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SANSMIC Validation

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Abstract

SANSMIC is solution mining software that was developed and utilized by SNL in its role as geotechnical advisor to the US DOE SPR for planning purposes. Three SANSMIC leach modes – withdrawal, direct, and reverse leach – have been revalidated with multiple test cases for each mode. The withdrawal mode was validated using high quality data from recent leach activity while the direct and reverse modes utilized data from historical cavern completion reports. Withdrawal results compared very well with observed data, including the location and size of shelves due to string breaks with relative leached volume differences ranging from 6 – 10% and relative radius differences from 1.5 – 3%. Profile comparisons for the direct mode were very good with relative leached volume differences ranging from 6 – 12% and relative radius differences from 5 – 7%. First, second, and third reverse configurations were simulated in order to validate SANSMIC over a range of relative hanging string and OBI locations. The first-reverse was simulated reasonably well with relative leached volume differences ranging from 1 – 9% and relative radius differences from 5 – 12%. The second-reverse mode showed the largest discrepancies in leach profile. Leached volume differences ranged from 8–12% and relative radius differences from 1 – 10%. In the third-reverse, relative leached volume differences ranged from 10 – 13% and relative radius differences were ~4 %. Comparisons to historical reports were quite good, indicating that SANSMIC is essentially the same as documented and validated in the early 1980's.

ACKNOWLEDGMENTS

The authors wish to thank Thomas Eyermann for a technical review of this report.

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Abbreviations and Nomenclature

BBL	–	Barrel (volume unit)
BH	–	Big Hill SPR site
BPD	–	Barrels per day
BM	–	Bryan Mound SPR site
CF	–	Concurrent fill - oil injected during leach
LF	–	Leach-fill – combined raw water and oil injection
MB	–	Thousand barrels
MBD	–	Thousand barrels per day
MMB	–	Million barrels
OBI	–	Oil-brine interface (depth)
RMS	–	Root mean squared
RW	–	Raw water (unsaturated brine)
V&V	–	Verification and validation
WH	–	West Hackberry SPR site
Bottom-Inject	–	Leach mode where raw water is injected thru lower of two strings. Formerly called direct leach.
Top-Inject	–	Leach mode where raw water is injected thru higher of two strings. Used primarily for roof development. Formerly called reverse leach.
SPR	–	Strategic Petroleum Reserve

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1 Executive Summary

SANSMIC is the solution mining software that was developed by Sandia National Laboratories (SNL) in the early 1980s. It is used by SNL in its role as geotechnical advisor to the US DOE Strategic Petroleum Reserve (SPR) for remedial leach planning, available drawdown estimation, cavern selection for crude oil delivery, and long term cavern stability predictions. As part of an ongoing effort to baseline software critical to SNL's SPR mission, this report documents a revalidation of SANSMIC software. Validation, in the context of this report, refers to both qualitative and quantitative comparisons to observed or measured data. This report does not verify that the physical models and equations have been programmed or solved correctly; nor does it validate the software outside its design assumption of tall, slender, cylindrical caverns.

Three SANSMIC leach modes – withdrawal, bottom-inject (direct-leach) and top-inject (reverse leach) – are validated with multiple test cases for each leach mode. The measured data consists of interpreted sonar survey data in the form of radius profiles (average cavern radius as a function of depth) and interpreted sonar survey volumes. No specific acceptance criteria were pre-defined. Instead, expected accuracies are determined from the comparisons of SANSMIC predictions and observed data. In addition, comparisons are made to historical SANSMIC results in order to assess whether there have been any discernible changes to the code since its development and original validation in the early 1980s.

The withdrawal mode is validated using recent, high quality data from the 2011 sale and subsequent remedial leach activities. Withdrawal leach is validated on three scales – small, medium, and large – roughly coinciding with quarter, half, and full cavern drawdowns. Results compare very well with observed data, including the location and size of shelves due to string breaks that move the raw water injection point up 100s of feet. Relative leached volume differences range from 6 – 10% and relative radius differences from 1.5 – 3%. It should be noted that relative measures do not include caverns for which there was a > 15% leached volume difference that could be attributed to inaccuracies in injected volumes.

The bottom-inject (direct-leach) mode is validated using data from completion reports for the sump and chimney stages of SPR cavern development. Sump and chimney development at SPR used various combinations of one or three simultaneously developed wells and either separate or combined sump and chimney stages. Several combinations of these configuration attributes are simulated. Profile comparisons are very good. Relative leached volume differences range from 6 – 12% and relative radius differences from 5 – 7%. Direct leach at full cavern scale is not validated.

The top-inject (reverse-leach) mode is also validated using cavern completion report data. First, second, and third reverse configurations are simulated in order to validate SANSMIC over a range of relative hanging string and OBI locations and over a range of injection rates and volumes. All the reverse-leach test cases available are leach/fill scenarios, which complicate interpretation of results in the region of OBI movement as the geometry in this region was unavailable for direct sonar measurement at the time.

First-reverse roof development is simulated reasonably well considering the high sensitivity to concurrent oil fill used to shape the roof. The largest differences are in the neighborhood of the injection depth where SANSMIC predicts a more rapid radius change in the transition region from the upper lobe to the neck of the cavern. Observations show a more gradual and deeper transition, possibly indicating a deeper injection jet penetration. Relative leached volume differences range from 1 – 9% and relative radius differences from 5 – 12%.

The second-reverse mode, used to expand the cavern mid-section, shows the largest discrepancies in leach profile of all the leach modes. SANSMIC profiles are more vertical and slightly barrel shaped between the injection point and the OBI, and shows the same rapid transition below the injection point. Observations indicate a more uniform and gradual taper. Leached volume differences range from 8 – 12% and relative radius difference from 1 – 10%.

In the third-reverse mode, the injection point is moved to a few hundred feet above the production location. In this configuration, the observed leach profile is rather symmetric and rounded with maximum radius change midway between the OBI and production point. SANSMIC again predicts a barrel like shape with a rapid transition region just below the injection point. Relative leached volume differences range from 10 – 13% and relative radius differences are ~4%.

Considering the input data were developed independently (not provided) the historical comparisons are quite good. Two of the four reverse-leach cases show shifts in the transition region just below the injection point that are indicative of an injection jet effect. Also, a few direct leach cases with very low injection points show different wall development near the floor. But, it is not clear whether the differences are due to input choices or the model. Thus, the conclusion is that the code has not changed significantly since its original development. It is interesting to note that this shift is also apparent in the observed vs. simulation comparisons.

In summary, given the assumed geometries, string configurations and uncorrected historical injection/fill rates and volumes, SANSMIC generally predicts leached volumes within ~10% and cavern radius within ~5%. Relative errors by leach mode are provided in Table 1-1.

Table 1-1. Relative Errors by Leach Type.

Leach Mode	Relative Volume Error, %	Relative Radius Error, %
Withdrawal	8	2
Bottom-Inject	12	6
Top-Inject	10	8
Overall	**9**	**6**

2 Introduction

As part of an ongoing effort of the Sandia National Laboratories (SNL) Strategic Petroleum Reserve (SPR) project to baseline software critical to its mission this report documents a new verification and validation of the Sandia developed solution mining code, SANSMIC. This document is one in a series that provides a Quality Assurance (QA) based pedigree for the software. The document set currently consists of the original theory (Russo 1981); User's Manual (Russo 1983); original verification (Reda and Russo 1983; Eyermann 1984; Reda and Russo 1984); a preliminary design document (Rudeen and Lord 2011); and recently released leach reports (Lord, Roberts et al. 2012; Rudeen, Weber et al. 2013; Weber, Gutierrez et al. 2013). The preliminary design document is to be finalized in the near future.

As clarification of terminology used in this document, *verification* is the process of showing that equations, models, and data are coded and solved correctly and *validation* shows that the model does an acceptable job of simulating the physical process for which it was designed. This is accomplished by comparing simulation results with real world data. This report intends to validate SANSMIC, basically assuming SANSMIC is a "black box". In the more formal software Quality Assurance (QA) lifecycle, these exercises are sometimes performed together and referred to as software Verification and Validation (V&V).

The validation exercise as reported in this document is performed due to multiple needs, namely: the age of the original documentation, a gap between its original usage for cavern development in the 1980-90 timeframe and more recent remedial leach activities to expand the SPR, availability of high quality leach data from the recent sale and remedial leach activities and a new group of users. In addition, re-validation exercises reported in a recent investigation (Rudeen, Lord et al. 2011) failed to reproduce bench-scale simulations as reported in the Reda and Russo reports (Reda and Russo 1983; Reda and Russo 1984), which led to questions as to whether the code has changed since its original documentation.

The *validation* reported herein compares simulation results with measured or observed data for three basic leach modes available in SANSMIC: withdrawal, bottom-inject direct-leach, and top-inject reverse-leach. Both the bottom and top leach modes include concurrent oil fill or moving OBI. At least two test cases of each mode are provided. This report does not *verify* that the theory reported by Russo in 1981 and 1983 has been implemented correctly. The preliminary and planned final design document will provide a "reverse engineered" theory by presenting equations and models from a close examination of the source code.

2.1 Background

The United States Strategic Petroleum Reserve (SPR) consists of an underground storage system which uses caverns leached (solution mined) in four salt domes (Big Hill, Bryan Mound, Bayou Choctaw and West Hackberry) located near the Gulf of Mexico in Texas and Louisiana. The SPR comprises 63 caverns containing approximately 700 million barrels (MMB) of crude oil.

Sandia National Laboratories is the geotechnical advisor to the US Strategic Petroleum Reserve.

2.1.1 Types of Leaching

There are three basic types of leaching utilized at the SPR: withdrawal, top-inject, and bottom-inject. Withdrawal leach requires only one brine string, presumably deeper than the OBI, through which raw water is injected thereby displacing and lifting the oil out of the cavern through the slick well. The OBI is moved upward within the cavern and leaching occurs below this depth. The typical leach pattern for a withdrawal leach is such that the majority of the leaching occurs at the injection depth tapering to near zero at the final OBI depth. This pattern can be interrupted or changed due to strategic string cuts or inadvertent string breaks.

Bottom-inject leach requires two hanging brine strings both of which are below the OBI. Bottom-inject leach, also known as direct-leach, positions the injection string below the production string which results in the majority of the leaching occurring near the injection string depth tapering up to the production string with less leaching occurring between the production string and the OBI. The extent of the tapering is dependent upon the distance between the injection and production depths, as well as the relative location of the OBI. The OBI may be stationary or moving within the cavern due to concurrent oil injection. Bottom- inject was used for sump and chimney development in the earliest stages of cavern development at the SPR.

Top-inject leach requires two hanging brine strings, both below the OBI, and was previously known as reverse-leach. Here the strings are opposite that of bottom-inject, in that the brine production string is deeper than the brine injection string. The primary leaching occurs near the injection depth up to the OBI, with leaching tapering down between the injection and production depths. The amount of leaching in a given region is dependent upon the distance between the injection depth and OBI as well as the relative location of the production string. Oil can be simultaneously injected for this configuration as well. This latter process is called leach-fill and was used extensively during the SPR cavern development. Three top-inject configurations were used: the first-reverse used a high injection point for roof development; the second-reverse, with the injection at mid-depth, was used for mid to upper cavern development; and third-reverse with injection near the bottom of the cavern for bottom to middle volume development. All three configurations are validated in this document.

Bottom-inject and top-inject is the terminology currently used by the SPR in place of the more traditional direct and reverse leach terminology used by industry because they are more descriptive. Both sets are used interchangeably in the remainder of this report with the historical terminology used when referencing and comparing with historical data contained in the SPR cavern completion reports.

Another common term in use at the SPR is remedial leach which refers to intentional and designed cavern leaching used to expand the available storage volume of a cavern. It is used to counter creep closure, provide working volume for small cavern-to-cavern transfers that are required during cavern workovers, and to increase the storage capacity of the SPR.

2.1.2 Data Sources

Several data sources are used in the compilation of this report. Cavern Completion Reports are available for select caverns of the Bryan Mound (BM) and West Hackberry (WH) sites (PB-KBB 1985a; PB-KBB 1985b; PB-KBB 1986a; PB-KBB 1986b; PB-KBB 1986c; PB-KBB 1986d). These reports summarize and tabulate the injection and production depths as well as give an estimate of the raw-water injection rates and durations on a monthly basis. The reports also give an estimate of the oil fill rates and volumes as well as periodic OBI locations. Finally, the reports provide sonar survey data in the form of incremental and cumulative cavern volume as a function of depth. The incremental volumes are converted to cavern average radii by assuming cylindrical geometry between depth stations. For cavern development simulations the oil and raw-water volumes and rates are treated as estimates due to stream splitting and the lack of accurate metering devices on individual caverns. Thus, SANSMIC predicted OBI locations were adjusted when significantly different than the observed OBI locations, since they are sensitive to both injection and cavern volume. Historically, SANSMIC has predicted leach efficiencies reasonably well. Leach efficiency within the context of this report is the volume of salt leached per unit volume of raw-water injected. Theoretically, leach efficiencies should be less than ~16-17%, dependent on temperature.

For more recent leach activity, daily and weekly reports and sonar survey data provide a much more accurate data set for building leach simulations. Sonar survey data consists of tables of radii as a function of azimuth (3 - 5 degree increments) and depth (10 - 20 ft intervals). Average radius at each recording station is calculated using a root mean squared (RMS) method that conserves cross-sectional area.

In the summer of 2011, the sale of 30.8 MMB of crude oil resulted in multiple caverns at three SPR sites (BH, BM, and WH) undergoing partial withdrawal. The volumes and rates of fluid movements are better known in these cases because of improvements in metering for individual caverns. Regular logging activities provide accurate string and interface locations and cavern geometries from sonar surveys are more readily available. Analyses are presented in this report for a limited number of caverns associated with the 2011 sale. More detailed analyses can be found in a prior report (Lord, Roberts et al. 2012). It is important to note that little cavern-scale data was available for verifying the large-scale withdrawal leach capabilities of SANSMIC until the 2011 sale and subsequent remedial leaching activities.

The 2011 sale provided a sufficient volume of ullage to allow for BM113 and BM114 to be leached to final design volume using a top-inject (reverse) leach. A leaching plan for BM113 is presented in (Lord, Roberts et al. 2011). As of this writing, only the first phase of the planned leach for BM113 is complete. A detailed analysis of the first phase is presented in (Rudeen, Weber et al. 2013). Though it has been the only reverse leach performed since cavern development it is not included in the validation because of significant deviations from the plan (broken string) and inaccuracies in the sonar (sound speed assumption) that make interpretation very difficult.

The 2011 sale also provided ullage to be used in the paired leaching of BH101 and BH104 using multiple withdrawal cycles as well as the emptying of WH105 for temporary conversion from sweet to sour crude oil. The partial refilling of WH105 using oil from WH106 resulted in substantial leaching in WH106 as well. A detailed analysis of each of these leaching activities is presented in a prior report (Weber, Gutierrez et al. 2013) with summary analysis presented here for the purpose of SANSMIC validation.

Excel workbooks utilized in the analysis of SANSMIC calculations and containing input and output data can be found on the SPR Team SharePoint site by navigating to the Documents/Shared Documents/SANSMIC/Validation folder.

2.1.3 SANSMIC History

SANSMIC was developed at Sandia in the early 1980's by A. J. Russo in order to accommodate the pressing directive to create additional petroleum storage caverns quickly. Previously, the SMRI code SALT77 was used, but the speed at which the caverns were to be filled resulted in a leach-fill scenario with a transient OBI, a capability not available in SALT77. The moving OBI was also required in the modeling of withdrawal leach. Several documents including a theoretical report (Russo 1981) and User's Manual (Russo 1983) and two experimental studies present verification and validation of SANSMIC (Reda and Russo 1983; Reda and Russo 1984). Russo (1983) provides comparisons to early cavern development data for both bottom and top leach (sump-chimney and roof development, respectively). The Reda and Russo reports present comparisons of SANSMIC simulations with laboratory-scale experimental results. However, calculations using the current version of the code were not been able to reproduce the earlier SANSMIC results (Rudeen, Lord et al. 2011). It is therefore possible that the current version of the code has gone through undocumented revisions or modeling was performed at the cavern-scale and results were scaled-down to the laboratory-scale. A repeat of some of the validation work presented in the SANSMIC User's Manual (Russo 1983) is documented in this report as a second attempt to reproduce past results but, this time, with cavern scale data. Early in the development of SPR caverns, an independent validation document was written by Eyermann (Eyermann 1984). He compared SANSMIC simulations to five caverns developed at West Hackberry (101, 103, 108) and Bryan Mound (103, 105). Volume and geometry comparisons are provided but there were no input details. The attempt at reproducing some of his results is also provided herein.

In this report, "SANSMIC" refers to the current version of SANSMIC and its results; "Russo," "Eyermann" and SANSMIC-83 will refer to the code and results as reported by Russo and Eyermann, respectively.

2.1.4 SANSMIC Application in the SPR

SANSMIC has a broad range of utility at SPR including: remedial leach planning, available drawdown estimation using pillar-to-diameter ratio, and cavern selection for crude oil delivery. It is currently being used in an investigation into the feasibility of leaching BM5 and WH9 to a more stable configuration. Recently, it was used in selecting and planning remedial leaching activities for the purpose of expanding the reserve's storage capacity and ullage. SANSMIC was used to identify available leaching zones and to estimate storage volumes that could be created which have minimal effect on cavern stability and available drawdowns.

The SPR caverns were designed for five drawdown cycles, presumably over a 20 year period. Over the reserve's lifetime, no full drawdown order has ever been given. Thus, only partial withdrawals, like that of the 2011 30 MMB sale, and other comparably small raw-water movements have occurred. The analysis of these movements has shed light on the potentially deleterious effect of small-volume raw-water movements near the bottom of caverns, which reduced pillar-to-diameter ratios and resulted in the loss of future drawdowns. Recently, SANSMIC was used to predict the future cavern geometry assuming multiple full-cavern drawdowns in order to calculate the projected P/D ratios and resulting number-of-available drawdowns until limiting P/D criteria are violated.

BM5 and WH9 are phase I caverns that were acquired by the SPR and are oddly shaped. It is thought that with prescribed leaching the accessible reserve volume would increase and geomechanical stability might be improved. The investigation is still in the earliest stages as the research and cost/benefit analyses are not complete at this time. If feasibility is shown, SANSMIC would be used in developing leaching plans. It is of note that phase I caverns generally fall outside of the normal geometry for which SANSMIC was written. Such geometry is untested and results are not verified. The implication is that any leach plan for developing odd-shaped phase-I caverns must be monitored closely.

2.2 Objectives and Scope

The objective of this report is to validate each of SANSMIC's available leaching modes – withdrawal, top-inject, bottom-inject including concurrent oil fill – by comparing simulation results with available data. Identification of trends in the difference between observed and SANSMIC predicted data could be used to improve SANSMIC models. No absolute measure of acceptability has been pre-defined for a successful validation. Instead, this report provides what level of accuracy can be expected from SANSMIC simulations.

Several simulations of each scenario are used to verify the consistency of identified trends. Within a given scenario, different scales of raw-water rates, raw water volumes and multiple, relative hanging string and OBI locations are investigated in order to add robustness to the validation.

Finally, where available, current SANSMIC results are compared with historical results in order to assess whether there have been significant changes to the code since its original documentation and validation.

2.3 Flow of Report

This report covers validation of the following leach capabilities of SANSMIC: withdrawal-leach (section 3), bottom-inject or direct-leach (section 4), and top-inject or reverse-leach (section 5).

At the end of each leach mode, there is a side-by-side comparison of all simulations of that type. The withdrawal leach validation investigates three withdrawal scales: small (10-30% cavern volume), medium (30-60% cavern volume), and large (60-100% cavern volume). The small withdrawals are from the 2011 sale and include BH103 and BH104. Two medium withdrawals are presented, BH101 and BH104, each of which underwent two withdrawal-fill cycles until half empty. Large withdrawals are covered by the WH105 conversion from sweet to sour and WH106 which was used to partially refill WH105.

Bottom-inject (direct leach) data are only available in SPR Cavern Completion Reports for the sump, chimney, and combined sump/chimney stages. BM104 is presented with separate sump and chimney stages; BM106 with a combined sump/chimney stage; and WH101's combined sump/chimney stage.

Top-inject (reverse leach) comparisons are almost exclusively available via the SPR Cavern Completion Reports. Three top-inject scenarios are investigated in order to cover a range of injection string, production string and OBI separation. First and second reverse leach stages are presented for WH101 (a sonar was not conducted following the third reverse leach stage and so this individual stage is not considered in this report). First, second, and third reverse leach stages are each presented for WH103, WH104, and WH105.

Leach mode validation coverage is summarized in Table 2-1. Note that several of the validation test cases discussed in this report overlap with validation/verification (V&V) exercises documented by Russo (Russo 1981; Russo 1983) and by Eyermann (Eyermann 1984). The overlapping validation exercises are footnoted in Table 2-1 and cover both top-inject and bottom-inject leach modes. Comparisons with historical verification results provide insight as to whether the SANSMIC code has undergone any significant changes since its original documentation in 1981-1983.

Table 2-1. Leach Mode Validation Coverage.
Shown is the section addressing the test case (App – Appendix).

	Withdrawal			Direct			Reverse		
	Small	Medium	Large	Sump	Chimney	Combined	Rev 1	Rev 2	Rev 3
BH103	3.1								
BH104	App	App							
BH101		3.2							
BM104				4.1[2]	4.2				
BM106						4.3[2]	App		
WH101						4.4[1,2]	5.1.1[1,2]	5.1.2[1]	
WH103							5.2.1[1]	5.2.2[1]	5.2.3
WH104							App	App	App
WH105			3.3				App	App	App
WH106			App						

1. Includes Eyermann validation data.
2. Includes Russo validation data.

In order to avoid duplicate discussions in subsequent analysis sections of this report, the layout used for each validation test case is described below. More specifically, each cavern's leaching stage or validation test case follows a similar format with a subsection covering the settings, pre and post geometry in the form of cavern average-radius profiles, and tabulation of leached volume statistics. Not all validation test cases are covered in detail in the body of the report. Test cases are covered in detail because they were representative, particularly interesting, or overlapped with the historical verification. All test case inputs are summarized in the Appendix.

In each detailed discussion, the settings subsection includes a timeline of events (Figure 2-1) displaying logging activities and raw water (blue) and oil injection (black) volumes in thousands of barrels per day (MBB) each day of known activity. Oil volumes (black) are shown as negative to avoid messy overlap with raw water injections or can be thought of as brine withdrawal. Since total volumes are conserved, modeling differences should be negligible. It is important to note that not only are the volumes from the completion reports estimates, but the exact dates of raw water injection are not known – they are reported as monthly totals or averages. The "OBI recalibration" marker (orange squares) refers to an adjustment made within the SANSMIC input file to move the OBI to the measured depth location in order to minimize effects of errors in oil transfer volumes and to focus more specifically on dissolution modeling. Adjustments are normally less than ~20 ft. The purple and green squares designate times of interface and sonar logging activities (y-values are meaningless). Finally, cumulative injected volume (red) is plotted with scale on the right in millions of barrels (MMB).

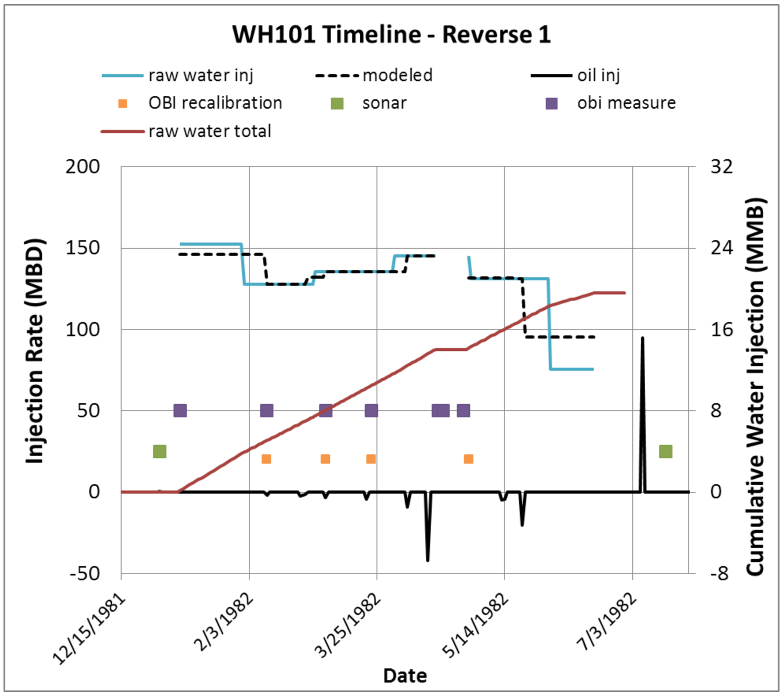


Figure 2-1. Sample Timeline.

A summary configuration table with rates, activity durations, as well as injection/production/OBI depths is also included as illustrated in Table 2-2 for BM104. Settings with more than one value (Injection depth, for example) usually indicate different values for different phases of the analysis or values for an ancillary simulation. A footnote describes notation. Here, for example, the injection depth was 4410 ft for the sump phase and 4341 ft for the chimney phase.

Table 2-2. Sample Configuration and Settings.

Setting	Value
Sonar dates	Borehole, 9/80, 7/81
Raw water injection dates	7/15/80 – 5/8/81 (sporadic injection downtime)
Activity duration, days	101; 132*
Injection depth, ft	4410; 4341*
Production depth, ft	4225; 2292*
Touch down depth, ft	4495
OBI start depth, ft	3226; 2187*
OBI end depth, ft	2187
Average raw water rate, BPD	73,280; 64,580*
Raw water volume, BBL	7,400,000; 8,530,000*
Oil rate, BPD	Small sporadic withdrawal and fill
Oil volume, BBL	Small

* Notation: Sump data; chimney data. Values are composites of three individual well datasets.

The settings section is concluded with a figure displaying the initial cavern geometry with annotations of the string and OBI depths. An example is shown in Figure 2-2. Here the initial geometry is labeled with the sonar date; the initial and final OBI (if measured) are indicated as are injection and production string depths.

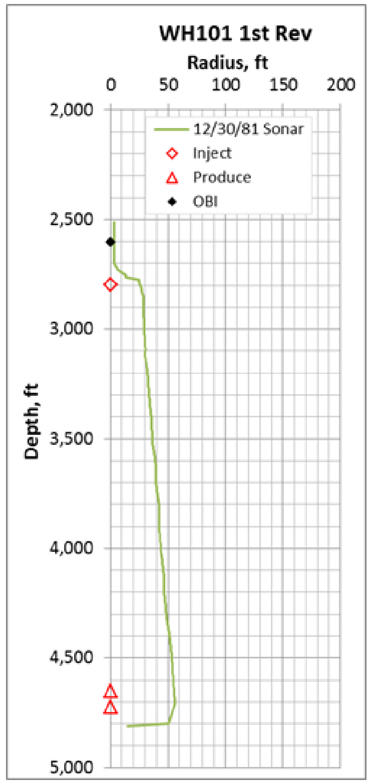
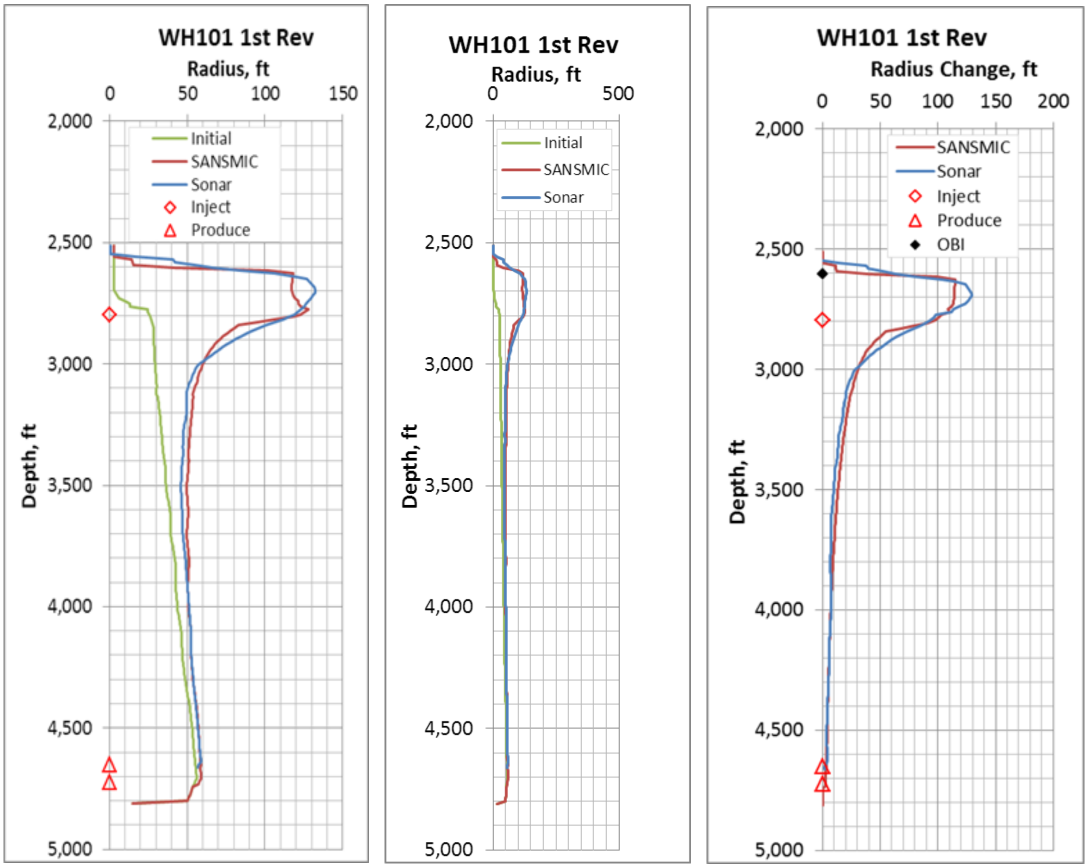


Figure 2-2. Sample Initial Configuration.

Following the settings section is a section covering pre and post leach cavern geometry comparisons, using average cavern radius versus depth profiles. The initial average radius cavern profile is derived from sonar survey data that comes in two forms - volume versus depth or radius versus azimuth at a series of depth stations. The change in geometry due to leaching is shown in two different figures. Figure 2-3(a) shows the initial and final average radius profiles, where initial cavern geometry is sonar data (green) and final geometry is shown for both SANSMIC predicted (red) and SONAR measured (blue). Note that the radius scale in Figure 2-3(a) is expanded by a factor >10 so differences are exaggerated and more readily interpreted. As a comparative example, the same data are plotted in Figure 2-3(b) at the same radius and depth scales giving a picture of the cavern “to scale”. Figure 2-3(c) shows the cavern average radius-change between the initial and final sonars (blue) and the radius-change as predicted by SANSMIC (red).



(a) Average Radius Profile (b) 1:1 Scaling (c) Radius-Change

Figure 2-3. Sample Average Radius Profiles.

The final section contains a discussion on leached volume statistical parameters. This section includes a table comparing the predicted and observed leached volume and leach efficiency as illustrated in Table 2-3. Leach efficiency is the leached volume divided by volume of injected raw water. The theoretical maximum is around 16-17% depending on raw water properties. Leached volume in this document is the change in volume over the depth range of leach activity, in order to eliminate sonar differences in regions not exposed to unsaturated brine.

Table 2-3. Sample Volume Statistics.

Parameter	Sonar	SANSMIC
Raw water injected, BBL	19,570,000	
Initial volume, BBL	2,030,000	
Leached volume, BBL	2,960,000	2,940,000
Leach efficiency	15.1%	15.0%
Relative volume difference	-0.8%	
Relative radius difference	5.2%	
Mean radius difference	-0.3	
RMS of radius difference	5.0	

Relative volume difference is the difference in volume leached (predicted-observed) divided by the surveyed leached volume; negative indicates SANSMIC under estimated leach volume. Relative radius difference is the absolute value of radius difference divided by the average measured cavern radius at that depth. Mean radius difference is the mean of the radius difference (predicted-observed) and can be small if over and under predictions cancel. RMS is the root-mean-squared of the radius difference (predicted-measured):

$$RMS = \sqrt{\frac{\sum\left(R_i^S - R_i^O\right)^2}{n}}$$

R_i^S = SANSMIC radius at depth i

R_i^O = Observed average radius at depth i

A value of 1-2 ft is within the sonar measurement error. Relative measures less than 10% are considered reasonable and less than 5% are considered very good. Relative volume difference greater than >15% probably indicates errors in injected raw water volume or significant sonar error. Experience over the last few years has indicated that SANSMIC predicts leached volume reasonably well.

To avoid unwanted numerical influences, volumes and radius statistics are calculated over carefully selected depth ranges that cover the range of leach activity – usually from the highest OBI to the highest floor location (simulated or observed). Total cavern volumes are typically only calculated for the initial sonar data and even though the initial sonar is used as input to SANSMIC, SANSMIC initial volume may be slightly different than the sonar data due to how the input is handled internally in SANSMIC. Accuracy to only 4 or 5 significant digits can be expected, so differences in cavern and injected volumes can be on the order of tens of thousands of barrels. Also, note that a typical sonar error of 1 ft (1%) in a cavern radius of 100 ft will integrate to ~10,000 BBL over 100 ft.

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3 Withdrawal Leach Validation Test Cases

The 2011 30 MMB sale and subsequent remedial leaching activities resulted in a large set of useable data for validating the withdrawal leach capabilities of SANSMIC. To test the full range of the withdrawal leach data, two caverns are simulated for each of three volume ranges – one is detailed below with a summary of the second in the appendix. For small withdrawals, in which 10-30% of the stored oil is withdrawn, caverns BH103 (this section) and BH104 (in appendix) are simulated, both of which were utilized in the 30 MMB sale in 2011. Medium withdrawals, covering 31-60% of volume removal, are represented by BH101 (this section) and BH104 (in appendix) which were involved in a two-cycle linked withdrawal leach. Large withdrawals (61-100% of oil volume) are validated with WH105 (this section) and WH106 (in appendix) in which WH105 was completely emptied for the temporary conversion from sweet to sour crude oil storage and WH106 was used to partially refill WH105.

3.1 BH103 Small Withdrawal Test Case

For the small withdrawal test cases, the volume of oil removed is between 10 and 30% of the cavern volume. That is, 1 to 3 MMB of raw-water is injected creating 160 to 500 MB of new cavern volume. BH103 is detailed below; BH104 is summarized in the appendix.

BH103 was a selected cavern in the 2011 30 MMB sale. Raw water injection occurred from approximately 6/29/2011 until 8/31/2011 resulting in approximately 11% of the oil being removed from the cavern.

3.1.1 Leaching Settings

A timeline of events for BH103 including raw water and oil injections rates; cumulative raw water volume; and logging activity is presented in Figure 3-1. Table 3-1 presents the string configuration and leach parameter settings. The initial sonar is shown in Figure 3-2 with the string and OBI depths annotated.

BH103 is a relatively small withdrawal with approximately 1.35 MMB of raw water injected. The duration of the raw water injection is typical of the other selected caverns, but the injection rate is only half that of the capabilities at the SPR. At the start of injection, the OBI was just above the injection depth. As it was a relatively small withdrawal, the OBI only rose ~200 ft.

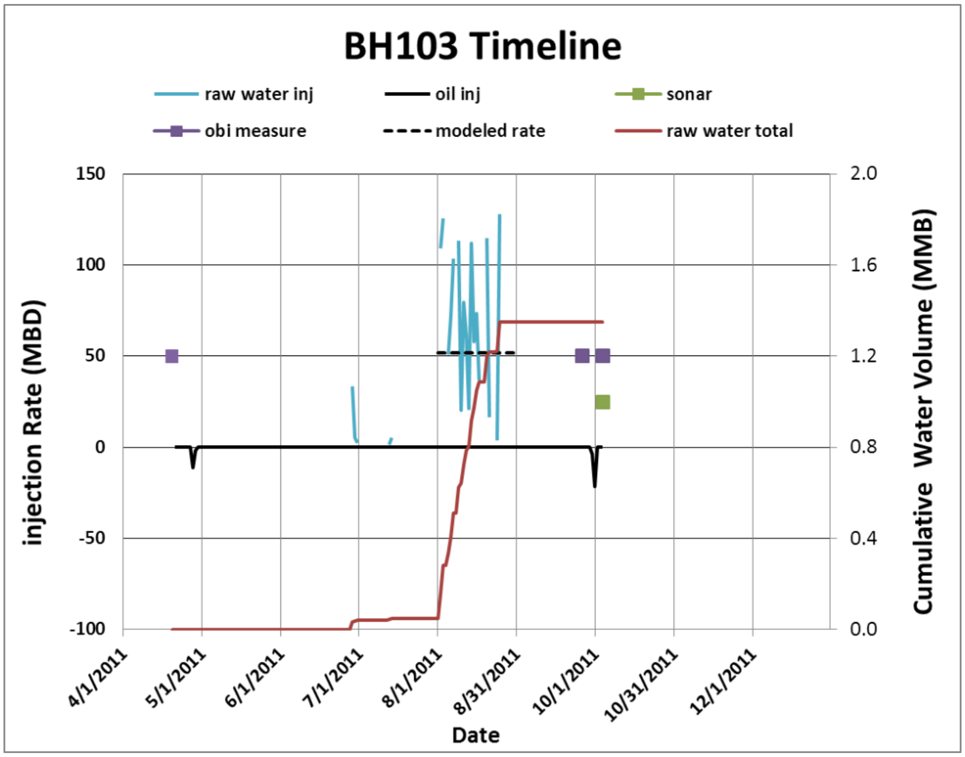


Figure 3-1. Timeline of BH103 Small Withdrawal.

Table 3-1. Leach Configuration Data for BH103 Small Withdrawal.

Setting	Value
Initial and final Sonar	4/23/2009 and 10/4/2011
Raw water injection period	6/29/2011-8/31/2011
Activity duration, days	RW: 26
Injection depth, ft	3856
OBI start depth, ft	3852
OBI end depth, ft	3643
Average raw water rate, BPD	51,980
Raw water volume, BBL	1,350,000

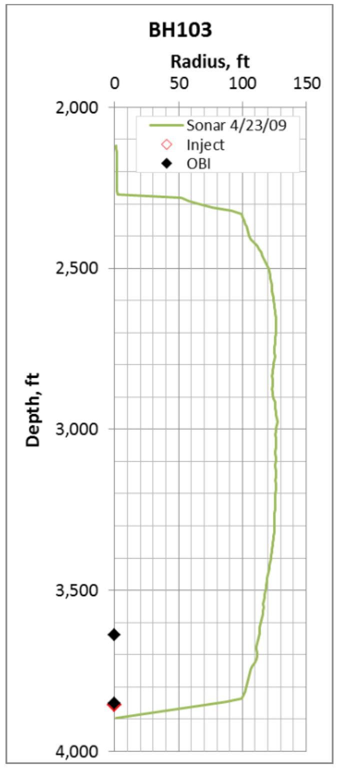


Figure 3-2. Initial Configuration of BH103 Small Withdrawal.

3.1.2 Geometry Comparison

The predicted and observed geometries due to the raw water injection are presented in Figure 3-3. There is good agreement between the predicted and measured final geometry. A slight variation is seen in the floor of the cavern – it appears to have risen more than is predicted by SANSMIC. However, there is an apparent salt-fall between 2800 and 3000 ft, that could have caused the floor rise. It is worth noting that BH103 has a history of significant salt-fall. From the 3D view of the cavern in Figure 3-3(a) it appears that the salt-fall could be extending a spine in the cavern wall. SANSMIC keeps track of floor rise internally and does not adjust the computational grid or adjust cavern radius to zero below the calculated floor. Thus, floor rise is not always apparent in radius profiles. SANSMIC does, however, account for floor rise in volume and wall exposure calculations.

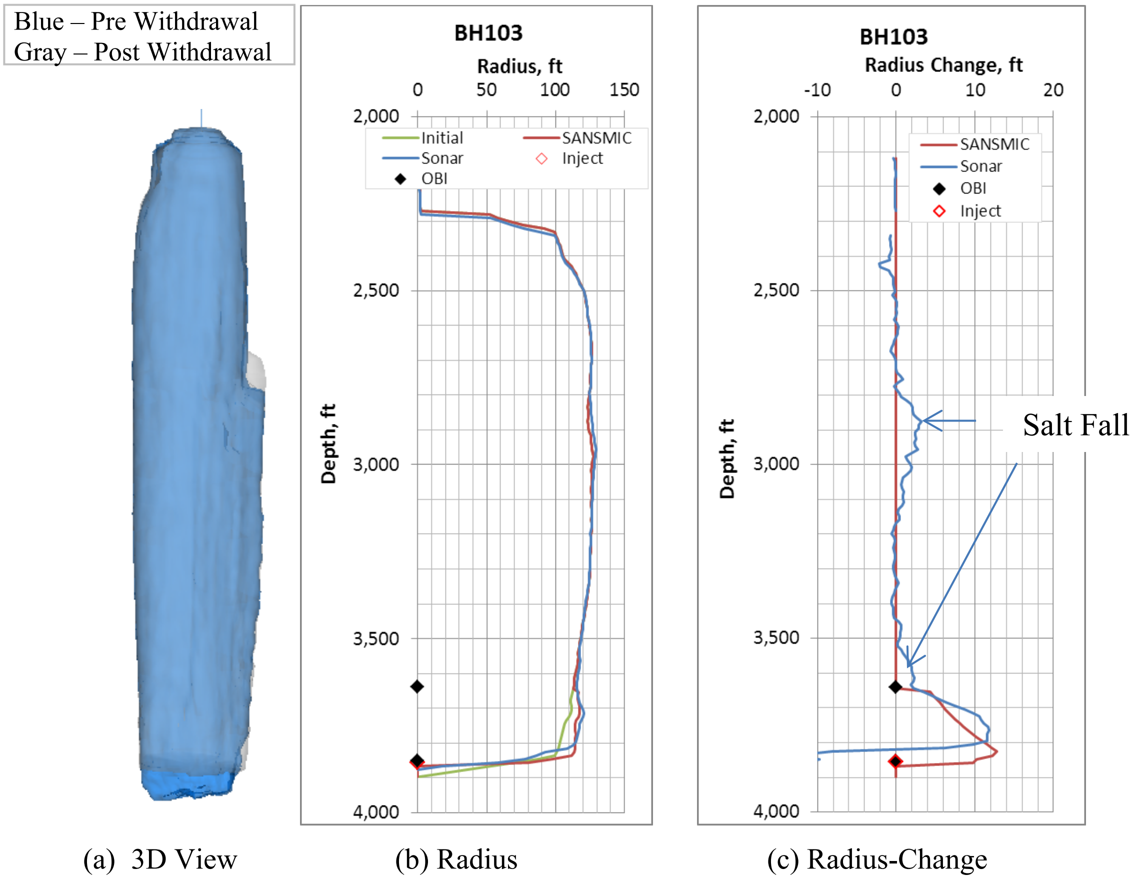


Figure 3-3. Sonar vs. SANSMIC Cavern Profiles for BH103 Small Withdrawal.

The radius-change as a function of depth is shown in Figure 3-3(c). As would be expected, SANSMIC predicts a radius-change only in the very lower portion of the cavern where raw water is present with the leaching tapering off as it approaches the final OBI depth. There are slight variations (< 5 ft) in the sonar above the final OBI (where leaching could not have occurred) and this is likely due to salt fall. The greatest discrepancy between the actual and predicted results is confined to the very bottom of the cavern near the cavern floor where salt fall has accumulated.

3.1.3 Leached Volume Comparison

A summary of the leached volumes and efficiencies are presented in Table 3-2. The leached volumes differ by 40 MB, which results in a difference in leach volume of -17.2%. Most of the volume discrepancy is in the very lowest depths affected by the cavern floor rise. A predicted leach efficiency of almost 14% is shown for SANSMIC, and observed efficiency is higher at 17%. Salt fall has likely affected the accuracy of the leached volume calculations.

Table 3-2. Volume Statistics for BH103 Small Withdrawal.

Parameter	Sonar	SANSMIC
Raw water injected, BBL	1,352,000	
Initial volume, BBL	12,413,000	
Leached volume , BBL	232,000	192,000
Leach efficiency, %	17.2	14.2
Relative leached volume difference	-17.2%	
Relative radius difference	1.6%	
Mean radius difference	-1.6	
RMS of radius difference	2.2	

3.2 BH101 Medium Withdrawal Test Case

For the medium withdrawal test cases discussed here, the volume of oil removed is between 31 and 60% of the cavern volume. That is, 3 to 6 MMB of raw-water are injected creating 450 to 1,000 MB of new cavern volume. BH101 is discussed below; BH104 is summarized in the appendix.

BH101 was used in a linked withdrawal leaching effort between BH101 and BH104. The injected raw water displaced the oil until the OBI was approximately half-way up the cavern. This was repeated a second time after the refilling of the cavern with oil from BH104 such that the cavern was half emptied twice. A more detailed analysis was conducted in a prior report (Weber, Gutierrez et al. 2013). Since the final sonar was taken after the second withdrawal, the two withdrawals are treated as a single event for validation purposes.

3.2.1 Leach Settings

A timeline of events for BH101 withdrawal is presented in Figure 3-4 and Table 3-3 presents the string configurations and leaching parameter settings. The initial sonar is shown in Figure 3-5 with brine string and OBI depths annotated. The first injection period lasted from 11/11/2011-1/5/2012 followed by the cavern being refilled. The second injection period lasted from 4/28/2012-8/8/2012, with the string being perforated at a depth of 3916 ft after plugging sometime after 5/21/2012.

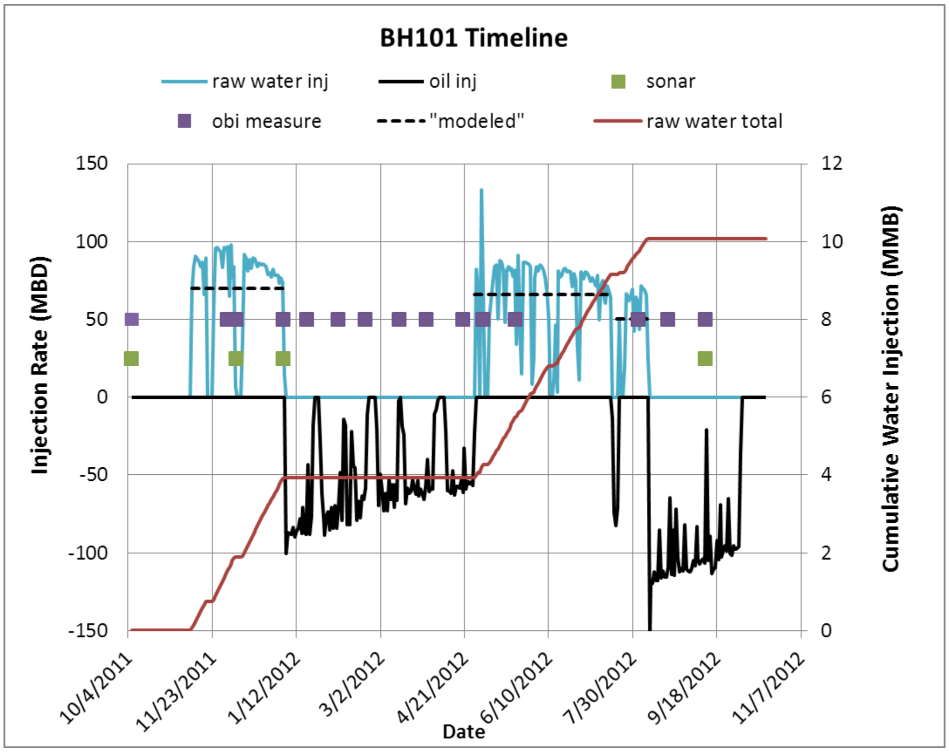
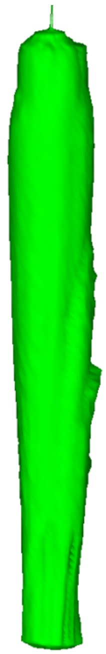


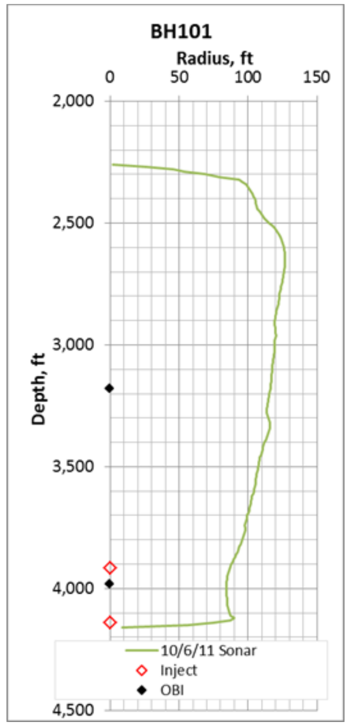
Figure 3-4. Timeline of BH101 Medium Withdrawal.

Table 3-3. Leach Configuration Data of BH101 Medium Withdrawal

Setting	Value*
Sonar dates	10/6/2011, 9/11/2012
Raw water injection dates (active days)	11/11/2011-1/5/2012 (56); 4/28/2012-8/8/2012 (98)
Oil injection dates (active days)	1/6/2012-4/27/2012 (112); 7/18/2012-10/2/2012 (59)
Injection depth, ft	4140 (3916 perforated string early 2nd cycle)
OBI start depth, ft	3760; 4110
OBI end depth, ft	3177; 3200
Average raw water rate, BPD	70,000; 63,000
Raw water volume, BBL	3,920,000; 6,190,000 (10,110,000 total)
Average oil rate, BPD	53,000; 98,000
Injected oil volume Injected, BBL	5,920,000; 5,770,000 (11,690,000 total)

* Notation: first withdrawal; 2nd withdrawal





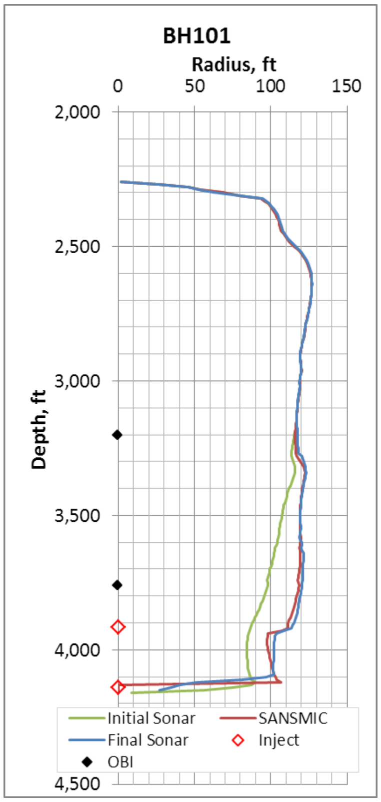
(a) 3D (b) Average Radius; injection string with break

Figure 3-5. Initial Configuration of BH101 Medium Withdrawal.

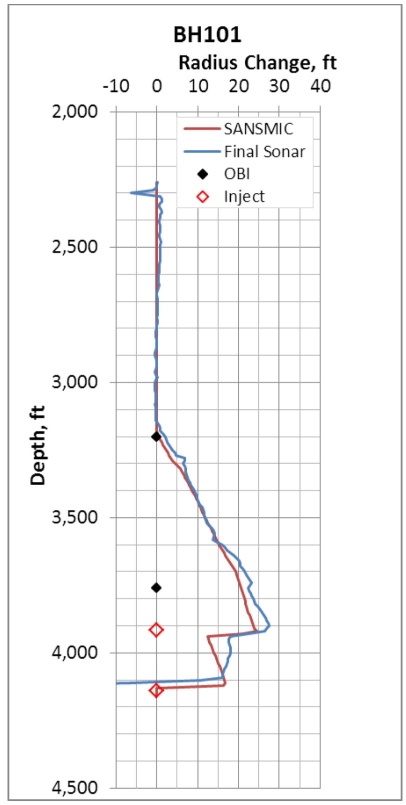
The injection depths are shown as red diamonds in the figure. The OBI started approximately one fifth of the way up the cavern wall, was displaced until it reached approximately one half the depth of the cavern. The cavern was then refilled and the OBI was again displaced until it was approximately one half of the way up the cavern wall. The maximum extent of oil movements are displayed in the figure with black diamonds

3.2.2 Geometry Comparison

The predicted and measured geometries due to the raw water injection are presented in Figure 3-6. There is good agreement between the predicted and final measured geometry. A slight variation is seen in the floor of the cavern as it appears to have risen more than is predicted in SANSMIC which may be due to the assumed insoluble fraction (0.04). SANSMIC predicts reasonably well the ledge formation caused by the string perforation at 3916 ft. SANSMIC slightly under predicts the volume created above both the initial and string break injection points. The original radius change shows a consistent offset of ~2 ft above the final OBI, where no leaching should have occurred, indicating possible sonar error. The error is removed for the comparisons shown (Figure 3-6b) by adjusting the final average radius by 1%. The radius-change shows very good agreement including the location and size of shelf resulting from the broken string at ~3900 ft and indicates only slight under prediction of leached volume, particularly just above the injection locations.



(a) Average Radius



(b) Radius-Change

Figure 3-6. Sonar vs. SANSMIC Profiles of BH101 Medium Withdrawal.
Bias in final sonar removed by adjusting final radius by 1%.

3.2.3 Leached Volume Comparison

A summary of the leached volumes and efficiencies, both measured and predicted are presented in Table 3-4. The leached volume and efficiencies reflect the slight under prediction of leached volume with a relative leached volume difference of more than -9%. A more thorough discussion is given in a prior report (Weber, Gutierrez et al. 2013).

Table 3-4. Volume Statistics for BH101 Medium Withdrawal.
Final sonar corrected by 0.99 to remove bias.

Parameter	Sonar	SANSMIC
Raw water injected, BBL	10,110,000	
Initial volume, BBL	12,370,000	
Leached volume, BBL	1,580,000	1,430,000
Leach efficiency, %	15.6	14.2
Relative volume difference	-9.5%	
Relative radius difference	1.5%	
Mean radius difference	-1.6	
RMS of radius difference	2.2	

3.3 WH105 Large Withdrawal Test Case

For the large withdrawal test cases the volume of oil removed is between 61 and 100% of the cavern volume. That is, 6 to 12 MMB of raw-water are injected creating 1 to 2 MMB of new cavern volume. WH105 is discussed below; WH106 is summarized in the appendix.

WH105 was the cavern selected to undergo temporary conversion from sweet crude oil storage to sour crude oil storage as described in (Weber, Gutierrez et al. 2013). As such, it was to be completely emptied and subsequently refilled with oil. Sporadic oil movements occurred after it had been emptied while decisions on storage of Bakken crude oil were made. The oil fill volumes were on the order of 10-250 MMB and occurred near the bottom of the cavern (>4200 ft). The 2 MMB withdrawal in July 2011 was part of the 30 MMB summer of 2011 sale.

3.3.1 Leach Settings

A timeline of events for WH105 is presented in Figure 3-7. Between the time of the initial sonar in 2004 and the large withdrawal in 2011 (not shown) there were small fresh water injections that were included in the simulations in order to create the proper initial conditions for the intended large withdrawal test case. WH105 underwent oil withdrawal during the 30 MMB sale from 7/16/2011-8/28/2011. The removal of the majority of the oil occurred from 11/4/2011-2/12/2012 along with many OBI measurements (purple squares). It was near the end of this period that the string broke (midway between the second and third injection periods in Figure 3-7). It was then partially refilled with oil from WH106 during the time period of 5/22/2012-7/11/2012 during which there were periodic injections of saturated brine (narrow blue spikes). Raw water was then injected from 8/20/2012 until 10/1/2012.

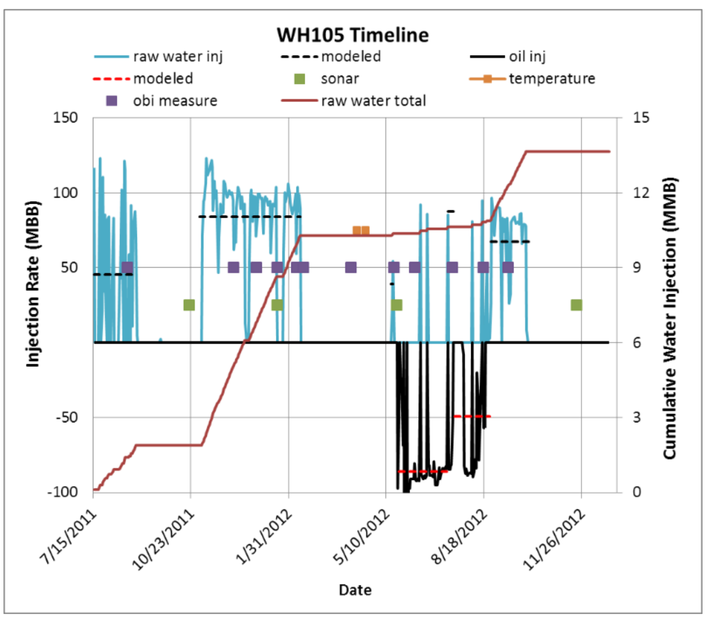
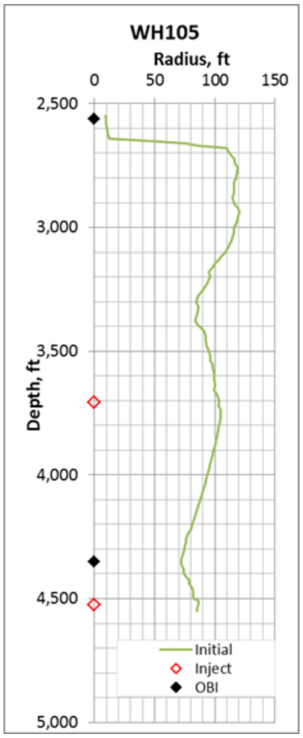


Figure 3-7. Timeline of WH105 Large Withdrawal.
Not shown are raw water injections between the initial sonar on 12/8/2004 and 7/15/2011.

Table 3-5 contains the configuration and leach settings for the withdrawal periods as well as the oil injection periods. Figure 3-8 shows the initial sonar with the string and OBI depths annotated on the axisymmetric geometry. The injection depths are also shown in the figure below.

Table 3-5. Leach Configuration Data of WH105 Large Withdrawal.

Setting	Value
Sonar dates	12/8/2004; 11/21/2012
Major raw water injection periods (duration in days)	multiple (320)
Oil Injection dates (active days)	5/22/2012-7/11/2012 (49); 7/13/2012-8/19/2012 (36)
Injection depth, ft	4564 (3707 broken string between 2/8/12-2/14/12)
OBI start depth, ft	4553
OBI end depth, ft	3382
Average raw water rates, BPD	61,120
Raw water volume, BBL	14,360,000
Average oil rate, BPD	70,410
Oil volume, BBL	5,990,000

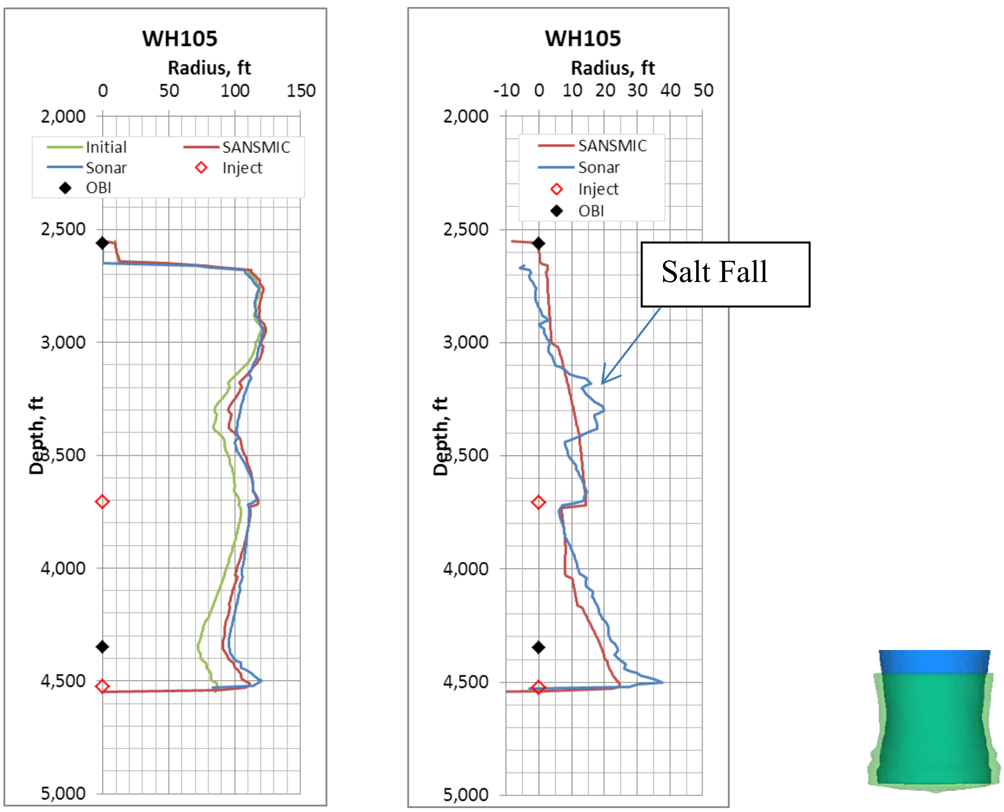


(a) 3D (b) Average Radius

Figure 3-8. Initial Configuration of WH105 Large Withdrawal.

3.3.2 Geometry Comparison

The predicted and measured geometries due to the raw water injection are presented in Figure 3-9. Again, there is reasonable agreement between the SANSMIC prediction and the observed result. SANSMIC over predicts volume creation in two disjoint regions 2650-3100 ft and 3400-3600 ft and under predicts from 3100-3400 ft and below 3800 ft. The large difference below 3900 ft is likely due, at least partially, to sonar error. This is evidenced by the sonar discrepancy seen in the 3D overlays in Figure 3-9(c), which are only partial cavern sonars below the existing OBI. The 2005 (green) sonar is larger than the 2004 (blue) sonar. The difference is unexpected because there were no water injections during this time period.



(a) radius (b) radius change (c) partial sonars from 2005(green), 2004(blue)

Figure 3-9. Sonar vs. SANSMIC Profiles of WH105 Large Withdrawal.

The radius-change as a function of depth shown in Figure 3-9(b) focuses in on the leach effects. Differences below 3700 ft are about a factor of two larger than seen in previous presentations, possibly due to the timing of the string break at 3707 ft or due to suspected sonar error. When sonar surveying through a hanging string, the sound speed is either estimated or measured below the end of string and used throughout the string length. Excluding the small region near 4500 ft and the salt fall, the difference between the sonar and SANSMIC in the change of radius is less than ~10 ft at any given depth and less than 5 ft above the string break.

3.3.3 Leached Volume Comparison

A summary of the leached volumes and efficiencies, both actual and predicted, is presented in Table 3-6. SANSMIC under estimates leached volume by ~10%. This difference leads to an observed leach efficiency of 16% and a SANSMIC predicted leach efficiency of 14%. An under measured cavern radius in the initial sonar could explain the higher than observed leached volume and efficiency.

Table 3-6. Volume Statistics for WH105 Large Withdrawal.

Parameter	Sonar	SANSMIC
Raw water injected, BBL	14,360,000	
Initial volume, BBL	10,050,000	
Leached volume, BBL	2,260,000	2,040,000
Leach efficiency	15.8%	14.2%
Relative volume difference	-9.8%	
Relative radius difference	3.2	
Mean radius difference	-1.3	
RMS of radius difference	4.4	

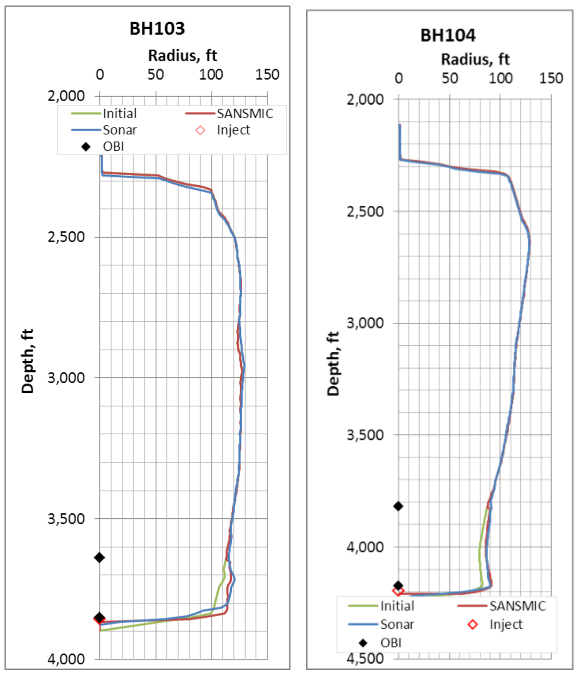
3.4 Comparisons of All Withdrawal Leach Test Cases

Cavern profiles and radius-change for all withdrawal test cases are provided in Figure 3-10 and Figure 3-11, respectively. The leach profile is generally tapered from the maximum radius at the injection point to nearly zero at the final OBI position, thus the change in radius is closely related to exposure time. Withdrawal leaches are modeled very well by SANSMIC including the shelf formation at the depth of string breaks which occurred in three of the six test cases. The good comparisons are reflected in the low relative volume and radius statistics in Table 3-7, with two exceptions: BH103 small withdrawal for which leach volume was difficult to resolve because of salt fall; and BH104 medium withdrawal which had an observed leach efficiency of 18%, higher than the theoretical maximum which may indicate either an under estimate of injected volume and/or sonar error.

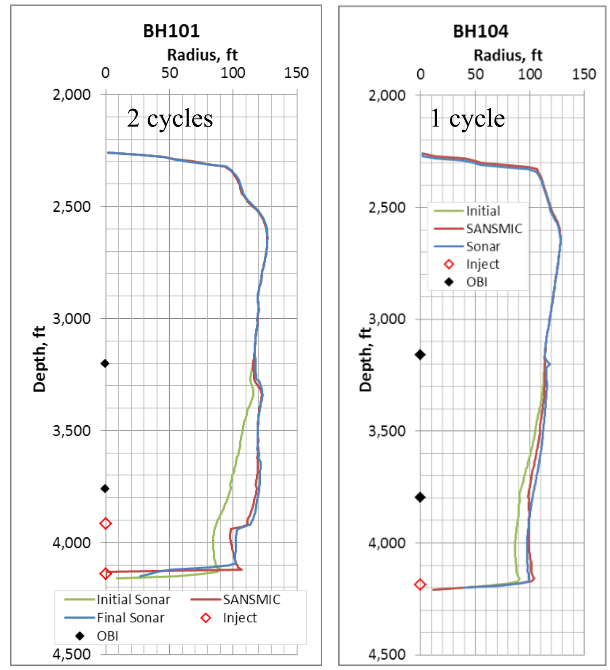
Table 3-7. Volume Statistics Summary for all Withdrawal Cases.

Cavern ID	Relative Volume	Relative Radius	Mean Radius Difference	RMS of Radius
BH103 (S)	-17.2%	1.6%	-1.6	2.2
BH104 (S)	6.3%	1.5%	-0.5	1.5
BH101 (M)	-9.5%	1.5%	-1.6	2.2
BH104 (M)	23.1%*	2.4%	-1.5	3.0
WH105 (L)	-9.8%	3.2%	-1.3	4.4
WH106 (L)	-5.7%	2.1%	0.9	2.7
Average(Abs)	7.8%	2.0%	–	–

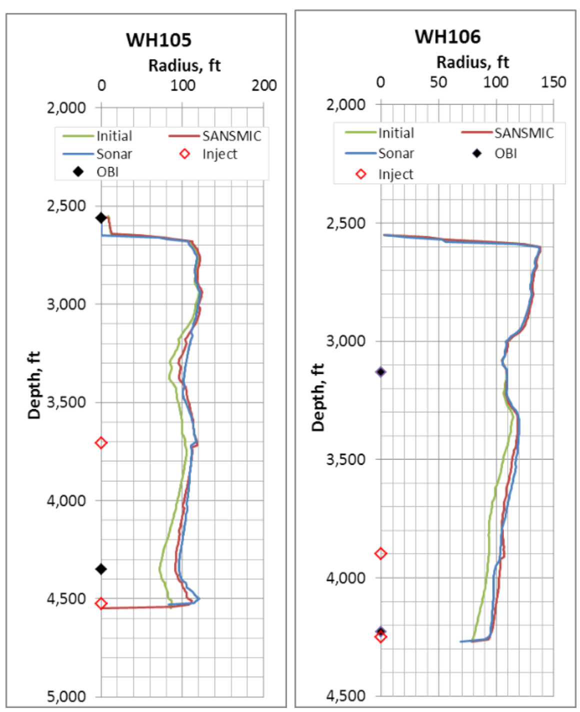
*18% efficiency is higher than theoretical maximum, therefore BH104(M) is excluded from the average.



(a)Small Withdrawal

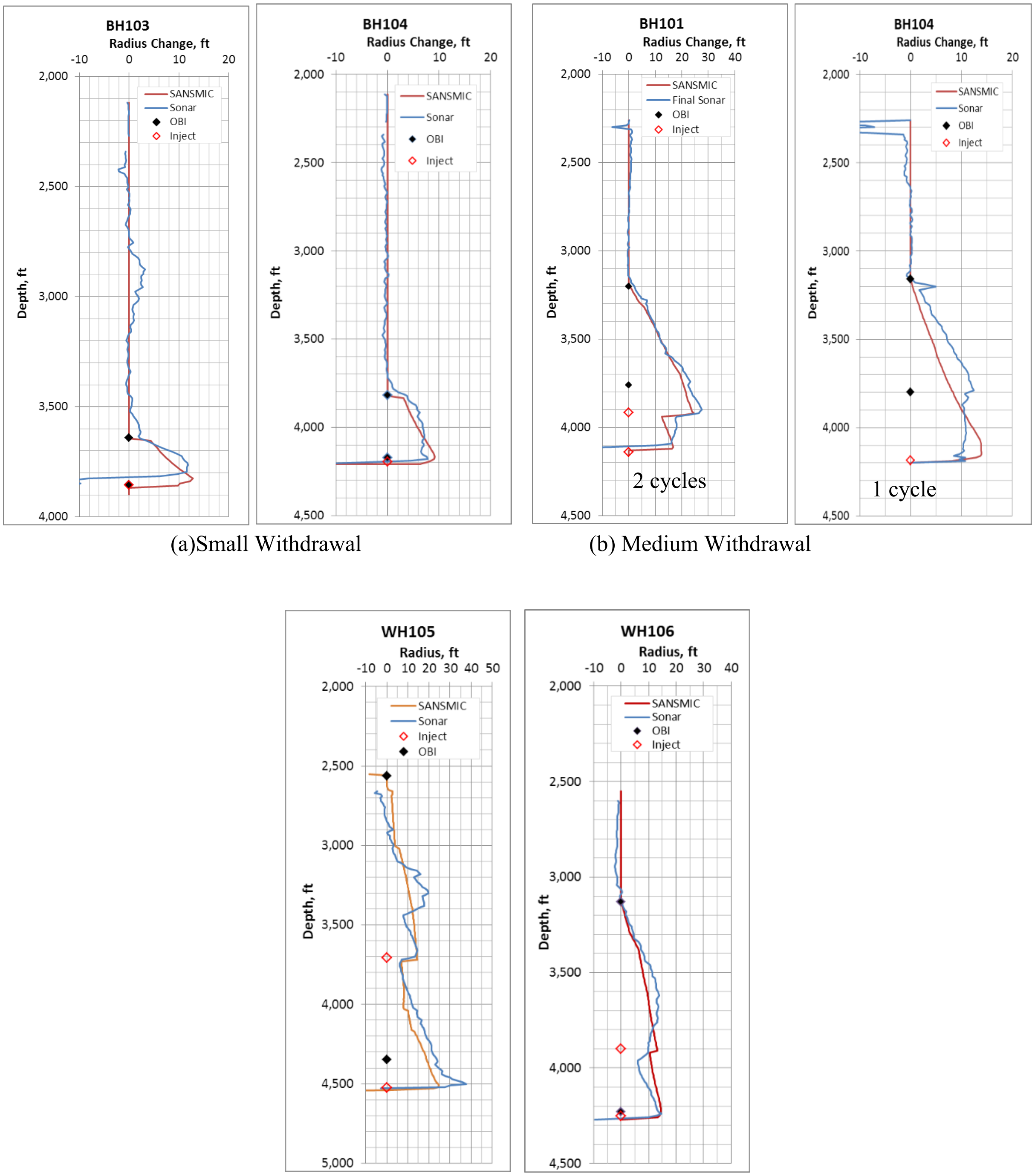


(b) Medium Withdrawal



(c)Large Withdrawal

Figure 3-10. Cavern Profile Comparisons for All Withdrawal Leach Test Cases.



(a)Small Withdrawal

(b) Medium Withdrawal

(c)Large Withdrawal

Figure 3-11. Radius-Change Comparisons for All Withdrawal Leach Test Cases.

4 Bottom-Inject Validation Test Cases

Bottom-inject leaching, also known as direct-leaching, requires the use of two hanging brine strings with the injection string below the production string. The OBI may be static, or in the case of leach-fill, moving deeper within the cavern. Bottom-injection was used at the SPR for cavern development during the initial sump and chimney phases. Several different sump/chimney configurations were employed for the 47 caverns developed by SPR because of both desire for time savings and significant plugging which resulted in down time. Choices included either simultaneous three-well development until coalescence or a single well; and either separate sump and chimney or combined sump/chimney stages. Separate sump and chimney stages required an intermediate work over for raising the production casing and the OBI. The combined sump/chimney used a single production location near the proposed roof location. All scenarios generally required periodic small cuts of the injection string because of the accumulation of insolubles. Modeling of the three wells' simultaneous development is done using a single well equivalent where injection rates are combined and average cavern radii are calculated from composite volume versus height data. Examples of several different scenarios are provided below.

4.1 BM104 Bottom-Inject Sump Development Test Case

BM104 was leached from three boreholes to the completion of the sump as recorded in the BM104 Completion Report (PB-KBB 1985a). The leaching activity was previously considered in the SANSMIC report by Russo (Russo 1981). However, Russo only simulated the B-well. Thus, only the B-well sump development is presented in this section for comparison with his work. This comparison gives insight as to whether there have been changes to SANSMIC since its original documentation in the 1981-'83 timeframe. Note that for this case the injection and production locations are only separated by approximately 200 ft.

4.1.1 Leaching Settings

Two simulations of the well-B sump development are shown – the first using the completion report data and the second using the injection data published in Russo. A timeline of events extracted from the completion report is presented in Figure 4-1 as well as the timeline comparing the modeled and reported injections. A marker for OBI recalibration (orange squares) indicates that the modeled OBI depth is adjusted to match the measured value given by the completion report. The figure shows the entire duration of the sump development. However, Russo compared SANSMIC data with a sonar survey taken on September 5, 1980 prior to the completion of the sump phase. Russo's example used and published flow rates that had been estimated by operations personnel. These data are shown in Table 4-1.

Table 4-2 contains the configuration and leach settings for the 45 day injection period up to the September 5, 1980 sonar. String and OBI positions are the same for both the Russo and completion report based simulations. Because the leach stage started from a wellbore, the starting geometry is a cylinder with 0.7 ft radius.

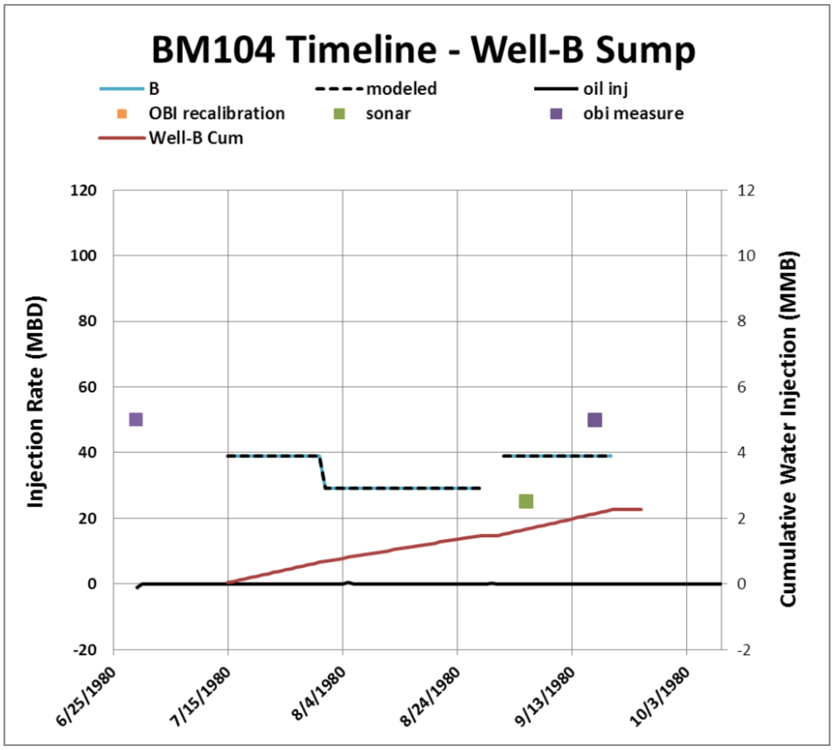


Figure 4-1. Timeline of BM104 Well-B Bottom-Inject Sump Development.

Table 4-1. Injection Data from Russo (1981) BM104 Sump Development.

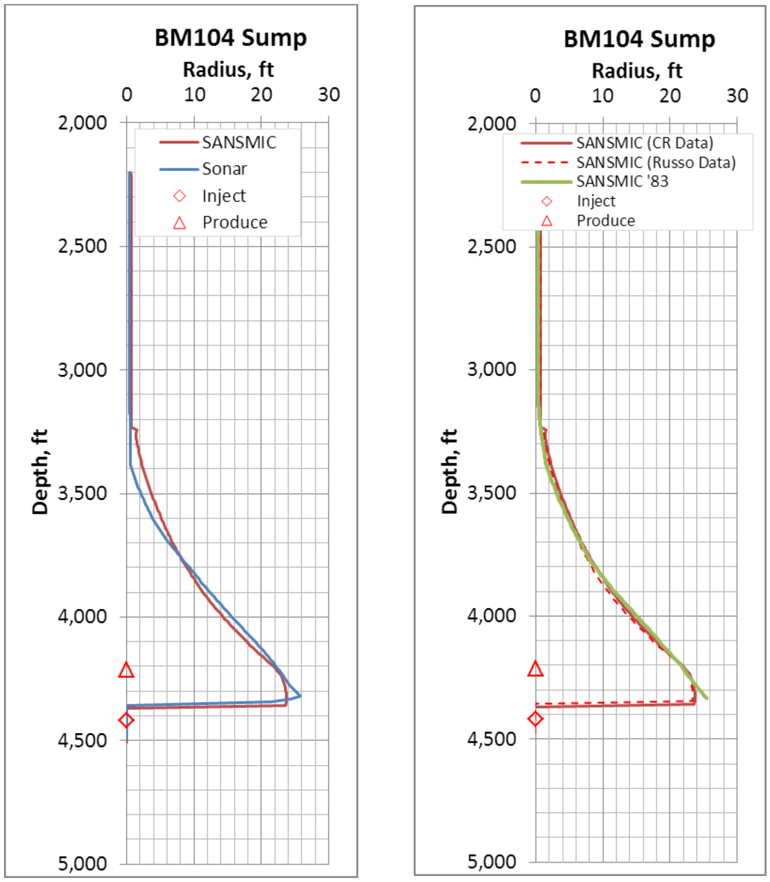
Day	Duration, days	Flow Rate	
		ft^3/hr	BPD
1	1	970.5	4,148
2	1	10,250.6	43,817
3	1	6,192.1	26,469
4	1	10,723.8	45,840
5-7	3	8,437.9	36,068
8-11	4	7,282.9	31,131
12-21	10	8,678.5	37,097
22-23	2	8,470.0	36,206
24-26	3	-	-
27-34	8	8,470.0	36,206
35	1	9,496.8	40,595
36-46	11	7,282.9	31,131
Total	**46**		**1,469,067**
Average			**34,164**

Table 4-2. Leach Configuration Data for BM104 Bottom-Inject Sump Development.

Setting	Value
Sonar dates	Borehole, 9/5/80
Raw water injection dates	7/15/80-9/5/80
Oil injection dates	none
Activity duration, days	17; 28 (45 total)
Injection depth, ft	4419
Production depth, ft	4213
Touch down depth, ft	4495
OBI start depth, ft	3226
OBI end depth, ft	3226
Raw water rate, BPD	39,000; 29,870
Raw water volume, BBL	1,500,000
Oil rate, BPD	0
Oil volume, BBL	0

4.1.2 Geometry Comparison

The predicted and resultant geometries due to the raw water injection are presented in Figure 4-2(a). Injection and production locations are shown by a red diamond and triangle, respectively. Also provided are Russo's '83 results and results from the current version of SANSMIC in Figure 4-2(b). SANSMIC and the sonar data are in very good agreement. SANSMIC slightly over-predicts the leached volume near the top of the sump and slightly under-predicts it near the bottom. The Russo and current SANSMIC results also compare very well except in the fact that as the wall of the cavern approaches the floor, it tends to roll over below the injection point. This behavior difference is likely due to minor changes in the code or selective results by Russo. There is essentially no difference in results between completion report data and Russo data implying that the injections utilized by Russo are more detailed with total injected volume conserved.



(a) Completion Report Data (b) Russo Data

Figure 4-2. Sonar vs. SANSMIC Profiles for BM104 Bottom-Inject Sump Development.

4.1.3 Leached Volume Comparison

A summary of the leached volumes and efficiencies, actual and predicted, is presented in Table 4-3. The configuration and initial geometry result in a lower leaching efficiency than seen in other leaching scenarios performed in developed caverns. The raw water is injected and mixed then extracted through the production string with much smaller resident time which leaves less time to saturate the brine. Leach efficiencies are ~7 %, but within expectations for the sump stage. Raw water injection data taken from the completion report is about 2% higher than used by Russo, which explains smaller errors when using the completion data, though the results are very similar. Relative radius difference is larger than might be expected (20-25%) based on the profile comparisons. This is due to the large values near the top of the sump where small differences in the OBI location result in large differences. Another contributing factor is due to the small radii of the entire cavern at this time resulting in a small divisor.

Table 4-3. Volume Statistics for BM104 Bottom-Inject Sump Development.

Parameter	Sonar	SANSMIC
Raw water injected, BBL	1,500,000; 1,470,000[1]	
Initial volume, BBL	630	
Leached volume, BBL	111,300; 112,800	104,400; 98,800
Leach efficiency	7.4%; 7.7%	7%; 6.7%
Relative volume difference	-6.2%; 12.7%	
Relative radius difference	24.7%; 20.9%	
Mean radius difference	1.02; 1.3	
RMS of radius difference	-1.1; 1.4	

1. Notation: Completion report results; Russo results

4.2 BM104 Bottom-Inject Sump and Chimney Development Test Case

BM104 was initially leached from three boreholes using separate sump and chimney stages as recorded in the BM104 Completion Report (PB-KBB 1985a). The report provides composite volume vs. depth data at the completion of the chimney development from which radius vs. depth data are derived for comparison with a SANSMIC simulation that combines the three boreholes into an equivalent single wellbore. For the composite sonar survey data the cumulative volume versus depth data are combined at each provided depth. Data for missing depths are interpolated. Incremental volumes and radii are then calculated from the composite volumes. Only two wells (A and B) are sonar surveyed at completion of the sump stage which complicates validation, thus, no validation is performed for the sump as an individual stage.

4.2.1 Leaching Settings

A timeline of events extracted from the completion report is presented in Figure 4-3 it also contains the timeline of the modeled and reported injections. Raw water and oil rates are combined over the three wells and averaged over a period of injection so the simulated daily rates are different than reported, but the total volume is conserved. A marker for OBI recalibration indicates that the OBI depth is modified within the input file to match the measured value given by the report. In this scenario, the OBI was moved at the beginning of the chimney phase. The injection, production and OBI location as well as other leach settings are presented in Table 4-4.

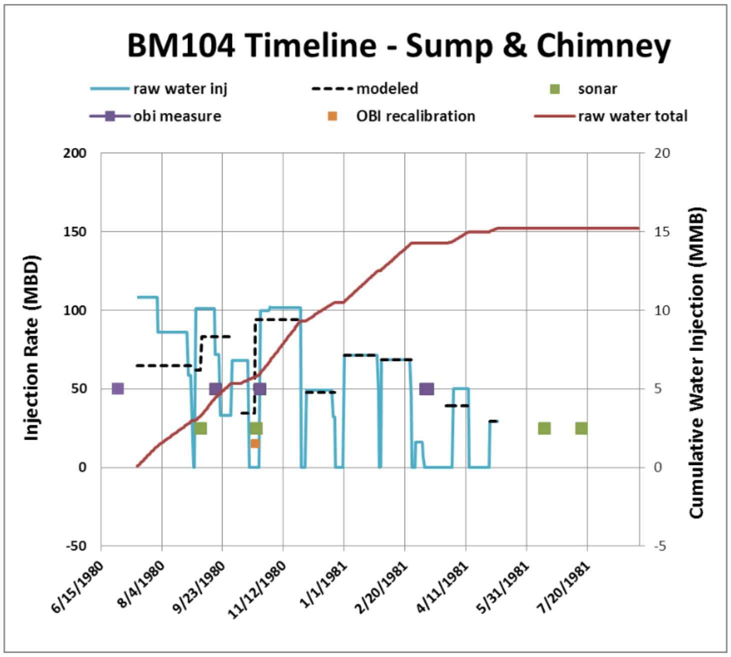


Figure 4-3. Timeline of BM104 Bottom-Inject Sump and Chimney Development.

Table 4-4. Leach Configuration Data of BM104 Bottom-Inject Sump and Chimney.

Setting	Value
Sonar dates	Borehole, 9/80, 7/81
Raw water injection dates	7/15/80 – 5/8/81 (sporadic injection downtime)
Activity duration, days	101; 132*
Injection depth, ft	4410; 4341*
Production depth, ft	4225; 2292*
Touch down depth, ft	4495
OBI start depth, ft	3226; 2187*
OBI end depth, ft	2187
Average raw water rate, BPD	73,280; 64,580*
Raw water volume, BBL	7,400,000; 8,530,000*
Oil rate, BPD	Small sporadic withdrawal and fill
Oil volume, BBL	Small

* Notation: Sump; chimney. Values are composites of the three well data

4.2.2 Geometry Comparison

The predicted and composite observed geometries due to the raw water injection are presented in Figure 4-4. SANSMIC and the composite sonar survey data are in fairly good agreement. SANSMIC over predicts the leached volume near the roof and under predicts in the region above the floor. As in the previous cases, SANSMIC predicts that the wall rolls over to vertical as it approaches the floor – more so than the observed data. Also, shown in Figure 4-3 is a comparison of the results at the end of the sump phase (green). The observed data is a composite of only wells A and B and thus about 1/3 smaller by volume than predicted which used injection for the all three wells. The trend is as expected.

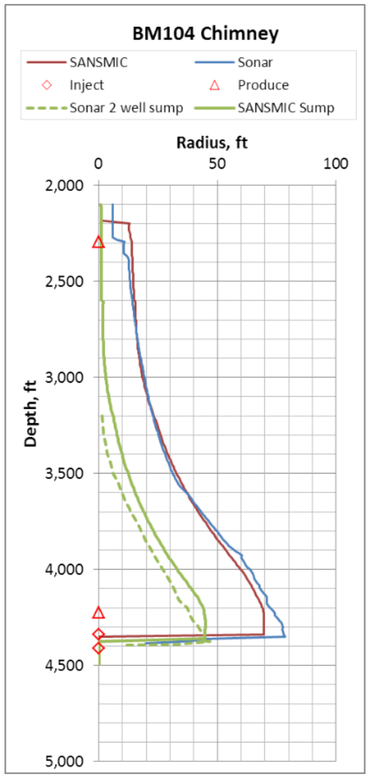


Figure 4-4. Cavern Profiles for BM104 Bottom-Inject Sump and Chimney Development.

4.2.3 Leached Volume Comparisons

A summary of the leached volumes and efficiencies, both actual and predicted are presented in Table 4-5 at the end of the chimney phase. The sump/chimney configuration results in a lower leaching efficiency than seen in later stages of cavern development due to the resident time of the raw water, but is within expectations.

Table 4-5. Volume Statistics for BM104 Bottom-Inject Sump and Chimney Development.

Parameter	Sonar	SANSMIC
Raw water injected, BBL	15,930,000*	
Initial volume, BBL	1,336*	
Leached volume, BBL	1,950,000*	1,730,000
Leach efficiency	12.2%	10.9%
Relative leach volume difference	-11.3%	
Relative radius difference	5.8%	
Mean radius difference	0.7	
RMS of radius difference	2.5	

* Composite of sonar surveys for three wells.

4.3 BM106 Bottom-Inject Sump and Chimney Development Test Case

BM106 was initially leached from three boreholes to the completion of the sump and chimney as a single stage as recorded in the BM106 Cavern Completion Report (PB-KBB 1985b). In this scenario, the injection string was located near the floor (4400 ft) and the production string was located near the depth of the proposed roof (2300 ft). This differs from BM104 as discussed earlier, where sump and chimney development were distinct phases separated by a workover used to move the production string from 4200 ft to 2300 ft depth. Individual well and composite volume vs. depth data at the completion of the stage are provided in the completion report from which radius vs. depth profiles were created. The leaching activity described here was previously considered in SANSMIC Reports (Russo 1981; Russo 1983) as a single well simulation prior to coalescence that was compared to sonar data from both well-A and well-B.

4.3.1 Leaching Settings

Two SANSMIC simulations are performed and presented – the first uses data from the completion report, the second uses data reported by Russo. Both simulations are for a single well. A timeline of events extracted from the completion report is presented in Figure 4-5 as well as a comparison of the modeled and reported injection rates. Russo's published injection rates consisted of two periods: one day at 64,452 BPD and 84 days at 28,195 BPD. Russo's reported injection period is less than the 109 days given in the completion reports and total injected volume is ~60 MBB (19%) less. A sonar survey was taken in July 1980 but the data was not provided in the completion report, however, Russo did show well-A and well-B average radii in a figure that was digitized and used as the final observed data for this analysis.

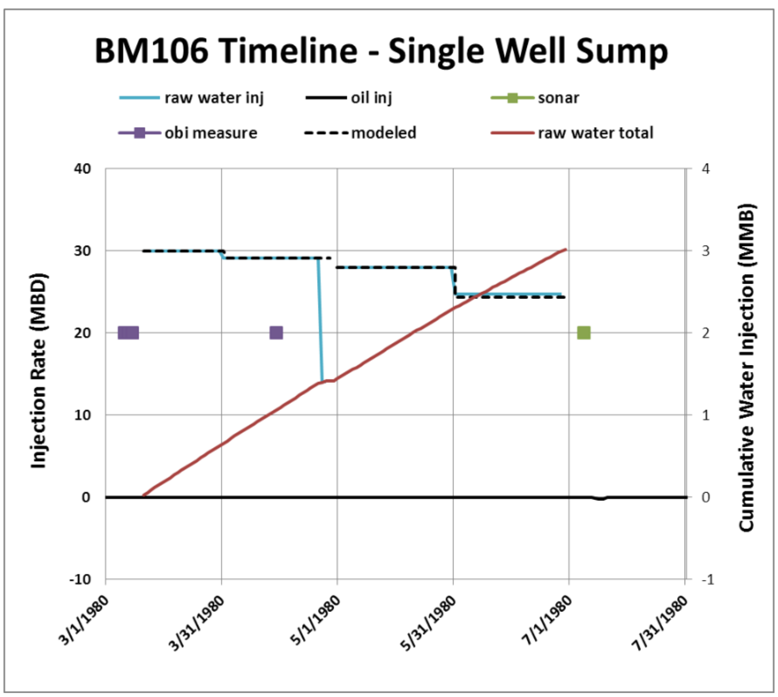


Figure 4-5. Timeline of BM106 Bottom-Inject Sump and Chimney Development.

Table 4-6 contains the configuration and leach settings for the injection period from the completion report. The initial configuration is a wellbore modeled as a cylinder with an initial radius of 0.7 ft.

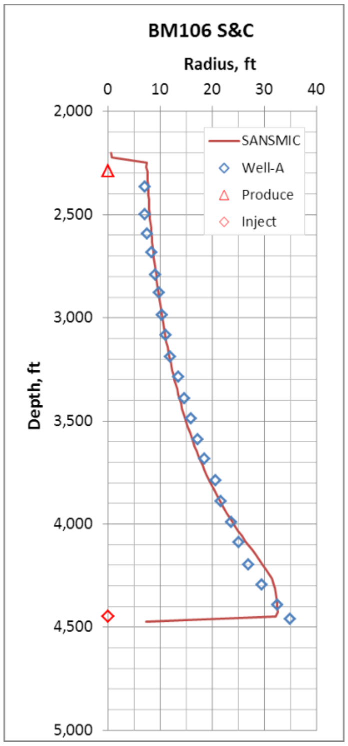
Table 4-6. Leach Configuration Data for BM106 Bottom-Inject Sump and Chimney Development.

Setting	Value[1]
Sonar dates	Borehole and 7/80
Raw water injection dates	3/10/80-6/30/80
Oil injection dates	Periodically and small throughout
Activity duration, days	109; 85
Injection depth, ft	4450
Production depth, ft	2284
Touch down depth, ft	4507
OBI depth, ft	2233
Average aw water rate, BPD	27,650; 28,620
Raw water volume, BBL	3,010,000; 2,430,000
Oil rate, BPD	0
Oil volume, BBL	0

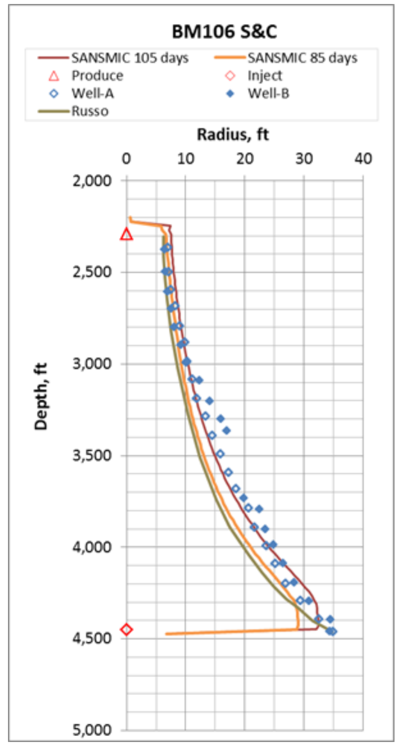
1. Notation: Completion Report data; Russo data

4.3.2 Geometry Comparison

The predicted and measured geometries due to the raw water injection are presented in Figure 4-6(a). The measured geometry (blue diamonds) is an axi-symmetric representation of a single well sump development. It is digitized from Figure 3 in (Russo 1981) since the sonar survey from July 1980 is not provided in the completion report. SANSMIC (red) appears to predict sump development fairly well except for slightly under-estimating the volume created in the mid-section of the cavern. Figure 4-6(b) compares the current simulation (red) with Russo's 1981 results (brown). Differences are significant and appear to be due to the 1981 simulation duration of only 85 days versus 109 days specified in the completion report. Also shown, is a second SANSMIC simulation using Russo's input (orange) which compares very well except for just above the floor. Here the current SANSMIC result rolls over and the wall is nearly vertical; whereas Russo's result continues to flare all the way to the floor. The difference is likely due to either a change in the bottom boundary condition, a change in the model near the injection point or selective results by Russo. The digitized data points for both well-A and well-B are also shown in Figure 4-6(b).



(a) Completion Report Data Source



(b) Comparisons with Russo (1981)

Figure 4-6. Sonar vs. SANSMIC Profiles of BM106 Bottom-Inject Sump and Chimney Development.

4.3.3 Leached Volume Comparison

A summary of the leached volumes and efficiencies, both observed and predicted are presented in Table 4-7. Here we see that the actual leach efficiency is higher than might be expected for a sump/chimney stage indicating an under estimation of raw water injection which is also reflected in the relative volume difference which is slightly high at ~12%.

Table 4-7. Volume Statistics for BM106 Bottom-Inject Sump and Chimney Development.

Parameter	Sonar	SANSMIC
Raw water injected, BBL	3,010,000; 2,430,000[1]	
Initial volume, BBL	630	
Leached volume, BBL	461,000	407,000
Leach efficiency	15.3%	13.5%
Relative volume difference	11.7%	
Relative radius difference	6.9%	
Mean radius difference	0.8	
RMS of radius difference	1.3	

1. Notation: Completion report data; Russo 1981 data

4.4 WH101 Bottom-Inject Sump and Chimney Development Test Case

WH101 is a single well cavern as are most of the West Hackberry caverns. During the SPR construction, studies indicated that substantial cost savings could be realized for one-well caverns. Additionally, the switch would not affect flow rates or development time due to the usage of larger casing. A combined sump/chimney stage was conducted and is simulated using the data provided by the WH101 Completion Report (PB-KBB 1986a). The analysis was also considered by both Russo (Russo 1983) and Eyermann (Eyermann 1984).

4.4.1 Leaching Settings

A timeline of events extracted from the completion report is presented in Figure 4-7 as well as a comparison of the modeled and reported injections. OBI measurements were conducted requiring one change to the OBI within the SANSMIC input file which is denoted by the OBI recalibration marker (orange square). Table 4-8 contains the configuration and leach settings for the simulation period. The initial configuration is a wellbore with a nominal radius of 0.7 ft.

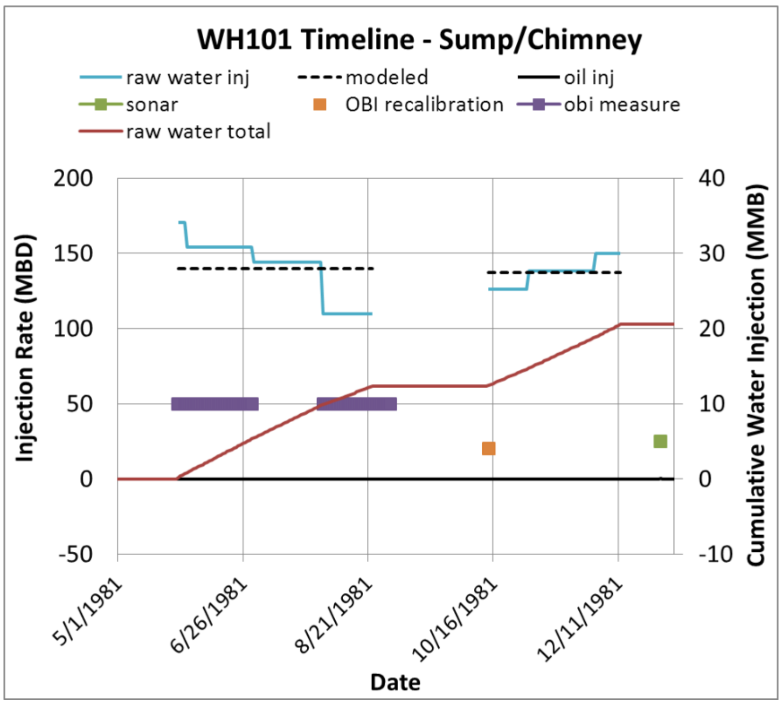


Figure 4-7. Timeline of WH101 Sump/Chimney Development.

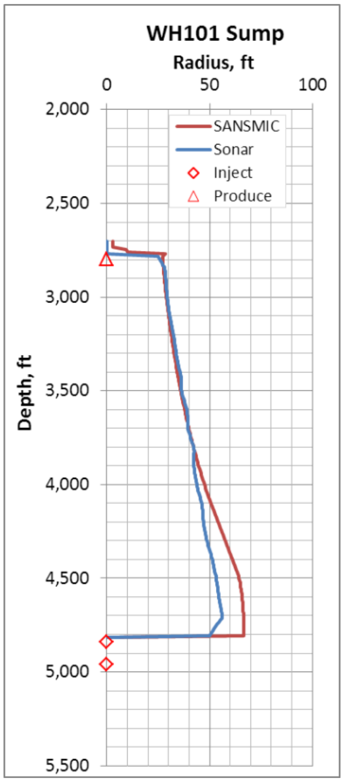
Table 4-8. Leach Configuration Data for WH101 Bottom-Inject Sump/Chimney Development.

Setting	Value[1]
Sonar dates	Borehole to 12/30/81
Raw water injection dates (days)	5/28/81-8/23/81(88)[2]; 10/14/81-12/12/81(60)[2]
Oil injection dates	Small, sporadic
Injection depth, ft	4960 (cut to 4840 on 10/14/81)
Production depth, ft	2796
Touch down depth, ft	5027
OBI start depth, ft	2761
OBI end depth, ft	2739
Raw water rate, BPD	140,000; 137,000
Raw water volume, BBL	1,2310,000; 8,220,000 (total=20,527,994)

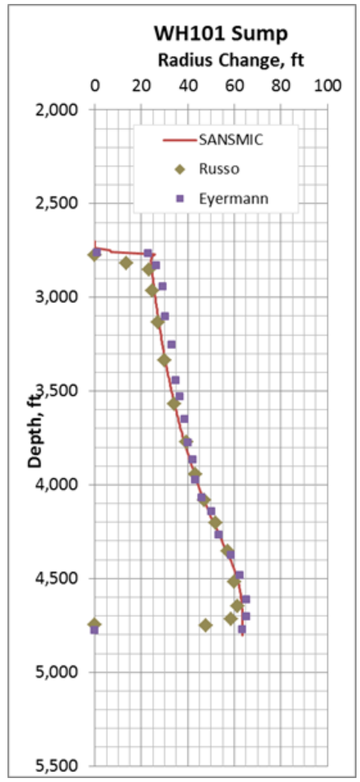
1. Notation: phase 1; phase 2
2. Sporadic injection downtime

4.4.2 Geometry Comparison

The predicted and measured geometries due to the raw water injection are presented in Figure 4-8(a). The modeled and observed results are very similar for depth 2800-3800 ft. Below 3800 ft, SANSMIC substantially over-predicts the volume created. This may be due to inaccurate raw water estimates. Figure 4-8(b) compares current results with digitized versions of both Russo and Eyermann results. Agreement is quite good considering the input data was derived independently and indicates that the code is essentially unchanged.



(a) SANSMIC vs. Observed



(b) Current, Russo (1983) and Eyermann (1984)

Figure 4-8. Sonar vs. SANSMIC Profiles for WH101 Bottom-Inject Sump/ Chimney Development.

4.4.3 Leached Volume Comparison

A summary of the leached volumes and efficiencies, both observed and predicted are presented in Table 4-9. SANSMIC significantly overestimates the volume leached in the lower half of the cavern, resulting in an overestimation of total volume by ~500,000 BBL (~24%). The observed leach efficiency is 9.8% which is small for this type of scenario indicating a likely error in injected raw water volume. The SANSMIC predicted leach efficiency is 12.2%.

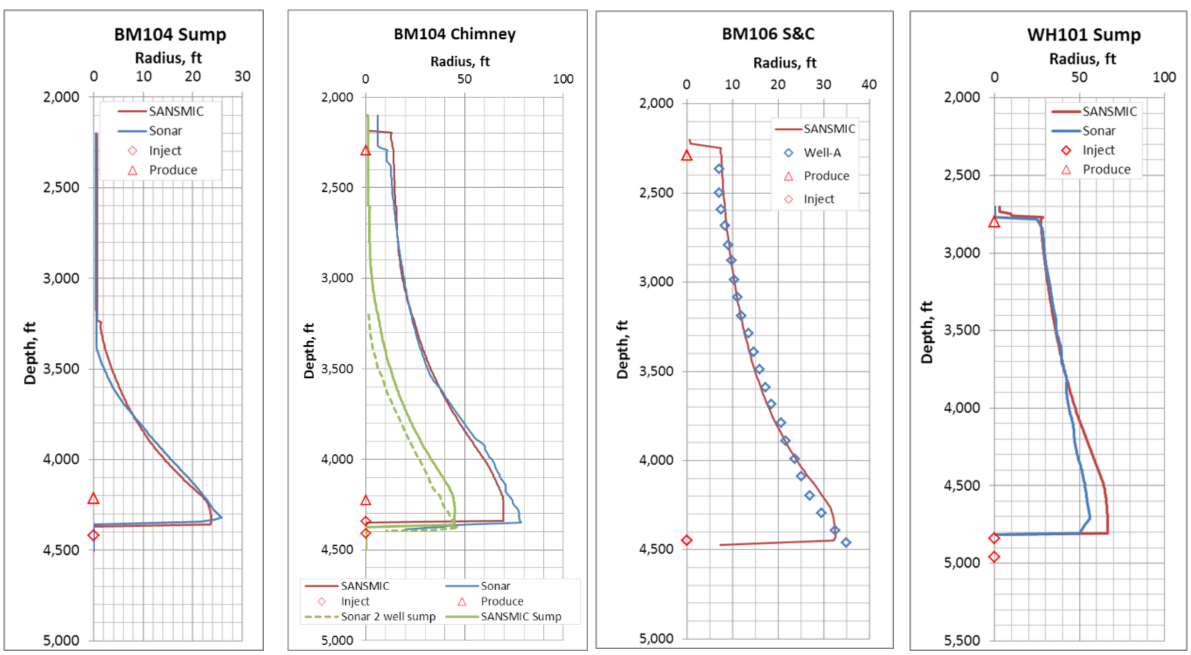
Table 4-9. Volume Statistics for WH101 – Sump/Chimney Development.

Parameter	Sonar	SANSMIC
Raw water injected, BBL	20,530,000	
Initial volume, BBL	11,700	
Leached volume, BBL	2,020,000	2,500,000
Leach efficiency	9.8%	12.2%
Relative volume difference	23.8%	
Relative radius difference	8.7%	
Mean radius difference	3.6	
RMS of radius difference	6.2	

4.5 Comparisons of Cavern Profiles for All Bottom-Inject Leach Test Cases

A comparison of cavern profiles for all bottom-inject direct leach test cases is provided in Figure 4-9. This includes one of three single-well (a, c) single well (d) and composite three-well cases (b). The biggest and most consistent difference between predicted and observed profiles is that the observed has continuous flaring as the wall approaches the floor of the cavern, where SANSMIC predictions roll over and display a more vertical approach near the floor.

The significant difference in the intermediate sump stage profiles (green) in Figure 4-9(b) is due to the sonar being a composite of only two available sonar surveys, whereas the model used a composite of injection data for all three wells. In Figure 4-9(d), both the leached volume and profile shape are off. The leached volume discrepancy could be caused by either injected volume error or excessive leaching in the SANSMIC model. Shape may be affected by the much higher injection rates at WH than at BM (140 vs. 30 MBD) and lack of a separate sump stage. Rates are higher because of the large, single-well design used at West Hackberry. Injection volume error is suspected because experience has shown reasonable agreement for predicted and observed leach efficiencies.



(a) BM104 1of 3 Wells (b) BM104 3-Well Composite (c) BM106 1 of 3 Wells (d) WH101 1-well

Figure 4-9. Cavern Profile Comparisons for all Bottom-Inject Test Cases.

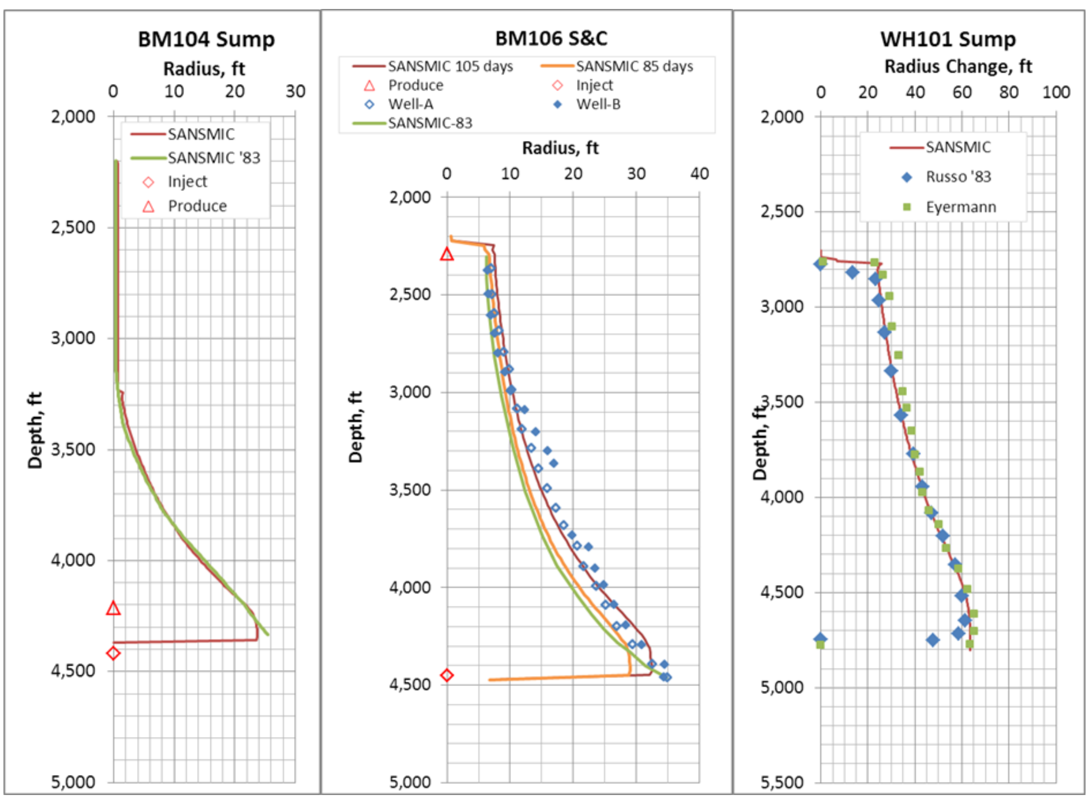
The reasonable comparisons (expect for WH101) are also reflected in the volume statistics provided in Table 4-10. However, relative leached volumes may be slightly higher than seen on the full cavern scale due to the relatively small leached volumes for the sump and chimney stages. The large relative volume shown for WH101 (24%) reflects the possibility of an inaccurate injection volume. This is also apparent in the leach efficiency (10% observed vs. 12% measured). The higher efficiency would be expected based on past experience. The high relative radius for BM104 is due to small wellbore radii at the top of the sump.

Table 4-10. Comparisons of Volume and Geometry Statistics for Bottom-Inject Leach Cases.

Cavern ID	Relative Volume	Relative Radius	Mean Radius	RMS of Radius Difference
BM104 – Sump	-6.2%	24.7%	-0.8	1.0
BM104 – Sump / Chimney	-11.3%	5.8%	0.7	2.5
BM106	11.7%	6.9%	0.8	1.3
WH101	23.8%	8.7%	3.6	6.2
Average(abs)*	11.5%	6.4%		

* Excludes WH101 because of injected volume issues.

Finally, comparisons of historical SANSMIC results are provided in Figure 4-10. Comparisons are very good considering input parameters were derived independently. The only apparent difference in the first two cases (from Russo 1981) is the wall as it approaches the floor. Whether the differences are due to coding changes is not discernible since in the first two cases, data was provided in a figure as height above the floor, and neither injection point nor insoluble treatment were provided. The third case shows very good agreement between current, Russo, and Eyermann results including the approach to the floor. The extra data in Figure 4-10(b) indicates good agreement between current and Russo (1983) for 85 days, but much better agreement between the current the measured data at 105 days.



(a) Predicted vs. Observed (b) 85 vs. 105 days (c) Historical Results

Figure 4-10. Comparisons of Historical SANSMIC Results.

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5 Top-Inject Validation Test Cases

Top-inject leaching, also known as reverse-leaching, requires the use of two hanging brine strings. In this scenario, the injection string is located above the production string. The OBI may be static, or in the case of leach-fill, moving deeper within the cavern. Top-injection was used at the SPR for cavern development during the multiple reverse stages to develop the roof of the cavern and then to expand the total volume. Additionally, a reverse leach stage was used in the recent expansion of BM113 (Rudeen, Weber et al. 2013). However, due to sonar imaging issues that make data interpretation difficult, the BM113 leach was deemed inappropriate for use in this validation exercise.

5.1 WH101

5.1.1 WH101 Top-Inject First-Reverse Test Case

Following the sump/chimney stage described in section 4.4, WH101 underwent reverse leaching to develop the roof of the cavern and increase the volume in the cavern midsection. The data to simulate the first-reverse stage is taken from the WH101 Cavern Completion Report (PB-KBB 1986a). The leaching activity described here is also found in prior SANSMIC documentation (Russo 1983; Eyermann 1984).

5.1.1.1 Leaching Settings

A timeline of events extracted from the completion report is presented in Figure 5-1 as well as the timeline of the modeled and reported injections. Raw water and oil rates are averaged over a period of injection such that the daily rate simulated is different than was reported, but the total volume is conserved. The orange markers in Figure 5-1 indicate that OBI recalibrations are performed. That is, the OBI depth is adjusted within the SANSMIC input file to match the measured value given by the report as a method of correcting for possible measurement errors and to focus more specifically on SANSMIC dissolution modeling errors.

Table 5-1 contains the string configurations and leach settings for the injection period. CF is used to denote concurrent fill with crude oil during the injection period.

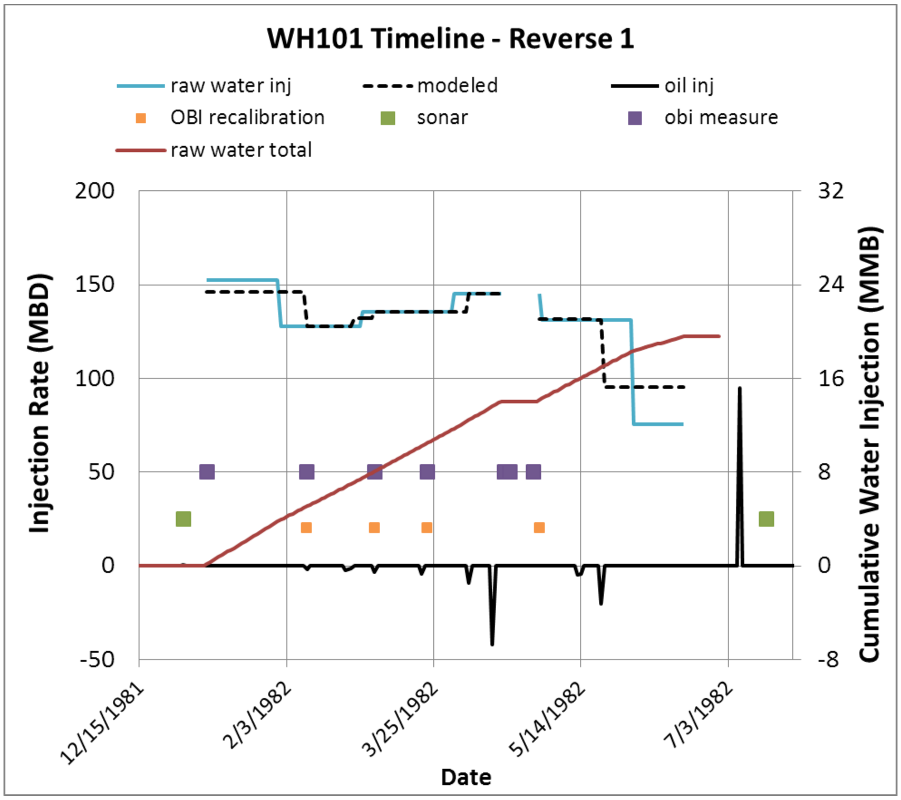


Figure 5-1. Timeline of WH101 Top-Inject First-Reverse.

Table 5-1. Leach Configuration Data for WH101 Top-Inject First-Reverse.

Setting	Value
Sonar dates	12/30/81 to 7/16/82
Raw water injection dates	1/7/82-6/18/82[1]
Oil injection dates	Sporadically throughout
Activity duration, days	RW: 151 CF: 8
Injection depth, ft	2796
Production depth, ft	4723 (cut to 4652 on 4/30/82)
Touch down depth, ft	4812
OBI start depth, ft	2604
OBI end depth, ft	Below 2606 – exact depth unknown
Average Raw water rate, BPD	129,600
Raw water volume, BBL	19,570,000
Average Oil rate, BPD	10,700
Oil volume, BBL	85,300

1 sporadic injection downtime

Figure 5-2 shows the initial cavern profile with string configurations and OBI depths annotated on the figure.

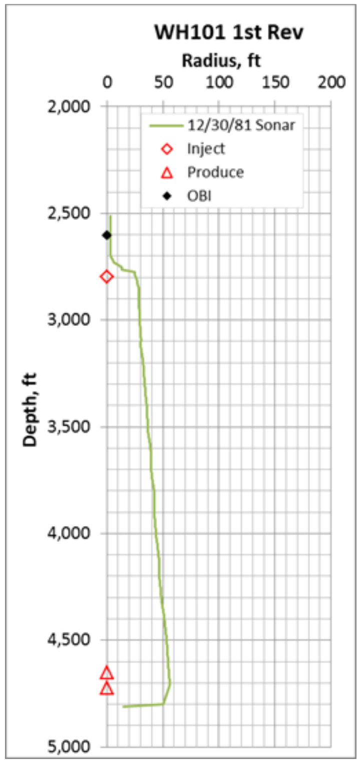
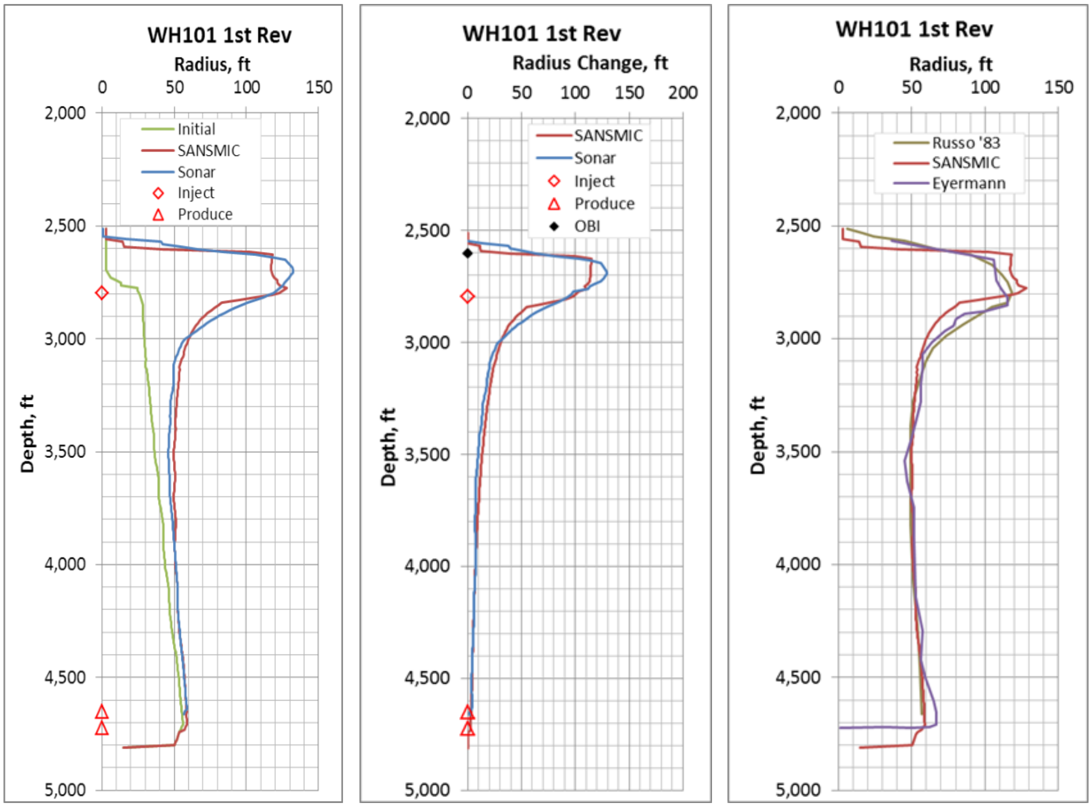


Figure 5-2. Initial Configuration of WH101 Top-Inject First-Reverse.

5.1.1.2 Geometry Comparison

The predicted and measured geometries due to the raw water injection are presented in Figure 5-3. SANSMIC under predicts the leaching of the roof of the cavern. It significantly under represents the radius in the region of 2650-2750 ft. The jagged geometry below the roof is due to the positioning of the OBI above the top of the chimney. SANSMIC can only dissolve salt radially whereas in the actual cavern there is significant upward leaching of an exposed roof. Another contributor to the error is inaccurate OBI movements with contributions from both inaccurate injection rates and inaccurate cavern wall locations. Below this region, SANSMIC under predicts the radius just below the injection point (2820-2970 ft) and then over predicts down to the production point (3000-3900 ft).

The radius-change as a function of depth is shown in Figure 5-3(b) which focuses on the leach pattern. The average difference in the change in geometry between the sonar and the SANSMIC prediction over the entire cavern is typically less than 5 ft. Differences ranged from less than 0.25 ft below 3900 ft to 13.5 ft just below the roof. Figure 5-3(c) compares historical results from Russo (1983) and Eyermann (1984). Roof differences are likely due to differences in fill history. The upper lobe shows reasonably consistent results for Russo and Eyermann with significant differences in the location of the transition region just below the injection point for the current SANSMIC results. This could be due to either differences in the injection jet model which moves the effective injection point downward or the injection location.



(a) Radius (b) Radius-Change (c) Eyermann (1984) and Russo (1983)

Figure 5-3. Sonar vs. SANSMIC Profiles of WH101 First-Reverse.

5.1.1.3 Leached Volume Comparison

A summary of the leached volumes and efficiencies, both observed and predicted, is presented in Table 5-2. The leached volumes and efficiencies are very similar differing only by 20 MB and ~0.1%, respectively.

Table 5-2. Volume Statistics for WH101 Top-Inject First-Reverse.

Parameter	Sonar	SANSMIC
Raw water injected, BBL	19,570,000	
Initial volume, BBL	2,030,000	
Leached volume, BBL	2,960,000	2,940,000
Leach efficiency	15.1%	15.0%
Relative volume difference	-0.7%	
Relative radius difference	5.2%	
Mean of radius difference	0.3	
RMS of radius difference	5.0	

5.1.2 WH101 Top-Inject Second-Reverse Test Case

After the roof development, a second-reverse stage was conducted for the purpose of increasing the volume in the midsection of the cavern. The leaching activity described here is also considered in Eyermann's work (Eyermann 1984). The data used to simulate the second-reverse stage is taken from the WH101 Completion Report (PB-KBB 1986a).

5.1.2.1 Leaching Settings

A timeline of events extracted from the completion report is presented in Figure 5-4 as well as the timeline of the modeled and reported injections. Raw water and oil rates have been averaged over a period of injection so the daily rate simulated is different than reported, but the total volume is conserved. An orange marker for OBI recalibration indicates that the OBI depth is adjusted within the input file to match the measured value given by the completion report. This recalibration is done to reduce the effects of injected water measurement errors and as a means of focusing more specifically on SANSMIC dissolution modeling.

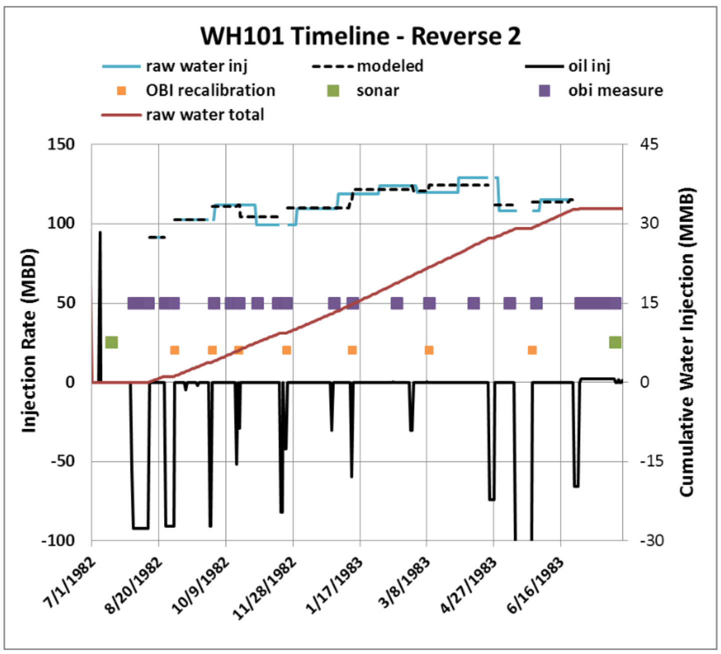


Figure 5-4. Timeline of WH101 Top-Inject Second-Reverse.

Table 5-3 contains the configuration and leach settings for the injection period. CF is used to denote concurrent fill during the raw water injection. Note that for the first eighteen days the leach was run in direct mode which reverses the roles of the injection and production strings. This was done to expand the lower cavern prior to expanding the midsection.

Figure 5-5 shows the initial configuration with the string and OBI depths annotated on the figure.

Table 5-3. Leach Configuration Data of WH101 Top-Inject Second-Reverse.

Setting	Value
Sonar dates	7/16/82 to 7/27/83
Raw water injection dates	8/13/82-6/30/83[1]
Oil injection dates	Periodically throughout
Activity duration, days	RW: 290 CF: 34
Injection depth, ft	4574, 3748[2]
Production depth, ft	3748, 4574
Touch down depth, ft	4650
OBI start depth, ft	2729
OBI end depth, ft	3134 (3220 at time of final Sonar)
Average Raw water rate, BPD	115,000
Raw water volume, BBL	33,390,000
Average Oil rate, BPD	85,600
Oil volume, BBL	2,910,000

1. Sporadic injection downtime.
2. Run in direct mode from 8/13 to 8/31/1982

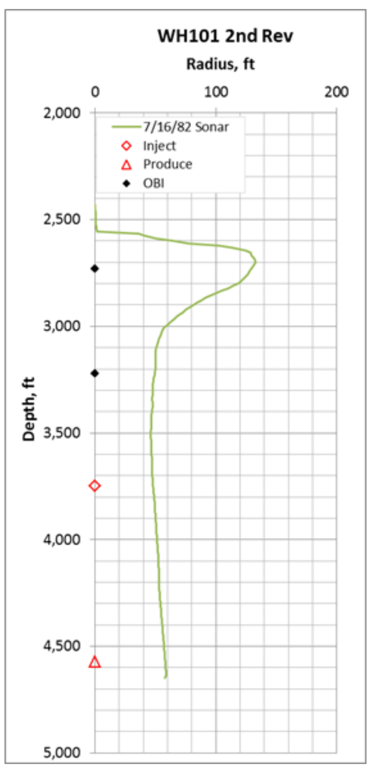
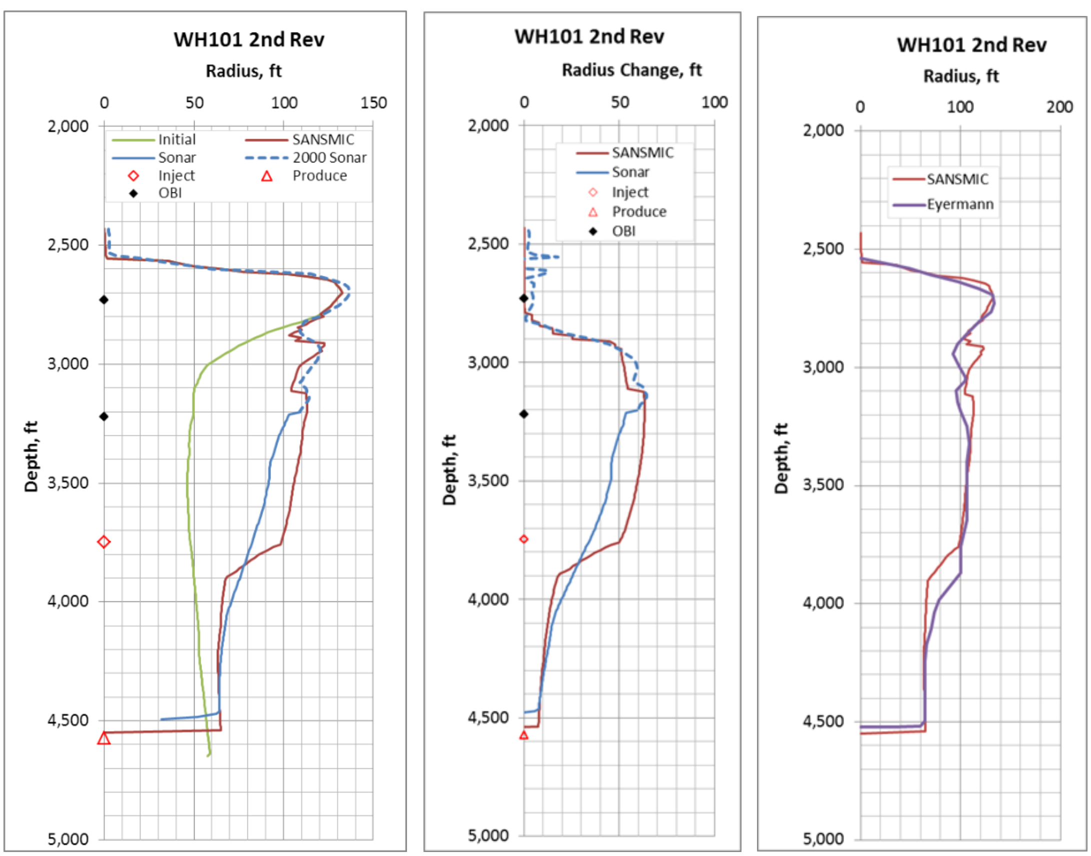


Figure 5-5. Initial Configuration of WH101 Top-inject Second-Reverse.

5.1.2.2 Geometry Comparison

The predicted and measured geometries due to the raw water injection are presented in Figure 5-6. Because of oil fill, the only sonar survey data obtained were at depths below the final OBI at 3220 ft (solid blue). The upper portion of the cavern is characterized using sonar data from the full cavern survey obtained in early 2000 (dashed blue). Note that from creation to 2000, this region is unchanged due to raw water exposure. SANSMIC slightly under estimates the leached area between the initial and final OBI (2729-3220) ft. It then over predicts fairly significantly from the OBI to the injection point (3220-3748 ft) and under predicts below the injection point (3830-4200 ft).

The radius-change as a function of depth is shown in Figure 5-6(b) which focuses more specifically on leaching effects. Clearly visible in the figure is the effect of the lowering of the injection string from 2796 ft (first-reverse) to 3748 ft. which expands vertically the region below the initial OBI (3220 ft) that is exposed to unsaturated brine. SANSMIC predicts a more uniform leaching pattern between the injection point and the OBI, while the data shows a more tapered leach pattern. Differences just below the initial OBI are a result of the different OBI movements in the region which are sensitive to both oil fill volumes and the cavern profile in the region.



(a) Radius (b) Radius Change (c) Eyermann (1984)

Figure 5-6. Measured vs. SANSMIC Predicted Profiles of WH101 Top-Inject Second-Reverse.

Finally, Figure 5-6(c) is a comparison with results presented by Eyermann (Eyermann 2008). The overall trends are similar but details are different over the range of the OBI movements. The differences are likely due to interpretation of oil fill volumes and timing and the handing of OBI locations. In the recent analysis, the OBIs are set as specified in the completion reports. Another significant difference is apparent below the injection point where Eyermann's results extend the region of large radii another 100 ft deeper (3300 -3400 ft). This could either be due to different injection locations or a change in the "jet" model which moves the injection point downward based on estimates of the raw-water injection-jet length. Curiously, this behavior is also seen in the BM106 and WH101 first reverses.

5.1.2.3 Leached Volume Comparison

A summary of the leached volumes and efficiencies, both observed and predicted, is presented in Table 5-4. The relative volume (19%) and efficiency (15.4% vs. 12.9%) differences indicate a possible overestimation of raw-water injection volume.

Table 5-4. Volume Statistics for WH101 Top-Inject Second-Reverse.

Parameter	Sonar	SANSMIC
Raw water injected, BBL	33,390,000	
Initial volume, BBL	4,970,000	
Leached volume, BBL	4,310,000	5,110,000
Leach efficiency	12.9%	15.4%
Relative volume difference	19%	
Relative radius difference	7.7%	
Mean radius difference	3.3	
RMS of radius difference	8.9	

5.2 WH103

5.2.1 WH103 Top-Inject First-Reverse Test Case

Following the sump/chimney stage (not modeled here), WH103 underwent top-inject reverse leaching to develop the roof of the cavern. The data used to simulate the first-reverse stage is taken from the WH103 Cavern Completion Report (PB-KBB 1986b). The leaching activity described here was also previously considered in Eyermann (Eyermann 1984). Oil injection was used to control and shape the roof.

5.2.1.1 Leaching Settings

A timeline of events extracted from the completion report is presented in Figure 5-7 as well as the timeline of the modeled and reported injections. Raw water and oil rates are averaged over a period of injection such that the daily rate simulated is different than reported, but the total volume is conserved. A marker for OBI recalibration indicates that the OBI depth is modified within the input file to match the measured value given by the report.

Table 5-5 contains the configuration and leach settings for the injection period. CF is used to denote concurrent fill or crude oil fill occurring during the injection period.

Figure 5-8 shows the initial cavern configuration with the string and OBI depths annotated on the figure.

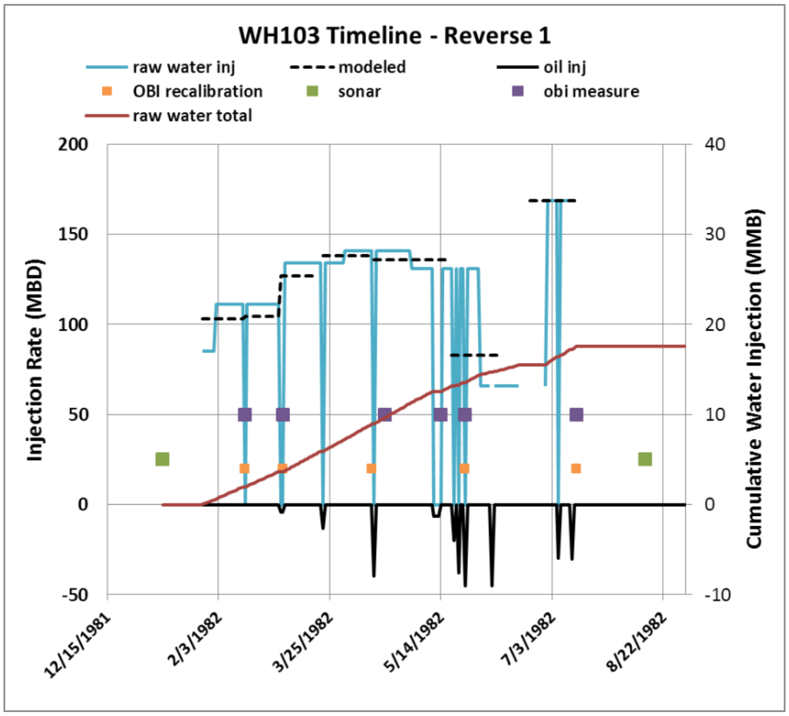


Figure 5-7. Timeline of WH103 Top-Inject First-Reverse.

Table 5-5. Leach Configuration Data of WH103 Top-Inject First-Reverse.

Setting	Value
Sonar dates	1/9/82 to 8/14/82
Raw water injection dates	1/27/82-7/14/82[1]
Oil injection dates	Sporadically
Activity duration, days	RW: 157 CF: 4
Injection depth, ft	2784, 4652[2]
Production depth, ft	4652, 2784[2]
Touch down depth, ft	4746
OBI start depth, ft	2636
OBI end depth, ft	2700
Average raw water rate, BPD	124,000
Raw water volume, BBL	19,000,000
Average oil rate, BPD	52,800
Oil volume, BBL	211,000

1. Includes sporadic injection downtime.
2. Switched to direct leach for last 7 days.

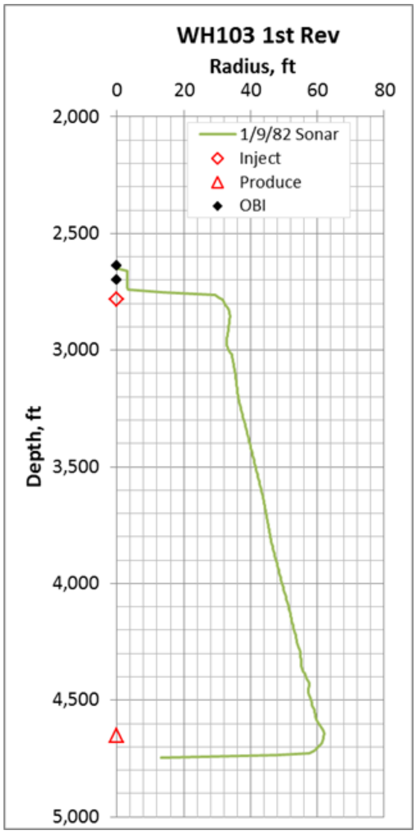
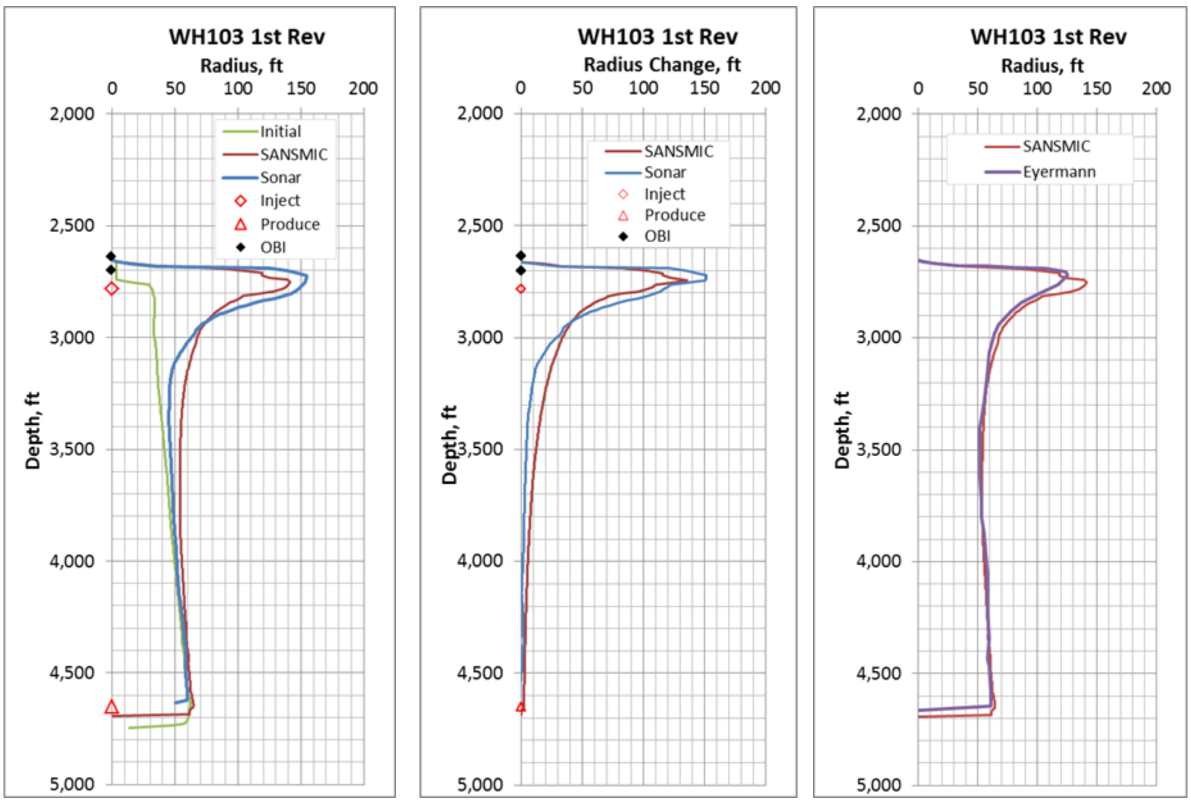


Figure 5-8. Initial Configuration of WH103 Top-Inject First-Reverse.

5.2.1.2 Geometry Comparison

The predicted and measured geometries resulting from the raw water injection are presented in Figure 5-9. SANSMIC under predicts the leached region in the upper lobe from the top of the cavern down to a depth of 2900 ft. Below this depth it generally over predicts the leached volume. Figure 5-9(b) displays the radius change to focus in more specifically on the leach pattern. A comparison with the result from Eyermann (Eyermann 1984) is provided in Figure 5-9(c), which indicates pretty good agreement except just below the roof. The different character is likely due to differences in handling oil injection and OBI location and/or the location of the roof in the initial chimney geometry. The recent analyses adjusts the OBI position to match the data provided in the completion report in order to more directly address dissolution modeling without the influence associated with the highly sensitive interface movement modeling.



(a) Radius (b) Radius Change (c) Eyermann (1984)

Figure 5-9. Measured vs. SANSMIC Predicted Cavern Profiles of WH103 Top-Inject First-Reverse.

5.2.1.3 Leached Volume Comparison

A summary of the leached volumes and efficiencies, both observed and predicted, is presented in Table 5-6. The leached volumes and efficiencies are very similar differing only by ~4% and 0.5% respectively. The relative radius difference, at ~12%, is large because it uses absolute value which eliminates the cancelation of both over and under prediction.

Table 5-6. Volume Statistics for WH103 Top-Inject First-Reverse.

Parameter	Sonar	SANSMIC
Raw water injected, BBL	19,010,000	
Initial volume, BBL	2,410,000	
Leached volume, BBL	2,500,000	2,600,000
Leach efficiency	13.2%	13.7%
Relative volume difference	4.0%	
Relative radius difference	11.9%	
Mean radius difference, ft	3.0	
RMS of radius difference, ft	9.4	

5.2.2 WH103 Top-Inject Second-Reverse Test Case

After the roof development of the first-reverse leach (previous section), a second-reverse stage was conducted for the purpose of increasing the volume in the midsection of the cavern. The leaching activity used to simulate the second-reverse stage is taken from the WH103 Completion Report (PB-KBB 1986b). The leaching activity described here is also considered in Eyermann's report (Eyermann 1984).

5.2.2.1 Leaching Settings

A timeline of events extracted from the completion report is presented in Figure 5-10 as well as the timeline of the modeled and reported injections. Raw water and oil fill rates are averaged over a period of injection so the daily rate simulated is different than reported, but the total volume is identical. A marker for OBI recalibration indicates that the OBI depth is adjusted within the input file to match measured values given by the completion report. This recalibration is done in order to account for possible errors in injected raw water measurement volumes and remove influence of the highly sensitive interface movement modeling.

Table 5-7 contains the configuration and leach settings for the injection period. CF is used to denote concurrent fill or oil fill occurring during the injection period.

Figure 5-11 shows the initial configuration with the string and OBI depths annotated on the figure.

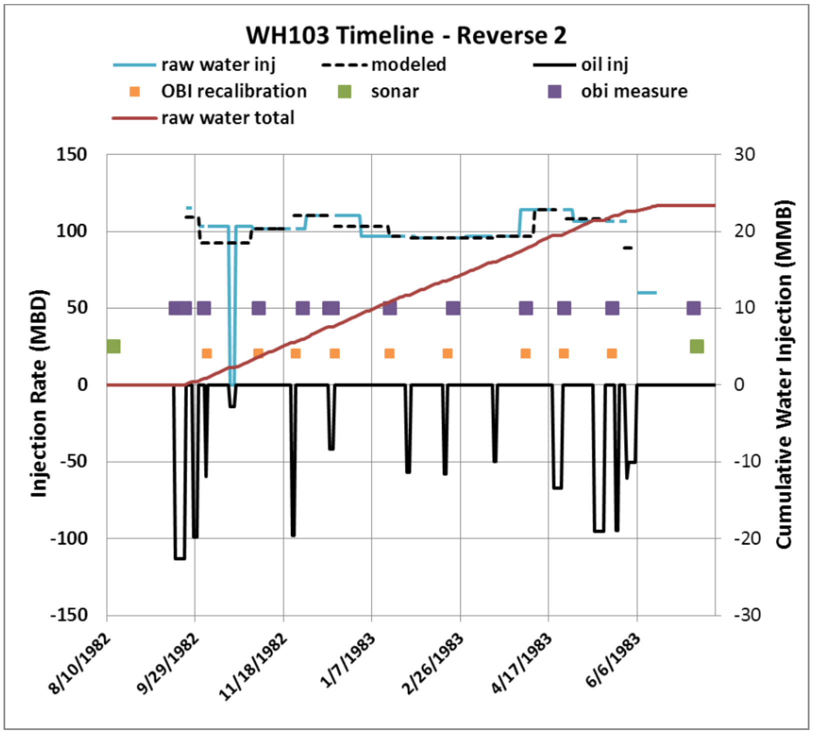


Figure 5-10. Timeline of WH103 Top-Inject Second-Reverse.

Table 5-7. Leach Configuration Data of WH103 Top-Inject Second-Reverse.

Setting	Value
Sonar dates	8/14/82 to 7/10/83
Raw water injection dates	9/24/82-6/8/83[1]
Oil injection dates	Periodically throughout and during downtime
Activity duration, days	RW: 234 CF: 37
Injection depth, ft	3745[2]
Production depth, ft	4546[2] (cut at 4502 after 197 days)
Touch down depth, ft	4638
OBI start depth, ft	2763
OBI end depth, ft	~3047 (3121 at time of sonar survey)
Ave raw water rate, BPD	101,000
Raw water volume, BBL	23,120,000
Average oil rate, BPD	80,000
Oil volume, BBL	2,150,000

1. Includes sporadic injection downtime.
2. First 8 days in direct mode with string roles reversed.

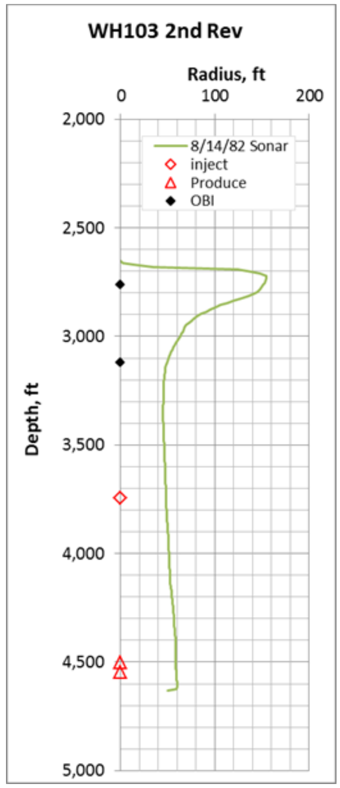
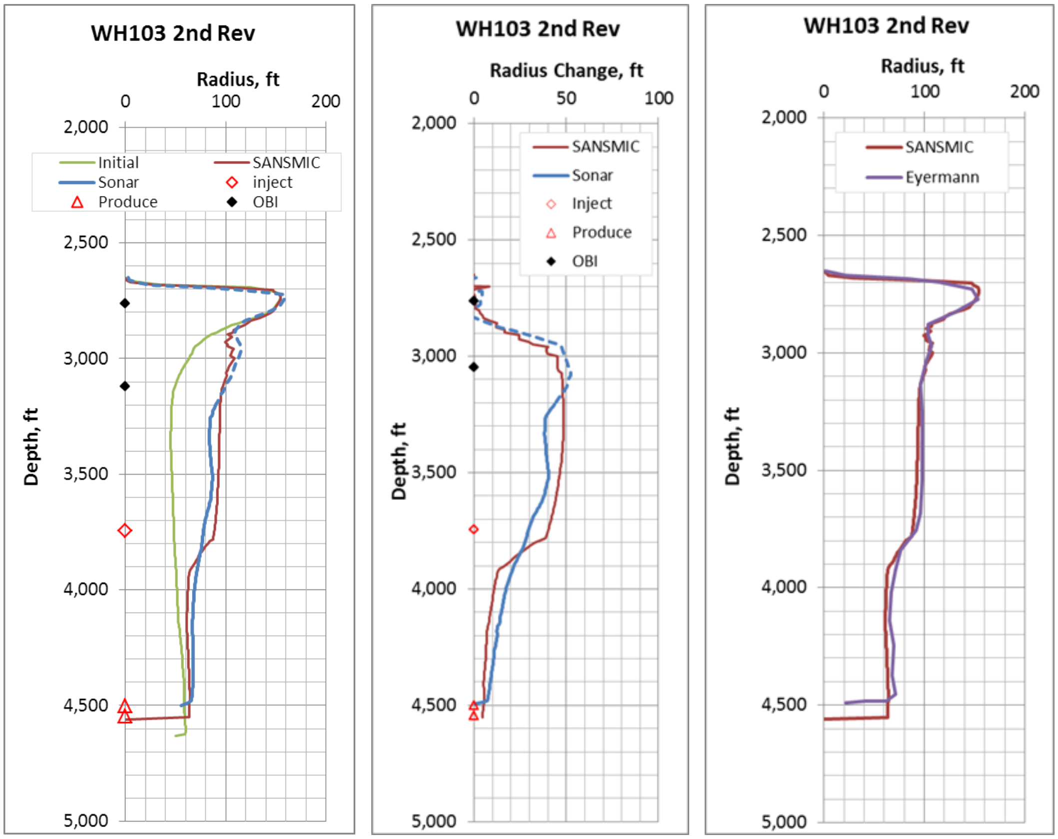


Figure 5-11. Initial Configuration of WH103 Top-Inject Second-Reverse.

5.2.2.2 Geometry Comparison

The predicted and measured geometries due to the raw water injection are presented in Figure 5-12. Because of oil fill, the only sonar survey data obtained are at depths below the final OBI at 3120 ft. The upper portion of the cavern is characterized using sonar data from the full cavern survey obtained in late 2000. Note that this region remains unexposed to unsaturated brine since its original development. SANSMIC slightly underestimates the leached area in the region of the OBI movement. It then over predicts from the lowest OBI down to just below the injection point (3200-3800 ft). It again under predicts below this injection point (3900 ft-floor).

The radius-change as a function of depth is shown in Figure 5-12(b), which focuses on the leach pattern – SANSMIC is more barrel shaped between the OBI and injection; observed is more tapered. A comparison with the historical simulation reported by Eyermann is shown in Figure 5-12(c). The results show very good aggreement considering input data was developed independently and results were digitized from figures in Eyermann's report.



(a) Radius (b) Radius-Change (c) Eyermann (1984)

Figure 5-12. Sonar vs. SANSMIC Profiles of WH103 Top-Inject Second-Reverse.

5.2.2.3 Leached Volume Comparison

A summary of the leached volumes and efficiencies, both measured and predicted are presented in Table 5-8. The leached volumes and efficiencies are similar differing by about ~8% and just over 1%. Performance measures are reasonable.

Table 5-8. Volume Statistics for WH103 Top-Inject Second-Reverse.

Parameter	Sonar	SANSMIC
Raw water injected, BBL	23,120,000	
Initial volume, BBL	4,860,000	
Leached volume, BBL	3,430,000	3,700,000
Leach efficiency	14.9%	16.0%
Relative volume difference	7.9%	
Relative radius difference	7.4%	
Mean radius difference	0.6	
RMS of radius difference	6.7	

5.2.3 WH103 Top-Inject Third-Reverse Test Case

After the second-reverse, the third-reverse stage was conducted for the purpose of increasing the volume lower in the cavern. The data used to simulate the third-reverse stage was taken from the WH103 Completion Report (PB-KBB 1986b).

5.2.3.1 Leaching Settings

A timeline of events extracted from the completion report is presented in Figure 5-13 as well as the timeline of the modeled and reported injections. Raw water and oil fill rates have been averaged over a period of injection so the daily rate simulated is different than reported, but the total volume is conserved. A marker for OBI recalibration indicates that the OBI depth is adjusted within the input file to match the measured value given by the completion report in order to account for possible errors in injected raw water measurements.

Table 5-9 contains the configuration and leach settings for the injection period. CF is used to denote concurrent fill or leach fill occurring during the injection period.

Figure 5-14 shows the initial configuration with the string and OBI depths annotated on the figure.

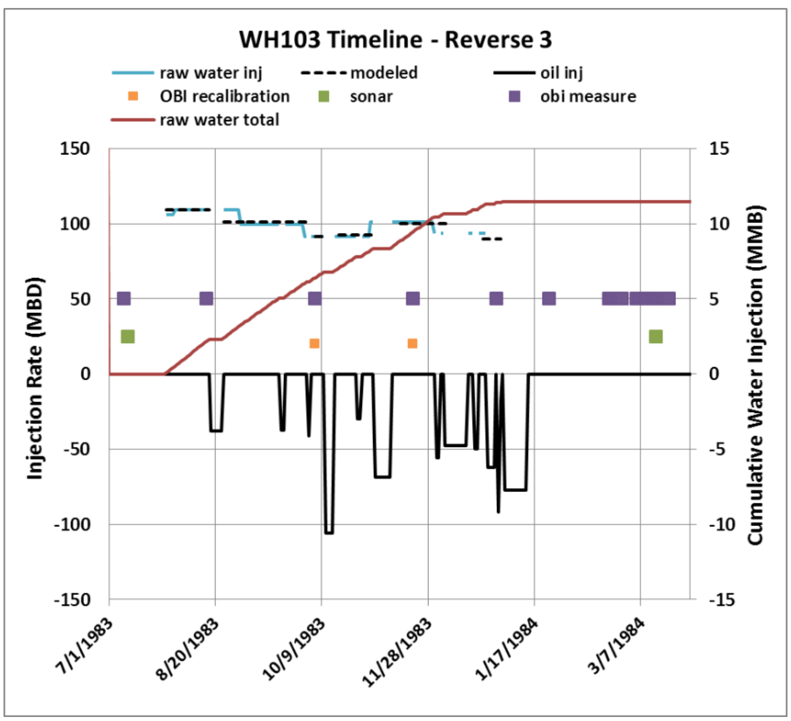


Figure 5-13. Timeline of WH103 Top-Inject Third-Reverse.

Table 5-9. Leach Configuration Data of WH103 Top-Inject Third-Reverse.

Setting	Value
Sonar dates	7/10/83, 3/14/84
Raw water injection dates	7/28/83 – 1/13/84[1]
Oil injection dates	Periodically throughout and during downtime
Activity duration, days	RW: 176 CF: 60
Injection depth, ft	4136
Production depth, ft	4371
Touch down depth, ft	4505
OBI start depth, ft	3113
OBI end depth, ft	3486 (3604 at time of sonar)
Average raw water rate, BPD	99,400
Raw water volume, BBL	12,030,000
Average oil rate, BPD	61,600
Oil volume, BBL	3,390,000

1. Includes sporadic injection downtime.

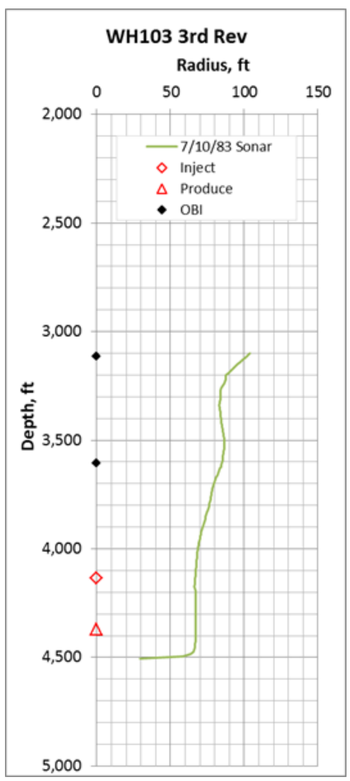
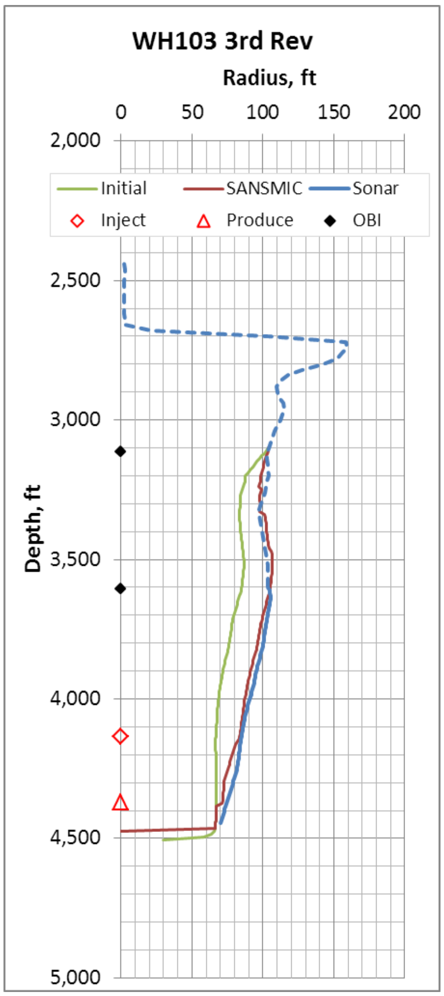


Figure 5-14. Initial Configuration of WH103 Top-Inject Third-Reverse.

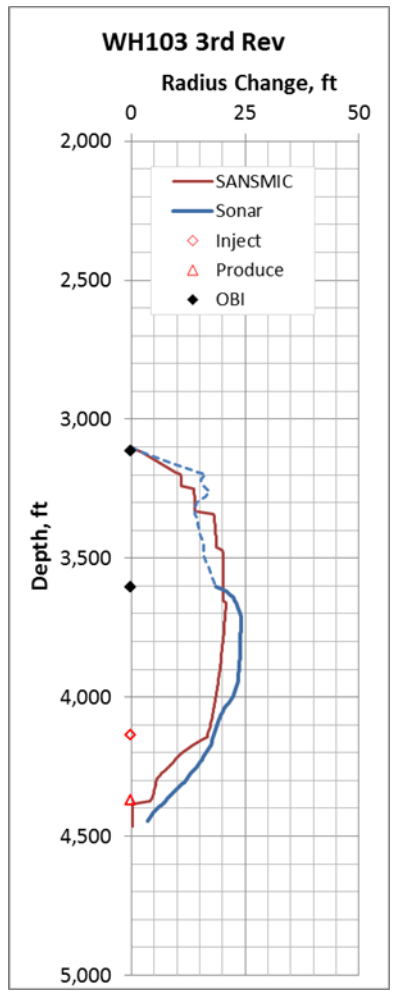
5.2.3.2 Geometry Comparison

The predicted and measured geometries due to the raw water injection are presented in Figure 5-15. Because of oil fill, the only sonar survey data available are at depths below the final OBI at 3600 ft. The upper portion of the cavern is therefore characterized using sonar data from the full cavern survey obtained in late 2000. This part of the cavern is unexposed to unsaturated brine since cavern development. SANSMIC appears to be in good agreement at all depths.

The radius-change as a function of depth is shown in Figure 5-15(b) and shows the same trends, but illustrates the leach pattern more explicitly.



(a) Radius



(b) Radius Change

Figure 5-15. Measured vs. SANSMIC Profiles of WH103 Top-Inject Third-Reverse.

5.2.3.3 Leached Volume Comparison

A summary of the leached volumes and efficiencies, both observed and predicted, is presented in Table 5-10. The leached volumes and efficiencies are only somewhat similar differing by 10% and more than 2%. However, raw water injections may show slight underestimation as evidenced by the high leach efficiency of 17.2%.

Table 5-10. Volume Statistics for WH103 Top-Inject Third-Reverse.

Parameter	Sonar	SANSMIC
Raw water injected, BBL	12,030,000	
Initial volume, BBL	4,600,000	
Leached volume, BBL	2,060,000	1,850,000
Leach efficiency	17.2%	15.3%
Relative volume difference	-10.2%	
Relative radius difference	3.8%	
Mean of radius difference	-2.1	
L2 Norm of radius difference	3.8	

5.3 Comparisons of All Top-Inject Test Cases

5.3.1 First-Reverse

Figure 5-16 displays comparisons of all *first*-reverse top-inject test cases. Trends and differences appear to be relatively consistent across all test cases. In most cases, SANSMIC focuses its leaching between the injection point and the slowly moving OBI with an abrupt decrease in radius below the injection depth. The observed leaching generally shows a deeper penetration in the upper lobe and tapers more uniformly while decreasing in radius below the injection point which could be interpreted as a deeper penetration of the injection jet. Below this region, SANSMIC slightly over predicts leaching down to the production point. However, two distinctive features are apparent. In "WH105 1st Rev" there is more leaching in the lower 2/3 of the cavern because of a much lower average injection rate – 90 MBD vs. 130+ MBD in the other test cases. In "BM106 1st Rev" the injection point is ~400 ft lower in the cavern resulting in a much deeper lobe with a more barrel shaped profile. Differences in the details of the roof profile reflect the OBI movement and shows that the shape is highly sensitive to the concurrent oil fill history which is only approximated. Considering this and the fact that SANSMIC cannot leach vertically, comparisons are quite reasonable.

Figure 5-17 provides a more detailed view of the actual leach pattern using radius-change profiles.

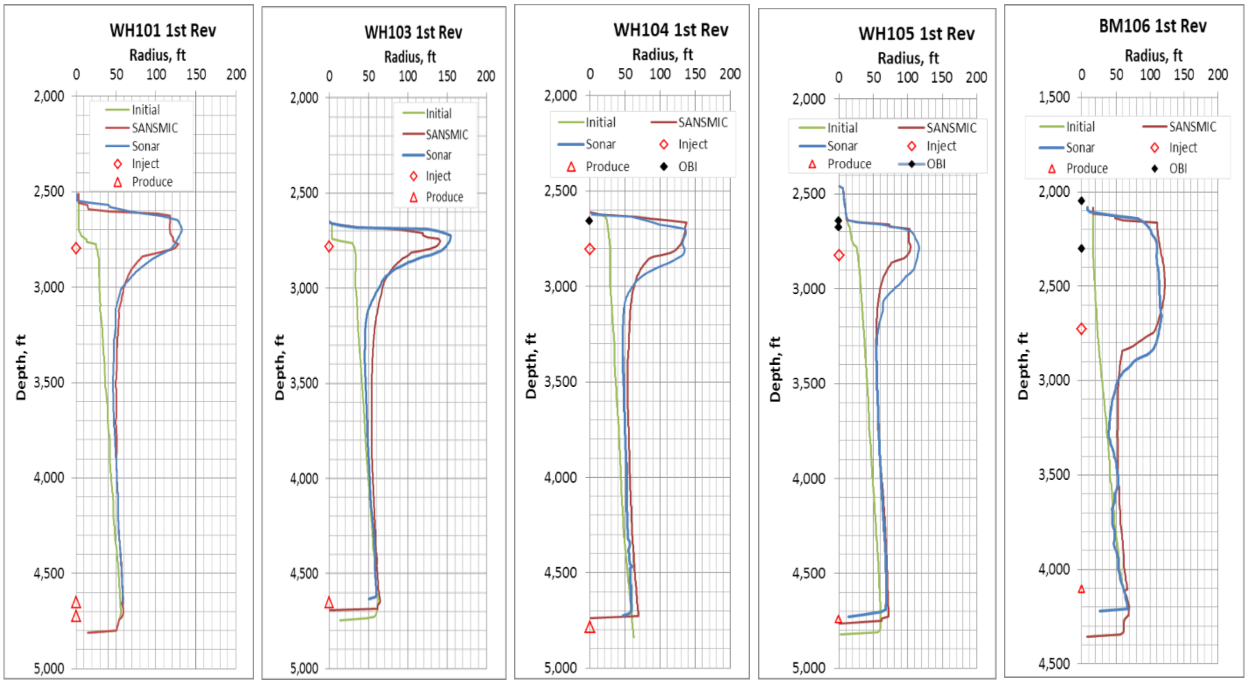


Figure 5-16. Cavern Profile Comparisons for Top-Inject First-Reverse Test Cases.

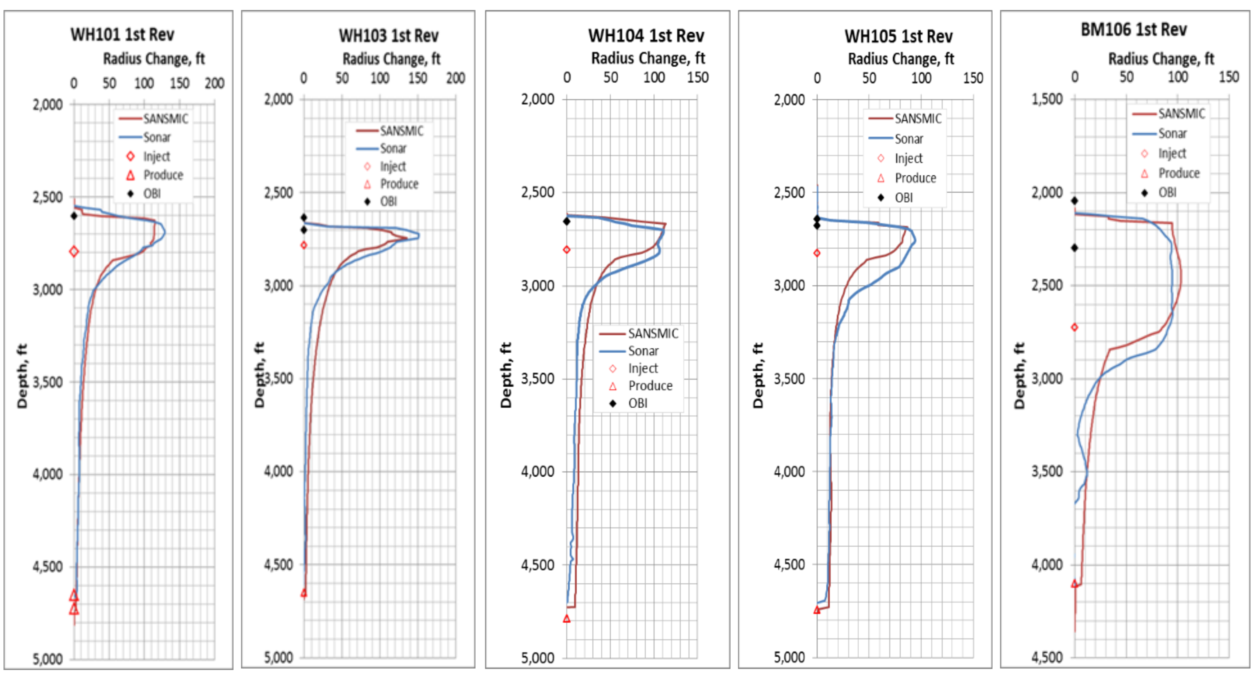


Figure 5-17. Radius-Change Comparisons for Top-Inject First-Reverse Test Cases.

5.3.2 Second-Reverse

Comparisons of all top-inject *second*-reverse profiles are provided in Figure 5-18. Corresponding radius-change profiles that more explicitly illustrate the leach pattern are shown in Figure 5-19. In a typical second-reverse, the injection point is moved much deeper into the cavern. The injection point is moved well below the OBI and below the cavern mid-point creating a uniform and gradually tapering leach pattern with depth. A more rapidly moving OBI is used to create a more vertical wall below the lobe formed during the first-reverse. Differences between the SANSMIC predicted and the observed leach profiles are more pronounced in these test cases than any other cases analyzed and are consistent across all test cases. The leach profile SANSMIC predicts for the second-reverse is more vertical with a slight barrel shape between the region of the moving OBI and the injection point with a rapid decrease in radius below the injection point. Below this transition region SANSMIC under predicts the leach radius. The injection point effect is obvious in the SANSMIC predicated profiles but is not discernible in the observed profiles. The over and under prediction tendency, however, results in a reasonable prediction of leached volume.

Volume statistics are provided in Table 5-11. Relative volumes below ~10% and relative radius differences below 5% are considered reasonable. Relative volumes greater than 15% may indicate injection measurement errors.

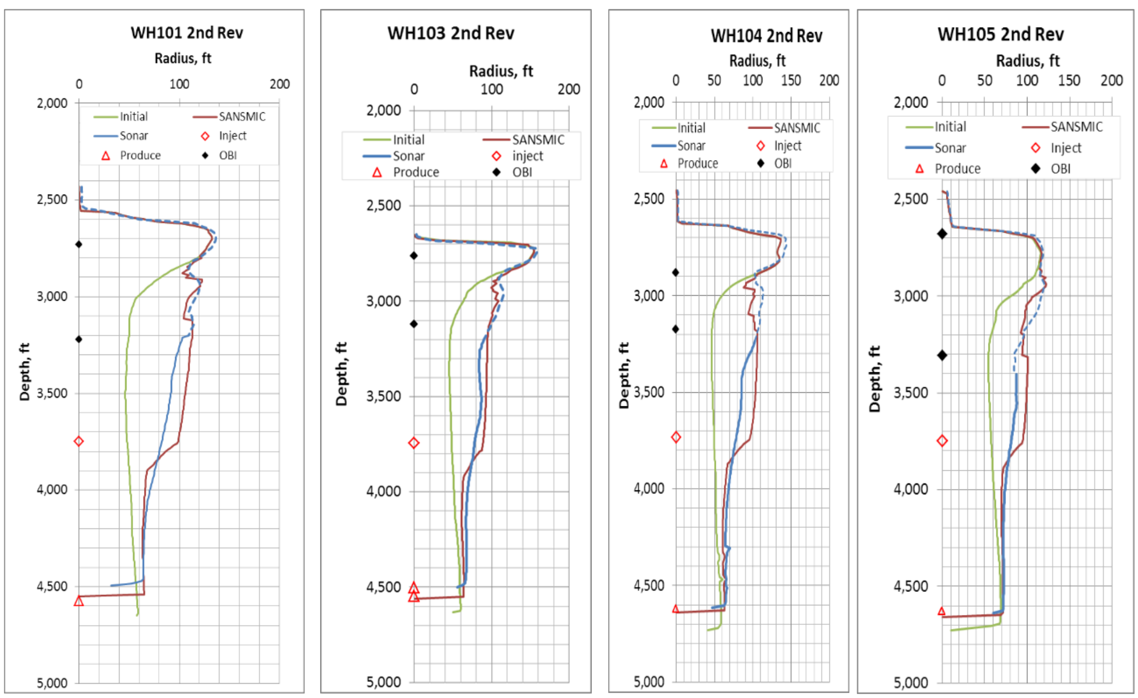


Figure 5-18. Cavern Profile Comparisons for Top-Inject Second-Reverse Test Cases.

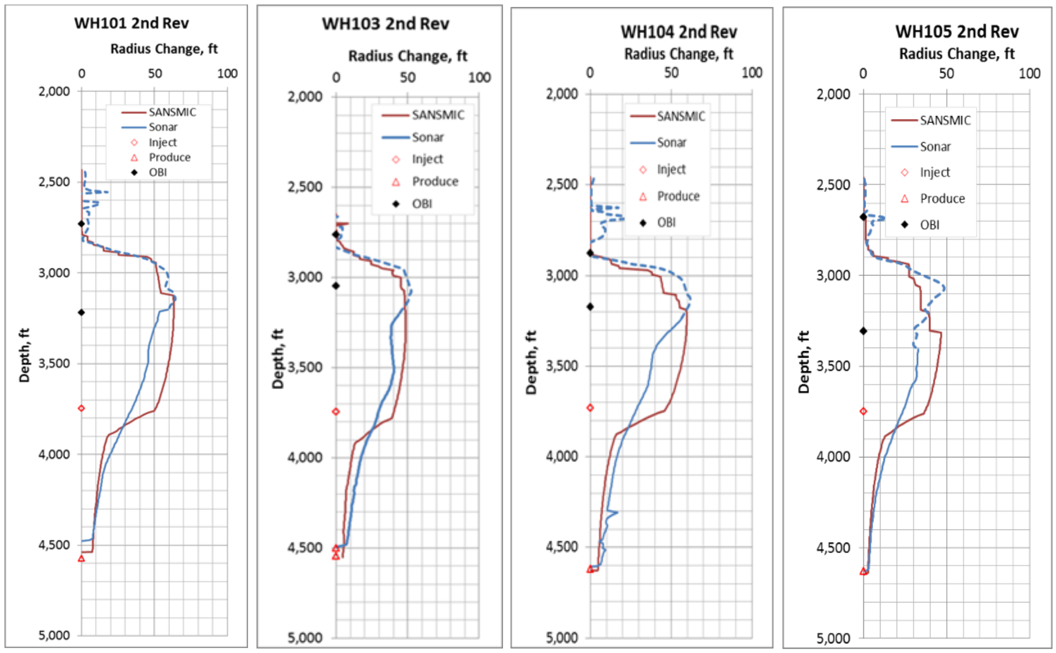


Figure 5-19. Radius-Change Comparisons for Top-Inject Second-Reverse Test Cases.

5.3.3 Third-Reverse

Comparisons of all top-inject *third*-reverse profiles are provided in Figure 5-20. Corresponding radius-change profiles that more explicitly illustrate the leach pattern are shown in Figure 5-21. The typical third-reverse continues the cavern development process by lowering the injection point even deeper into the cavern to a point a few hundred feet above the production point which is near the bottom of the cavern. Again, the OBI continues to be lowered by continued injection of oil fill. The leach pattern generated by the third reverse is generally symmetric about the mid-point between the starting OBI and the production point. It has a rounded taper from the OBI to the maximum radius-change at the mid-point and back to the bottom of the leach region. The SANSMIC predicted leach pattern is consistent across the test cases shown in Figure 5-20 and is slightly more barrel-shaped in the mid-section while showing a rapid decrease in radius just below the injection point similar to the 1st and 2nd reverse cases. Profiles compare reasonably well with relative volume differences (Table 5-11) above 10% and relative radii differences are around 4% – lower, because of the large cavern radius.

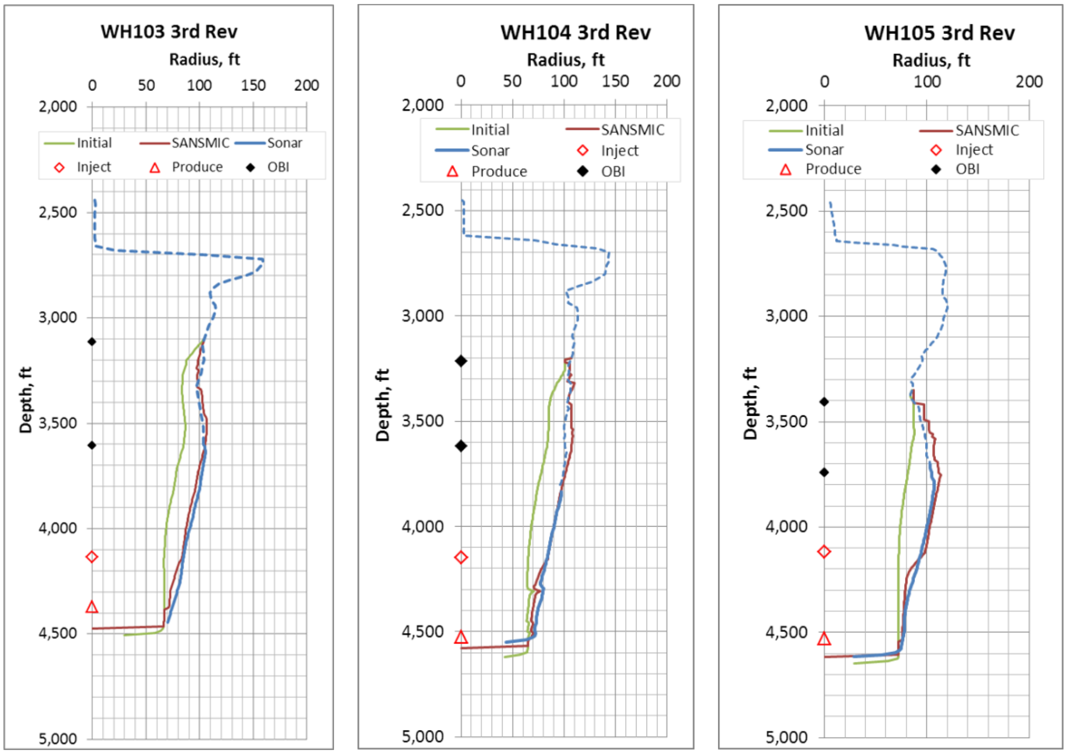


Figure 5-20. Cavern Profile Comparisons for Top-Inject Third-Reverse Test Cases.

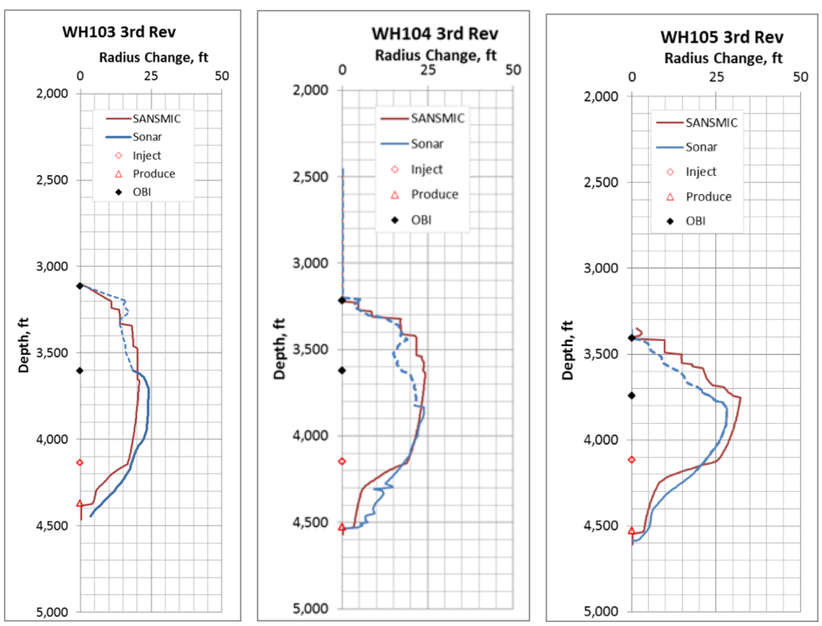


Figure 5-21. Radius-Change Comparisons for Top-Inject Third-Reverse Test Cases.

Table 5-11. Summary Volume Statistics for Top-Inject Test Cases.

Cavern ID	Relative Volume	Relative Radius Difference	Mean Radius Difference, ft	RMS of Radius Difference, ft
First-Reverse Test Cases				
WH101	-0.7%	5.2%	-0.3	5.0
WH103	4.0%	11.9%	3.0	9.4
WH104	16.6%	12.8%	3.9	9.9
WH105	-18.3%	6.0%	-3.6	10.1
BM106	8.5%	14.1%	3.5	11.4
Average(Abs)*	7%	10%	–	–
Second-Reverse Test Cases				
WH101	19.5%	7.7%	3.3	8.9
WH103	7.9%	7.4%	0.6	6.7
WH104	11.6%	10.4%	1.9	10.8
WH105	11.1%	6.6%	1.6	7.8
Average(Abs)*	10%	8%	–	–
Third-Reverse Test Cases				
WH103	-10.2%	3.8%	-2.1	3.8
WH104	9.4%	3.7%	0.5	4.2
WH105	16.8%	4.4%	1.9	4.7
Average(Abs)*	12%	4%	–	–

*averages only include simulations without suspected injection issues.

5.3.4 Historical Comparisons

All historical top-inject reverse-leach simulations analyzed in this report are provided in Figure 5-22, this includes comparisons with Russo's original work (Russo 1981; Russo 1983) and Eyermann's simulations (Eyermann 1984). Considering most of the input data has been developed independently the comparisons are quite good. Differences near the roof can be attributed to the high sensitivity of roof profiles to concurrent oil fill histories which are only approximated. WH101 shows two regions of significant differences: the region around 300 ft is due to OBI history during the 2nd reverse (the current analyses matched OBI measurements when available); and, the large radius transition near 3900 ft which is shifted vertically by ~100 ft. From the analyses in previous sections, this is likely due to a shift in the injection location – either through input or, less likely, by an injection jet model. The shift may also be apparent in "WH101 1st Rev" at 2850 ft. The variation in floor location could be due to insoluble modeling, insoluble fraction or initial geometry assumptions. Thus, given the results discussed, no significant code changes since the early 1980 are apparent, except for the possibility of an injection jet model.

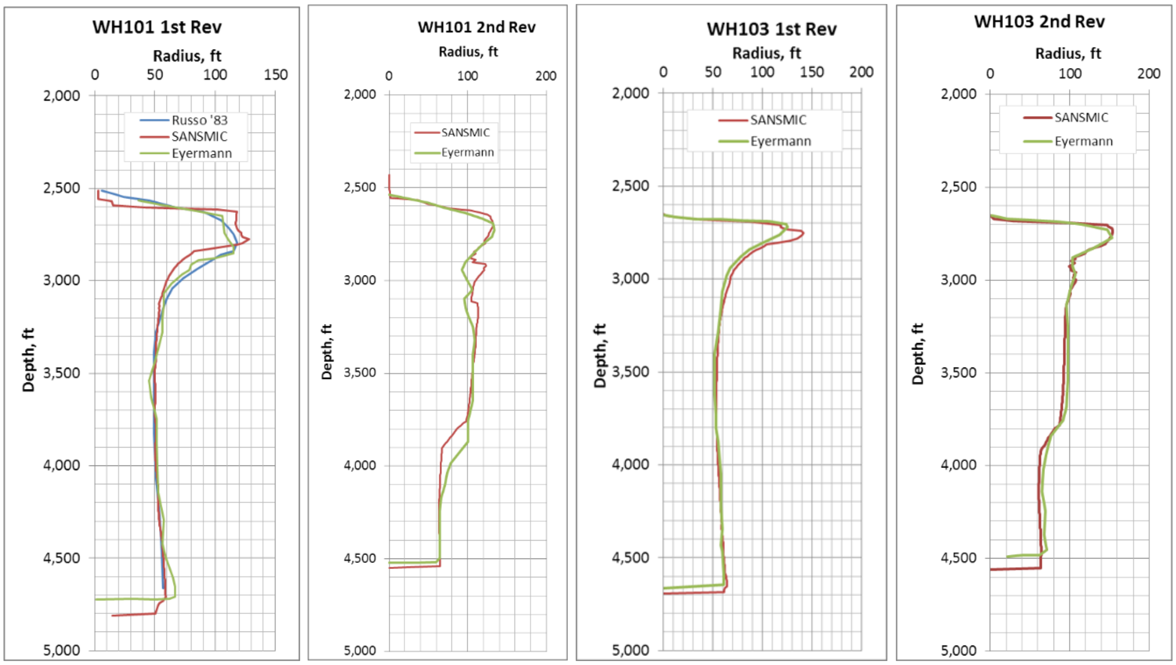


Figure 5-22. Comparison of Current and Historical SANSMIC Results.

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6 Conclusions and Recommendations

Three SANSMIC leach modes – withdrawal, bottom-inject (direct-leach) and top-inject (reverse leach) – are validated with multiple test cases for each leach mode. Validation, in the context of this report, refers to both qualitative and quantitative comparisons to observed or measured data. The measured data consists of interpreted sonar survey data in the form of radius profiles (average cavern radius as a function of depth) and interpreted sonar survey volumes. No specific acceptance criteria were pre-defined. Instead, expected accuracies are determined from the comparisons of SANSMIC predictions and observed data. In addition, comparisons are made to historical SANSMIC results in order to assess whether there have been any discernible changes to the code since its development and original validation in the early 1980s.

The withdrawal mode is validated using recent, high quality data from the 2011 sale and subsequent remedial leach activities. Withdrawal is validated on three scales – small, medium and large – roughly coinciding with quarter, half, and full cavern drawdowns. Results compare very well with observed data, including the location and size of shelves due to string breaks that move the raw water injection point up 100s of feet. This is good news, as most current leaching activity at the SPR is due to oil movements. Relative leached volume differences ranged from 6-10% and relative radius difference from 1.5 to 3%. It should be noted that relative measures do not include caverns for which there is a >15% leached volume difference that could be attributed to inaccuracies in injected volumes.

The bottom-inject (direct-leach) mode is validated using data from completion reports for the sump and chimney stages of SPR cavern development. Sump and chimney development at the SPR used various combinations of one or three simultaneously developed wells and either separate or combined sump and chimney stages. Several combinations of these configuration attributes are simulated. Profile comparisons are very good. Relative leached volume differences range from 6 – 12% and relative radius differences from 5 – 7%. Direct leach at full cavern scale is not validated.

The top-inject (reverse-leach) mode is also validated using cavern completion report data. First, second, and third-reverse configurations are simulated in order to validate SANSMIC over a range of relative hanging string and OBI locations and over a range of injection rates and total injected volumes. All the reverse leaching test cases are leach/fill scenarios, which complicates interpretation of results in the region of OBI movement and results in regions that were not sonar surveyed.

First-reverse roof-development is simulated reasonably well considering the high sensitivity to concurrent oil fill used to shape the roof. The largest differences are in the neighborhood of the injection location where SANSMIC predicts a more rapid radius change in the transition region from the upper lobe to the neck of the cavern. Observations show a more gradual and deeper transition, possibly indicating a deeper injection jet effect. Slower injection (90 MBD instead of 130^{+} MBD) results in larger and uniform development below the transition region. Relative leached volume differences range from 1 – 9% and relative radius differences from 5 – 12%.

The second-reverse mode, used to expand the cavern mid-section, shows the largest discrepancies in leach profile of all the leach modes. However, SANSMIC predictions both under and over-estimate leached radius resulting in a reasonable leached volume. SANSMIC profiles are more vertical and slightly barrel-shaped between the injection point and the OBI, and show the same rapid transition below the injection point. Observations indicate a more uniform and gradual taper. Relative leached volume differences range from 8 – 12% and relative radius differences from 1 – 10%.

In the third-reverse mode, the injection point is moved to a few hundred feet above the production location. In this configuration, the observed leach profile is rather symmetric and rounded with the maximum radius change midway between the OBI and production point. SANSMIC again predicts a barrel like shape with a rapid transition region just below the injection point. However, over and underestimates result in reasonable leached volume. Relative leached volume differences range from 10 – 13% and relative radius differences are ~4 %.

Considering most of the input data are developed independently (not provided), the historical comparisons are quite good. The small differences that do occur are in regions of interface movements resulting from concurrent oil fill. Interface location is highly sensitive to both oil injection history and cavern profile, therefore, small deviations in this region are to be expected. Two of the four reverse-leach cases show shifts in the transition region just below the injection point that are indicative of an injection jet affect. Also, a few direct leach cases with very low injection points showed different wall development near the floor. But, it is not clear whether it is due to input choices or, less likely, the model. It is interesting to note that this shift is also apparent in the observed vs. simulation comparisons. The authors, however, conclude that the current software is essentially the same as was documented in the early 1980s.

In summary, given the assumed geometries, string configurations and uncorrected historical injection/fill rates and volumes, SANSMIC generally predicts leached volumes within ~10 % and cavern radius within ~6%. Relative errors by leach mode are provided in Table 6-1.

Table 6-1. Relative Errors by Leach Type.

Leach Mode	Relative Volume Error, %	Relative Radius Error, %
Withdrawal	8	2
Bottom-Inject	12	6
Top-Inject	10	8
Overall	9	6

6.1 Recommendations

The simulations and analyses in this report use published injection data that are suspected of having accuracy issues because of the metering technologies available and implemented during cavern development. As was done by Eyermann (Eyermann 1984), it is recommended that simulations with suspected injection rates, indicated by unrealistic leach efficiencies or large discrepancies in leached volume, be rerun with scaled rates in order to come up with better performance expectations before the data are used for SANSMIC upgrades.

For example, SANSMIC includes a dissolution rate correction term in the reverse leach mode that was based on heuristic arguments and empirical fits to limited reverse leach data. The data set generated and analyzed for this report provides an expanded basis for updating the reverse leach correction term.

Phase I caverns held by the SPR were obtained from industry in the late 1970s and early 1980s rather than developed to SPR design specifications. They are highly variable in their geometry and are outside the assumed geometry of the SANSMIC model – tall, slender cylinders. Predictions of the future stability of phase I caverns is dependent on accurate prediction of the effects of operational and remedial leach activities on cavern geometry. SANSMIC is currently used for predicting leaching of these caverns but validity in these configurations is unknown. Therefore, it is recommended that leaching data sets outside the standard SPR cavern configuration be pursued.

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Appendix: Summary Configuration Tables

The Excel workbooks utilized in the analysis of SANSMIC calculations and containing SANSMIC input and output data can be found on the SPR Team SharePoint site by navigating to the Documents/Shared Documents/SANSMIC/Validation folder.

In the tables below, an OBI depth of 0 implies the OBI is to be determined by SANSMIC based on oil fill. If the OBI depth is stated to be non-zero, the OBI is set as specified.

Small Withdrawals

BH103 Small Withdrawal								
Stage	**Injection Depth, ft**	**Production Depth, ft**	**OBI Depth, ft**	**Injection Rate, BPD**	**Oil Fill Rate, BPD**	**Duration, Days**	**Work Over, Days**	**Comment**
1	3856	3847	3852	51,981	0	26	71	BH103 Chimney
Total				**1,351,506**	**0**	**26**	**71**	
Average				**51,981**	**0**			
Days				**26**	**0**			

BH104 Small Withdrawal								
Stage	**Injection Depth, ft**	**Production Depth, ft**	**OBI Depth, ft**	**Injection Rate, BPD**	**Oil Fill Rate, BPD**	**Duration, Days**	**Work Over, Days**	**Comment**
1	4196	4180	4174	71,917	0	19	50	BH104
Total				**1,366,423**	**0**	**19**	**50**	
Average				**71,917**	**0**			
Days				**19**	**0**			

Medium Withdrawals

BH101 Medium Withdrawal								
Stage	**Injection Depth, ft**	**Production Depth, ft**	**OBI Depth, ft**	**Injection Rate, BPD**	**Oil Fill Rate, BPD**	**Duration, Days**	**Work Over, Days**	**Comment**
1	4139	3759	3759	70,016	-	56	0.083	BM101 Leach Plan Step 1 - withdrawal 11/11/2011
2	4139	3759	0	-	52,861	112	0.083	BM101 - oil-fill 1/6/12-4/28/12 Step 2
3	4139	3759	0	65,952	-	34	0.083	BM101 - withdrawal 4/28/12-7/17/12 Step 3
4	3916	3759	0	65,952	-	46	0.083	BM101 - withdrawal 4/28/12-7/17/12 with string break at 5/31/2012 Step
5	3916	3759	0	2	60,531	4	0.083	BM101 - oil-fill 7/18/2012-7/21/12 Step 5
6	3916	3759	0	50,580	-	18	0.083	BM101 - withdrawal 7/22/12-8/8/12 Step 6
7	3916	3759	0	2	100,592	55	89	BM101 - oil-fill 8/9/12-10/2/12 Step 7
Total				**10,107,614**	**11,695,116**	**325**	**89.5**	
Average				**47,454**	**68,392**			
Days				**213**	**171**			

BH104 Medium Withdrawal								
Stage	**Injection Depth, ft**	**Production Depth, ft**	**OBI Depth, ft**	**Injection Rate, BPD**	**Oil Fill Rate, BPD**	**Duration, Days**	**Work Over, Days**	**Comment**
1	4186	3798	3798		27,011	50	6	BH104 Leach Plan Step 1 - oil fill
2	4186	3798	0	48,344		113	0.083	
3	4186	3798	0		60,193	104	0.08	
4	4186	3798	0	93,087		57	89	
Total				**10,768,831**	**7,610,622**	**324**	**95.16**	
Average				**63,346**	**49,420**			
Days				**170**	**154**			

Large Withdrawals

WH105 Large Withdrawal								
Stage	**Injection Depth, ft**	**Production Depth, ft**	**OBI Depth, ft**	**Injection Rate, BPD**	**Oil Fill Rate, BPD**	**Duration, Days**	**Work Over, Days**	**Comment**
1	4526	2600	4350	15,000	0	43	100	WH105 Step 1 - Brine inj 10/11/2005-12/26/2005
2	4526	2600	4520	45,602	0	43	64	WH105 - brine inj 7/16/11-8/28/11 Step 2
3	4526	2600	0	84,060	0	97	2	WH105 - brine inj 11/4/11-2/12/12 Step 3a
4	3707	2600	0	84,060	0	3	92	WH105 - brine inj 11/4/11-2/12/12 Step 3b - broken string
5	3707	2600	0	38,988	0	2	5	WH105 - brine inj 5/16/12-5/17/12 Step 4
6	3707	2600	0		85,891	49	0.5	WH105 - oil inj 5/22/12-7/11/12 Step 5
7	3707	2600	0	87,702	0	5	0.5	WH105 - brine inj 7/12/12,6/14/12,6/21/12,8/6/12-8/7/12 Step 6
8	3707	2600	0		49,351	36	0.5	WH105 - oil inj 7/13/12-8/19/12 Step 7
9	3707	2600	0	67,496	0	42	51	WH105 - brine inj 8/20/12-10/1/12 Step 8
Total				**14,363,204**	**5,985,295**	**320**	**315.5**	
Average				**61,120**	**70,415.24**			
Days				**235**	**85**			

WH106 Large Withdrawal								
Stage	**Injection Depth, ft**	**Production Depth, ft**	**OBI Depth, ft**	**Injection Rate, BPD**	**Oil Fill Rate, BPD**	**Duration, Days**	**Work Over, Days**	**Comment**
1	4252	4229	4229	90,776		57	0.5	WH106 Step 1 - Brine inj 5/25/12-7/20/12
2	4252	4229	0	2	73,473	8	0.5	WH106 Step 2 - Oil injection 7/21/12-7/28/12
3	3899	4229	0	73,228		23	0.5	WH106 Step 3 - Brine inj 7/29/12-8/20/12
4	3899	4229	0	2	68,223	47	16	WH106 Step 4 - Oil injection 8/21/12-10/6/12
Total				**6,858,586**	**3,794,265**	**135**	**17.5**	
Average				**50,804**	**68,987**			
Days				**135**	**55**			

Bottom Inject - Direct Leach

BM104 Sump from Completion Report								
Stage	**Injection Depth, ft**	**Production Depth, ft**	**OBI Depth, ft**	**Injection Rate, BPD**	**Oil Fill Rate, BPD**	**Duration, Days**	**Work Over, Days**	**Comment**
1	4419	4213	3226	39000	0	17	0	BM104 Jul
2	4419	4213	3226	29870	0	28	3	BM104 Aug
Total				**1499360**	**0**	**45**	**3**	
Average				**33319.11**	**0**			
Days				**45**	**0**			

BM104 Sump From Russo 1983								
Stage	**Injection Depth, ft**	**Production Depth, ft**	**OBI Depth, ft**	**Injection Rate, BPD**	**Oil Fill Rate, BPD**	**Duration, Days**	**Work Over, Days**	**Comment**
1	4419	4213	3226	4,148	0	1	0	$ BM104 Russo Sump
2	4419	4213	3226	43,817	0	1	0	BM104 day 2
3	4419	4213	3226	26,469	0	1	0	BM104 day 3
4	4419	4213	3226	45,840	0	1	0	BM104 day 4
5	4419	4213	3226	36,068	0	3	0	BM104 day 5-7
6	4419	4213	3226	31,131	0	4	0	BM104 day 8-11
7	4419	4213	3226	37,097	0	6	0	BM104 day 12-17
8	4419	4213	3226	37,097	0	4	0	BM104 day 18-21
9	4419	4213	3226	36,206	0	2	0	BM104 day 22-23
10	4419	4213	3226	0	0	3	0	BM104 day 24-26
11	4419	4213	3226	36,206	0	8	0	BM104 day 127-34
12	4419	4213	3226	40,594	0	1	0	BM104 day 35
13	4419	4213	3226	31,131	0	11	0	BM104 day 36-46
Total				**1,469,065**	**0**	**46**	**0**	
Average				**34,164**	**0**			

BM104 Sump and Chimney – composite of 3 wells

Stage	Injection Depth, ft	Production Depth, ft	OBI Depth, ft	Injection Rate, BPD	Oil Fill Rate, BPD	Duration, Days	Work Over, Days	Comment
1	4410	4225	3226	73,286	-13	53	0	BM104 Chimney 7/15-9/5
2	4410	4225	3226	73,286	-10	48	12	BM104 9/6-10/23
3	4341	2292	2187	75758	0	50	9	BM104 11/5-12/24
4	4341	2292	0	69,587	0	54	27	BM104 1/3-2/25
5	4341	2292	0	37,307	0	20	17	BM104 3/25-4/13
6	4341	2292	0	29,240	0	8	53	BM104 5/1-5/8
Total				15,927,544	-1169	233	118	
Average				68,359	0			
Days				233	0			

BM106 Sump and Chimney – 1 well before coalescence								
Stage	**Injection Depth, ft**	**Production Depth, ft**	**OBI Depth, ft**	**Injection Rate, BPD**	**Oil Fill Rate, BPD**	**Duration, Days**	**Work Over, Days**	**Comment**
1	4450	2284	2233	30000	0	21	0	BM106 mar
2	4450	2284	2233	29067	0	27	3	BM106 apr
3	4450	2284	2233	28000	0	31	0	BM106 may
4	4450	2284	2233	24363	0	30	5	BM106 jun
Total				**3013699**	**0**	**109**	**8**	
Average				**27649**	**0**			
Days				**109**	**0**			

Top Inject - Reverse Leach

BM106 1st Rev								
Stage	**Injection Depth, ft**	**Production Depth, ft**	**OBI Depth, ft**	**Injection Rate, BPD**	**Oil Fill Rate, BPD**	**Duration, Days**	**Work Over, Days**	**Comment**
1	2729	4104	2150	167,750	0	54	10	BM106 First Reverse
2	2729	4104	0	172,750	0	74	9	BM106 2/7-4/21/81
3	2729	4104	2120	172,933	0	56	5	BM106 5/1-6/25/81
4	2729	4104	0	157,295	0	32	13	BM106 7/1-8/1/81
Total				**36,559,688**	**0**	**216**	**37**	
Average				**169,258**	**0**			
Days				**216**	**0**			

WH101 1st Rev								
Stage	**Injection Depth, ft**	**Production Depth, ft**	**OBI Depth, ft**	**Injection Rate, BPD**	**Oil Fill Rate, BPD**	**Duration, Days**	**Work Over, Days**	**Comment**
1	2,796	4723	2604	145,937	0	34	0	WH101 First Reverse
2	2,796	4723	2556	127,807	0	13	0	WH101 2/10-2/22
3	2,796	4723	0	127,807	1,849	3	0	WH101 2/23-2/25
4	2,796	4723	0	132,169	0	7	0	WH101 2/26-3/4
5	2,796	4723	0	135,440	0	18	0	WH101 3/5-3/22
6	2,796	4723	2590	135,440	0	14	0	WH101 3/23-4/5
7	2,796	4723	0	145,012	8,878	1	0	WH101 4/6/2014
8	2,796	4723	0	145,012	0	7	0	WH101 4/7-4/13
9	2,796	4723	0	145,012	41,982	1	0	WH101 4/14/2014
10	2,796	4723	0	145,012	0	3	12	WH101 4/15-4/17
11	2,796	4652	2606	131,768	0	19	0.0417	WH101 4/30/82-5/20/82 exclude 5/13/2014 5/14/2014
12	2,796	4652	0	131,032	9,635	3	0.0417	WH101 leach fill 5/21/1982 5/13/2014 5/14/2014

WH101 1st Rev								
Stage	**Injection Depth, ft**	**Production Depth, ft**	**OBI Depth, ft**	**Injection Rate, BPD**	**Oil Fill Rate, BPD**	**Duration, Days**	**Work Over, Days**	**Comment**
13	2,796	4652	0	95,226	0	28	28	WH101 5/22/82-6/18/82
Total				**19,569,193**	**85,312**	**151**	**40.083**	
Average				**129,597**	**10,664**			
Days				**151**	**8**			

WH101 2nd Rev								
Stage	**Injection Depth, ft**	**Production Depth, ft**	**OBI Depth, ft**	**Injection Rate, BPD**	**Oil Fill Rate, BPD**	**Duration, Days**	**Work Over, Days**	**Comment**
1	4574	3748	2729	139,862	-	12	0	WH101 Second Reverse
2	4574	3748	0	-	90,736	7	0	WH101 8/25-8/31/82 oil fill
3	3748	4574	2786	102,600	-	26	0	WH101 9/1-9/26
4	3748	4574	0	-	94,135	2	0	WH101 9/27-9/28
5	3748	4574	2826	110,952	-	19	0	WH101 9/29-10/18/82
6	3748	4574	2830	111,935	40,368	2	0	WH101 10/19/82
7	3748	4574	0	104,203	-	31	0	WH101 10/20-11/21/82
8	3748	4574	0	-	62,036	4	0	WH101 11/22-11/23/82
9	3748	4574	2882	110,007	-	47	0	WH101 11/24/82-1/10/83
10	3748	4574	0	114,258	44,879	2	0	WH101 1/11/83
11	3748	4574	2896	121,538	-	43	0	WH101 1/12-2/23/83
12	3748	4574	0	123,857	30,480	2	0	WH101 2/24-2/25/83
13	3748	4574	0	120,868	-	12	0	WH101 2/26-3/9/83
14	3748	4538	2902	124,594	-	45	0	WH101 3/10-4/23/83
15	3748	4538	0	-	73,935	4	0	WH101 4/24-4/27/83
16	3748	4538	0	111,890	-	17	0	WH101 4/28-5/14/83
17	3748	4538	0	-	119,313	11	0	WH101 5/15-5/25/83
18	3748	4538	3112	113,785	-	28	0	WH101 5/26-6/22/83
19	3748	4476	0	115,308	-	4	31	WH101 6/23-6/25/83

WH101 2nd Rev								
Stage	**Injection Depth, ft**	**Production Depth, ft**	**OBI Depth, ft**	**Injection Rate, BPD**	**Oil Fill Rate, BPD**	**Duration, Days**	**Work Over, Days**	**Comment**
Total				**33,387,376**	**2,911,202**	**318**	**31**	
Average				**115,129**	**85,624**			
Days				**290**	**34**			

WH103 1st Reverse								
Stage	**Injection Depth, ft**	**Production Depth, ft**	**OBI Depth, ft**	**Injection Rate, BPD**	**Oil Fill Rate, BPD**	**Duration, Days**	**Work Over, Days**	**Comment**
1	2784	4652	2656	102,983	-	19	0	WH103 First Reverse
2	2784	4652	2668	104,310	-	16	0	WH103 2/15-3/3
3	2784	4652	2679	126,859	-	18	0	WH103 3/4-3/21/82
4	2784	4652	0	-	13,410	1	0	WH103 3/22/1982 oilinj
5	2784	4652	0	138,268	-	22	0	WH103 3/23-4/13/82 RWinj
6	2784	4652	0	-	49,640	1	0	WH103 4/14/1982 oilinj
7	2784	4652	2682	135,723	-	34	0	WH103 4/15-5/24/82 RWinj
8	2784	4652	0	-	103,100	1	0	WH103 5/25/1982 oilinj
9	2784	4652	2691	82,791	-	23	0	WH103 5/26-6/17/82 RWinj
10	2784	4652	0	-	45,000	1	12	WH103 6/17/1982 oilinj
11	2784	4652	0	168,762	-	14	0	WH103 6/30-7/13/82 RWinj
12	4652	2784	2700	168,762	-	7	24	WH103 7/14-7/21 Withdrawal
Total				**19,013,772**	**211,150**	**157**	**36**	
Average				**124,273**	**52,788**			
Days				**153**	**4**			

WH103 2nd Reverse								
Stage	**Injection Depth, ft**	**Production Depth, ft**	**OBI Depth, ft**	**Injection Rate, BPD**	**Oil Fill Rate, BPD**	**Duration, Days**	**Work Over, Days**	**Comment**
1	4546	3745	2763	109,157	-	8	0	WH103FirstReverse
2	3745	4546	2833	92,392	-	29	0	WH10310/6-11/22/82a RW inj
3	3745	4546	2837	101,815	-	19	0	WH10310/6-11/22/82b RW inj
4	3745	4546	0	-	47,669	5	0	WH10311/23-11/24/82 oil inj
5	3745	4546	2871	110,200	-	20	0	WH10311/25-12/13/82 RW inj
6	3745	4546	0	-	125,055	3	0	WH10312/14-12/16/82 oil inj
7	3745	4546	2894	103,421	-	31	0	WH10312/17-1/26/83a RW inj
8	3745	4546	2894	97,065	-	10	0	WH10312/17-1/26/83b RW inj
9	3745	4546	0	-	114,089	2	0	WH1031/27-1/28/83 oil inj
10	3745	4546	0	95,821	-	19	0	WH1031/29/-2/16/83 RW inj
11	3745	4546	0	-	58,000	2	0	WH1032/17-2/18/83 oil inj
12	3745	4546	2922	95,821	-	26	0	WH1032/19/83-3/16/83 RW inj
13	3745	4546	0	-	49,800	2	0	WH1033/17-3/18/83 oil inj
14	3745	4546	0	96,806	-	21	0	WH1033/18-4/7/83 RW inj
15	3745	4502	2932	114,185	-	13	0	WH1034/7-4/19/83 RW inj
16	3745	4502	0	-	67,186	5	0	WH1034/20-4/24 oil inj
17	3745	4502	2976	108,360	-	25	0	WH1034/25-5/24/83 RW inj
18	3745	4502	0	-	95,100	8	0	WH1035/25-5/26/83 oil inj
19	3745	4502	3047	89,075	-	8	32	WH1035/27-6/8/83 RW inj
Total				**23,118,686**	**2,154,018**	**256**	**32**	
Average				**100,955**	**79,778**			
Days				**229**	**27**			

WH103 3rd Reverse								
Stage	**Injection Depth, ft**	**Production Depth, ft**	**OBI Depth, ft**	**Injection Rate, BPD**	**Oil Fill Rate, BPD**	**Duration, Days**	**Work Over, Days**	**Comment**
1	4136	4371	3113	109,379	-	21	0	WH103 Third Reverse
2	4136	4371	0	-	37,932	6	0	WH103 8/18-8/23 oil inj
3	4136	4371	0	101,188	-	40	0	WH103 8/24-10/2/83 RW inj
4	4136	4371	0	-	63,723	3	0	WH103 10/3/1983 oil inj
5	4136	4371	3164	91,241	-	7	0	WH103 10/4-10/10/83 RW inj
6	4136	4371	0	-	105,619	4	0	WH103 10/11-10/14/83 oil inj
7	4136	4371	0	92,284	-	19	0	WH103 10/15-11/2/83 RW inj
8	4136	4371	0	-	60,849	10	0	WH103 11/3-11/10/83 oil inj
9	4136	4371	3332	99,880	-	24	0	WH103 11/11-12/5/83 RW inj
10	4136	4371	0	-	48,837	15	0	WH103 12/6-12/16/83 oil inj
11	4136	4371	0	89,610	-	9	0	WH103 12/17-12/25/83 RW inj
12	4136	4371	0	-	71,089	17	25	WH103 1/3/84-1/13/84 oil inj
13	4136	4371	0	88,500	-	1	35	WH103 2/7/1984 RW inj
Total				**12,028,672**	**3,390,795**	**176**	**60**	
Average				**99,411**	**61,651**			
Days				**121**	**55**			

WH104 1st Reverse								
Stage	**Injection Depth, ft**	**Productio n Depth, ft**	**OBI Depth, ft**	**Injection Rate, BPD**	**Oil Fill Rate, BPD**	**Duration, Days**	**Work Over, Days**	**Comment**
1	2807	4785	2624	159,506	-	10	0	WH104 First Reverse
2	2807	4785	2622	159,543	-	30	0	WH104 12/23-2/1/82b
3	2807	4785	2626	135,972	1,702	3	0	WH104 2/2-2/4/82
4	2807	4785	0	131,722	-	28	0	WH104 2/5-3/4/82
5	2807	4785	0	106,224	12,214	5	0	WH104 3/5-3/9/82
6	2807	4785	0	106,224	675	13	0	WH104 3/10-3/25/82a
7	2807	4785	2640	106,224	-	3	42	WH104 3/10-3/25/82b
8	2807	4708	2645	123,360	-	18	0	WH104 5/7-5/25/82
9	2807	4708	0	123,360	119,800	1	0	WH104 5/25/1982
10	2807	4708	2656	96,399	-	24	11	WH104 5/26-6/18/82
11	2807	4708	0	133,466	-	6	0	WH104 6/30-7/5/82
12	2807	4708	0	106,224	30,000	1	0	WH104 7/6/1982
13	2807	4708	0	142,677	-	8	0	WH104 7/7-7/14/82
14	4708	2807	0	131,468	-	31	18	WH104 7/15-8/14/82
Total				**23,489,546**	**224,751**	**181**	**71**	
Average				**129,776**	**9,772**			
Days				**181**	**23**			

WH104 2nd Reverse								
Stage	**Injection Depth, ft**	**ProductionDepth, ft**	**OBI Depth, ft**	**Injection Rate, BPD**	**Oil Fill Rate, BPD**	**Duration, Days**	**Work Over, Days**	**Comment**
1	3735	4621	2881	100,996	-	19	0	WH104 Second Reverse
2	3735	4621	0	-	65,372	1	0	WH104 11/18/1982
3	3735	4621	2891	103,796	-	27	0	WH104 11/19-12/15/82
4	3735	4621	0	-	45,101	1	0	WH104 12/16/1982
5	3735	4621	2901	102,591	-	20	0	WH104 12/17-1/5/83
6	3735	4621	0	95,161	53,188	2	0	WH104 1/6-1/7/83
7	3735	4621	2933	95,161	-	20	0	WH104 1/8-1/27/83

WH104 2nd Reverse								
Stage	**Injection Depth, ft**	**ProductionDepth, ft**	**OBI Depth, ft**	**Injection Rate, BPD**	**Oil Fill Rate, BPD**	**Duration, Days**	**Work Over, Days**	**Comment**
8	3735	4621	0	95,161	60,608	2	0	WH104 1/28-1/29/83
9	3735	4621	0	100,605	-	18	0	WH104 1/30-2/16/83
10	3735	4621	0	101,286	112,070	1	0	WH104 2/17/1983
11	3735	4621	2955	107,116	-	70	0	WH104 2/18-4/28/83
12	3735	4621	0	-	151,500	2	0	WH104 4/29-4/30/83
13	3735	4621	2998	101,429	-	25	0	WH104 5/1-5/25/83
14	3735	4621	0	-	96,577	7	0	WH104 5/26-6/1/83
15	3735	4621	0	111,621	-	6	0	WH104 6/2-6/7/83
16	3735	4621	3085	-	61,250	1	0	WH104 6/8/1983
17	3735	4621	0	111,308	-	31	0	WH104 6/9-7/9/83
18	3735	4621	0	-	152,389	3	0	WH104 7/10-7/12/83
19	3735	4621	3174	110,542	-	12	0	WH104 7/13-7/24
20	4621	3735	0	110,542	-	3	25	WH104 7/25-7/27/83
Total				**26,781,525**	**1,947,591**	**271**	**25**	
Average				**104,615**	**97,380**			
Days				**256**	**20**			

WH104 3rd Reverse								
Stage	**Injection Depth, ft**	**ProductionDepth, ft**	**OBI Depth, ft**	**Injection Rate, BPD**	**Oil Fill Rate, BPD**	**Duration, Days**	**Work Over, Days**	**Comment**
1	4147	4527	3215	95,823	-	31	0	WH104 Third Reverse
2	4147	4527	0	70,845	131,576	3	0	WH104 10/3-10/5/83
3	4147	4527	3265	106,267	-	19	0	WH104 10/6-10/24/83
4	4147	4527	0	106,267	130,582	2	0	WH104 10/25-10/26/83
5	4147	4527	3311	113,186	-	40	0	WH104 10/27-12/5/83
6	4147	4527	0	-	125,743	4	0	WH104 12/6-12/9/83
7	4147	4527	0	90,815	30,804	7	0	WH104 12/10-12/16/83
8	4147	4527	3412	87,836	-	19	0	WH104 12/17/83-1/4/84

WH104 3rd Reverse								
Stage	**Injection Depth, ft**	**ProductionDepth, ft**	**OBI Depth, ft**	**Injection Rate, BPD**	**Oil Fill Rate, BPD**	**Duration, Days**	**Work Over, Days**	**Comment**
9	4147	4527	0	-	148,816	5	0	WH104 1/5/84-1/9/84
10	4147	4527	0	76,667	-	5	14	WH104 1/10-1/14/84
11	4147	4527	0	76,667	-	3	0	WH104 1/29-1/31/84
12	4147	4527	0	7,385	67,843	3	0	WH104 2/1-2/3/84
13	4147	4527	0	7,385	-	12	0	WH104 2/4-2/15/84
14	4147	4527	0	-	130,997	3	0	WH104 2/16-2/18/84
15	4147	4527	0	7,385	-	11	57	WH104 2/19-2/29/84
16	3624	4510	2974	-	61,250	1	0	WH104 6/8/1983
17	3624	4510	0	111,308	-	31	0	WH104 6/9-7/9/83
18	3624	4510	0	-	152,389	3	0	WH104 7/10-7/12/83
19	3624	4510	3063	110,542	-	12	0	WH104 7/13-7/24
20	4510	3624	0	110,542	-	3	25	WH104 7/25-7/27/83
Total				**18,160,708**	**3,233,509**	**217**	**96**	
Average				**90,352**	**104,307**			
Days				**201**	**31**			

WH105 1st Reverse								
Stage	**Injection Depth, ft**	**ProductionDepth, ft**	**OBI Depth, ft**	**Injection Rate, BPD**	**Oil Fill Rate, BPD**	**Duration, Days**	**Work Over, Days**	**Comment**
1	2824	4744	2643	78,200	-	21	0	WH105 First Reverse
2	2824	4744	2645	93,796	-	24	0	WH105 3/27-4/19
3	2824	4744	2647	108,138	-	20	0	WH105 4/20-5/9
4	2824	4744	0	119,400	5,033	2	0	WH105 5/10-5/11/82
5	2824	4744	2648	119,400	-	13	0	WH105 5/12-5/24/82
6	2824	4744	0	119,400	65,914	1	0	WH105 5/25/1982
7	2824	4744	2668	80,250	-	24	11	WH105 5/26-6/18/82
8	2824	4744	0	102,092	-	13	0	WH105 6/30-7/12/82
9	2824	4744	2672	10,500	1,944	9	0	WH105 7/13-7/21/82
10	4719	2824	0	90,418	-	55	5	WH105 7/22-9/14/82
11	4719	2824	0	99,375	-	16	16	WH105 9/20-10/5/82
Total				**17,877,150**	**93,476**	**198**	**32**	
Average				**90,289**	**7,790**			
Days				**198**	**12**			

WH105 2nd Reverse								
Stage	**Injection Depth, ft**	**ProductionDepth, ft**	**OBI Depth, ft**	**Injection Rate, BPD**	**Oil Fill Rate, BPD**	**Duration, Days**	**Work Over, Days**	**Comment**
1	3749	4630	2678	92,600	-	11	0	WH105 Second Reverse
2	3749	4630	0	-	70,591	14	0	WH105 11/19-12/2/82
3	3749	4630	2826	95,600	-	9	0	WH105 12/3-12/11/82
4	3749	4630	0	-	100,114	2	0	WH105 12/12-12/13/82
5	3749	4630	2856	95,600	-	14	0	WH105 12/14-12/27/82
6	3749	4630	0	-	75,390	3	0	WH105 12/28-12/30/82
7	3749	4630	2892	98,160	-	5	0	WH105 12/31-1/4/83
8	3749	4630	0	-	55,373	2	2	WH105 1/5-1/6/83
9	3749	4630	2895	105,005	-	37	0	WH105 1/9-2/14/83
10	3749	4630	0	115,200	70,233	2	0	WH105 2/15-2/16/83

WH105 2nd Reverse								
Stage	**Injection Depth, ft**	**Productio nDepth, ft**	**OBI Depth, ft**	**Injection Rate, BPD**	**Oil Fill Rate, BPD**	**Duration, Days**	**Work Over, Days**	**Comment**
11	3749	4630	2915	116,340	-	30	0	WH105 2/17-3/18/83
12	3749	4630	0	-	155,000	1	0	WH105 3/19/1983
13	3749	4630	2929	114,418	-	22	0	WH105 3/20-4/15/83a
14	3749	4630	0	111,200	52,427	5	0	WH105 3/20-4/15/83b (4/11-4/15)
15	3749	4630	0	-	104,853	5	0	WH105 4/16-4/20/83
16	3749	4630	3003	108,500	-	12	0	WH105 4/21-5/2/83
17	3749	4630	0	95,000	53,773	5	0	WH105 5/3-5/7/83
18	3749	4630	0	95,000	-	12	0	WH105 5/8-5/18/83
19	3749	4630	0	-	93,165	12	0	WH105 5/19-5/30/83
20	3749	4630	3189	127,376	-	17	0	WH105 5/31-6/18/83
21	3749	4630	0	129,400	100,075	2	0	WH105 5/31-6/18/83b (6/17-6/18)
22	3749	4630	0	-	100,075	4	0	WH105 6/19-6/22/83
23	3749	4630	0	126,450	-	16	33	WH105 6/23-7/7/83
Total				**21,751,573**	**4,594,579**	**242**	**35**	
Averag e				**109,304**	**80,607**			
Days				**199**	**57**			

WH105 3rd Reverse								
Stage	**Injection Depth, ft**	**Productio nDepth, ft**	**OBI Depth, ft**	**Injection Rate, BPD**	**Oil Fill Rate, BPD**	**Duration, Days**	**Work Over, Days**	**Comment**
1	4117	4528	3405	101,935	-	49	0	WH105 Third Reverse
2	4117	4528	0	-	180,019	3	0	WH105 10/7-10/9/83
3	4117	4528	3494	88,200	-	22	0	WH105 10/10-10/31/83
4	3117	4528	0	-	106,490	3	0	WH105 10/14/81
5	4117	4528	0	106,200	-	13	0	WH105 11/4-11/16/83
6	4117	4528	0	-	66,182	2	0	WH105 11/17-11/18/83
7	4117	4528	0	106,200	-	12	0	WH105 11/19-11/30/83
8	4117	4528	0	79,100	55,905	6	0	WH105 12/1-12/16/83a

WH105 3rd Reverse								
Stage	**Injection Depth, ft**	**ProductionDepth, ft**	**OBI Depth, ft**	**Injection Rate, BPD**	**Oil Fill Rate, BPD**	**Duration, Days**	**Work Over, Days**	**Comment**
9	4117	4528	3630	79,100	31,209	10	0	WH105 12/1-12/16/83b (12/7-12/16)
10	4117	4528	0	79,100	-	14	1	WH105 12/17-12/30/83
11	4117	4528	0	-	75,362	1	0	WH105 1/1/1984
12	4117	4528	0	100,300	30,102	12	79	WH105 1/2-1/14/84
Total				**13,166,815**	**2,075,997**	**147**	**80**	
Average				**95,412**	**56,108**			
Days				**138**	**37**			

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