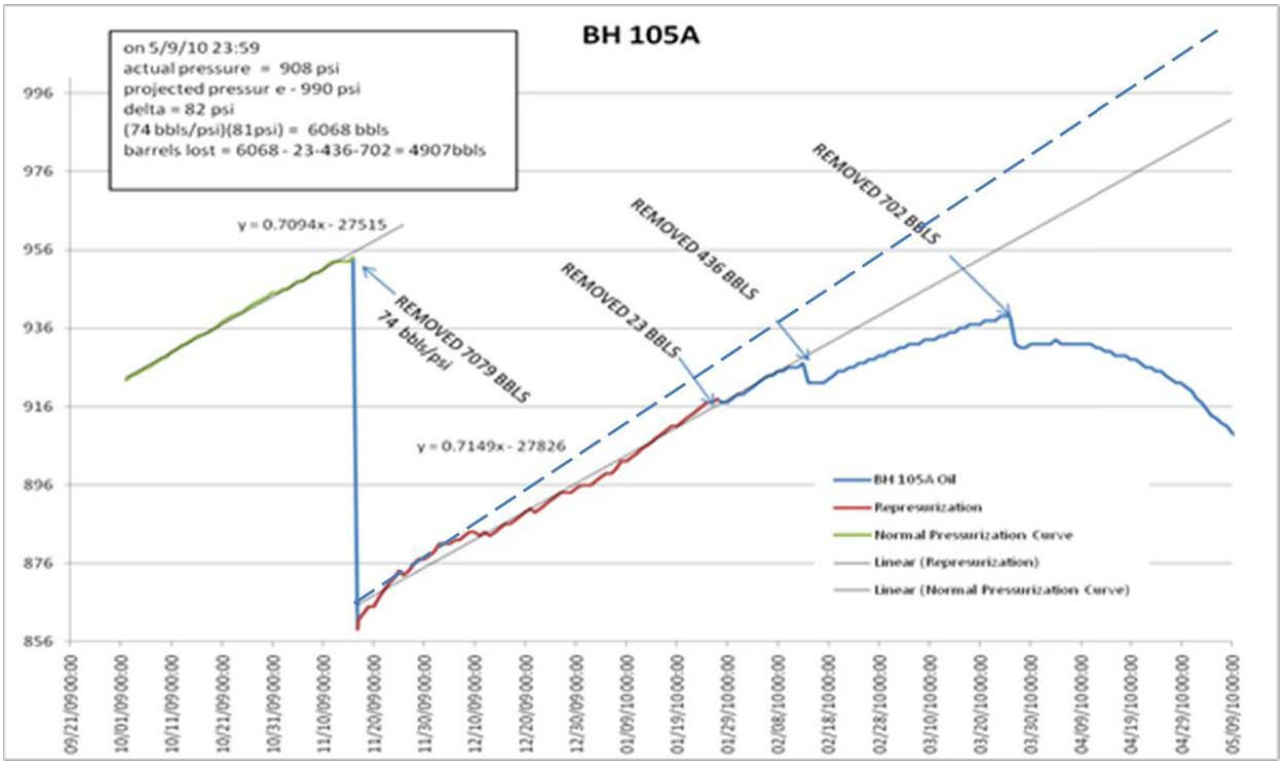


Figure 2-10. Pressure Histories and Results Summary, Reproduced from Ehgartner (2010a).

[3] The MS PowerPoint slides did not include any discussion, so the discussion presented herein represents the author's interpretation. Regardless of the interpretation, the new analysis resulted in a reduced estimate of the oil leak volume.

3 BH114 WELLHEAD PRESSURE ANALYSIS

Oil and brine wellhead pressures are automatically captured many times an hour by site operations, and a single representative value for each cavern is evaluated daily by the CAVEMAN application in order to detect leaks. These pressure data are also maintained in a database for follow-up analysis if necessary.

3.1 CAVEMAN Analysis

Figure 3-1 shows a comparison of measured and CAVEMAN predicted wellhead pressures for the period 2010 through 2012. CAVEMAN consistently over-predicted the re-pressurization rate significantly[4]. The saw-tooth behavior of the predicted pressure is due to the periodic resetting of the CAVEMAN "days-into-cycle" variable to zero, which causes the predicted pressure to equal the measured pressure for that day. Thus, using the CAVEMAN predicted pressure as the baseline will likely over estimate leakage. Again, the last re-pressurization cycle in Figure 3-1 contains the suspect re-pressurization cycle, which is hard to interpret in the figure. Figure 3-2 presents the last measured re-pressurization cycle overlaid with several of the earlier re-pressurization cycles (normalized to common pressure instead of days-into-cycle) and more clearly presents the deviation from historical behavior. The deviation appears to start around day 40 or mid July 2012.

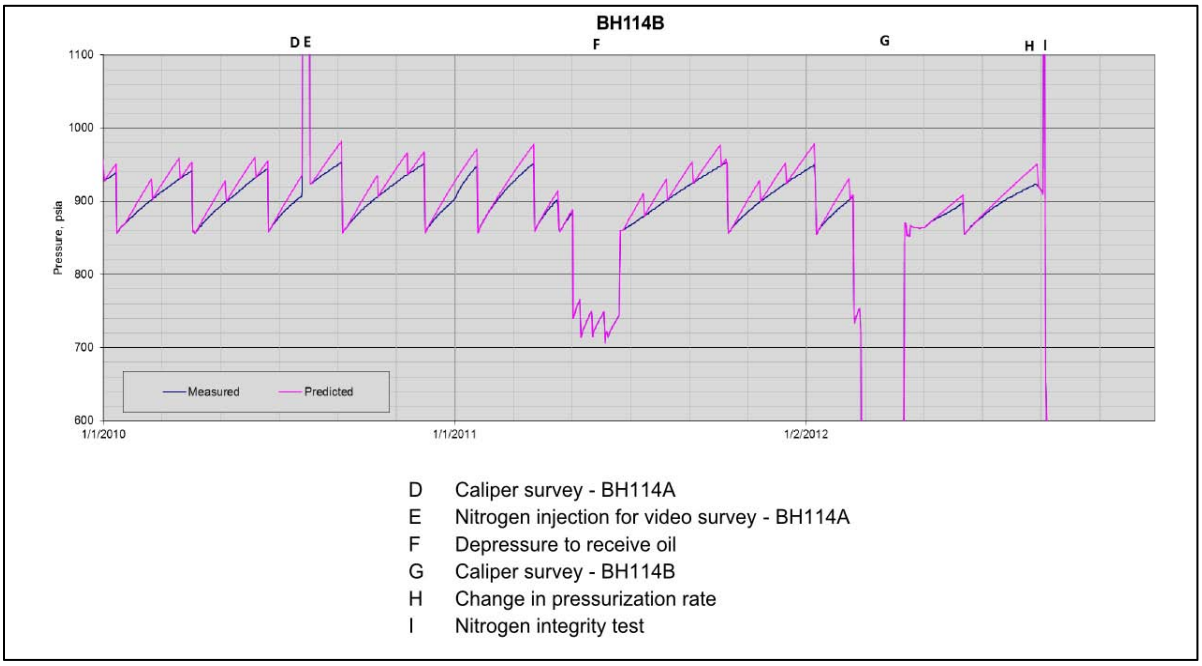


Figure 3-1. CAVEMAN-Generated Overlay of Measured and Predicted Pressure Histories for BH114.

[4] The poor CAVEMAN prediction appears to be due to the use of creep parameters determined prior to fill of BH114. Apparently, creep parameters from post-fill analyses reported in 2009 have not been implemented for any caverns. (Ehgartner, April 29, 2009. Subtask 1.3 Activity A4 Re-Optimization of CAVEMAN Parameters)

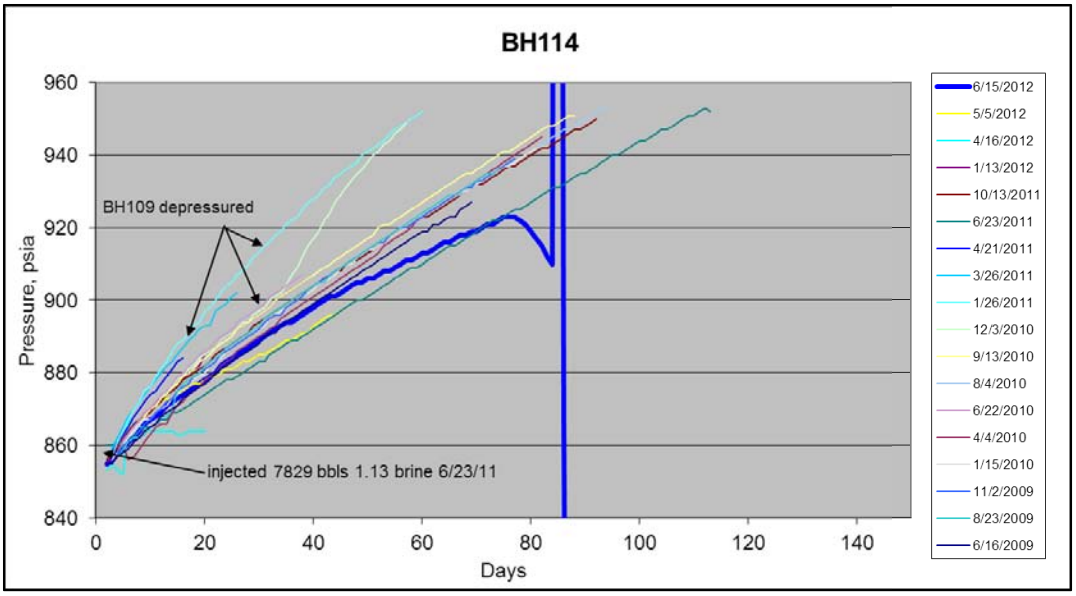


Figure 3-2. BH114 Cavern Re-Pressurization Histories. Bold blue line is most recent re-pressurization history showing significant deviation from historical (repeat of Figure 1-1).

3.2 Analysis of BH114 Pressure Data Assuming Linear Re-pressurization

Because the CAVEMAN predicted pressure history is suspect, a projection of a linear fit to data on either side of 7/13/2012 is used as the best-estimate behavior of the re-pressurization cycle. CAVEMAN predicted (purple), best-estimate (green) and measured (blue) pressure histories are overlaid in Figure 3-3. As in the BH105 analysis presented above, the total leaked oil volume can be estimated from the difference in final predicted and measured pressures and the overall compressibility of the cavern, which has been estimated by CAVEMAN at 74 bbls/psi. The resulting total leaked oil volumes are 2480 bbls for the Best-Estimate and 3560 bbls for the CAVEMAN-Predicted baseline re-pressurization rates. Cumulative volume histories are provided in Figure 3-4 and 7-day moving-average leak rates are provided in Figure 3-5. The data indicate a leak rate under 30 bbl/day from mid-July until late August when rates jumped to almost 200 bbls per day.

The actual start date of the leak is indeterminate and a function of the chosen "best estimate". However, based on the presented data, it is likely to be between mid-July and the first of August 2012. Regardless, more than 90% of the leakage occurred after August 1, 2012.

Sandia recommends proceeding with a best estimate of 2,480 bbl oil leaked from BH114A for this event. Note the cavern was rapidly depressurized after the nitrogen tests of September 5, and maintained at near zero wellhead pressure until the isolation workover at the end of September.

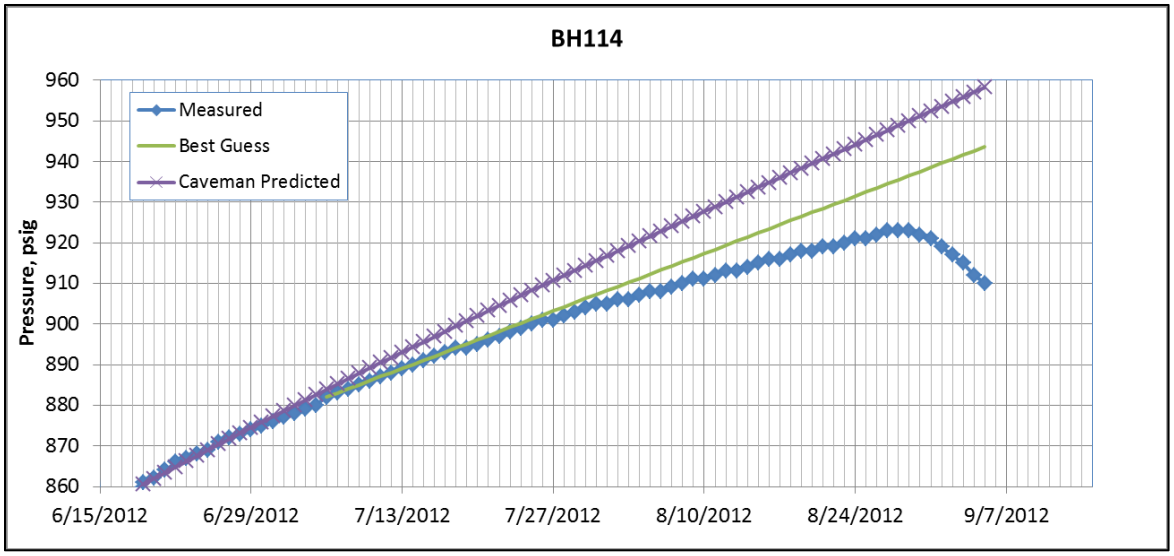


Figure 3-3. BH114 Re-Pressurization Histories.

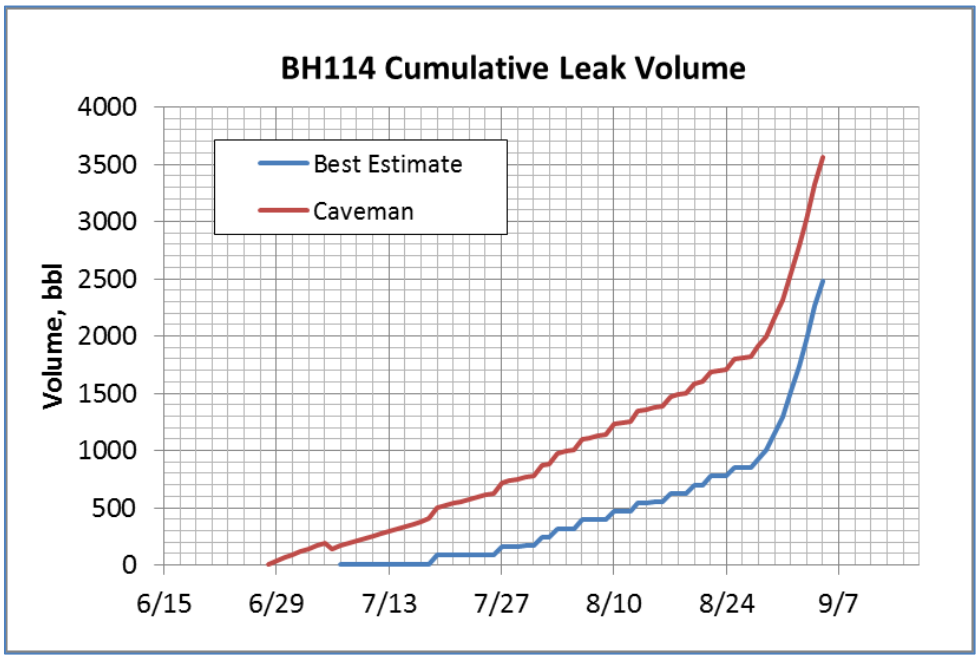


Figure 3-4. BH114 Cumulative Oil Leak Volume Histories.

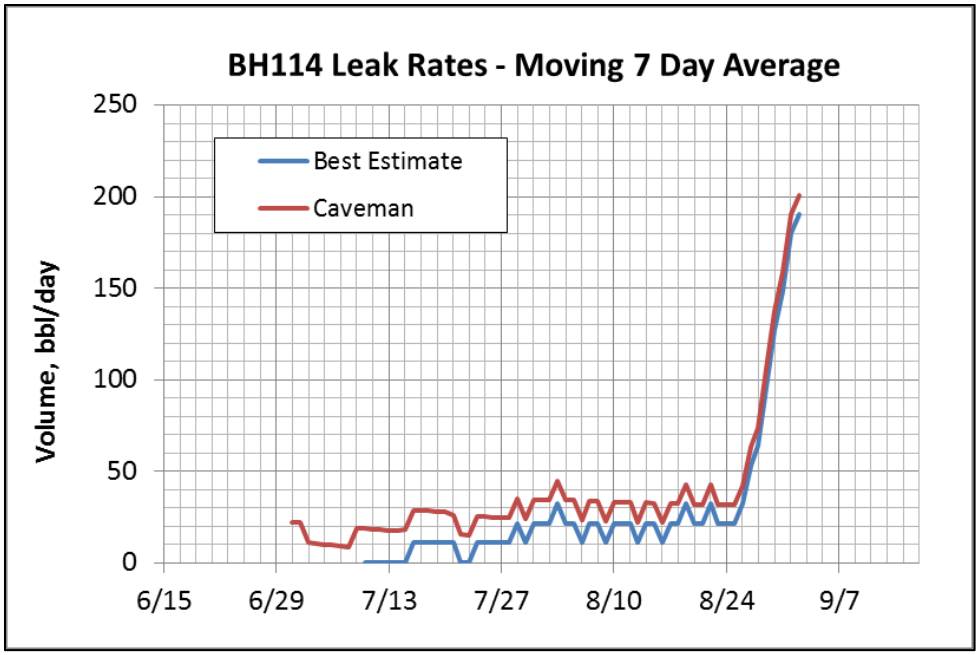


Figure 3-5. BH114 Oil Leak Rates, 7-Day Moving Average.

4 BH114 CASING INSPECTION

4.1 BH114A MSC and Camera Survey Results from 2010

Slick well BH114A was surveyed by multi-sensor caliper on July 14, 2010 (Cassidy 2010d), about 2 years prior to the appearance of pressure loss in the cemented casing. A follow-on camera survey was run on July 28, 2010, under a nitrogen cap. An area of major concern was identified by the MSC in the 1620-1630 ft. depth interval because the caliper fingers appeared to exceed the outside diameter of the casing. A representation of the raw arm data and the min, max, and avg. diameters obtained from the MSC run over this interval are shown in Figure 4-1. Recall the salt-caprock interface depth was near 1630 ft. according to the depth reference chart (Figure 2-2). The casing collar immediately above the area of concern can be seen right at 1590 ft. The collar immediately below the trouble area is at 1631 ft. according to the joint summary shown in Table 4-1. It appears that the damage occurred about 5 feet above the lower collar, and not necessarily at the collar itself.

An alternative perspective of the trouble zone is shown in radial plots of the arm data at selected depths. Figure 4-2 shows radial plots for 1624 and 1625 ft., where maximum deformation is observed. The blue perimeter represents arm data (radial magnification = 5), and the green circle represents the largest circular tool clearance diameter that will fit within this perimeter. The MSC data clearly indicated a casing deformation problem at about 1625 ft. depth, which is right at the salt-caprock interface.

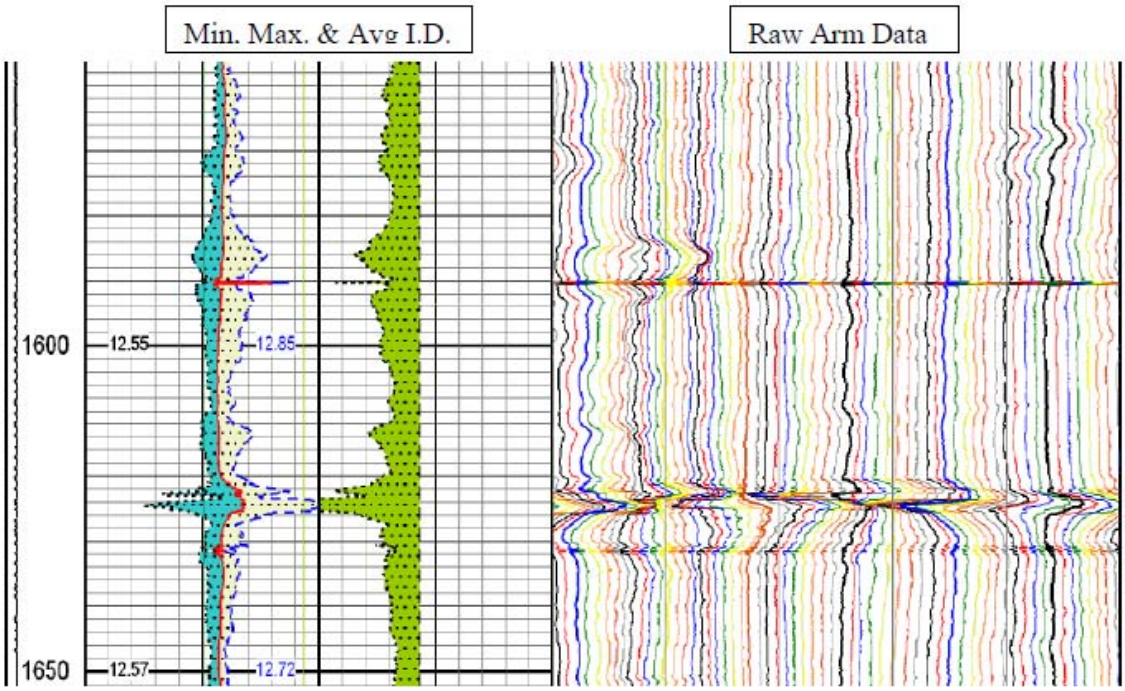


Figure 4-1. Raw arm MSC data along with min, max, and avg ID for BH114A well on July 14, 2010, over depth interval 1550-1650 ft., reproduced from (Cassidy 2010d).

Table 4-1. Joint summary table for BH114A, reproduced from Cassidy (2010d).

COMPANY DYN MCDERMOTT
WELL BH 114 A

JOINT			REMAINING WALL		
NO.	DEPTH	LENGTH	In	% LOSS	CODE
52	2081.0	29.1	0.49	-2.0	?
51	2038.4	42.6	0.33	31.4	2
50	1997.2	41.3	0.36	24.1	2
49	1957.5	39.7	0.32	33.8	2
48	1916.6	40.9	0.33	31.2	2
47	1875.3	41.3	0.36	24.7	2
46	1835.2	40.1	0.35	27.2	2
45	1793.8	41.3	0.34	28.6	2
44	1753.1	40.7	0.30	38.0	2
43	1712.4	39.7	0.36	24.9	2
42	1672.3	41.2	0.31	28.9	2
41	1631.0	41.3	0.28	36.0	2
40	1590.5	40.5	-0.13	123.5	P
39	1549.5	41.0	0.16	63.5	4
38	1508.1	41.4	0.30	30.8	2
37	1471.8	36.3	0.29	33.5	2
36	1430.1	41.7	0.31	29.0	2
35	1389.7	40.4	0.32	25.6	2
34	1349.5	40.2	0.32	24.6	2
33	1308.5	41.0	0.30	30.7	2
32	1268.0	40.5	0.31	27.4	2
31	1227.4	40.6	0.32	26.0	2
30	1186.2	41.2	0.26	39.8	2
29	1144.4	41.8	0.25	34.3	2
28	1102.1	42.2	0.24	37.1	2

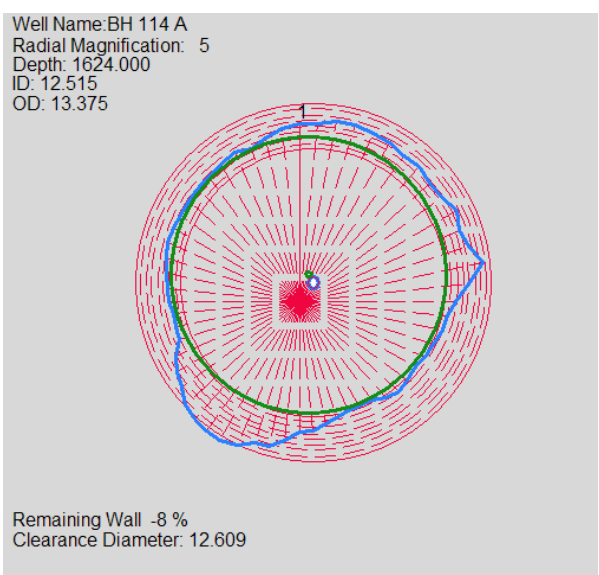
JOINT			REMAINING WALL		
NO.	DEPTH	LENGTH	In	% LOSS	CODE
27	1060.2	41.9	0.27	27.8	2
26	1018.8	41.4	0.25	33.5	2
25	977.8	41.0	0.26	31.3	2
24	936.1	41.7	0.27	30.1	2
23	893.8	42.3	0.29	24.5	2
22	853.7	40.1	0.30	21.9	2
21	819.6	34.1	0.28	28.6	2
20	780.3	39.6	0.27	29.6	2
19	742.6	38.3	0.28	25.8	2
18	703.7	39.0	0.28	26.3	2
17	661.4	42.2	0.28	26.2	2
16	622.7	38.7	0.29	23.3	2
15	580.3	42.4	0.28	26.0	2
14	538.4	41.9	0.29	24.1	2
13	496.3	42.2	0.28	26.1	2
12	453.7	42.6	0.27	28.7	2
11	411.6	42.1	0.28	27.1	2
10	369.4	42.2	0.28	26.9	2
9	327.7	41.7	0.28	25.7	2
8	285.7	42.0	0.26	31.2	2
7	243.6	42.1	0.26	31.8	2
6	201.3	42.3	0.29	23.0	2
5	159.4	41.9	0.27	29.3	2
4	118.7	40.7	0.27	30.0	2
3	76.2	42.5	0.25	34.3	2

LOG DATE: 7/14/10 SHEET 1 OF 2

COMPANY DYN MCDERMOTT
WELL BH 114 A

JOINT			REMAINING WALL		
NO.	DEPTH	LENGTH	In	% LOSS	CODE
2	34.7	41.5	0.23	38.4	2
1	0.0	34.7	0.16	57.9	3

JOINT			REMAINING WALL		
NO.	DEPTH	LENGTH	In	% LOSS	CODE



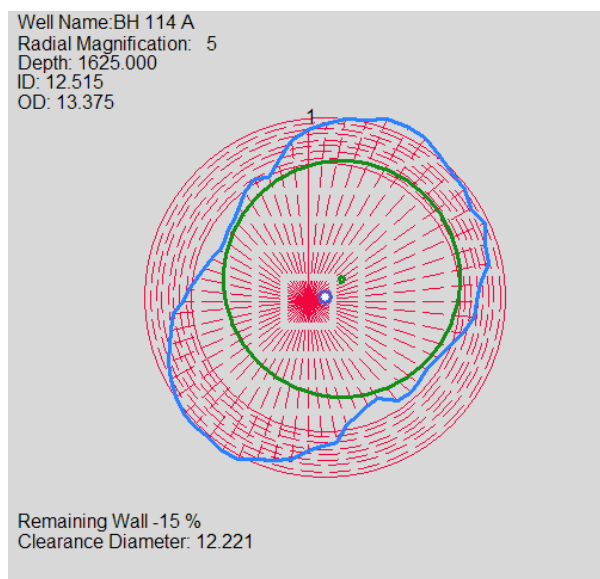


Figure 4-2. Radial plots of arm data at selected depths of 1624 and 1625 feet where maximum deformation is observed.

Camera survey images from July 28, 2010 are shown in Figure 4-3. Pitting is observed at several depths right in the zone of maximum radial deformation. No obvious casing breach can be seen from these images. Also note that the pressure history for this cavern did not show any conspicuously problematic behavior until August 2012, so it appears that the casing was deformed, but not hydraulically breached, at the time of the MSC and camera runs in July 2010.

As a result of the July 14, 2010 MSC, this well was designated by DM as category red 3, severe deformation, with deformation greater than the wall thickness of the casing.

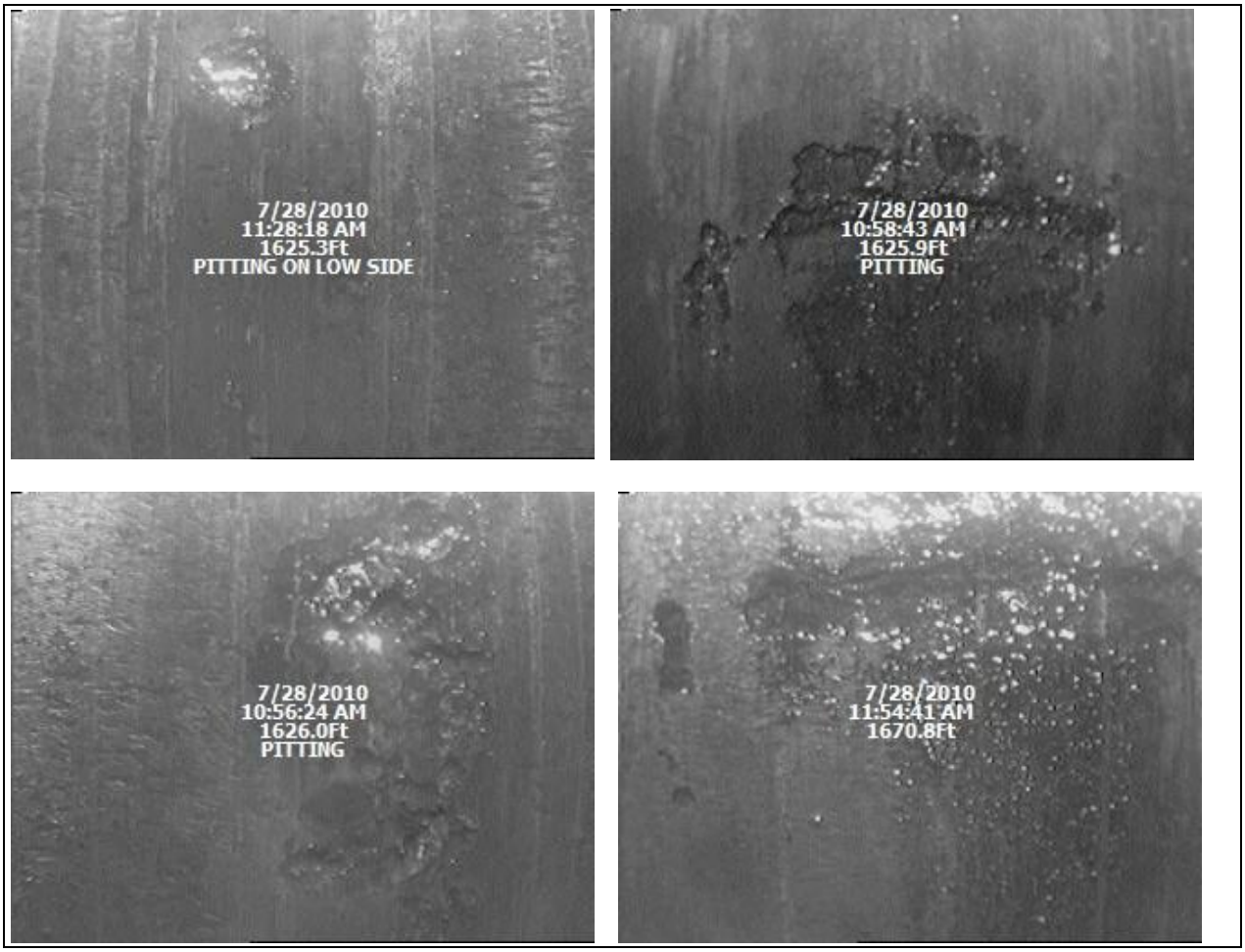


Figure 4-3. Camera images of BH114A slick well under nitrogen, taken on July 28, 2010. Pitting is noted at depths shown. No obvious casing breach is seen from these images.

4.2 BH114B MSC Results from 2012

BH114B was surveyed by multi-sensor caliper on March 22, 2012. The interpretation report by Cassidy (2012) stated that "significant external deformation has occurred at 1630 feet," which corresponds to the salt-caprock interface. A representation of the raw arm data and the min, max, and avg. diameters obtained from the MSC run over this interval are shown in Figure 4-4. Note the anomalies at 1630 feet. The associated joint table (Table 4-2) indicates that the deformation coincides with a collar at 1629.5 feet. As a result of the March 22, 2012 MSC, this well was designated by DM as category red 3, severe deformation, with deformation greater than the wall thickness of the casing.

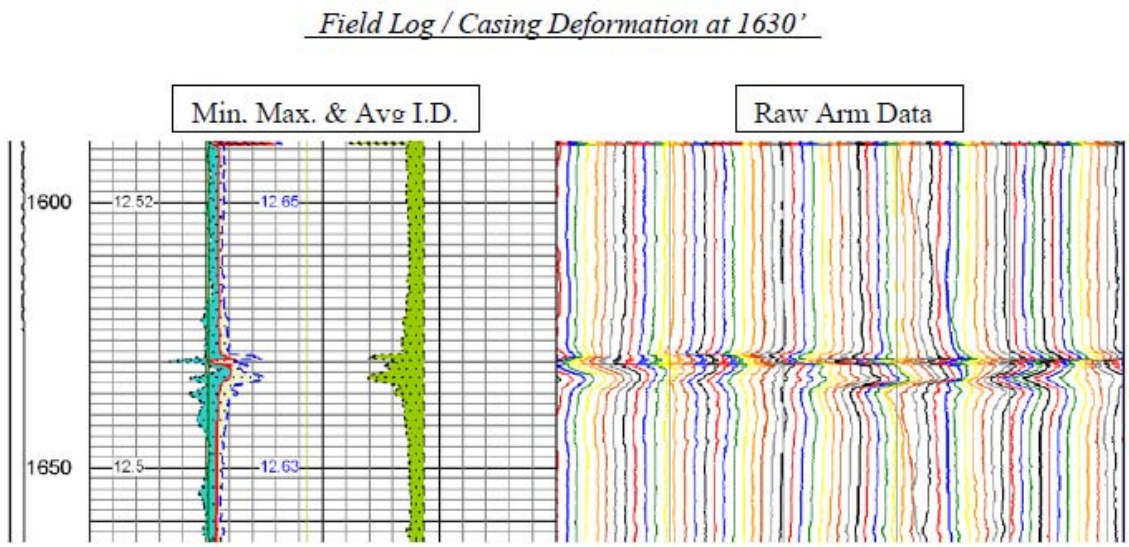


Figure 4-4. Raw are MSC data along with min, max and avg. ID for BH114B well on March 22.

Table 4-2. Joint summary table (joints 29-53) for BH114B, reproduced from (Cassidy 2012).

COMPANY DM PETROLEUM
WELL BH 114B

JOINT			REMAINING WALL		
NO.	DEPTH	LENGTH	in	% LOSS	CODE
53	2080.0	45.0	0.39	18.5	U
52	2037.5	42.5	0.38	21.5	2
51	1995.0	41.8	0.40	18.0	U
50	1954.2	41.7	0.38	21.6	2
49	1914.3	39.9	0.41	15.1	U
48	1873.3	41.0	0.37	22.5	2
47	1832.4	40.9	0.42	12.0	U
46	1792.0	40.4	0.38	20.6	2
45	1751.5	40.5	0.37	23.7	2
44	1710.8	40.7	0.38	20.7	2
43	1669.3	41.5	0.35	18.3	U
42	1629.5	39.8	0.19	56.9	3
41	1589.2	40.3	0.34	22.0	2
40	1547.9	41.3	0.35	17.9	U
39	1507.0	40.8	0.34	21.6	2
38	1466.7	40.4	0.33	22.8	2
37	1425.4	41.3	0.36	16.8	U
36	1384.7	40.8	0.36	16.9	U
35	1342.8	41.9	0.36	15.3	U
34	1306.7	36.1	0.35	19.3	U
33	1269.7	37.0	0.36	15.4	U
32	1227.8	41.9	0.36	16.7	U
31	1185.6	42.2	0.31	19.7	U
30	1151.9	33.7	0.31	18.2	U
29	1111.9	40.0	0.31	18.9	U

LOG DATE: 3/22/12

6 SANDIA GEOMECHANICS SIMULATIONS FOR WELL STRAIN

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, with a specific emphasis on BH114.

6.1 Big Hill Well Casing Damage

6.1.1 BH105 & 109 Deformation and Failure at Salt-Caprock Interface

Wellhead pressure monitoring of BH105 indicated that a fluid leak started around the beginning of December, 2009 (shown previously in Figure 2-7), and persisted for about 5 months until the cavern was de-pressured in May, 2010. Multi-sensor caliper surveys of the A-well on May 25 (Cassidy 2010a) and B-well on Jun 9 (Cassidy 2010b) revealed significant deformations in the cemented casings near the salt-caprock interface around 1630 ft. Graphical interpretations of the multi-arm caliper surveys taken in 2010 for both wells are shown in Figure 6-1. The leak was ultimately attributed to a mechanical failure in the B-well (Moore 2011).

Figure 6-1. Visualizations of Casing Deformations Interpreted from Multi-Arm Caliper Surveys of BH105A and B, reproduced from Cassidy (2010a) and Cassidy (2010b).

A similar pattern was seen for the BH109B, with significant deformation identified in the cemented casing around the salt-caprock interface near 1630 ft. based on a January 31, 2010 multi-arm caliper survey (see Figure 6-2). The caliper log indicates that the casing at the joint at the cross section at 1631 ft. has probably parted because the clearance diameter exceeds the casing diameter by 0.5 inches, much greater than typically seen at a joint. Loss of pressure integrity was identified from daily well monitoring data around the beginning of October 2010 and persisted for about 2.5 months until the cavern was de-pressured, and the leak was confirmed

by nitrogen testing in December, 2010 (Moore 2011). Sandia hypothesizes that the damage in both the BH105 and 109 well systems could have been caused by salt-caprock interface movement induced by cavern closure due to salt creep.

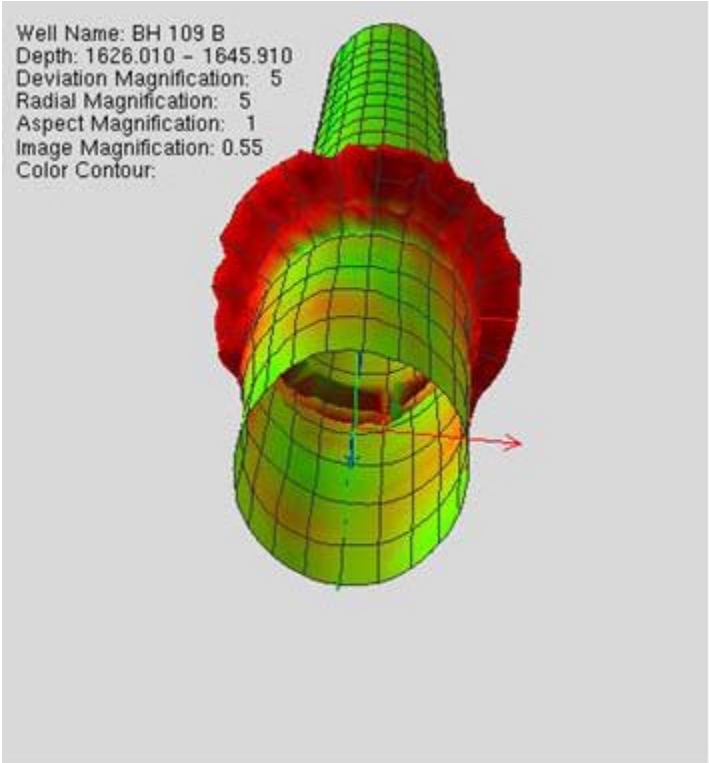


Figure 6-2. Visualization of Cemented Casing Deformation in BH109B Surveyed on January 31, 2010, Reproduced from Cassidy (2010c).

6.1.2 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 casing of BH105 and BH109 failed, respectively, from shear stress that exceeded shear strength 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.

6.1.3 Horizontal displacement at salt-caprock interface

The predicted direction and magnitude of relative horizontal movement at the top of salt, above the center of each cavern at simulated 2010 calendar year is shown in Figure 6-3 (reproduced from Park and Ehgartner (2012)). 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.

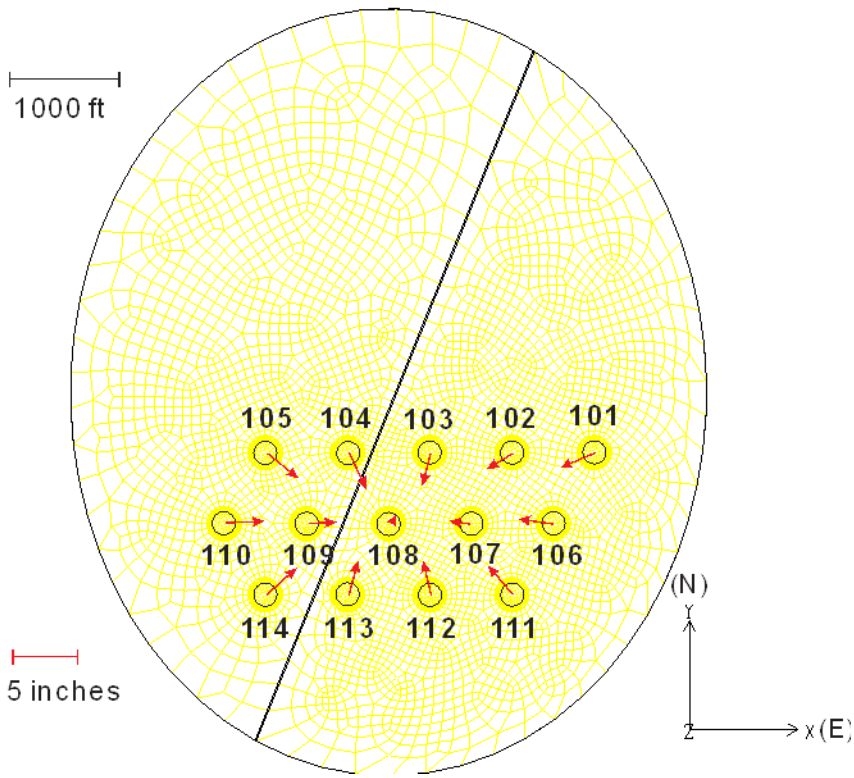


Figure 6-3. Predicted Direction and Magnitude of Horizontal Movement on the Salt Top Above the Center of Each Cavern at 2010 Calendar Year (reproduced from Park and Ehgartner (2012).

6.1.3.1 Vertical displacement at salt-caprock interface

Figure 6-4 shows the predicted vertical strain in the interface between caprock and salt dome above the center of each cavern at the 2010 calendar year. The strains above Caverns 107, 108, and 109 are larger than others. Actually, the casing of BH Well 109B failed at the joint (1630 ft. depth) and oil leaked. The cause of failure would be a tensile stress created by the downward movement of salt dome top. Caverns 101, 105, 110, 111 and 114 make up a majority of the outermost caverns. The horizontal node movement above Cavern 114 is predicted to be most, while the vertical strain is predicted to be relatively small.

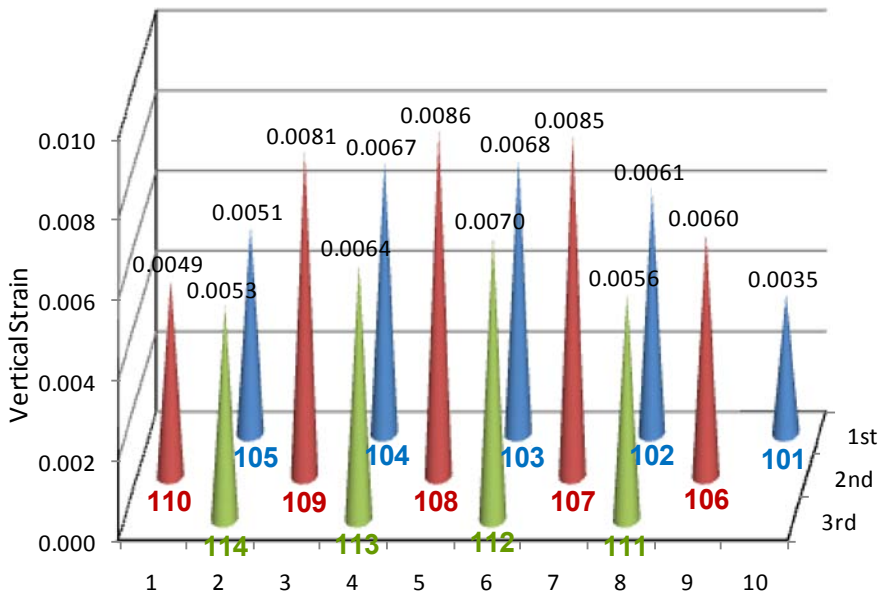


Figure 6-4. Predicted Vertical Strain in the Interface Between Caprock and Salt Dome Above the Center of Each Cavern at 2010 Calendar Year (reproduced from Park and Ehgartner (2012).

Figure 6-5 shows the predicted vertical strain as a function of time in the interface between salt dome and caprock above the center of each cavern. The well casing of BH109 failed due to excessive vertical strain at 20 years after the initial leach was completed (2010 calendar year). The vertical strain was predicted to be 8.1 millistrains when the well casing of BH109 failed at the joint. Therefore, 8.1 millistrains may be used as a vertical strain failure limit (dash line in Figure 6-5). Table 6-1 lists the predicted time when the well casing of each cavern is predicted to fail due to vertical strain using this 8.1-millistrain failure threshold.

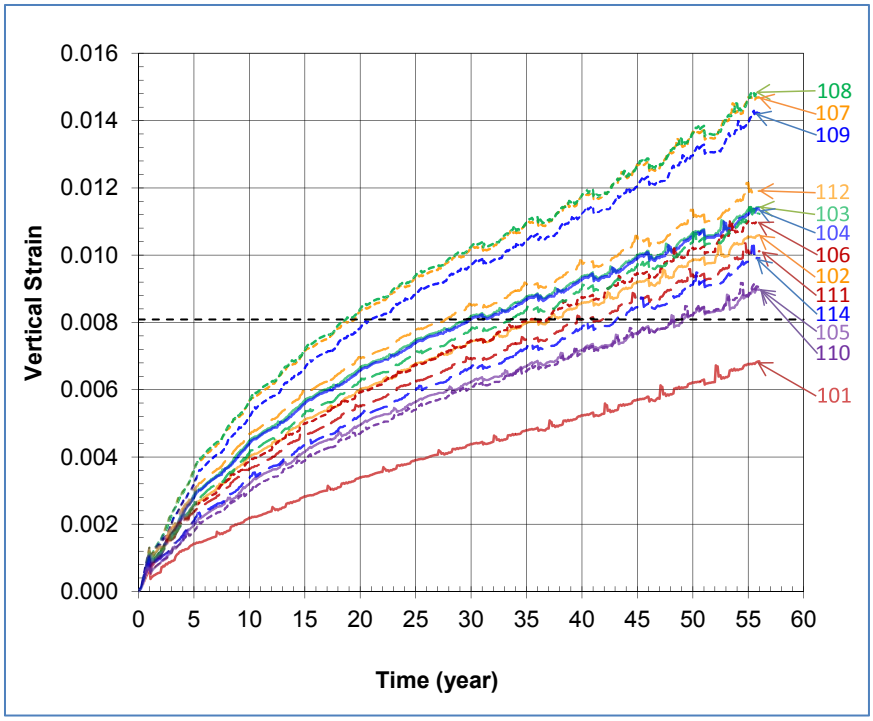


Figure 6-5. Predicted Vertical Strain in the Interface Between Caprock and Salt Dome Above the Center of Each Cavern.

Table 6-1. Predicted Well Casing Fail Date Due to Vertical Strain Using BH109B as Reference.

Cavern	Predicted Well Casing Fail Date		Remark
	Since initial leach (year)	Date	
101	> 56		Failure not predicted
102	36.08	Jan-2026	Failure not predicted without drawdown
103	28.67	Aug-2018	
104	29.08	Jan-2019	
105	47.08	Jan-2037	Failure not predicted without drawdown
106	34.00	Dec-2023	Failure not predicted without drawdown
107	18.58	Jul-2008	May fail in the near future
108	17.75	Sep-2007	May fail in the near future
109	20.00	**Dec-2009**	**Failed**
110	47.17	Feb-2037	Failure not predicted without drawdown
111	41.67	Aug-2031	Failure not predicted without drawdown
112	26.75	Sep-2016	
113	32.67	Aug-2022	Failure not predicted without drawdown
114	42.17	Feb-2032	Failure not predicted without drawdown

6.1.3.2 Shear failure from horizontal displacement

Figure 6-6 shows simulation results for the ratio of relative horizontal movement to vertical distance between salt dome top and caprock bottom above the center of each cavern over time. The well casing of BH105 failed due to shear displacement at 20 years after the initial leach (2010 calendar year). The ratio was calculated to be 0.19 when the well casing failed. Therefore, the ratio of 0.19 can be used as for an approximate shear displacement failure limit (dash line in Figure 6-6). If this criterion is applicable to all the wells, *the well casing of BH114 was also predicted to fail in the near term, which it did.* Figure 6-7 shows casing deformation for BH114A at the salt-caprock interface; compare to Figure 6-1. Table 6-2 lists the predicted time when the well casing of each cavern is predicted to fail due to shear displacement.

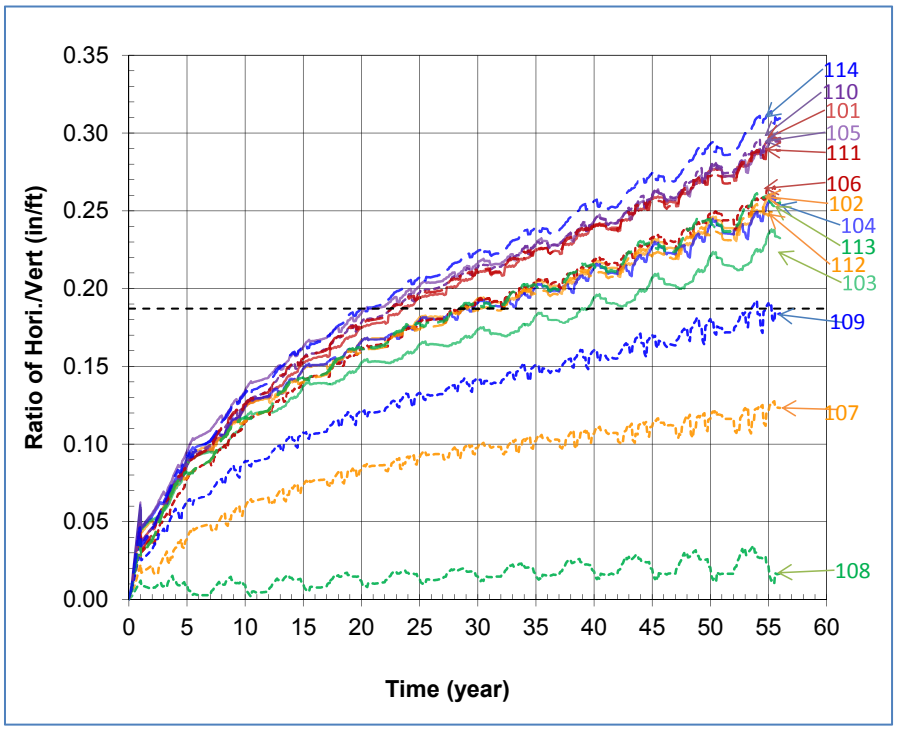


Figure 6-6. Relative Ratio of Horizontal Displacement to Vertical Distance Between Salt Dome Top and Caprock Bottom Above Center of Each Cavern.

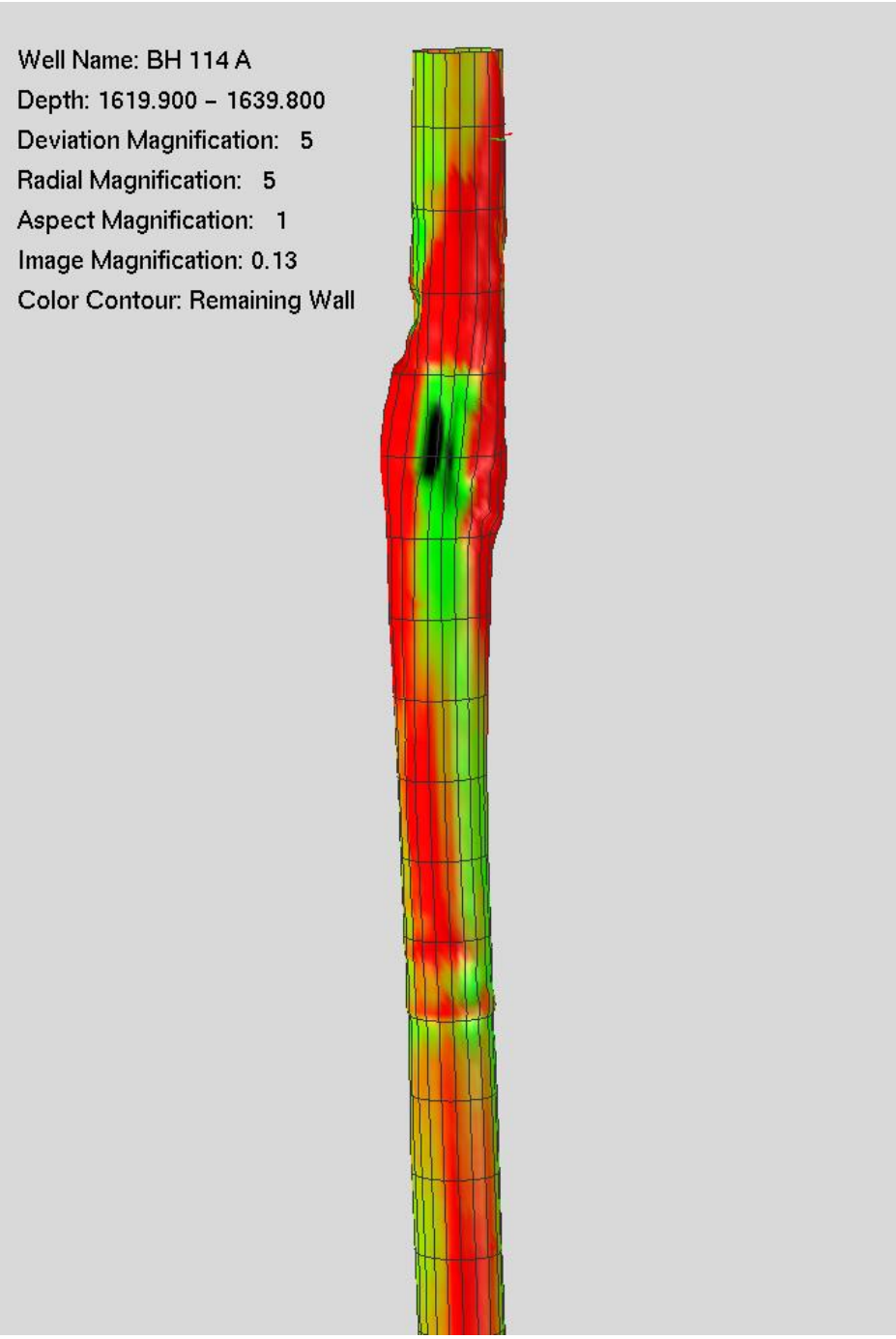


Figure 6-7. View of Casing Deformation at Salt-Caprock Interface for Well BH114A.

Table 6-2. Predicted Well Casing Fail Date Due to Shear Displacement.

BH Cavern	Predicted[a] Well Casing Fail Date		Remark
	Since initial leach (year)	Calendar date	
101	22.58	Jul-2012	May fail in near future
102	27.58	Jul-2017	
103	37.92	Nov-2027	Failure not predicted without drawdown
104	27.83	Oct-2017	
105	19.33	**Apr-2009**	**Failed**
106	27.58	Jul-2017	
107			Failure not predicted
108			Failure not predicted
109	52.58	Jul-2042	Failure not predicted without drawdown
110	21.58	Jul-2011	May fail in near future
111	21.50	Jun-2011	May fail in near future
112	27.83	Oct-2017	
113	27.50	Jun-2017	
114	19.00	**Dec-2008**	**Failed**

[a] - In this simulation, leaching due to periodic five year drawdowns starts at 31 years (2020 calendar year).

The causes of the damaged casing segments are a result of vertical and horizontal movements of the interface between the caprock and salt dome. The cavern volume closure due to salt creep produces movement between the salt top and caprock bottom. The displacement rates of the top and the bottom differ. This difference facilitates development of horizontal shear and vertical tensile stresses.

The nodes on the top of the salt layer move horizontally toward Cavern 108, which is located in the center of the fourteen caverns. The magnitudes of the horizontal movements above the outermost Caverns 101, 105, 110, 111 and 114 are larger than those of the other caverns. Using the horizontal displacement of the failed well of Cavern 105 as a failure criterion applicable to the other wells predicts that the well casings of Caverns 101, 110, 111 and 114 are in jeopardy of failing by shear stress in the near future.

On the other hand, the distances between nodes on the salt top and the caprock bottom above the center of each cavern increase over time. The increased distances above the inner Caverns 107, 108, and 109 are larger than others. Using the vertical displacement of the failed well of Cavern 109 as a failure criterion applicable to the other wells predicts that the well casings of Cavern 107 and 108 may be in imminent danger of failing by tensile stress due to excessive vertical strain.

6.2 Recommendations for Pressurization Schedule Prior to Remedial Workovers

The Sandia geomechanics team discussed the options of holding the cavern at zero wellhead pressure versus pressuring up to normal operating pressure once the plug is in place and holding there until the required depressurization for workover. BH114 is a normally-shaped cavern, so the only real concern about cavern stability due to a pressure change lies in the possibility of salt falls, and that is mostly dependent on the internal geometry of the cavern. Consensus was that added creep closure during the 6-8 weeks at zero pressure was more problematic than any geomechanical effects of a single pressure cycle on the generally stable BH114 cavern. Hence, Sandia recommends that the cavern be re-pressured to normal operating range (provided the temporary plug will safely allow) until the remediation workover begins (see Appendix A: BH114 Re-pressurization Memo).

7 DISCUSSION OF WELL MONITORING PRIORITIES FOR BIG HILL

Both DM and Sandia have separately developed grading systems for evaluating well integrity, and there is ongoing interest in merging these into a comprehensive approach that seeks to ideally prevent pressure failure and fluid loss from SPR cavern wells to the environment. Such an approach will require monitoring, evaluation, modeling, and mitigation components coupled with a high level of cooperation among DOE, the M&O contractor, Sandia, and the field services companies involved. Sandia sees a new comprehensive approach as a necessary goal for maintaining well integrity over the lifetime of the SPR.

7.1 Well Grading Approaches

The analysis of Big Hill well failures in this report provides an opportunity to begin a discussion on integrating the various approaches of well integrity grading in order to optimize well monitoring. Current approaches include:

1. DM casing inspection principles (from Wynn (2012)):
    a. Red: Needs remediation
        i. Red 1 – Failed or leaking borehole (pressure data, system is not hydraulically tight)
        ii. Red 2 – Failed state-required MIT (nitrogen test)
        iii. Red 3 – Severity of Deformation (ID deformation greater than wall thickness or deformation beyond OD of casing or the brine string cannot pass through the deformation) in stress induced areas (salt cap interface, sulfur lens, above caprock)
    b. Yellow: Requires monitoring
        i. Showing signs of deformation in stress-induces areas but does not meet the Red 3 criteria. Re-survey on 5-year schedule.
    c. Green: Less frequent monitoring
        i. Very minor to no deformation. Should be monitored on a 10-year schedule.
2. Sandia casing deformation grading from MSC (from Sattler and Ehgartner (2011)):
    a. Sandia examined selected wellbore geometry variables that were processed from the multi-arm caliper surveys, namely shear, strain, and ovality.
    b. A color grading system was built based on ranges of the selected variables

c.

KEY	range of shear		microstrains		ovality	
low	0	0.05	0	5	0	0.15
medium	0.05	0.1	5	10	0.15	0.3
high	0.1	0.15	10	20	0.3	0.5
very high	>0.3		>20		>.5	

d. The Sandia report did not specify actions based on their color-coding, though they did imply that the "high" and "very high" graded caverns should be on a "watch list".

3. CAVEMAN pressure history:
   a. Unexplained downward oil wellhead pressure deviations over several days
      i. Follow-up actions typically involve isolating wellhead from surface piping and running nitrogen test and possible MSC to diagnose leak. If leak is confirmed, remediation is required, and designation is Red 1.
4. Sandia geomechanics predictive modeling for wellstrain (Park and Ehgartner 2012):
   a. Sandia has generated predictions of horizontal and vertical deformation in the vicinity of the salt-caprock interface. Observed well failures in BH109, 105, and 114 have set expectations for critical ranges in the model, and caverns that show similar modeled well deformation to failed caverns are identified as high risk.

7.2 Comparison of Grading Results

Color maps showing grading results for the DM casing inspection workbook (Wynn 2012) and the Sandia analysis of the multi-arm caliper surveys are shown in Figure 7-1 and Figure 7-2, respectively. Differences are summarized in Table 7-1. Note that during Sandia's last evaluation of well monitoring priorities, not all the multi-arm caliper surveys had been completed, so there are wells which were not ranked. This is also true for the DM recommendations, but to a lesser degree.

In Table 7-1, differences between the DM and Sandia rankings are identified in the column labeled "Similarity". Only wells where both rankings were available were evaluated for differences. Since the Sandia rankings involved multiple criteria, a single, overall ranking was derived based from the original ranking data. The DM rankings were obtained from the most recent entries in the DM well integrity spreadsheet.

Of the 16 wells where the rankings could be compared, 6 differences in rankings were identified. In each case where there were differences between the two ranking techniques, the Sandia ranking indicated a higher priority. In five cases, the Sandia rankings indicated a "red" ranking, where the DM ranking indicated a lower priority. Although a significant number of differences in rankings were identified, a similarity in the rankings of the remaining wells (10) provides confidence in the ranking procedures.

As discussed above, there is an ongoing effort to merge these ranking techniques. These efforts should be augmented with the convening of appropriate parties to work through any ranking differences and move forward on the development of a common ranking procedure. In the meantime, it is recommended that the M&O contractor and Sandia revisit those wells where ranking differences were identified; particularly those which Sandia ranked as red but which were at a lower priority in the DM ranking.

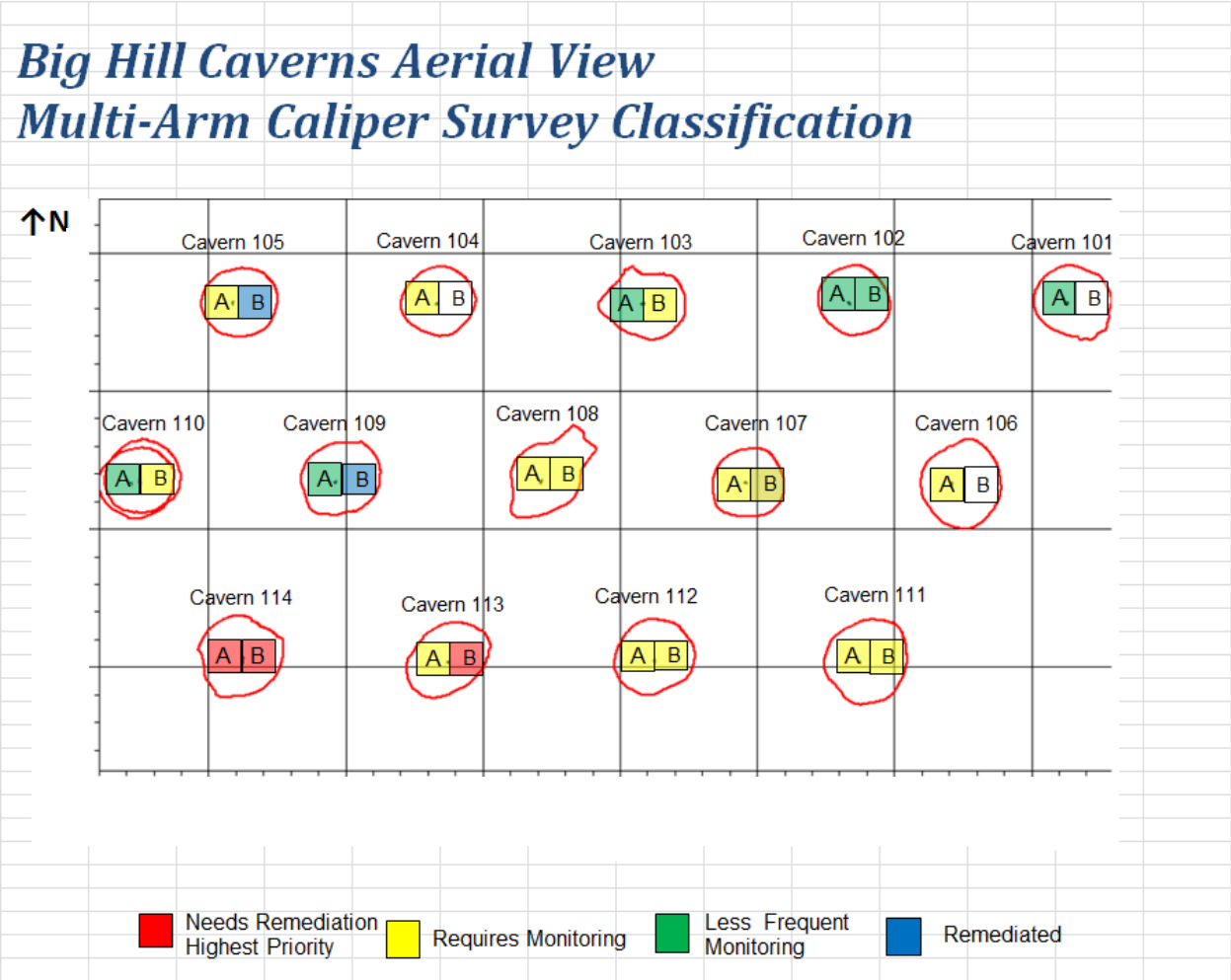


Figure 7-1. Map of DM Color-Coding for Well Integrity at the Big Hill Site, Reproduced from Wynn (2012).

Table 1. BH Shear, Strain and Ovality at the Salt/Caprock Interface Data from Weatherford Multi Arm Caliper

Well	105a	105b	104a		103a		102a		101
Horizontal displ., in	1.09	1.2	0.74		0.38		0.41		0.68
Vertical distance, ft	8.5	4	5.3		4.5		10		14
Shear, in/ft	0.13	0.3	0.14		0.08		0.04		0.05
Relative strain	med	very high	high		high		low		low
Micro-strains	8	>20	~, <12		7		0		3
Ovality, in	0.3	>0.5	0.2		0.1		0.1		0.1
Orientation, deg	12	-6	276		0		132		6
Well	110a		109a	109b	108a		107a		106a
Horizontal displ., in	0.12		0.44		0.44		0.49		0.9
Vertical distance, ft	3		5.5		5		7		7
Shear, in/ft	0.04		0.08		0.09		0.07		0.13
Relative strain	med		high		med		med		high
Micro-strains	4		15	12	6		5		11
Ovality, in	0.1		0.35	0.038	0.3		0.2		0.2
Orientation, deg	-18		-324		114		54		24
Well	114a		113a		112a		111a		
Horizontal displ., in	1.01		1.15		0.38		0.8		
Vertical distance, ft	11		9		8		9		
Shear, in/ft	0.09		0.13		0.05		0.09		
Relative strain	high		high		med		high		
Micro-strains	>20		18		7		8		
Ovality, in	>0.5		0.25		0.25		0.35		
Orientation, deg	138		180		246		162		

KEY

	Range of shear, in/ft		Micro-strains		Ovality, in	
	Min	Max	Min	Max	Min	Max
low	0	0.05	0	5	0	0.15
medium	0.05	0.1	5	10	0.15	0.3
high	0.1	0.15	10	20	0.3	0.5
very high	>0.3		>20		>.5	

Bold indicates failed well integrity (BH105b and 109b)

Figure 7-2. Map of Sandia Color-Coding for the Big Hill Site, After Sattler and Ehgartner (2011).

Table 7-1. Summary of Differences Between DM and Sandia Well Integrity Color Grading Maps.

Well ID	SNL Ranking	DM Ranking	Similarity
BH-101A	Green	Green	
BH-101 B		*(2016)*	
BH-102 A	Green	Green	
BH-102 B		Green	
BH-103 A	Yellow	Green	DIFFERENT
BH-103 B		Green	
BH-104 A	RED	Yellow	DIFFERENT
BH-104 B		*(2013)*	
BH-105 A	Yellow	Yellow	
BH-105 B	RED	Remediate	
BH-106 A	RED	Yellow	DIFFERENT
BH-106 B		*Yellow*	
BH-107 A	Yellow	Yellow	
BH-107 B		*Yellow*	
BH-108 A	Yellow	Yellow	
BH-108 B		*Yellow*	
BH-109 A	RED	Green	DIFFERENT
BH-109 B	RED	Remediate	
BH-110 A	Green	Green	
BH-110 B		Yellow	
BH-111 A	RED	Yellow	DIFFERENT
BH-111 B		Yellow	
BH-112 A	Yellow	Yellow	
BH-112 B		Yellow	
BH-113 A	RED	Yellow	DIFFERENT
BH-113 B		RED	
BH-114 A	RED	RED	
BH-114 B		RED	

7.3 Concept for Big Hill Well Integrity Grading Meeting

Given the findings in sections 7.1 and 7.2 above indicating the complexity of issues behind grading wells for monitoring and remediation, Sandia suggests that SPR convene a working group meeting to review, in detail, the available data and write a well integrity monitoring and mitigation plan for Big Hill based on the outcome of that meeting. A meeting concept is outlined here:

1. Purpose
    a. Develop a well integrity monitoring and mitigation plan for the Big Hill site and all current 28 cavern wells based on a joint working session.
2. Participants
    a. DOE representative
    b. DM cavern integrity and BH site cavern engineer
    c. SNL well integrity team
3. Venue
    a. Big Hill site
    b. At least one, maybe two days to complete meeting agenda
4. Protocol
    a. Review pertinent technical data for all 28 cavern wells at Big Hill site
    b. Reach consensus on monitoring and mitigation plan for <u>all 28 wells</u>
    c. Publish a joint working group report and submit to DOE on a schedule determined by the working group
5. Technical data considered (at a minimum)
    a. Geologic data
        i. Top of salt
        ii. Subsidence history
        iii. Spine and fault locations
        iv. Drilling records, focus on problems encountered
    b. Caliper surveys
        i. DM multi-arm caliper survey workbook
        ii. Surveys with visualization data
    c. Workovers
        i. Published workover plans and completion reports
    d. Mechanical Integrity Tests

    i. Published test reports from 2007 and 2012(?)
    ii. Include special nitrogen tests even if not official MIT

e. CAVEMAN pressure monitoring
    i. Measured wellhead pressure data
    ii. Model predictions and delta from measured
    iii. Implied creep rates

f. Cavern shapes
    i. Sonar surveys
        1. Implications on roof stability and well interactions

g. Sandia reports
    i. Ehgartner and Sattler caliper survey analyses
    ii. Park and Ehgartner Big Hill wellstrain modeling

h. DM reports
    i. Casing integrity reports by Moore

i. SMRI reports

The volume of technical data required to support this meeting will require some time and effort to compile. Sandia would like DM/DOE input on the completeness of the above list and will require some joint planning in order to gather, analyze and develop a data package that can be reviewed during the proposed working group meeting at Big Hill.

If successful, this template will be used to convene similar working group meetings at the other three SPR sites in FY13-14.

8 CONCLUSIONS AND RECOMMENDATIONS

Sandia conducted a review of the technical data pertaining to the BH114A well failure in summer, 2012, and summarized their findings in this report. Scope included review of well history reports, mechanical integrity tests, caliper surveys, wellhead pressure histories, and prior geomechanics simulations at the cavern and dome scales relevant to well strain and deformation.

Specific conclusions and recommendations follow:

1. Sandia concurs that the BH114A leak was likely due to a shear and/or tensile mechanical failure of the cemented string near the salt-caprock interface.
2. Sandia estimates that the fluid lost due to the mechanical failure of BH114A during the period July 16 - September 5, 2012, is about 2,480 bbl of oil.
3. After placing the isolation plug below the leak horizon in the A-well, Sandia recommends that the cavern be re-pressurized to its normal operating range while waiting for the start of the remedial workover in order to minimize creep. The phase II-III caverns are at more risk of problems due to cumulative creep closure over a period of weeks to months than from a single pressure cycle between workovers.
4. Numerous differences between the DM and Sandia color maps of well grading need to be addressed in detail, with all stakeholders coming to consensus on path forward.
5. The continued monitoring, analysis, modeling, and mitigation of the SPR cavern wells should be advised by a joint technical working group that includes expert technical representation from DOE, the M&O contractor (DM) and the geotechnical contractor (Sandia). The group should convene on a periodic basis, perhaps quarterly, to review new data, analyses, interpretations, and modeling results and pass formal advice up to management on recommended and required actions in presentations and reports as related to preserving well integrity.

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APPENDIX A: BH114 RE-PRESSURIZATION MEMO

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September 19, 2012
Recommendations for BH114 Re-pressurization prior to Remedial Workover

Sandia was asked during the September 17, 2012 weekly Cavern Workover Integrity Management Team Meeting what advice it could offer on cavern pressure maintenance for cavern BH 114 prior to a scheduled remedial workover for both A- and B-wells, estimated to commence in November, 2012. The current plan[1] outlined by DM is to de-pressure the cavern and install a plug in the A-well below the leak horizon in order to isolate the leak zone from the cavern oil. After that, a waiting period of 6-8 weeks is anticipated until all the components are available to start the remedial workover. The remedial workover will likely entail fitting both wells with 10 ¾" cemented liners and require about 3 months start to finish, assuming no new problems are discovered during the workover.

The Sandia geomechanics team discussed the options of holding the cavern at zero wellhead pressure versus pressuring up to normal operating pressure once the plug is in place and holding there until the required depressurization for workover. Consensus was that added creep closure during the 6-8 weeks at zero pressure was more problematic than any geomechanical effects of a single pressure cycle on the generally stable BH114 cavern. **Hence, Sandia recommends that the cavern be re-pressured to normal operating range (provided the temporary plug will safely allow) until the remediation workover begins.**

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[1] Letter to Mr. Douglas O. Johnson, Texas Railroad Commission, from Mark Erskine, DM Petroleum Operations Company, re: Status of Big Hill 114A, API#42-245-31614, dated September 6, 2012.

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