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Bryan Mound SPR Cavern 113 Remedial Leach Stage 1 Analysis

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Bryan Mound SPR Cavern 113 Remedial Leach Stage 1 Analysis

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Abstract

The U.S. Strategic Petroleum Reserve implemented the first stage of a leach plan in 2011-2012 to expand storage volume in the existing Bryan Mound 113 cavern from a starting volume of 7.4 million barrels (MMB) to its design volume of 11.2 MMB. The first stage was terminated several months earlier than expected in August, 2012, as the upper section of the leach zone expanded outward more quickly than design. The oil-brine interface was then re-positioned with the intent to resume leaching in the second stage configuration. This report evaluates the as-built configuration of the cavern at the end of the first stage, and recommends changes to the second stage plan in order to accommodate for the variance between the first stage plan and the as-built cavern. SANSMIC leach code simulations are presented and compared with sonar surveys in order to aid in the analysis and offer projections of likely outcomes from the revised plan for the second stage leach.

Acknowledgments

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Table of Contents

Figures

Tables

Nomenclature

BPD	– Barrels per day
BM	– Bryan Mound SPR site
EOT	– End of tubing (depth)
HS	– Hanging string (depth)
MB	– Thousand barrels
MBD	– Thousand barrels per day
MMB	– Million barrels
OBI	– Oil-brine interface depth
PMD	– Project Management Directive
Bottom-Inject	– A conventional leach where raw water is injected thru the lower of two strings. Formerly called direct leach.
Top-Inject	– A conventional leach where raw water is injected thru the higher of two strings. Formerly called reverse leach.

EXECUTIVE SUMMARY

The objective of the report is to present results of an analysis of the first stage of the remedial leach of Bryan Mound cavern 113 (BM113) and to compare results against the BM113 Leach Plan (Rudeen and Lord 2012). The Leach Plan called for leaching BM113 from its current volume of 7.4 MMB to its original design volume of 11.2 MMB in two stages – a top-inject leach (100 MBD for 225 days, 3.4 MMB leached) followed a bottom-inject leach (100 MBD for 56 days, 0.6 MMB leached).

On August 21, 2012, after ~95 days of leaching (~40% complete), raw water injection into BM113 was stopped in order to perform a sonar survey for assessing progress of the top-inject leach. This sonar survey data and a survey taken on 12/13/11 are the primary data sources for the analysis presented in this report.

Leach efficiency, defined as (leached volume)/(injected raw water volume), based on sonar data was greater than theoretical at ~20%. SANSMIC predicted leach efficiency was between 13 and 15%. The discrepancy between measured and predicted leached volume ranges from 500 MB to 700 MB. The implied error relative to cavern volume is 7-10% and the implied error in cavern radius is 3-5%. Analyses identified two primary sources of the discrepancy: (1) the presence of unsaturated brine in the cavern at the time of 12/13/11 sonar survey used as the initial geometry, and (2) since the 8/21/12 sonar survey was taken through a hanging string, a sound speed of saturated brine was assumed for the entire height of the cavern. Analysis of the earlier sonar survey indicated a variation in sound speed of ~3–4% from top to bottom. Thus, the error due to the sound speed assumption is on the order of the implied radius error. Bounding calculations using affected volume and a relative radius error give adjusted leach efficiencies between 14 and 18%, closer to historical values. The implied radius error was confirmed by the sonar survey operator who reported a 1 ft (in 45 ft) difference in the distance to the broken injection string between the 12/13/2011 sonar (without casing) and the 8/21/2012 sonar (with casing).

The conclusion of the analysis of the BM113 Stage 1 leach is that the leach proceeded much differently than planned (see Figure E-1), with more enhanced leaching in the upper quarter of the leached region than predicted by SANSMIC due to both modeling inaccuracies and deviations from the plan. The deviations from the plan included – OBI placement in the wide upper section of the cavern instead of below it, no oil fill to smooth the transition at the interface and loss of 370 ft of the injection string (at 3000 ft). The 8/21/12 sonar likely has a 2–4% error in radius (4–9% in volume) roughly in the region above the initial injection point at 3368 ft. Both the 12/13/11 and 8/21/12 sonar surveys were taken in a non-static cavern with significant leaching (>100 MB) occurring after the surveys. The final post-leach cavern geometry should be accurately known after leaching is completed, if the final sonar survey is taken either through the slick hole after the hanging string has been removed or it is delayed until the brine in the cavern is saturated.

Based on quick turnaround analysis of the 8/21/12 sonar survey, with concurrence by Sandia, the stage 1 top-inject leach was terminated early and repositioning of the OBI for the stage 2 bottom-inject leach was initiated. Strapping data collected during the repositioning confirmed that the 8/21/12 sonar slightly over estimated the radius just below the interface; however, the comparison improves with depth (and time). It should be noted that the strapping data were obtained weeks to months after leaching was stopped so they include some additional leaching from unsaturated brine present in the cavern at the time of the last survey.

The recommendation is to proceed with the Stage 2 bottom-inject leach with the following modified leach configuration:

- Reposition OBI from 2456 feet to 2700 feet
- Leave string positions as is (BM113A HS = 3950 ft, BM113B HS=3000 ft)
- Proceed with bottom-inject leach, (injection at 3950 ft brine production at 3000 ft)
- Raw water flow rate – same as stage 1, nominally 100 MBD
- Lengthen duration from original 56 days to 158 days to achieve original plan volume of 11.2 MMB (a factor ~3 longer due to early termination of stage 1)
- Monitor progress by performing sonar surveys at 30 days (3 MMB raw water injected) and if proceeding as planned, every 60 days thereafter.

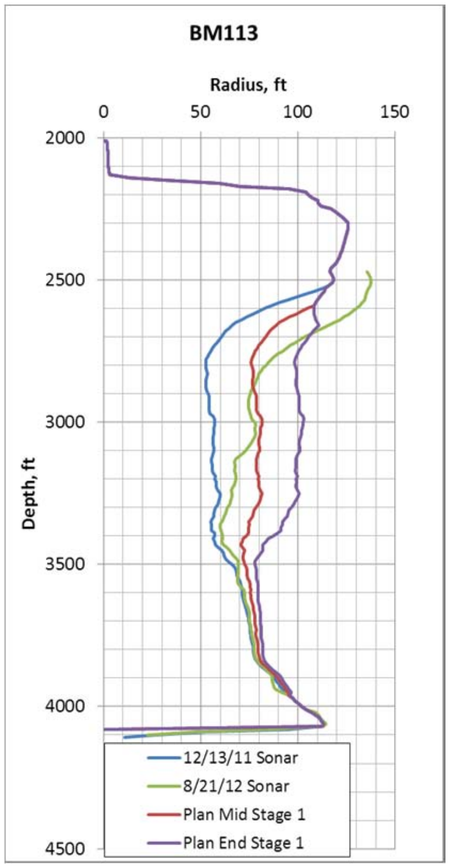

Figure E-1. Axisymmetric Average-Radius Cavern Profiles Plan vs. Sonar Survey.

1 OBJECTIVES

The objective of the report is to present results of an analysis of measured leach data generated during the first stage of the remedial leach of Bryan Mound cavern 113 (BM113) and to compare results against data published in the BM113 Leach Plan (Rudeen and Lord 2012). The plan was based on predictions generated by the Sandia-developed solution-mining code SANSMIC (Russo 1981). The plan called for leaching BM113 from its current volume of 7.4 MMB to its original design volume of 11.2 MMB in two stages – a top-inject leach (100 MBD for 225 days, 3.4 MMB leached) followed a bottom-inject leach (100 MBD for 56 days, 0.6 MMB leached).

On August 21, 2012, after ~95 days of leaching (~40% complete), raw water injection into BM113 was stopped in order to perform a sonar survey for assessing progress of the top-inject leach. Sonar survey data from 12/13/2012 and 8/21/2012 and raw water injections to this point in time were the primary data sources for the analysis. The intent of the analysis is to determine if the remedial leach is proceeding according to plan and to advise project management of any required changes to the plan or expectations.

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2 REVIEW OF LEACH PLAN

Table 2-1 provides a summary of Sandia's leach plan for completion of BM113 to 11.2 MMB (Rudeen and Lord 2012) and a summary of the actual leach implementation and performance as of the 8/21/2012 sonar survey. The Leach Plan provided SANSMIC predicted results for three possible scenarios: 100 MBD leach/fill (column 2), 24 MBD leach/fill (column 3) and a 100 MBD leach with incremental fill (column 4). In all three cases a top-inject leach string configuration was used in the first stage (raw water injection above brine production). A leach/fill scenario was recommended because it was used during the original cavern development – it avoids structurally unstable overhangs at the oil/brine interface and provides more customized leach control. Note that this report discusses only the first stage of two planned stages. The first stage was a top-inject leach focusing on the upper half of the cavern the second stage reversed the roles of the two hanging string and lowered the OBI creating a bottom-inject leach to develop the bottom half of the cavern. The actual leach was nominally at 100 MBD so the following comparisons are between columns 2 and 5 in Table 2-1.

Table 2-1. BM113 Leach Plan Versus Actual for the First Top-Inject Leach Stage.

	100 MBD	24 MBD	100 MBD with incremental fill	Actual as of 8/21/12
Top-Inject leach				
Injection depth, ft	3368	3368	3368	Start – 3368 End – 3000 (broken string)
Production depth, ft	3950	3950	3950	3950
OBI start depth, ft	2520	2520	2534	2460 est.
OBI end depth, ft	2655	2655	2633	2462 (from sonar)
Raw water rate, BPD	100,000	24,000	100,000	103,500
Raw water volume, MMB	22.500	22.488	22.500	9.80 or ~44% complete
Oil rate, BPD	4000	1000	3 fills of 225 MB at 56.25 day intervals	0
Oil volume, BBL	900,000	937,000	675,000	0
Leach Duration, days	225	937	4 stages of 56.25 days (225 days total)	95
Volume leached, MMB	3.409	3.619	3.420	2.0, ~59% of plan at completion and 50–60% higher than expected for actual duration.
Leach efficiency at stage completion	0.15	0.16	0.15	20%

The top-inject leach required that a 2nd hanging string be added to the cavern in BM113A to a depth of 3950 ft. for brine production. The original hanging string in BM113B, to be used for raw water injection, was set at 3368 ft., where it broke during the oil withdrawal used to position the OBI (see Appendix A). At the time of the 8/21/12 sonar, the end of the BM113A injection string was located at ~3000 ft. indicating a possible salt block fall and loss of an additional ~370 ft. of casing.

The plan recommended that the OBI be positioned at 2520-2534 ft. in the upper part of the transition region between the wide top and slender neck of the cavern in order to avoid increasing the maximum radius of the cavern. The OBI was measured on 3/7/2012 at 2456 ft. In late April, 19 MB of oil were added to the cavern and leaching began on 5/12/2012. Thus, the initial OBI was around 2460 ft. or at least 60 ft. higher than planned. The actual OBI was located in the wide part of cavern instead of in the upper transition region, which resulted in an increase in the cavern maximum radius by about 10 ft.

The average raw water injection rate was ~103.5 MBD for 95 days (maximum was 117.6 MDB) for a total injected volume of 9.8 MMB or about 44% of planned for the stage.

The plan called for oil fill at a constant rate of 1000-4000 BPD or incremental fills of 225 MBD at 56 day intervals. Actual leaching proceeded without any oil fill.

Difference in cavern volume below 2460 ft. between the 8/21/2012 and 12/13/2011 sonars was 2.0 MMB for a leach efficiency of 2.0/9.8 = 20%, which is above the theoretical value of 16% and well above the SANSMIC predicted efficiency of 13% for the actual period of leach. Note that at the completion of stage 1 SANSMIC predicted a leach efficiency of 15%. Historically, SANSMIC has predicted leach efficiencies fairly well.

3 SANSMIC SIMULATIONS

Results from two SAMSMIC simulations will be discussed below. The first is the prediction of the leach with continuous fill from the BM113 Leach Plan. The second is a new SANSMIC simulation that modeled the actual leach performance, which included average injection rates, actual duration, actual OBI and a string break half way through the leach. The timing of the string break was determined from a parameter study which modeled string breaks at ¼, ½ and ¾ of the way through the stage. Figure 3-1 provides a comparison of the two SANSMIC calculations - planned and as-built. In Figure 3-1 the innermost blue profile is the 12/13/11 sonar data used as the initial cavern geometry, the green and purple profiles are the planned profiles midway and at the end of the top-inject leach. The orange curve is the SANSMIC "as-built" at the time of the 8/21/11 sonar. Note in the figure that the cavern radius scale is exaggerated by a factor ~6. Comparisons of the green and orange curves are at roughly the same raw water injection, and thus volumes leached are similar. However, the as-built shows the effects of the OBI location moved from the transition region up into the bottom of the upper lobe; the lack of fill that would have smoothed the transition between the unleached and leached portions of cavern wall; and the reduced leaching between 3000 and 3500 ft because of the string shortening from 3368 to 3000 feet. Also apparent in the figure is that less than half of the planned leach volume has been created (area between orange and purple curves).

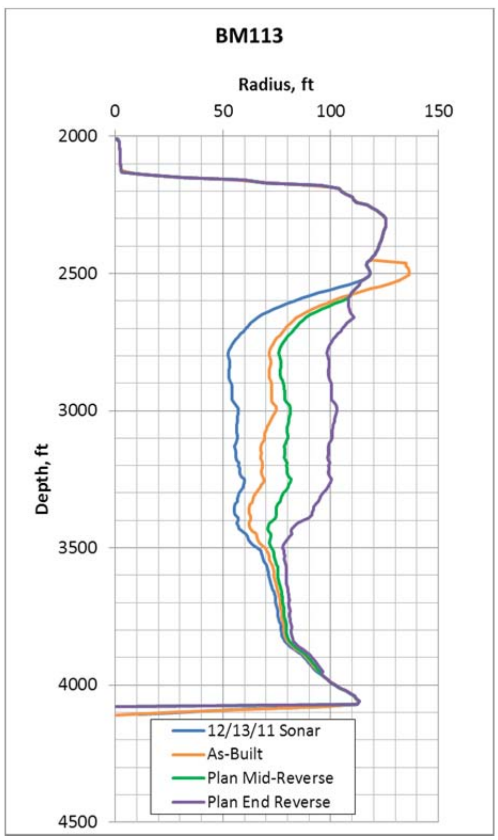
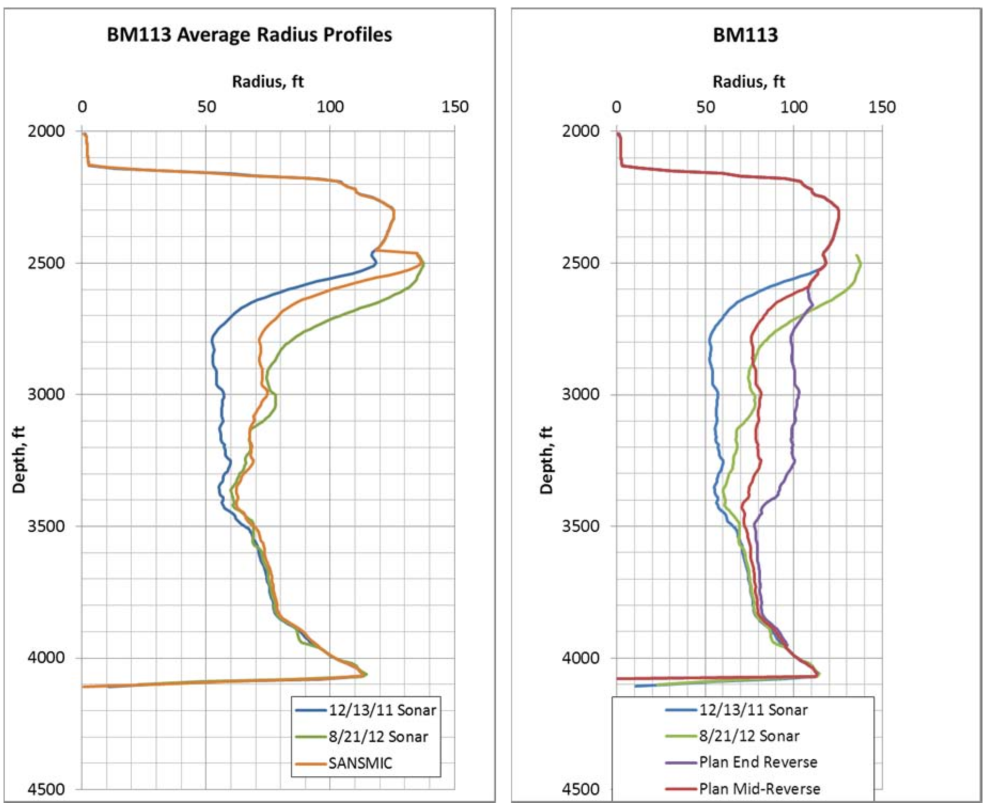


Figure 3-1. SANSMIC Predicted Axisymmetric Average-Radius Cavern Profiles for Planned and As-Built Simulations.

Figure 3-2a shows axisymmetric, average-radius comparisons of the sonar data from 12/13/2011(blue), 8/21/2012(green) and the SANSMIC as-built simulation (orange). The leaching was focused in the upper half of the cavern below the OBI=2456 ft. and tapers to zero near the bottom of the cavern. A large 15 ft. overhang is evident at the OBI for both SANSMIC and the 8/21/2012 sonar data. However, no sonar was taken in the oil above the OBI so the actual slope of the overhang is unknown. It is likely that the overhang was washed out to some degree or collapsed. Note also the large difference between SANSMIC and the 8/21/2012 sonar between 2600 and 2900 ft. The enhanced leaching in this region is probably real and indicates possible inaccuracies in the SANSMIC salt dissolution and plume models. However, the magnitude is likely influenced by both the broken string and whatever caused the enhanced leaching efficiency.

Figure 3-2b compares axisymmetric, average-radius profiles for the SANSMIC predicted planned leach and the results of the 8/21/12 sonar survey. Actual and planned differ significantly for the same reasons as the SANSMIC planned and as-built comparisons discussed above, but with enhanced leaching shown in the 8/21/12 sonar data between 2600 and 2900 ft.

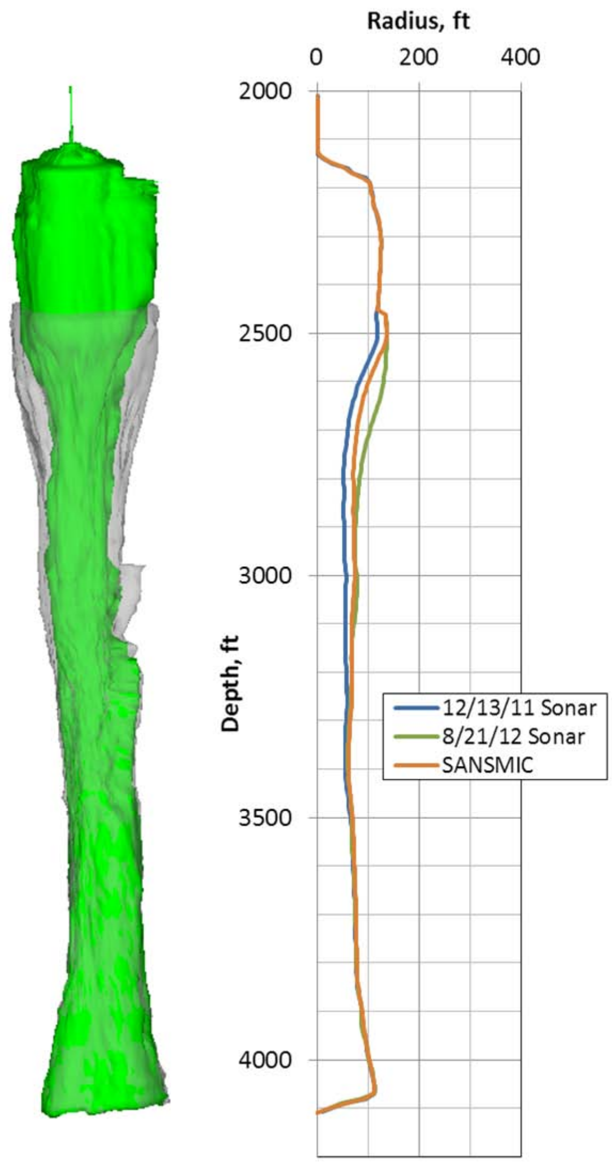


(a) SANSMIC As-Built vs. Sonar (b) SANSMIC Plan vs. Sonar

Figure 3-2. Axisymmetric Average-Radius Cavern Profiles.

3.1 3D Sonar Comparisons

A snapshot of a 3D overlay of the pre-leach (12/13/11) and mid-stage 1 (8/21/12) sonar data is provided in Figure 3-3a. The corresponding axisymmetric profiles are provided in Figure 3-3b. Visible in the figure are: the interface near 2500 ft (apparent overhang maybe exaggerated because no survey was performed in the oil); a region of enhanced salt dissolution between 2600 and 2900 ft; the extension of a spine on the right (NE) side of the cavern just below 3000 ft; and, very little leaching below 3300 ft. Examination of the full 3D plot shows relatively uniform leaching circumferentially, except at the spine.



(a) 3D Sonar (b) Axisymmetric

Figure 3-3. 3D and Axisymmetric Overlays of 12/13/11 (Pre-leach) and 8/21/12 (Mid-Stage 1) Sonar and SANSMIC Profiles.

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4 LEACH ANALYSIS

4.1 Leach Efficiencies

Parameters related to estimating leach efficiency are provided in Table 4-1. Leach efficiency, defined as (leached volume)/(injected raw water volume), based on sonar data is 2.02 MMB/9.8MMB = 0.20 (greater than theoretical value of ~0.16). SANSMIC predicted a leach volume of 1.29 MMB for the same raw water injection for a predicted leach efficiency of 1.29 MMB/9.8 MMB = 0.13. In order to bound the expected behavior, estimates assuming 15% efficiency are also included in the table. The discrepancy between sonar measured and predicted leach volume ranges from 500,000 to 700,000 BBL. The implied error relative to cavern volume is 7-10% and the implied error in cavern radius is 3-5%. The sonar operator estimated sonar error to be 1 ft for radii < 100' and 1% for radii > 100').

Table 4-1. Leach Efficiency Parameters.

Parameter	Value	Comment
Raw water injected, MMB	9.83	-
12/13/11 sonar volume below z=2462, MMB	4.88	-
8/21/12 sonar volume below OBI = 2462 ft, MMB	6.90	-
Leached Volume, MMB	2.0	-
Leach efficiency	20%	Exceeds theoretical maximum value ~0.16; Typical values are 13 to 15%
SANSMIC predicted leach Efficiency to this point	13% -15%	13% at time of sonar; 15% at end of stage
Predicted leach volume, MMB	1.29	1.29 to 1.47 MMB
Volume discrepancy, MB	700 – 500	At 13 and 15% efficiency, respectively
Implied sonar volume relative error	7–10%	About 300-500 BBL/ft
Implied sonar radius relative error	3–5%	Error when using local sound speed is 1% at 100.

The source of the larger than expected leach efficiency is in the raw water injection volume and/or the leached volume or, more specifically, one or more of the following:

- Raw water injection was underestimated (not likely)
- Unsaturated brine present in the system after the initial sonar (likely)
- Salt block fall or high volume of insolubles (not likely)
- Sonar error (most likely sound speed assumption)
- Non-halite salts (K^+) (not likely)

Each is addressed in detail below.

4.1.1 Raw Water Injection Estimates

The total raw water injected would have to be off by 3.3 to 5.4 MMB (0.5/0.15, 0.7/0.13, respectively) to account for the extra 500 to 700 MB of leached volume, which is highly unlikely.

4.1.2 Unsaturated Brine Present at Time of Initial Sonar

The 12/13/11 sonar used as the starting point for both sonar survey and SANSMIC analyses was taken very near the end of a withdrawal. Raw water injection was stopped and the sonar survey was performed the next day. This was followed by two more days of raw water injection. Therefore, at the time of the survey there was an unknown volume of unsaturated brine in the cavern and even more was added, implying that significant leaching took place after the sonar was taken and before raw water was injected for the top-inject leach that started 5 month later in May 2012. This leached volume would enhance the apparent leached volume and leach efficiency for the top-inject leach. SANSMIC calculations of the oil withdrawal in preparation for remedial leach, estimated the volume leached after the 12/13/11 sonar survey to be ~140,000 BBL.

The volume leached after the 12/13/11 sonar survey could equivalently been incorporated by including the post sonar injections and an “effective” raw water injection with a volume estimated from brine saturation present at the time of the sonar.

4.1.3 Salt Block Fall

Salt block fall cannot account for the excess *cavern volume* because any volume gained in the region of salt fall is lost at the bottom of the cavern where the block ends up (in saturated brine). However, salt fall or (high fraction of insolubles) can possibly account for the apparent leach enhancement in the transition region between 2500 and 2900 ft and can contribute to ullage volume by moving *unusable volume* located below the hanging string upward in the cavern. Evidence of salt block fall has been seen in earlier sonar data on several occasions. This evidence includes highly non-symmetrical leaching combined with an equivalent rise in the cavern floor which can be visualized by overlaying horizontal and/or vertical slices from consecutive sonars. A small rise (a few feet) in the cavern floor is expected even without salt block fall due to insolubles present in the halite salts, which are usually around 4% by volume.

Figure 4-1 shows a sequence of horizontal cross-sections of sonar data from 12/13/11 and 8/21/12 at depths, in feet, of 2462 (just below OBI), 2640 (maximum leach radius), 2900 (bottom of enhanced leach region) and 2990 (top of early salt block fall). Figure 4-1(a) and (b), containing cross-sections in the region of enhanced leaching, show relatively uniform leaching for all azimuths. Figure 4-1(c), bottom of the enhanced region, shows somewhat uniform leaching with some preferential leach in the ENE direction. In Figure 4-1(d) a large anomaly is apparent in the NE direction which is likely due to a salt block fall which appears to be propagating upward based on analysis of earlier sonars for BM113 (not shown). This missing “salt block” is not in the region of enhanced leaching and its volume is relatively small as evidenced by the only slight increase in cavern average radius at this depth.

Figure 4-2 provides a vertical slice of the sonar data from 12/13/11(green) and 8/21/12(red). As expected, the red line is outside the green line (within measurement error) on the sides of cavern due to leaching. The red line is located inside the green line at the center of the floor of the cavern due to accumulation of insolubles and possible salt block fall that does not dissolve in the saturated brine located at the a bottom of the cavern. Accumulation appears to be small. The blue dashed line located at ~4000 ft is located where the floor would be if the enhanced leaching was due to a 500 MB salt block fall.

Because of the uniformity of leaching in the region where most of the leaching occurred and the lack of a significant floor rise, the conclusion is that the enhanced leaching between 2500 and 2900 ft. is not due a large amount of salt block fall or unusual amount of insolubles.

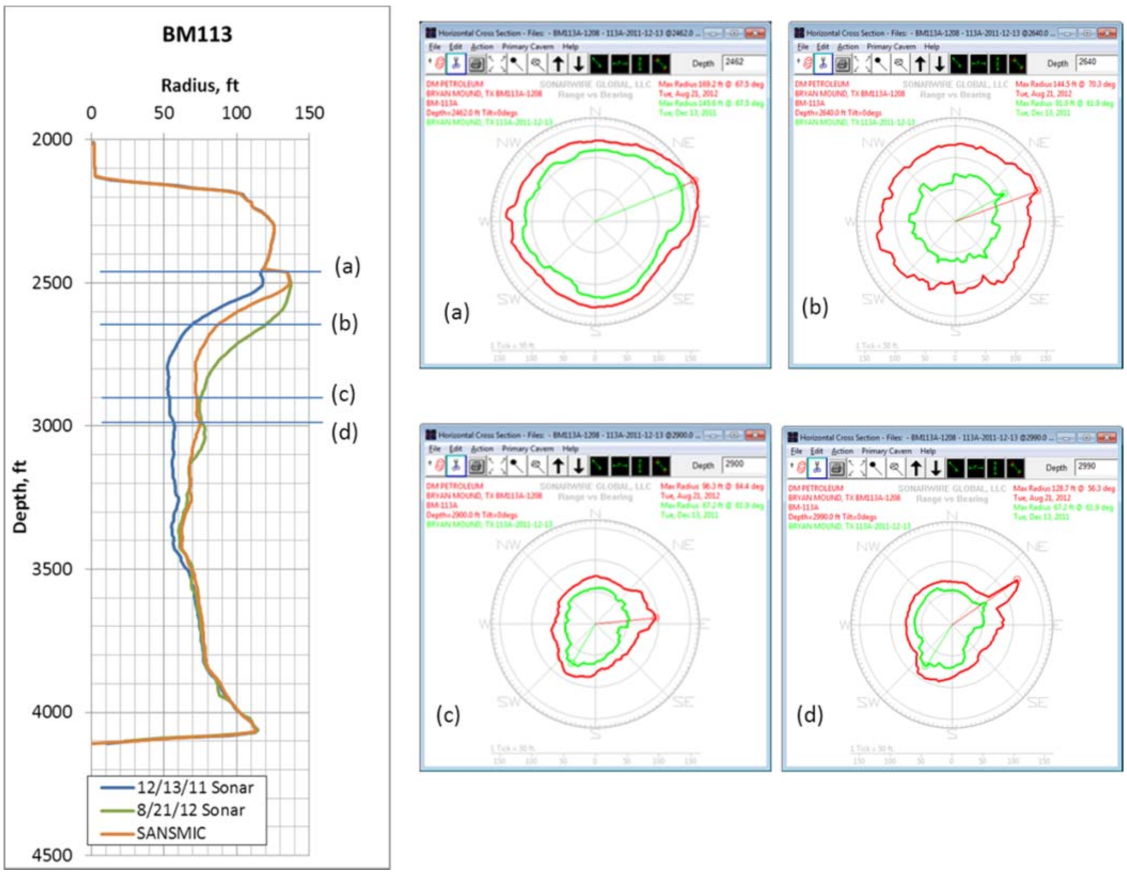


Figure 4-1. Average-Radius Cavern Profiles and Sonar Cross-Sections at Critical Depths for BM113.

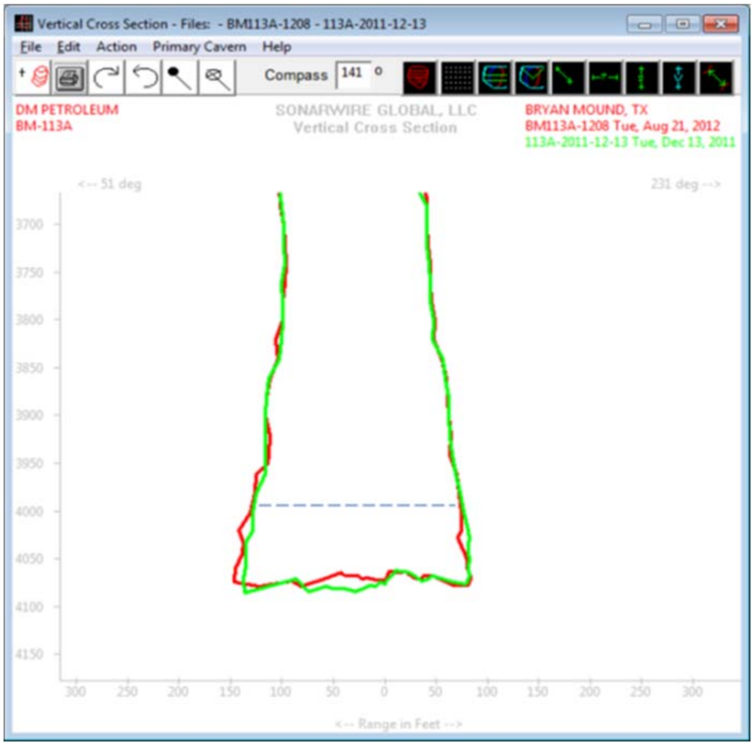


Figure 4-2. Representative overlay of vertical cross-section for sonar data from 12/13/11 and 8/21/12. Blue dotted line is the approximate location of floor that would be associated with a 500 MB salt fall.

4.1.4 Non-Halite Salts – Effluent Brine Properties

Another source of possible enhanced leaching would be the presence of large amounts of non-halite salts, most likely potassium chloride (KCl). The combined solubility of sodium and potassium salts is much larger the solubility of just sodium chloride (halite). Periodically during leaching operations the effluent brine is sampled and tested for temperature, saturation and concentrations of specific dissolved solids including Na^+ and K^+. Figure 4-3 provides a history of the ratio of Na^+ to K^+ ions present in the effluent brine. Note that the units are (mmol)/L/(mol/L), thus a value of 1 means the concentration of K^+ is 1000 times smaller than Na^+. The history shown in Figure 4-3 implies that the amount of potassium salt relative to halite is quite small and remained constant during the leach. From these data, there is no evidence that the leaching encountered a potassium salt anomaly and/or leached a volume greater than would be expected for NaCl.

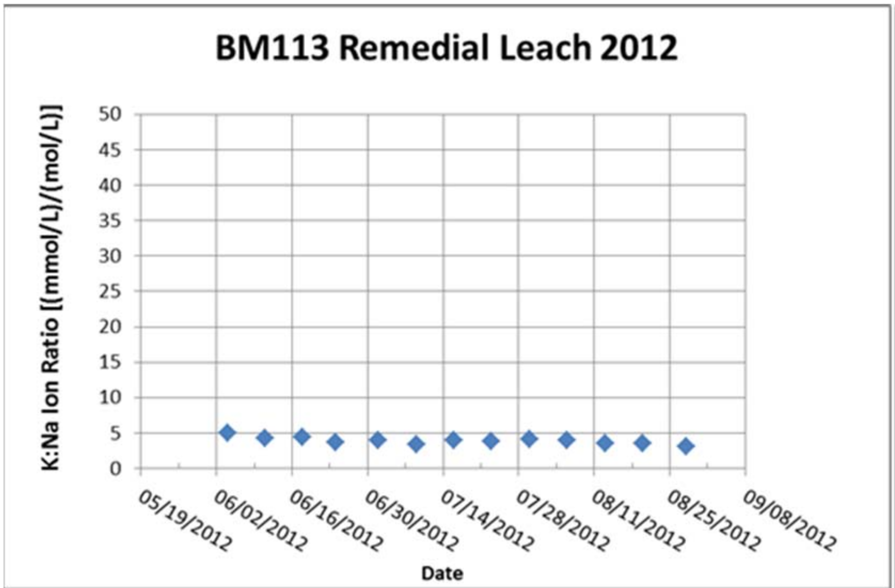


Figure 4-3. K:Na Ratio History for Brine Production Stream During Leach.

4.1.5 Brine Salinity and Temperature

Effluent brine was sampled twice daily for temperature (°F) and salinity (g NaCl/kg brine). Average effluent brine temperature was 93.3 °F, while average salinity was 264 g NaCl/kg brine. Saturated pure NaCl brine at 100°F has a salinity of about 267 g NaCl/kg brine, hence the brine analyzed here is nearly saturated. Temperature and salinity are shown with time in Figure 4-4. The salinity appeared to pass through a startup transient in the first week beginning around 275 ppt and then stabilized at a value around 265 ppt for the remainder of the operation.

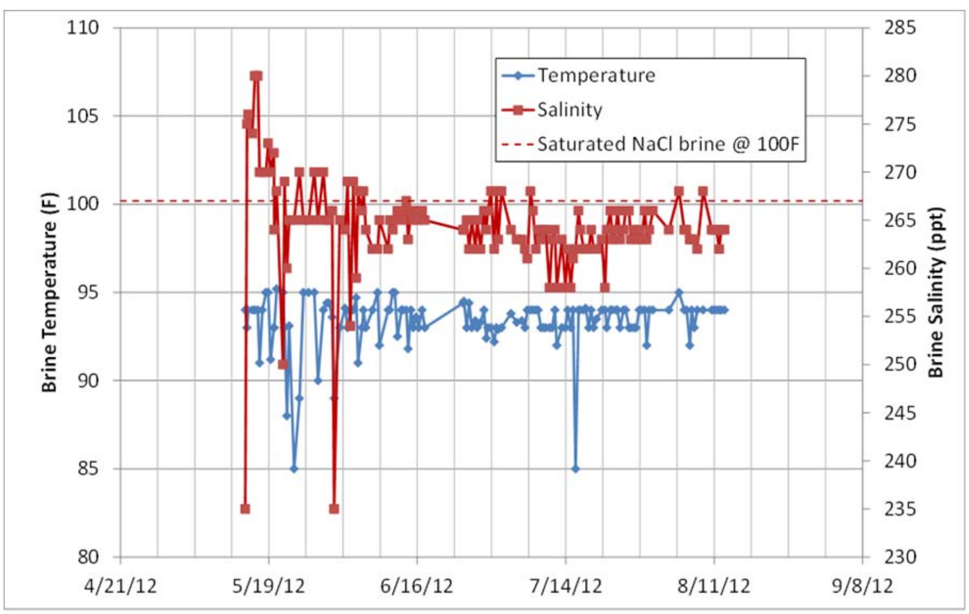
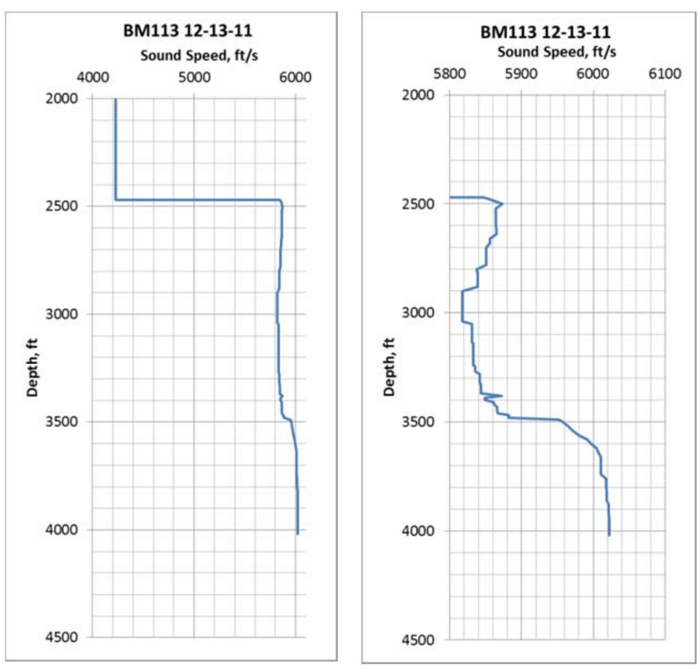


Figure 4-4. Temperature and Salinity History for Brine Production Stream During Leach.

4.1.6 Sound Speed Assumption

The cavern radius relative error of 3-5% implied by the leached volume discrepancy in the 8/21/12 survey (see Table 4-1), could be related to the use of a constant sound speed of 6026 fps for sonar data interpretation, which was measured at the bottom of the cavern in saturated brine. Note, however, that the 12/13/11 sonar was taken through the slick hole before the new hanging string was set, allowing for local sound speed measurements. The 8/21/2012 sonar was taken through the new hanging string which does not allow for obtaining a local sound speed measurement and limits sonar imaging to only the brine section of the cavern. Variations of sound speed on the order of 5800 to 6000 fps (top to bottom) or about 3.4% were seen in the 12/12/11 sonar, which is on the order of the implied relative error in cavern radius of 3-5%.

Figure 4-5 provides the sound speed profiles from the 12/13/2011 sonar survey. Figure 4-5(a) includes both oil (~4200 fps) and brine (5820-6020 fps) phases. The OBI is clearly apparent in the figure at ~2460 ft. Recall that the sonar was taken during withdrawal stage with injection at 3368’ due to a broken hanging string. Figure 4-5(b) zooms in on the brine phase. Below 3500’ or below the injection point (with possible injection jet effect), the sound speed indicates nearly saturated brine with a sound speed of ~ 6020 fps. The decrease in sound speed above 3500 ft. reflects the effect of the rising raw water plume with sound speed varying between 5820 and 5880 fps. The relative change in sound speed of ~3.4% and the profile shape implies that using the sound speed of saturated brine at bottom of the cavern could over estimate cavern radius above the injection point enough to account for much of the leached volume discrepancy.



(b) Oil and brine (b) Rescaled for brine phase only

Figure 4-5. Sound Speed Profiles from the 12/13/11 Sonar Survey Performed Through the Slick Hole.

4.1.7 Re-interpret the Dec 2011 and Aug 2012 Surveys for Distance Between Strings

An attempt was made to estimate the sound speed error in the upper part of the cavern for the 8/21/11 sonar data by using sonar signal reflections off of the hanging strings. Recall that the 12/13/11 sonar, (through the slick hole) used a locally measured sound speed. The 8/21/12 sonar used a sound speed for saturated brine. The sonar operator was asked to provide sonar determined distances to the injection string from both the 12/13/11 and 8/21/12 surveys. The results were 45 ft for 12/13/11 survey and 46 ft for the 8/21/12 surveys, or a relative difference of 1/45 = 0.022 or 2.2% (± 2.2), similar to both the 3-5% radius discrepancy and the 3.4% difference in measured sound speed in the 12/13/11 survey. Thus, the saturated brine sound speed assumption used in the 8/21/12 sonar is a likely source of much of the leached volume discrepancy.

An accurate estimate of the volume error associated with the sound speed assumption is not possible, because the distribution of unsaturated brine within the cavern on 8/21/12 is unknown. However, crude bounding estimates can be made by bounding the affected volume and the apparent volume relative error. Affected volume can be bounded by the total brine volume below the OBI (V_u = 5.4 MMB) and the brine volume above end of the injection string (V_l = 3.3 MMB). Relative volume error, ε_v, due to the sound speed is a function of the square of the radius error, ε_r, as follows:

$$\varepsilon_{v,l} = 1\text{-}(1+\varepsilon_{r,l})^2 = 1\text{-}(1+0.022)^2 = 0.044$$

$$\varepsilon_{v,u} = 1\text{-}(1+\varepsilon_{r,u})^2 = 1\text{-}(1+0.044)^2 = 0.090$$

where,

$$\varepsilon_{r,l} = 1/45 = 0.022$$

$$\varepsilon_{r,u} = 2/45 = 0.044$$

Subscripts *u* and *l* designate upper and lower bounds, respectively. The upper bound relative radius error, $\varepsilon_{r,u}$ = 0.044, assumes the distance between the strings was the 1 ft measured difference plus the sonar error of 1 ft. Thus, the resulting bounding volume corrections associated with the sound speed assumption are:

$$\varepsilon_{v,l}\, V_l = 0.044(3.3 \text{ MMB}) = 145 \text{ MB}$$

$$\varepsilon_{v,u}\, V_u = 0.090(5.4 \text{ MMB}) = 486 \text{ MB.}$$

4.1.8 Adjusted Leach Efficiency

In summary, the apparent volume leached (V_a=2,000 MB) during the top-inject leach was enhanced by (1) leaching occurring after the 12/13/11 sonar survey but before the start of the top-inject leach (ΔV_1= 140 MB) and (2) overestimating cavern radius by assuming a sound speed of saturated brine in the upper part of the cavern which actually contained unsaturated brine with a lower sound speed (ΔV_2 = 145 to 486 MB). A corrected leach efficiency, *E*, can be bounded by applying these two leached volume corrections as follows:

$$V_{lch}/V_{inj} = (V_a - \Delta V_1 - \Delta V_2)/V_{inj}$$

E_u = (2,000-140-145)/ 9.80 = 0.175 (upper bound)

E_l = (2,000-140-486)/ 9.80 = 0.140 (lower bound)

The upper bound is close to the theoretical maximum and the lower bound is very similar to SANSMIC predicted, both compare reasonably well with historical values.

5 MODIFICATIONS TO THE LEACH PLAN

Preliminary analysis of the 8/21/2012 sonar survey resulted in the decision to terminate the stage 1 top-inject leach early. The early termination was based on (1) the loss of ~370 ft of hanging string, (2) the leached volume estimated from the 8/21/12 sonar survey and (3) the average cavern radius profiles. At that time the raw water injection was 44% of planned and leached volume was 59% of planned (now known to be in error - leached volume should also have been around 44% of planned). Continuing the top-inject leach would have over focused the leach in the upper part of the cavern because of the shortened injection string. So, a decision was made to stop the top-inject leach stage at this point and proceed with lowering the OBI in preparation for the planned 2nd stage bottom-inject leach. The early termination of the top-inject leach means the either the leach volume will have to be made up for by lengthening the duration of the bottom-inject leach stage and/or by reducing the final cavern volume goal of 11.2 MMB. Simple volume scaling says the bottom-inject leach stage must be extended by a factor of 2-3 in order to compensate for the volume not leached in stage 1. This requires additional SANSMIC analyses to determine if there are any detrimental effects to cavern geometry from using the shortened string position, the extended bottom-inject leach duration and associated increases in raw water injection. If just lengthening the duration of the bottom-inject leach alters the cavern geometry in a geomechanically adverse way, the follow-up stages will have to be redesigned or goals adjusted.

5.1 Strapping Data During Reposition Of OBI

At the time that the decision was made to terminate the stage 1 top-inject leach early, it was also decided to reposition the OBI at ~2700 ft or roughly in middle of the transition from the wide top to more slender mid-section of the cavern. Injection of ~2.1 MMB of oil to move the interface from 2462 ft to 2700 ft has proceeded slowly because of operational difficulties at the site. However, during that time several interface measurements were made that coupled with transfer volumes provided “strapping” data (oil volume vs. depth). Assuming cylindrical geometry between interface measurements, cavern average radii can be calculated that can be used to verify the sonar data. Figure 5-1 summarizes the results of the “strapping” analysis with an overlay of radii calculated from strapping data (red triangles) and the axi-symmetric cavern profiles from the 8/21/12 sonar data (blue line). Results indicate good agreement with slightly larger sonar radii just below the interface and better agreement for the lower two points. Volume difference in this region is ~120,000 BBL. It is worth noting that even though there appears to be a 2-4% over estimation of radius in the sonar data from the sound speed assumption, this amounts to only 2-4 ft which is hard to detect in the figure. Also, the interface data was taken weeks to months after the sonar so some additional leaching has occurred and is possibly captured in the strapping data, therefore, possibly improving the comparison.

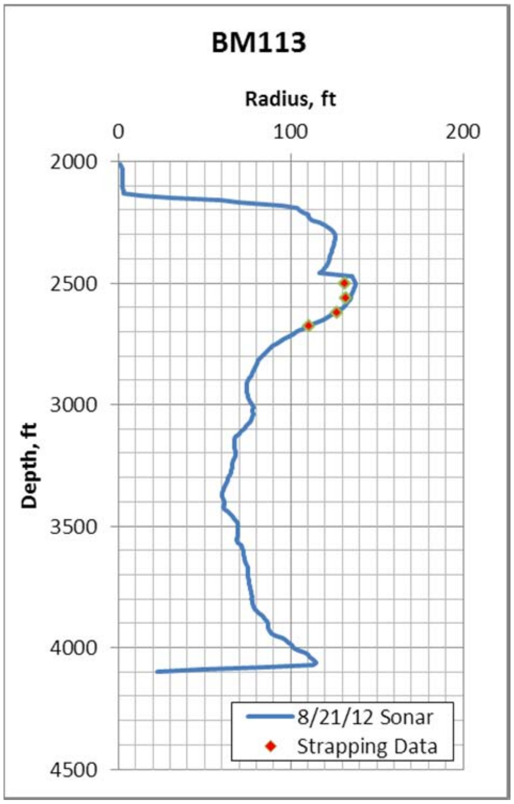


Figure 5-1. Strapping Data from Repositioning OBI for Stage 2 Bottom-Inject.

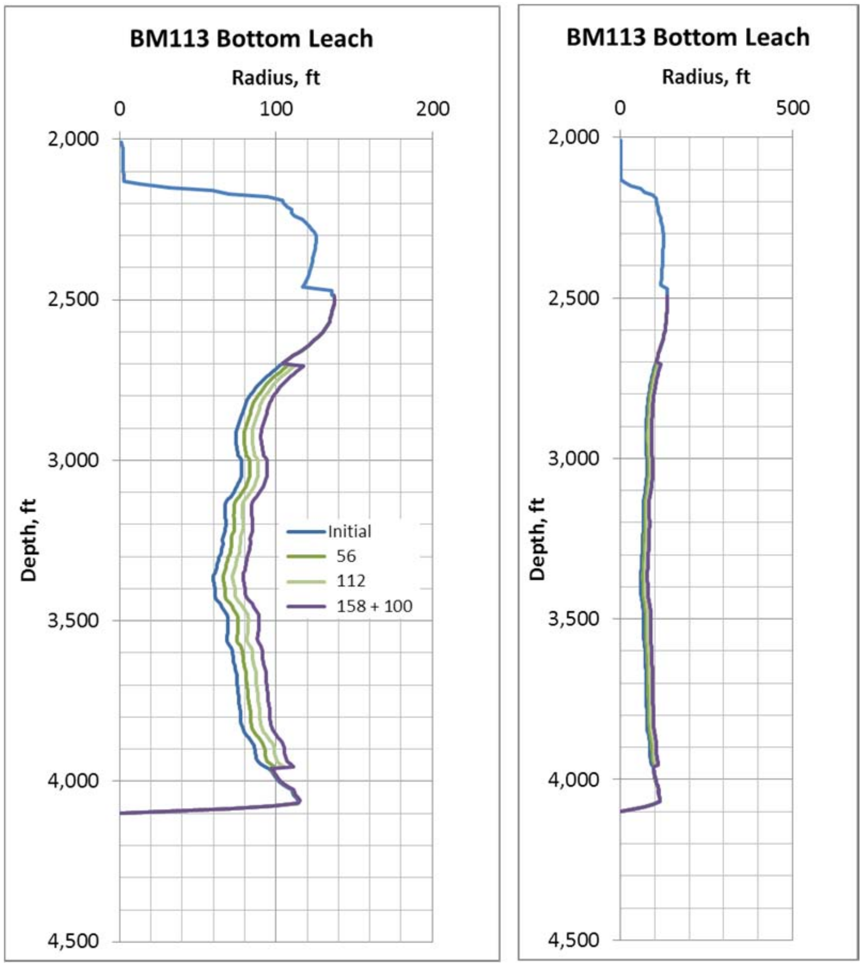
5.2 A Preliminary Continuation Plan

The original Stage 2 bottom-inject leach SANSMIC simulation was modified as follows to evaluate a preliminary bottom-inject leach plan:

- Initial geometry is the axisymmetric representation of the 8/21/12 sonar survey
- String depths were adjusted to match actual string depths at the end of Stage 1 (well A HS= 3950 ft and well B HS = 3000 ft)
- OBI set at 2700 ft, the location of the recently completed oil injections to reposition the OBI
- Injection rates left at 100 MBD
- Leach duration was lengthened by to 158 days (a factor of 2.8) with intermediate evaluations at 56 (original plan) and 112 days.

Results are summarized in Figure 5-2 as axisymmetric profiles at 3 different times during the bottom-inject leach. The final time includes 100 days equilibration time after leach is completed. At the times displayed in Figure 5-2 leaching adds 0.62, 1.26 and 2.0, MMB to the cavern for total volumes of 9.8, 10.5 and 11.2 MMB, respectively. Corresponding leach efficiencies were 9.5, 10.4 and 12%, respectively. The modeled leaching uniformly expanded the cavern between the injection point at 3950 ft and the OBI at 2700 ft, without enlarging either the foot or roof sections of the cavern. The strong shelf and overhang at those locations are artifacts of the

SANSMIC models and likely will be washed out to some degree during the actual leach. The changes to cavern geometry should not have an adverse effect on its geomechanical stability.



Note: 158+100 means 158 days of injection plus 100 days at rest.

Figure 5-2. SANSMIC Axisymmetric Cavern Profiles Predictions for Stage 2 Bottom-Inject Leach. Aspect Ratios are ~6:1 (Left) and 1:1 (Right).

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6 SUMMARY AND RECOMMENDATIONS

The conclusion of the analysis of the BM113 Stage 1 leach is that the leach proceeded much differently than planned, with more enhanced leaching in the upper quarter of the leached region than predicted by SANSMIC due to both modeling inaccuracies and deviations from the plan – primarily OBI placement, no fill and string breakage. The 8/21/12 sonar likely has a 2-4% error in radius (4-9 % in volume) roughly in the region above the initial injection point at 3368 ft. However, the 8/21/12 sonar survey is an intermediate result. Both the 12/13/11 and 8/21/12 sonar surveys were taken in a non-static caverns with significant leaching (100 MB) occurring after the surveys. The final post-leach cavern geometry should be accurately known after leaching is completed, if the final sonar survey is taken either through the slick hole after the hanging string has been removed or it is delayed until the brine in the cavern is assumed saturated.

The recommendation is to proceed with Stage 2 with the following modified leach configuration:

- Reposition OBI from 2462 feet to 2700 feet (completed)
- Leave string positions as is (well A HS = 3950 ft, well B 3000 ft)
- Proceed with bottom-inject leach, (injection at 3950 ft brine production at 3000’)
- Raw water flow rate – same as stage 1, nominally 100 MBD
- Lengthen duration from original 56 days to 158 days to achieve original plan volume of 11.2 MMB (a factor ~3 longer due to early termination of stage 1)
- Monitor progress by performing sonar surveys at 30 days (3 MMB raw water injected) and if proceeding as planned every 60 days thereafter.

7 REFERENCES

Rudeen, D. K. and D. L. Lord, 2012. "2012 Leach plan for Completion of BM113 to 11.2 MMB." Geotechology & Engineering, Sandia National Laboratories, Albuquerque, NM.

Russo, A. J., 1981. "A Solution Mining Code for Studying Axisymmetric Salt Cavern Formation." Unlimited Release SAND81-1231, Sandia National Laboratories, Albuquerque, NM.

8 APPENDIX A: ANALYSIS OF THE OIL WITHDRAWAL TO REPOSITION OBI FOR COMPLETION OF BM113 LEACH

8.1 Introduction

SANSMIC is a solution mining code used by Sandia to simulate leaching scenarios for the Strategic Petroleum Reserve (SPR). SANSMIC has recently been used for the simulation of the expansion of Bryan Mound cavern 113 from 7.4 to 11.2 MMB. Three leach plans were developed at Sandia using SANSMIC (Rudeen and Lord 2012). The plan that was implemented is similar to the 100 MBD with fill cases, but with no fill. The analysis presented herein deals only with the withdrawal to reposition the OBI that occurred prior to the planned leach-to-completion operations.

8.2 Data Summary and Retrieval

Data was pulled from multiple sources including:

- Cavern geometry from several sonars surveys
- Injection rates from a copy of the CaveMan 'Transfers' worksheet
- Initial string and OBI positions from Weekly Reports

8.2.1 Sonar Data

There were sonars completed for BM113 wellhead A on 10/26/1995, 1/1/2005, 11/16/2011, 12/01/2011, 12/13/2011, and 8/21/2012 and for BM113 wellhead B on 10/16/1997. The sonar from 11/16/2011 was used as the initial cavern shape for the analysis and results were compared to the sonar data from 12/13/2011. It is important to note that although the initial cavern shape is taken from 11/16/2011, the actual leaching process began on 11/4/2011. The SANSMIC runs begin with the cavern shape of the 16th but since the injection began on the 4th, a short analysis was done to determine the average specific gravity of the brine within the cavern as well as to determine the depth of the OBI in order to establish the initial conditions for the analysis.

Looking at the sonar data in Figure A-1 from 11/16/2011 (pre-leach), it is evident that a portion of the neck of the cavern (depths 2860-3800 ft) is not characterized very well using an equivalent axisymmetric geometry and the hanging string may in fact be closer to the wall than to the center of the cavern (depths 3140-3680 ft).

The sonar taken on 12/13/2011 (post-withdrawal), shown in Figure A-2, continues these characteristics.

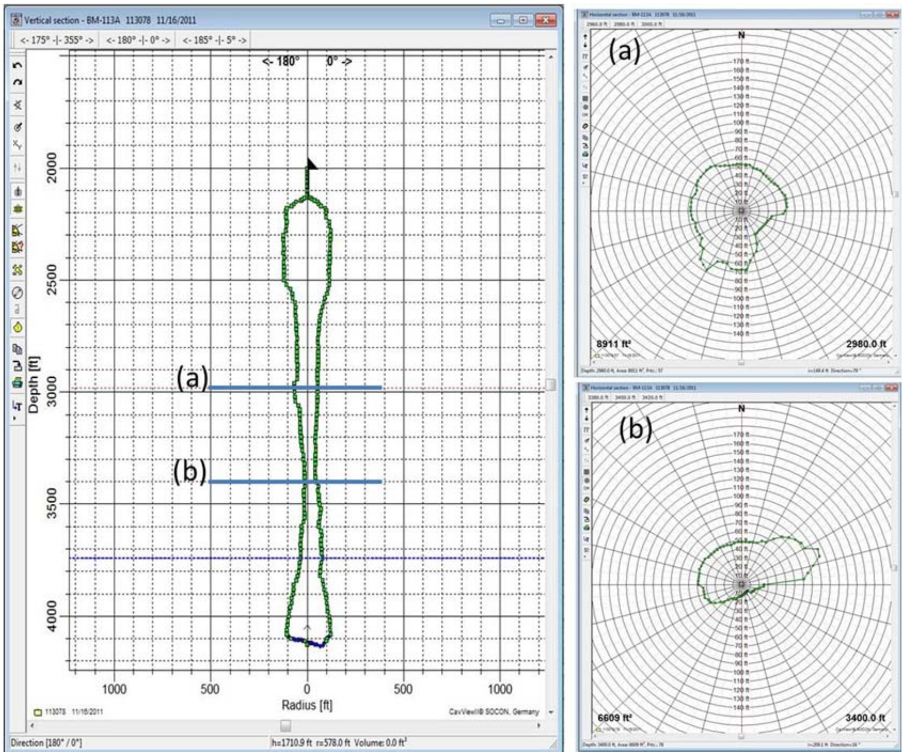


Figure A-1. Sonar for 11/16/2011. (a) Depth=2980 ft, (b) Depth=3400 ft.

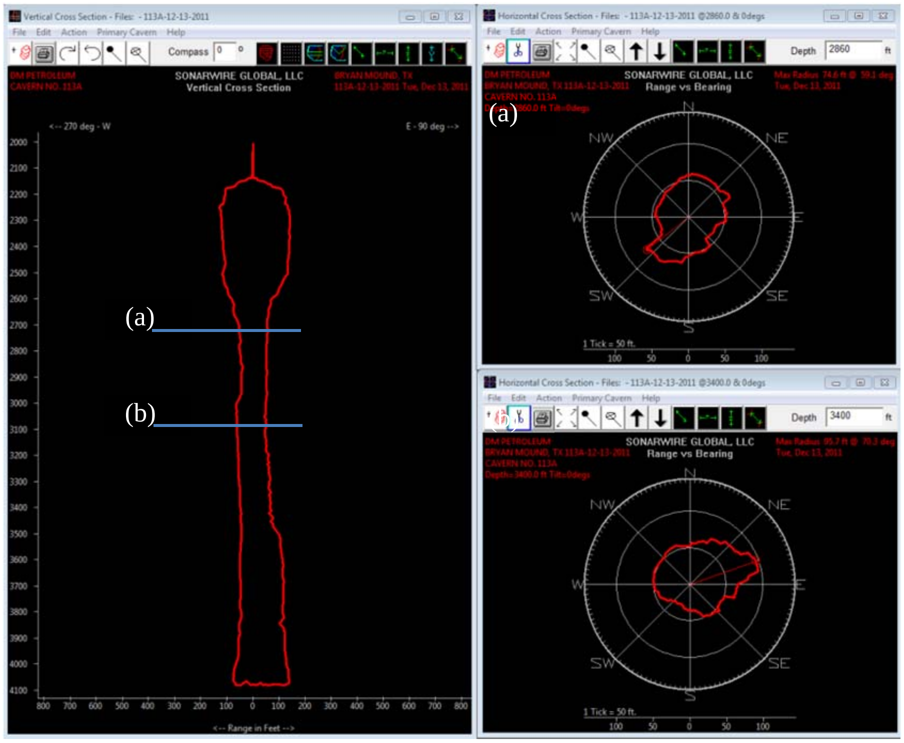


Figure A-2. Sonar for 12/13/2011. (a) Depth=2960 ft, (b) Depth=3400 ft.

8.2.2 *Injection Rates and Types of Fill*

The injection rates of the oil and brine are taken from the 'Transfers' worksheet from a recent CaveMan report. Table A-1 provides a summary of the injection data for the entire withdrawal period 11/4/11 to 12/16/11.

Table A-1. Injection Rate for the Oil Withdrawal of BM113.

Date	Action	Avg. Rate, BPD	Days	Tot. Vol., MMB	Work Over, Days
11/4/11-12/16/11	Brine in	105,715	41*	4.33	88

8.2.3 *Injection and Production Locations*

The data used to determine the injection and production point locations are also found in Weekly Reports. The injection string broke during withdrawal, however, the exact date is unknown. A parameter study used to address the uncertainty of when the string broke is presented in section 0 with results provided in section 8.4. A summary of the published hanging string data for both wells A and B are provided in Table A-2.

Table A-2. Lengths of Hanging Strings A and B.

Date Measured	Length, ft
3/18/2011	B=3872
10/5/2011	B=4090
10/5/2011*	B=3368
3/7/2012 10/5/2011	A=3950 B=3368

* denotes that the latest log date remained the same but the depth changed as a result of the 12/13/11 sonar survey.

8.2.4 *OBI Placement*

The locations of the OBI, also taken from the Weekly Reports are provided in Table A-3.

Table A-3. Depth of OBI, Date Measured and Report Date for BM113.

Report*	Well A		Well B	
	Date of Log	Depth, ft	Date of Log	Depth, ft
20110821	6/29/2011	4080	3/18/2011	3872
20111013	6/29/2011	4080	10/5/2011	4070
20111215	12/13/2011	2470	10/5/2011	4070
20120314	3/7/2012	2456	10/5/2011	4070

* filename template: BMWK YYYYMMDD.xls

8.3 SANSMIC Settings for Timing of String Break

A series of scoping SANSMIC simulations were conducted in order to reproduce the measured results of the BM113 withdrawal leach as closely as possible. These trial simulations are also discussed in a SNL internal memorandum (Weber and Rudeen 2012). The SANSMIC settings relevant to the current discussion are presented in Table A-4. Stages 1 and 2 model the oil withdrawal phase used to reposition the OBI for the top leach. Stage 2 is included to incorporate the string break at 3368 ft. Since the sonar on 11/16/11 was taken after injection had begun (on 11/4/11) the initial SG in the cavern was set to 1.105 which was determined from the caverns average SG after 12 days from one of the initial scoping calculations. The depth of the OBI was determined similarly.

Table A-4. SANSMIC Settings for BM113 Withdrawal.

Name	Stage 1	Stage 2
Type	Withdrawal	Withdrawal
Workover, days	2	2
Duration, days	10	20
Injection, ft	40 (4090)*	762 (3368)
Production, ft	50 (4080)	50 (4080)
OBI, ft*	295(4080)	---+
Injection Rate, BPD	104,051	104,051
SG_{inj}	1.0025	1.0025
SG_0	1.105	---+

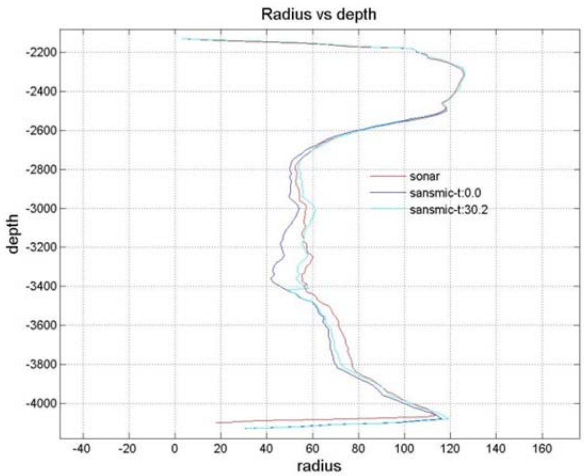
* Height(depth) in feet. Height is measured from initial cavern bottom. Depth is measured from Braden head flange.
\+ code determined

A parameter study was performed in an attempt to determine when the string breakage occurred during the withdrawal to position the OBI. The settings used in the three additional simulations are identical as in Table A-4 except the duration of the Stages. Table A-4 assumes the string breaks after 10 days and is hereafter referred to as Test A. Test B assumes the break after 15 days, Test C assumes the break after 20 days and Test D assumes the break occurs after 25 days. The modifications would be seen in the “Duration” for Stage 1 and 2 being replaced by 15 days. for Test B. Similar modifications are made for Test C and Test D. Note that total modeled duration is the same for all case at 30 days (41 total days – 11 days prior to sonar).

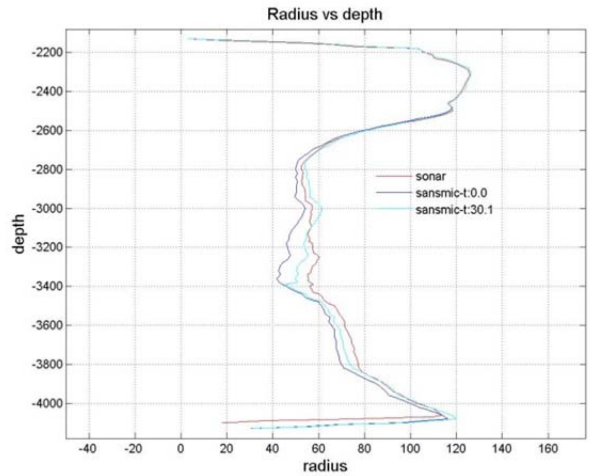
8.4 Results of Timing of String Break

8.4.1 Profile Comparisons

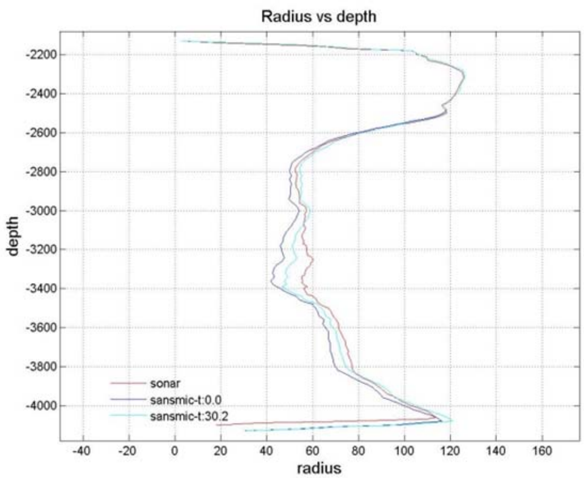
The cavern profiles predicted by SANSMIC representing the multiple timings of possible string breakages during the withdrawal are presented in Figure A-3 and are compared to the sonar taken on 12/13/2011. Shelves are evident in Test A at a depth of 3410 ft. and Test B at a depth of 3380 ft. No overhang is observable in either Test C or Test D. In the middle of the cavern however, the difference between measured and predicted remained large. The difference is likely due a combination of salt block fall and exposure of an uncompleted chimney in well B discussed in detail in Lord (Editor) (2011) and shown as preferential leach on the SE wall in Figure A-1(b) and Figure A-2(b).



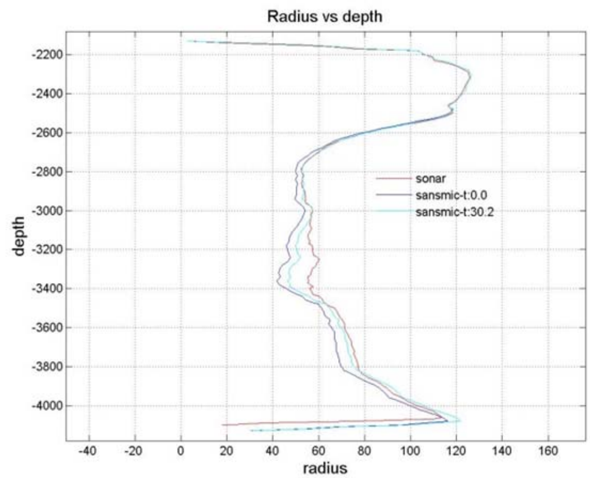
(a) Test A – string breaks after 10 days



(b) Test B – string breaks after 15 days



(c) Test C – string breaks after 20 days

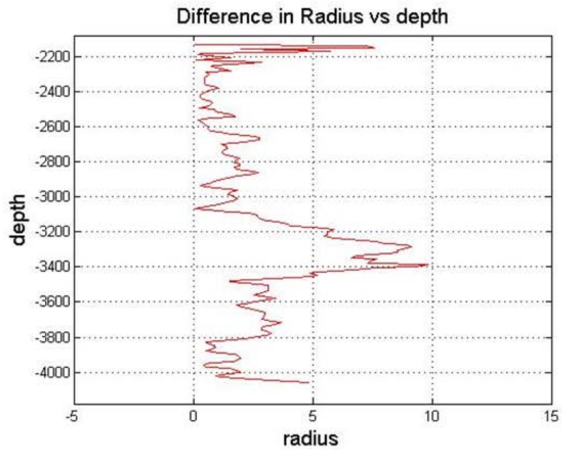


(d) Test D – string breaks after 25 days

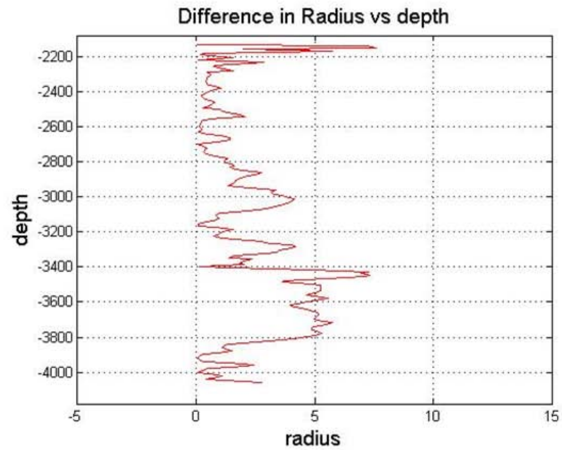
Figure A-3. Cavern Profiles for Test A, B, C, and D.

Test D agrees well with the upper region (2600ft - 3080ft) as well as the lower (3480ft - 3840ft), but does poorly in the center (3080ft - 3480ft). Test C is similar. Test A agrees well with the top and middle (2600ft - 3420ft), but not with the bottom (3420ft - 3840ft). Test B agrees only moderately well, but for all regions. Upon examination of the OBI, production, and injection depths it is notable that the OBI is above the “break” in the string after 12 days which implies water injection would have been through oil (modeled as at the interface by SANSMIC) and explains why the shelf is slightly lower for Test A (10 days) than in Test B (15 days).

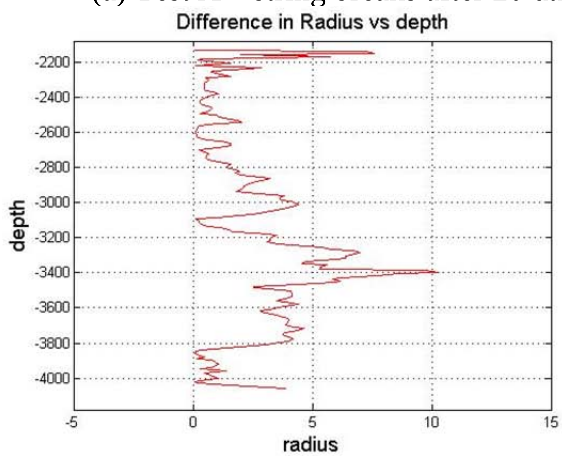
The radii differences from Test A, B, C, and D are shown in Figure A-4.



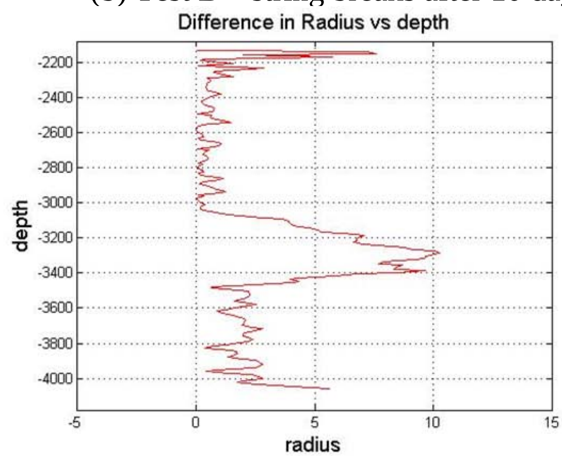
(a) Test A – string breaks after 20 days.



(b) Test B – string breaks after 10 days.



(c) Test C – string breaks after 15 days.



(d) Test D – string breaks after 25 days.

Figure A-4. Differences Between Sonar and SANSMIC Profiles.

8.4.2 Statistics

In order to quantify which SANSMIC results were most similar to the sonar data, norms and error statistics were calculated and are presented in Table A-5. In order to calculate the norms and statistics the sonar and SANSMIC output of the radius data were linearly interpolated and the differences were calculated. The maximum, minimum, and mean of the differences were evaluated and scaled L_1 (average difference) and L_2 (similar to RMS) norms were also calculated. The norm of a vector is a measure of the size or length of the vector or in this case the overall magnitude of the difference between measured and modeled cavern average radii. The L_2 norm is the Euclidean distance, a mathematical representation of the “as the crow flies” distance. The scaled L_2 used to compare profiles is as follows:

$$\frac{L_2}{n} = \frac{\sqrt{\sum |x_i|^2}}{n}$$
$$x_i = r_{i,Sonar} - r_{i,SANSMIC}$$

where r_i is radius at depth i and n is the number of depths included in the analysis. The division by n is used to normalize for comparisons of dataset with a different number of data points.

The L_1 norm is also known as the "taxi cab" norm as it is the distance a car would drive to reach a destination. The scaled L_1 norm used to compare profiles is represented as:

$$\frac{L_1}{n} = \frac{\sum|x_i|}{n}$$

As shown in Table A-5 the norm values are similar but since the values decrease from Test A to Test D (later failure) for three of the five categories it is reasonable to assert that the string broke late in the withdrawal stage or at about 25 days. Note that the data in the region of the assumed salt fall (3200 – 3400 ft) were not included in the statistics because SANSMIC cannot model it.

Table A-5. Norms and Quantifications.

Test	Differences, ft			Norms	
	Max	Min	Mean	L_2	L_1
A	7.5962	0.011	2.1261	0.2298	2.1261
B	7.5962	0.013	1.9047	0.2014	1.9047
C	7.5962	0.013	1.6591	0.1670	1.6591
D	7.5962	0.008	1.2800	0.1460	1.2800

Based upon the norm and statistical data, Test D has the best results. Its values are lowest for the four meaningful categories ("Max" is controlled by noise at the top of the cavern where no leaching occurred).

8.4.3 Cavern Volume

The total cavern volume is initially about 6.86 MMB and on 12/13/2011 it is predicted by SANSMIC to be approximately 7.34 (as shown in Figure A-5) which is an increase of approximately 0.480 MMB. The injection of 4.33 MMB of unsaturated brine during this period gives a leach efficiency of 11%. However, the final leached volume will be larger because no post-withdrawal work-over was included in the model and the unsaturated brine present in the cavern will continue to leach. Results for sonar data are similar, because the large volume increase in the neck region is countered by a corresponding floor rise.

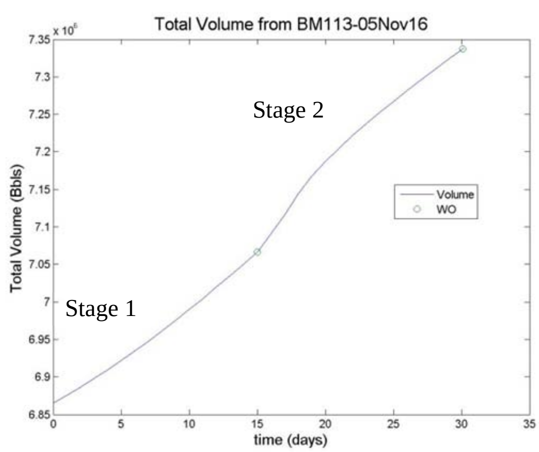


Figure A-5. Test C – Total Cavern Volume History

8.5 Conclusions

The withdrawal leach proceeded with minor deviation from expectations due to the string breakage at 3386 ft and apparent salt block fall in the same region. Leach efficiency for the period of withdrawal from 11/4/2011 to 12/13/2011 according to the SANSMIC simulation was 11%. It may be inferred from the parameter study that the string broke late in the withdrawal around 25 days after the initial sonar was taken on 11/16/2011.

8.6 References for Appendix

Rudeen, D.K and D.L. Lord, 2012. "2012 Leach Plan for Completion of BM113 to 11.2 MMB". SNL Letter Report, April 2012.

Weber, P.D. and D.K. Rudeen, 2012. "2012 Leach Plan and As-Built for Bryan Mound Cavern 113 to 11.2 MMB". SNL memorandum for the record, December 2012.

Lord, D.L. (Editor), 2011. "Albuquerque Leaching Technical Exchange Summary Report - Sandia Contribution, SPR Capacity Maintenance Program US Strategic Petroleum Reserve", SNL letter report, December 2011.

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