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Hanging String Cuts in SPR Caverns: Modeling Investigation and Comparison with Sonar Data

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ABSTRACT

Investigation of leaching for oil sales includes looking closely at cavern geometries. Anomalous cavern “features” have been observed near the foot of some caverns subsequent to partial drawdowns. One potential mitigation approach to reducing further growth of preexisting features is based on the hypothesis that reducing the brine string length via a “string cut” would serve to move the zone associated with additional leaching to a location higher up in the cavern and thus away from the preexisting feature. Cutting of the hanging string is expected to provide a control of leaching depth that could be used to “smooth” existing features and thus reduce geomechanical instability in that region of the cavern. The SANSMIC code has been used to predict cavern geometry changes (i.e., the extent of cavern growth with depth) based on variable input parameters for four caverns: West Hackberry 11 (WH11), West Hackberry 113 (WH113), Big Hill 104 (BH104), Big Hill 114 (BH114). By comparing the initial sonar geometry with resultant geometries calculated by the SANSMIC code, conclusions may be drawn about the potential impact of these variables on future cavern growth. Ultimately, these conclusions can be used to assess possible mitigation strategies such as the potential advantage of cutting versus not cutting a brine string. This work has resulted in a recommendation that a hanging string cut of 80 ft in WH11 would be beneficial to future cavern geometry, while there would be little to no benefit to string cuts in the other three caverns investigated here. The WH11 recommendation was followed in 2019, resulting in an operational string cut. A sonar performed after the string cut showed no adverse leaching in the area of the preexisting flare, as expected from the results of the preliminary SANSMIC runs described in this report. Additional SANSMIC modeling of the actual amount of injected raw water resulted in good agreement with the post-cut sonar.

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EXECUTIVE SUMMARY

Investigation of leaching for oil sales includes looking closely at cavern geometries. Anomalous cavern "features" have been observed near the foot of some caverns subsequent to partial drawdowns. The features include localized zones of increased cavern diameter and may be exacerbated by continued leaching of the cavern in the zone near the end of the brine string (i.e., hanging string). The existence of anomalous features may lead to geomechanical instabilities that could eventually result in salt falls and ensuing brine string damage.

One potential mitigation approach to reducing further growth of preexisting features is based on the hypothesis that reducing the brine string length via a "string cut" would serve to move the zone associated with additional leaching to a location higher up in the cavern and thus away from the preexisting feature. Cutting of the hanging string is expected to provide a control of leaching depth that could be used to "smooth" existing features and thus reduce geomechanical instability in that region of the cavern.

The SANSMIC code has been used to predict cavern geometry changes (i.e., the extent of cavern growth with depth) based on variable input parameters for four caverns: West Hackberry 11 (WH11), West Hackberry 113 (WH113), Big Hill 104 (BH104), Big Hill 114 (BH114). The input parameters considered here were the length of brine string cuts, number of brine string cuts, number of leaches, and flow conditions for each leach. By comparing the initial sonar geometry with resultant geometries calculated by the SANSMIC code, conclusions may be drawn about the potential impact of these variables on future cavern growth.

An important conclusion from this study is that the growth of adverse cavern geometry features appears to be avoidable by cutting the end of the brine string in some instances. Some combinations of input parameters were found to result in a reduction of adverse leaching. The general principle behind this behavior seems to be that leaching during water injection primarily takes place between the end of tubing (lowest point of the hanging string where fresh water enters the cavern) and the oil-brine interface (a point higher in the cavern where the top layer of oil meets the lower layer of brine). Additionally, the longer that leaching takes place with the hanging string near a large radius feature, the more it grows. Cutting of the string is shown to move the zone of leaching away from preexisting, problematic cavern geometry features. However, the development of additional (undesired) secondary features is also possible with the flow volumes associated with partial drawdowns. Another finding is that flow rate is not a dominant variable in determining leaching outcomes given the same total volume injected, but there is an impact of total volume injected on determining leaching outcomes.

Ultimately, these conclusions can be used to assess possible mitigation strategies such as the potential advantage of cutting versus not cutting a brine string. This work has resulted in the conclusion that a hanging string cut of 80 ft in WH11 could be beneficial to future cavern geometry, while there would be little to no benefit to string cuts in the other three caverns investigated here. An operational string cut was implemented in WH11 in 2019 as a result of this recommendation. It was found to have led to no adverse leaching in the area of the preexisting flare, as expected from the results of the preliminary SANSMIC runs described in this report. Additional SANSMIC modeling of the actual amount of injected raw water resulted in good agreement with a post-cut sonar.

ACRONYMS AND DEFINITIONS

Abbreviation	Definition
bbls	barrels
BH104	Big Hill 104
BH114	Big Hill 114
CY2018	Calendar year 2018
EOT	End of tubing
MMbbls	Million barrels
OBI	Oil-brine interface
SANSMIC	Sandia Solution Mining Code
SNL	Sandia National Laboratories
SPR	Strategic Petroleum Reserve
WH11	West Hackberry 11
WH113	West Hackberry 113

1. INTRODUCTION

Investigation of leaching for oil sales includes looking closely at cavern geometries (Chojnicki 2019). Anomalous cavern "features" have been observed near the foot of some caverns subsequent to partial drawdowns. The features include localized zones of increased cavern diameter and may be exacerbated by continued leaching of the cavern in the zone near the end of the brine string (i.e., hanging string) (Eldredge et al. 2013). The existence of anomalous features may lead to geomechanical instabilities that could eventually result in salt falls and ensuing brine string damage.

One potential mitigation approach to reducing further growth of preexisting features is based on the hypothesis that reducing the brine string length via a "string cut" would serve to move the zone associated with additional leaching to a location higher up in the cavern and thus away from the preexisting feature. Cutting of the hanging string is expected to provide a control of leaching depth that could be used to "smooth" existing features and thus reduce geomechanical instability in that region of the cavern. Partial drawdowns impact cavern geometry differently than full drawdowns (e.g., via preferential leaching at the cavern bottom) as leaching primarily occurs in the depths of a cavern between the end of the brine string (end of tubing; EOT) (bottom of the zone) to the oil-brine interface (OBI) (top of the zone) (Weber et al. 2014).

As an example, anomalous cavern growth (e.g., flaring of cavern floor) has been observed in WH11 and may lead to geomechanical instabilities via the "sharp" feature observed near the cavern floor as shown in Figure 1-1 (Chojnicki 2019). Because leaching during water injection is known to take place between the end of the brine string and the OBI, it is hypothesized that moving the end of the brine string up in the cavern would also move the leaching zone further up in the cavern, avoiding further development of the flared feature and instead creating a less sharp cavern profile (Figure 1-2).

The work described here includes the description of a methodology and workflow to facilitate mediation of further anomalous cavern growth by considering brine string cuts under variable conditions in a single cavern of known initial geometry. The methodology has been described elsewhere in a study on WH11 (Zeitler and Chojnicki 2020). This report includes the results of the application of this methodology to four caverns (WH11, WH113, BH104, BH114). Ultimately, this approach could be used to answer the following questions in anticipation of making recommendations for ensuring stable cavern growth:

1. Can cutting brine strings reduce flaring of cavern floors in sales caverns?
2. What specific recommendation can be made for ensuring a stable cavern geometry over time?
3. How does the initial cavern geometry impact the potential for geometry change?

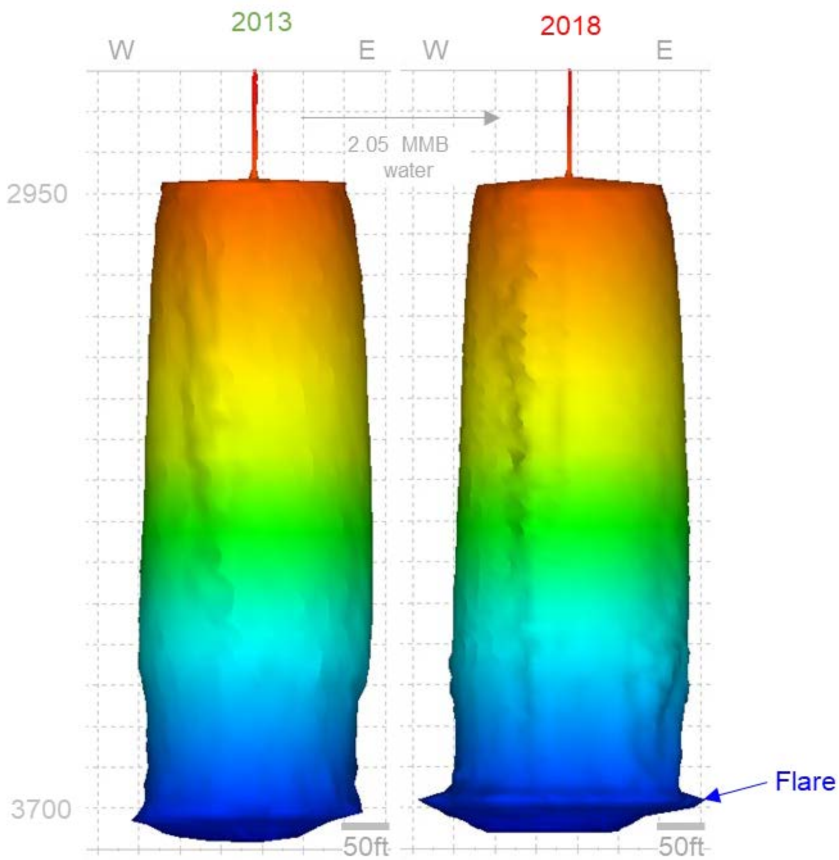

Figure 1-1. (left) Pre- and (right) Post-sale sonars of WH11 showing the formation of a flare feature after 2.05 MMbbls of water was injected for oil withdrawal in 2014 (0.1 MMbbls) and 2017 (1.9 MMbbls).

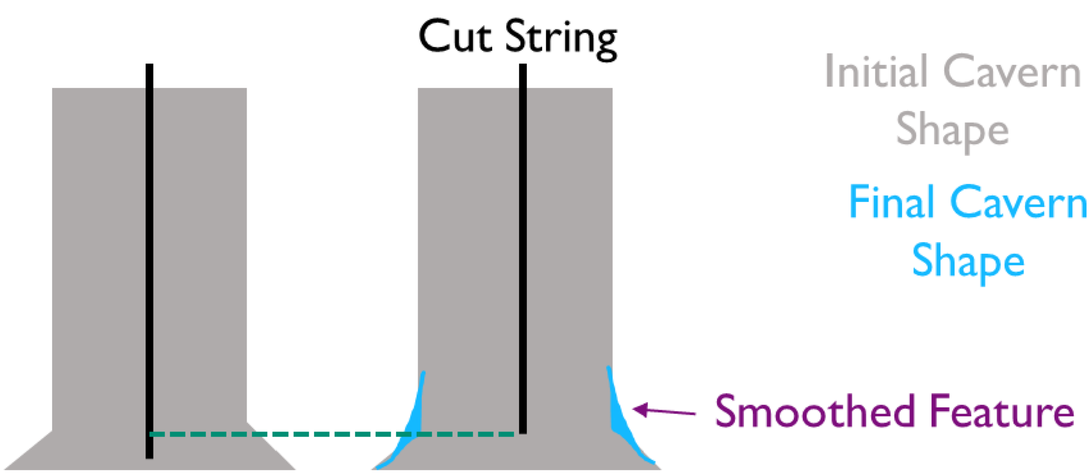

Figure 1-2. Schematic representation of cavern WH11, showing potential for cut string to lead to smoothing of cavern floor feature. The flare at the floor (or wing) in the initial cavern shape was primarily caused by partial leaching during the 2017 sales (see Chojnicki (2019) for more information).

2. APPROACH

The SANSMIC (Sandia Solution Mining Code) code was developed at Sandia National Laboratories (SNL) for modeling leaching during cavern creation and has since been used to track leaching during other transfer operations (i.e., fills and withdrawals) in SPR caverns (Russo 1983, Weber et al. 2014). Various leaching modes have been incorporated in the code, including leaching during water injection/oil extraction. The impact of leaching on cavern geometry can be measured by comparing the pre- and post-leach cavern geometries. Typically, the code has been used to check cavern growth following oil sales wherein a cavern geometry is computed given the pre-sales cavern geometry (obtained from cavern sonars) and known injection data during sales (Weber et al. 2013, Chojnicki 2019). However, the code can also be used in a predictive manner to anticipate changes to an initial cavern geometry under given injection assumptions. In either case, a one-dimensional, axisymmetric representation of the cavern geometry is the model input and output.

In the approach outlined here, the SANSMIC code is used to predict cavern geometry changes (i.e., the extent of cavern growth with depth) based on variable input parameters. By comparing the initial sonar geometry with resultant geometries calculated by the SANSMIC code, conclusions may be drawn about the potential impact of these variables on future cavern growth. Ultimately, these conclusions could be used to assess possible mitigation strategies such as the potential advantage of cutting versus not cutting a brine string. In the case of WH11, a post-cut sonar was available and an additional run of the SANSMIC code is used for comparison of cavern geometries.

Input for the SANSMIC code may be broadly categorized as cavern-dependent (i.e., those parameters that vary across caverns) or operations-dependent (i.e., those parameters that may be changed from a caverns operation standpoint). Examples of cavern-dependent input are initial cavern geometry and the initial location of the OBI. Examples of operations-dependent parameters are hanging string length (i.e., location of the end of the brine string) and the flow conditions (i.e., rate and duration) for brine or raw water entering the cavern during a drawdown.

3. METHODOLOGY

The methodology for analyzing string cuts for the four caverns investigated here consists of 33 runs of the SANSMIC code for each cavern. The methodology was used previously for the WH11 cavern and documented in Zeitler and Chojnicki (2020) (Appendix B); the methodology and results from that study are reproduced here for completeness. Additionally, the results for three additional caverns (WH113, BH104, and BH114) are described in this report.

For each SANSMIC run, the initial geometry was based on an axisymmetric representation of the 2018 cavern sonar and an OBI location which was the SANSMIC-estimated OBI position after the CY2018 sales. An axisymmetric representation is created by averaging the cavern radius at each depth. The SANSMIC input assumptions (cavern bottom depth, initial hanging string depth, OBI depth, and initial cavern volume) are summarized for the four caverns in Table 3-1.

Table 3-1. Cavern Characteristic Assumptions for SANSMIC Runs

Cavern Name	Cavern Bottom Depth (ft)	Initial Hanging String Depth (ft)	OBI Depth (ft)	Initial Cavern Volume (MMbbls)
WH11	3750	3735	3510	8.5
WH113	4630	4622	4360	11.3
BH104	4200	4176	3840	14.3
BH114	4130	4081	3660	12.8

Each of the 33 runs for each cavern consisted of independent combinations of the following input parameters: length of brine string cuts, number of brine string cuts, and number of leaches (Table 3-2). Eleven combinations of string cut lengths/number of string cuts/number of leaches were used, with each of three flow conditions applied to each combination.

Table 3-2. Lengths of Hanging String Cuts Considered For Each Combination of Number of Cuts and Leaches

Number of Cuts	Number of Leaches	
	1	5
0	0 ft	0 ft
1	20 ft, 60 ft, 100 ft	20 ft, 60 ft, 100 ft
5	-	20 ft (5 x 4 ft), 60 ft (5 x 12 ft), 100 ft (5 x 20 ft)

As a baseline, simulations were performed for the case where the string was not cut (0 cuts) to determine the extent of leaching without mitigation and compare it with the extent of leaching which included mitigation from a single cut (1 cut) in a single sale (1 leach) or multiple sales (5 leaches) or multiple cuts (5 cuts) in multiple sales (5 leaches) with one cut after each sale.

For each cavern, total cut lengths of zero, 20 ft, 60 ft, and 100 ft were examined. These distances were chosen based on the dimensions of the feature observed in the most recent WH11 sonar, but were kept consistent across all caverns. For cases with five cuts, each cut was $1/5^{th}$ of the total cut length (e.g., for a total cut length of 100 ft, there was first a cut of 20 ft and a leach, then a second cut of 20 ft and a leach, then a third cut of 20 ft and a leach, then a fourth cut of 20 ft and a leach, and finally a fifth cut and a leach). As an example, the initial brine string depth (end of string) for the WH11 cavern was 3735 ft (15 ft from the cavern bottom); a cut of 100 ft would result in a string depth of 3635 ft.

For each cavern, three flow conditions were examined which were based on the range of values observed for water injection rates and durations in the 2017 sales. Flow condition 1 has a low flowrate for a long duration and flow condition 2 has a high flow rate for a short duration with an equivalent volume of injected water as flow condition 1. Thus, a comparison of results from flow conditions 1 and 2 reveals the effects of flow rate and duration on leaching outcomes. Flow condition 3 has the same rate as flow condition 2 and a longer duration to reach twice the total volume as flow conditions 1 and 2. Thus a comparison of results from flow conditions 2 and 3 reveals the effect of the total volume of water injected. The exact values used for each condition are summarized in Table 3-3.

Table 3-3. Flow Conditions On a Per Leach Basis

Flow Condition	Flow Rate (bbls/day)	Flow Duration per Leach (days)	Volume per Leach (bbls)
1	10000	50	500000
2	50000	10	500000
3	50000	20	1000000

A distinct run name was developed to identify each run of the SANSMIC code with the cavern name, number of cuts, total cut length, number of leaches, and flow conditions making up part of the name. The "key" to run names is the following: [*Cavern Name*]_C[*Number of Cuts*]_[*Total Cut Length*]L[*Number of Leaches*]F[*Flow Condition Identifier*]. For example, WH11_C1_100L1F1 is a run of the West Hackberry 11 cavern with a single cut of 100 ft and a single leach under flow condition 1. As another example, BH104_C1_60L5F3 is a run of the Big Hill 104 cavern with a single cut of 60 ft and five leaches under flow condition 3.

A Windows executable of the SANSMIC code was used. Preprocessing and postprocessing tools were developed for the WH11 investigation (Zeitler and Chojnicki 2020) to aid in the workflow, reducing manual steps in the process and the potential for user errors; those tools were used for all caverns in the current work. On the preprocessing side, the *SANSMICsetup.sh* shell script was used to assemble a SANSMIC input file from two other files, a cavern geometry file (which contains initial geometry information for the cavern of interest) and a SANSMIC input file template (which contains a general framework for the SANSMIC input file). With a run of the *SANSMICsetup.sh* script, the template is populated by command line input, which provides the cavern name, initial brine string height, OBI height, injection rate, injection duration, total cut length, number of cuts, and number of leaches and then combined with the cavern geometry file to produce a SANSMIC input file suitable for running.

When SANSMIC is run, a number of output files are produced including a *.out* file that includes the final cavern geometry. The *postSANSMIC.py* script was developed in Python to extract final cavern geometry information from the *.out* file and produce three files: 1) a *.tbl* file (which contains columnar data on a nodal basis); 2) a *.stats* file (which contains a single line of input and output data useful for run verification); and 3) a *.png* file (a graphics file containing a plot of initial and final cavern geometries, as well as initial and final OBI locations). See Table A-1 through A-4 in Appendix A for summaries of input parameters and output data for the 33 SANSMIC runs for each cavern.

3.1. Initial Cavern Geometries

For each SANSMIC run, the initial geometry was based on an axisymmetric representation of the 2018 cavern sonar and an OBI location which was the SANSMIC-estimated OBI position after the CY2018 sales. An axisymmetric representation is created by averaging the cavern radius at each depth. Figures in the subsections below present the sonar geometry, axisymmetric representation of the sonar geometry, and axisymmetric representation of the SANSMIC-estimated geometry for each cavern.

3.1.1. West Hackberry 11 (WH11)

The geometry of the WH11 cavern shows an existing feature, an abrupt flare that juts out ~35 ft at a depth of ~3700 ft (Figure 3-1). The current cavern volume is approximately 8.5 MMbbls. The volume of oil in the cavern at the time of the 2018 sonar was approximately 6.0 MMbbls.

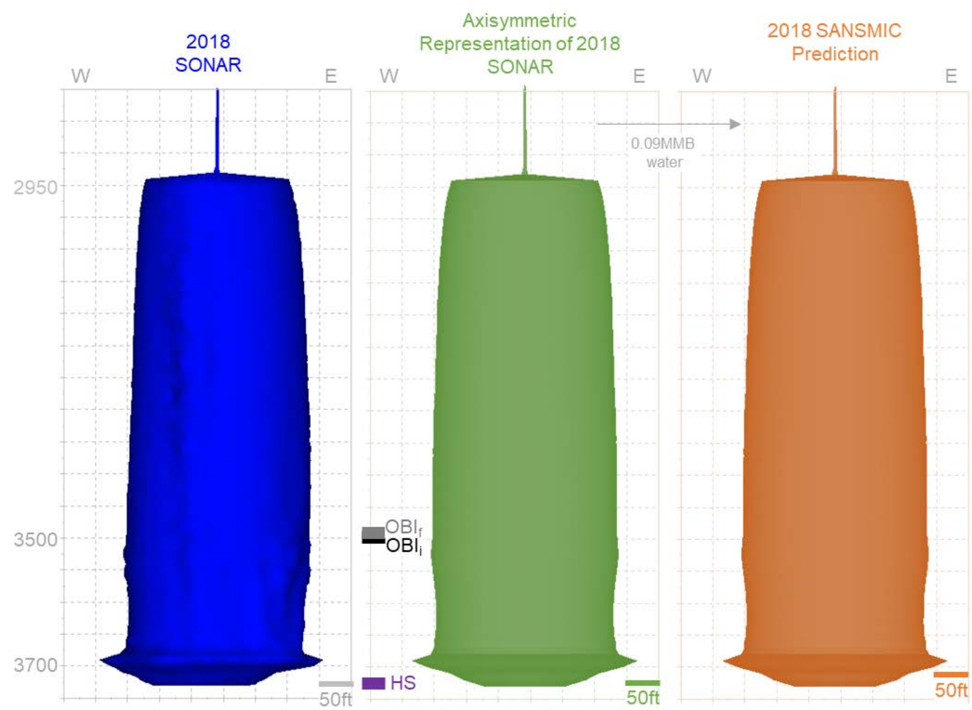

Figure 3-1. (left) The WH11 2018 sonar geometry, (middle) the axisymmetric representation of that sonar used as an input for modeling the effects of the 0.09 MMbbls of water injected in WH11 during 2018, and (right) the SANSMIC-calculated final cavern geometry including the 0.09 MMbbls injection (CY2018 sales) which was the starting geometry for WH11 in this study.

In Section 4.1.4, a different initial cavern geometry was used for a single SANSMIC run. That WH11 cavern geometry was based on the same 2018 sonar, but includes angled measurements of the cavern floor.

3.1.2. West Hackberry 113 (WH113)

The geometry of the WH113 cavern shows a slight, outward flare of about 5 ft over the lowest ~300 ft. The flaring is not as abrupt and distinct as in the case of WH11 (Figure 3-2). The current cavern volume is approximately 11.3 MMbbls. The volume of oil in the cavern at the time of the 2018 sonar was approximately 9.9 MMbbls.

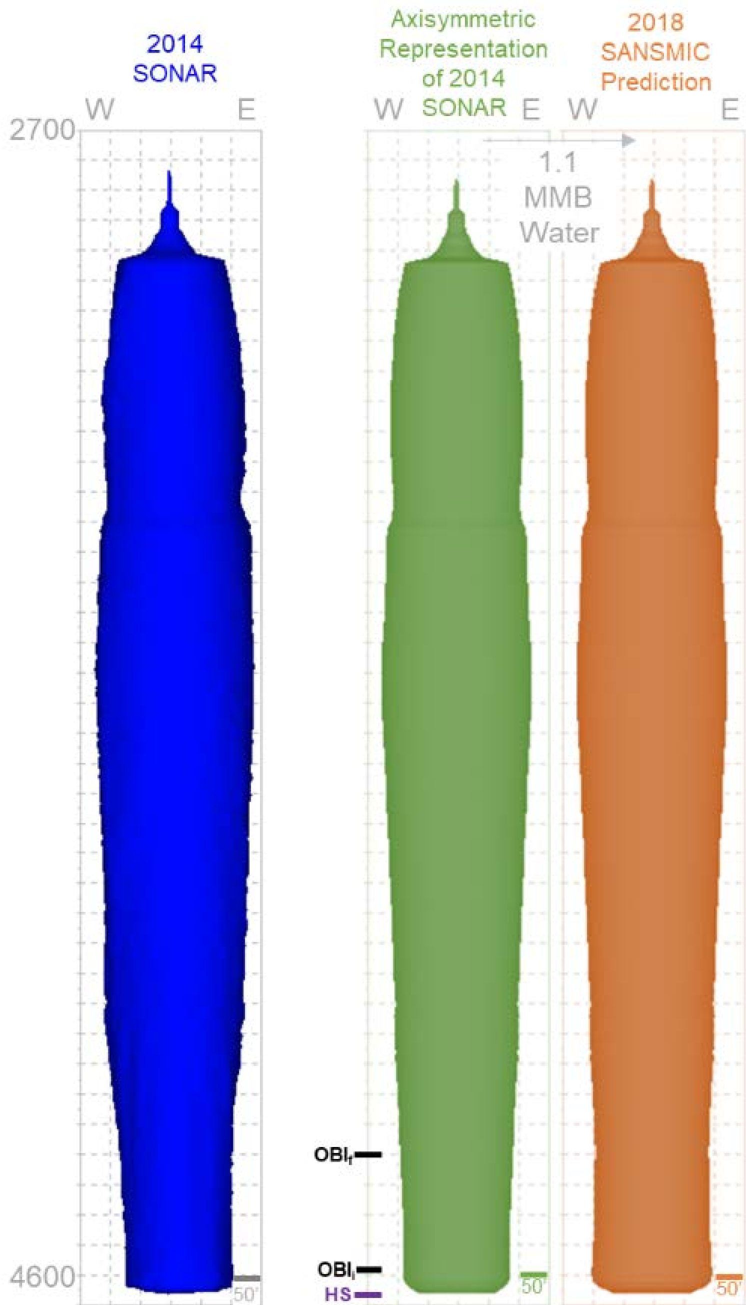

Figure 3-2. **(left) The WH113 2018 sonar geometry, (middle) the axisymmetric representation of that sonar used as an input for modeling the effects of the 1.1 MMbbls of water injected in WH113 during 2018, and (right) the SANSMIC-calculated final cavern geometry including the 1.1 MMbbls injection (CY2018 sales) which was the starting geometry for WH113 in this study.**

3.1.3. Big Hill 104 (BH104)

The geometry of the BH104 cavern shows a slight, outward flare of about 10 ft over the lowest ~300 ft (Figure 3-3). The flaring is not as abrupt and distinct as in the case of WH11. The current cavern volume is approximately 14.3 MMbbls. The volume of oil in the cavern at the time of the 2018 sonar was approximately 11.7 MMbbls.

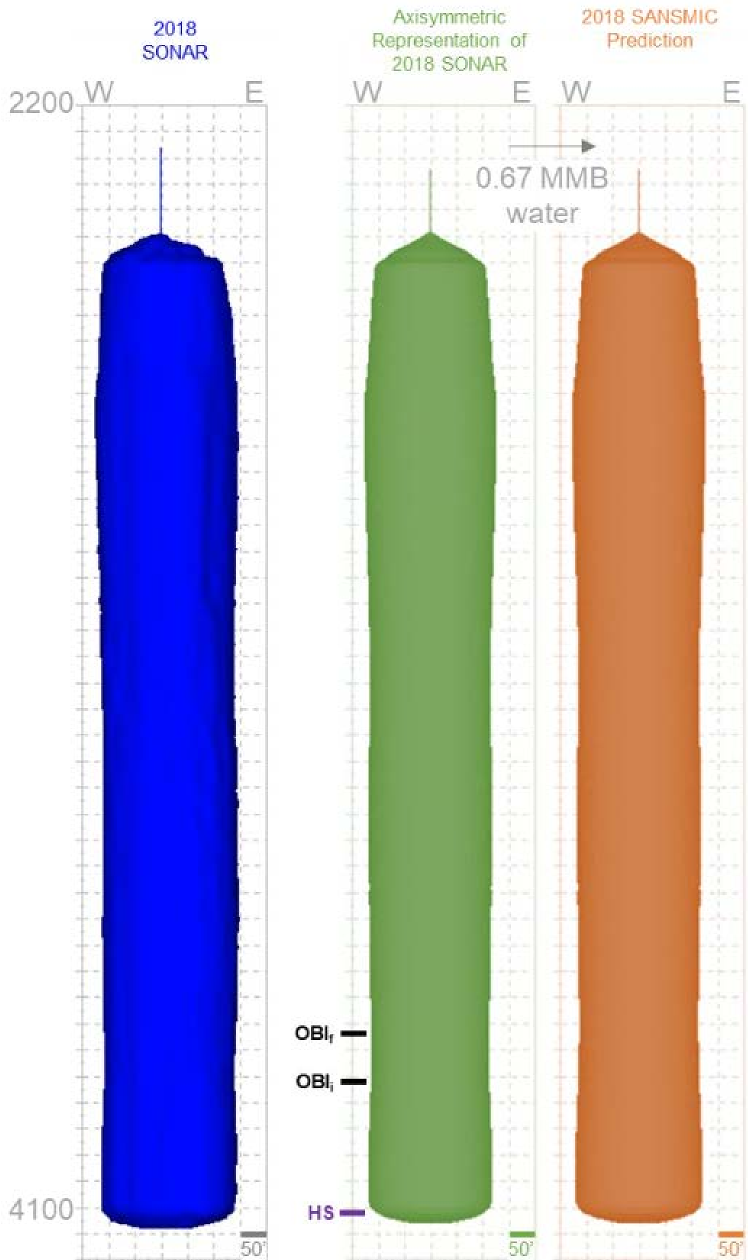

Figure 3-3. (left) The BH104 2018 sonar geometry, (middle) the axisymmetric representation of that sonar used as an input for modeling the effects of the 0.67 MMbbls of water injected in BH104 during 2018, and (right) the SANSMIC-calculated final cavern geometry including the 0.67 MMbbls injection (CY2018 sales) which was the starting geometry for BH104 in this study.

3.1.4. *Big Hill 114 (BH114)*

The geometry of the WH113 cavern shows an outward flare of about 20 ft over the lowest ~50 ft, with the radius maximized at a depth of ~4100 ft (Figure 3-4). The flaring is not as abrupt and distinct as in the case of WH11. The current cavern volume is approximately 12.8 MMbbls. The volume of oil in the cavern at the time of the 2018 sonar was approximately 10.7 MMbbls.

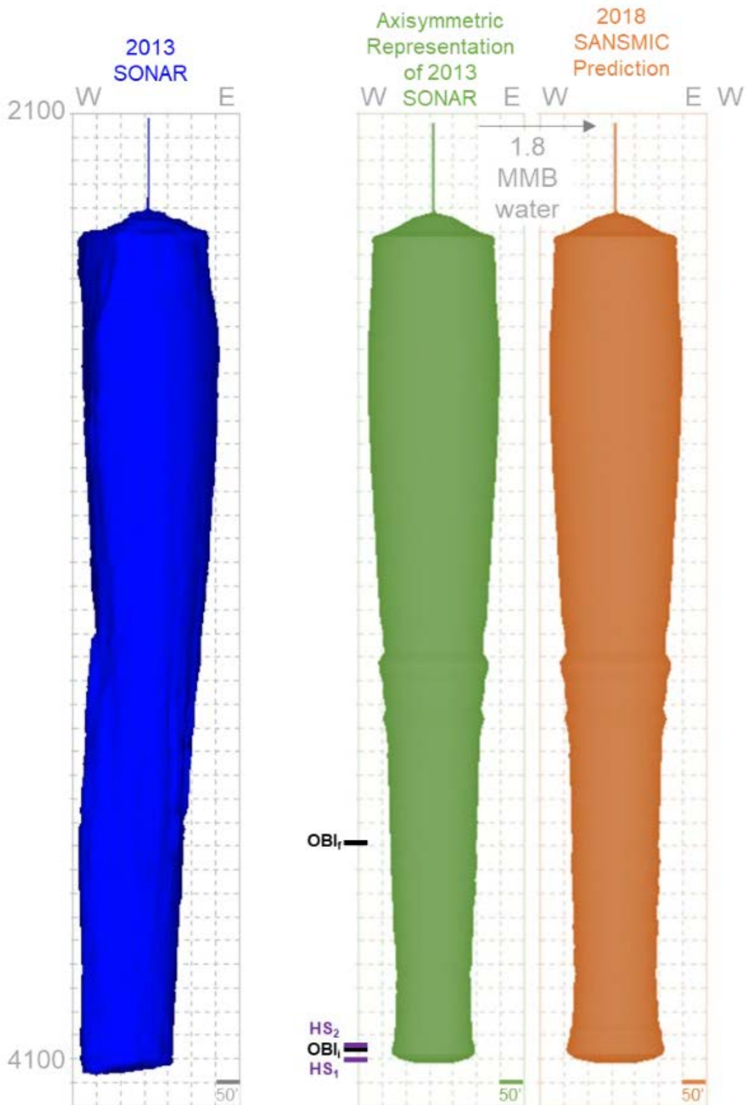

Figure 3-4. (left) The BH114 2018 sonar geometry, (middle) the axisymmetric representation of that sonar used as an input for modeling the effects of the 1.8 MMbbls of water injected in BH114 during 2018, and (right) the SANSMIC-calculated final cavern geometry including 1.8 MMbbls injection (CY2018 sales) which was the starting geometry for BH114 in this study.

4. RESULTS

This section contains a discussion of the results of SANSMIC modeling for the WH11 (Section 4.1), WH113 (Section 4.2), BH104 (Section 4.3), and BH114 (Section 4.4) caverns.

4.1. West Hackberry 11 (WH11)

An example of SANSMIC output is presented in Figure 4-1. This figure shows what SANSMIC predicts will happen after the next sale in WH11 without a string cut based on flow conditions like those in condition 1 (red line; WH11_C0_0L1F1) and the initial geometry (i.e., the output geometry from SANSMIC modeling of the 2018 leaching, denoted "Initial Geometry"). In this case, the cavern radius has increased for depths below 3470 ft, including the feature at 3700 ft. This output demonstrates that without mitigation, that feature will continue to grow in this cavern.

Comparisons of the cavern geometries output from the 33 SANSMIC runs with the initial cavern geometry for WH11 are presented in Figure 4-2 to Figure 4-7. Note that the scales for radius and depth are not the same in these figures. Based on these results, Zeitler and Chojnicki (2020) recommended that an 80 ft cut be made to the hanging string in WH11.

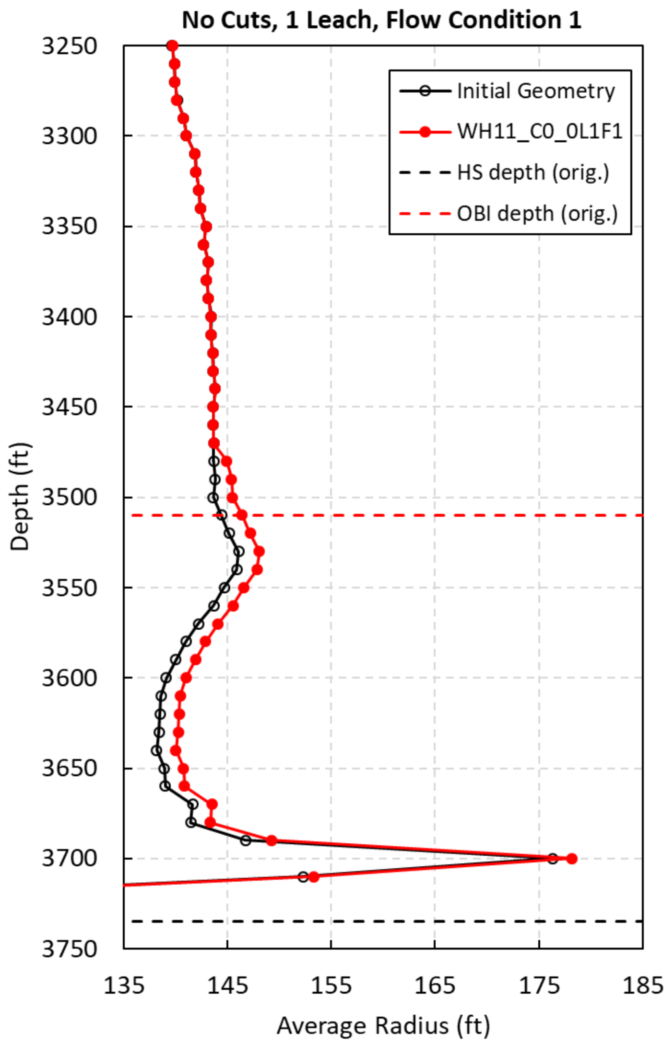

Figure 4-1. Comparison of (red) SANSMIC-predicted WH11 geometry for no string cut, single leach, flow condition 1 (WH11_C0_0L1F1) case with (black) the initial geometry, a SANSMIC-generated, axisymmetric representation of the cavern geometry after the CY2018 sales

4.1.1. Baseline – No Change (No Cuts of the String)

Results are described below for the baseline case of no string cuts for one or five sales.

4.1.1.1. One Sale

Figure 4-2 shows the cases of "no cut," a single leach, and three flow conditions (3 total cases); these scenarios examine the leaching that may happen after one sale if there are no changes to string length. The use of flow conditions 1 and 2 (which have an identical total number of injected bbls) results in almost identical final geometries with leaching up to a depth of 3480 ft, while the use of flow condition 3 (twice the total number of injected bbls) results in increased leaching, including leaching up to a depth of 3430 ft. All cases show an increased radius of the feature at 3700 ft.

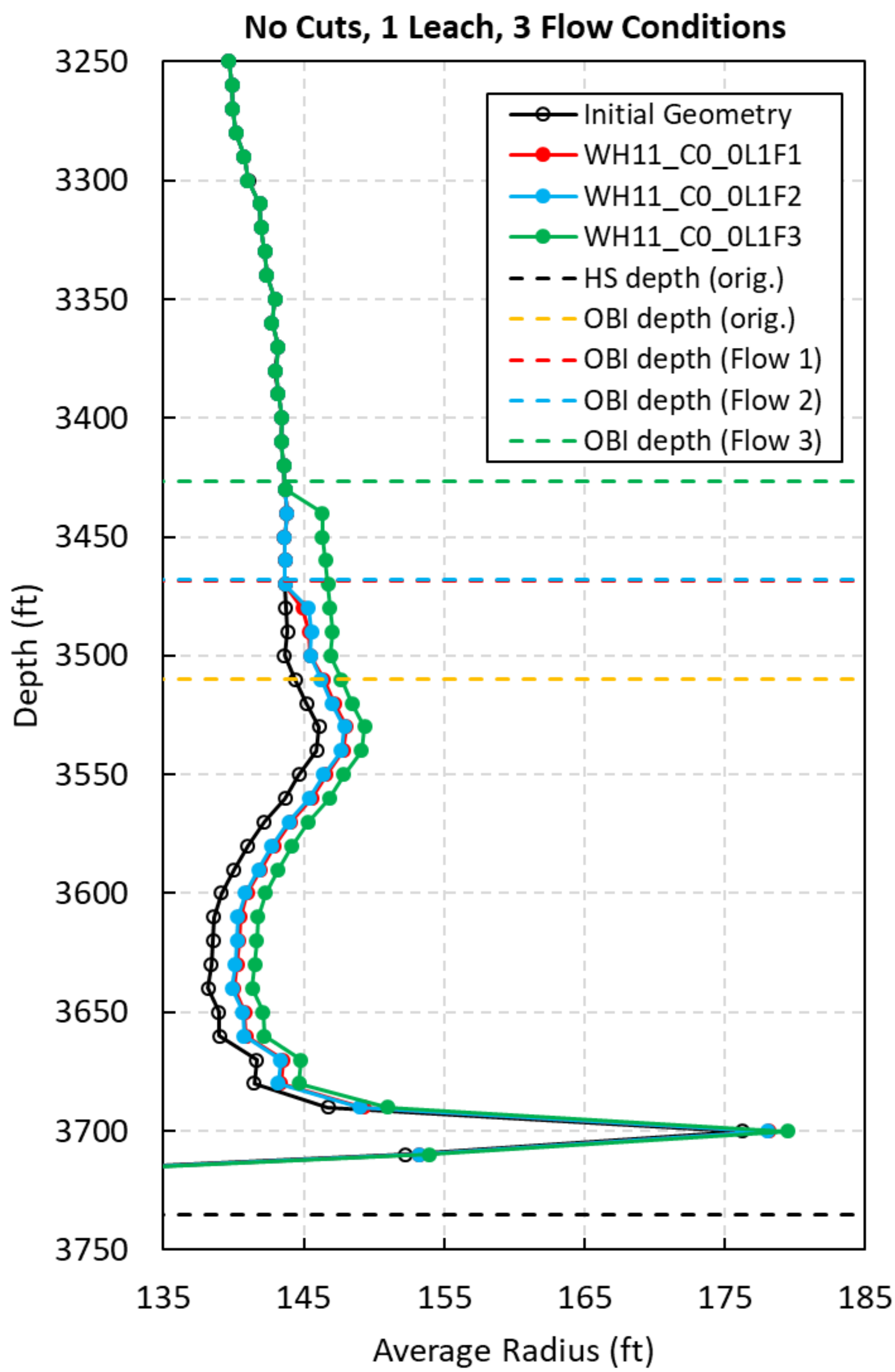

Figure 4-2. **Predicted WH11 geometries for no string cuts and a single leach with flow condition 1 (red), 2 (blue) and 3 (green) compared with the starting geometry (black).**

4.1.1.2. Multiple Sales

Figure 4-3 shows the cases of "no cut," five leaches, and three flow conditions (3 total cases); these scenarios examine the leaching that may happen after five sales if there are no changes to the string length. Similar to the single leach cases shown in Figure 4-2, the use of flow conditions 1 and 2 (which have an identical total number of injected bbls) results in almost identical final geometries with leaching up to a depth of 3310 ft, while the use of flow condition 3 (twice the total number of injected bbls) results in increased leaching, including leaching up to a depth of 3080 ft. All cases show an increased radius of the feature at 3700 ft.

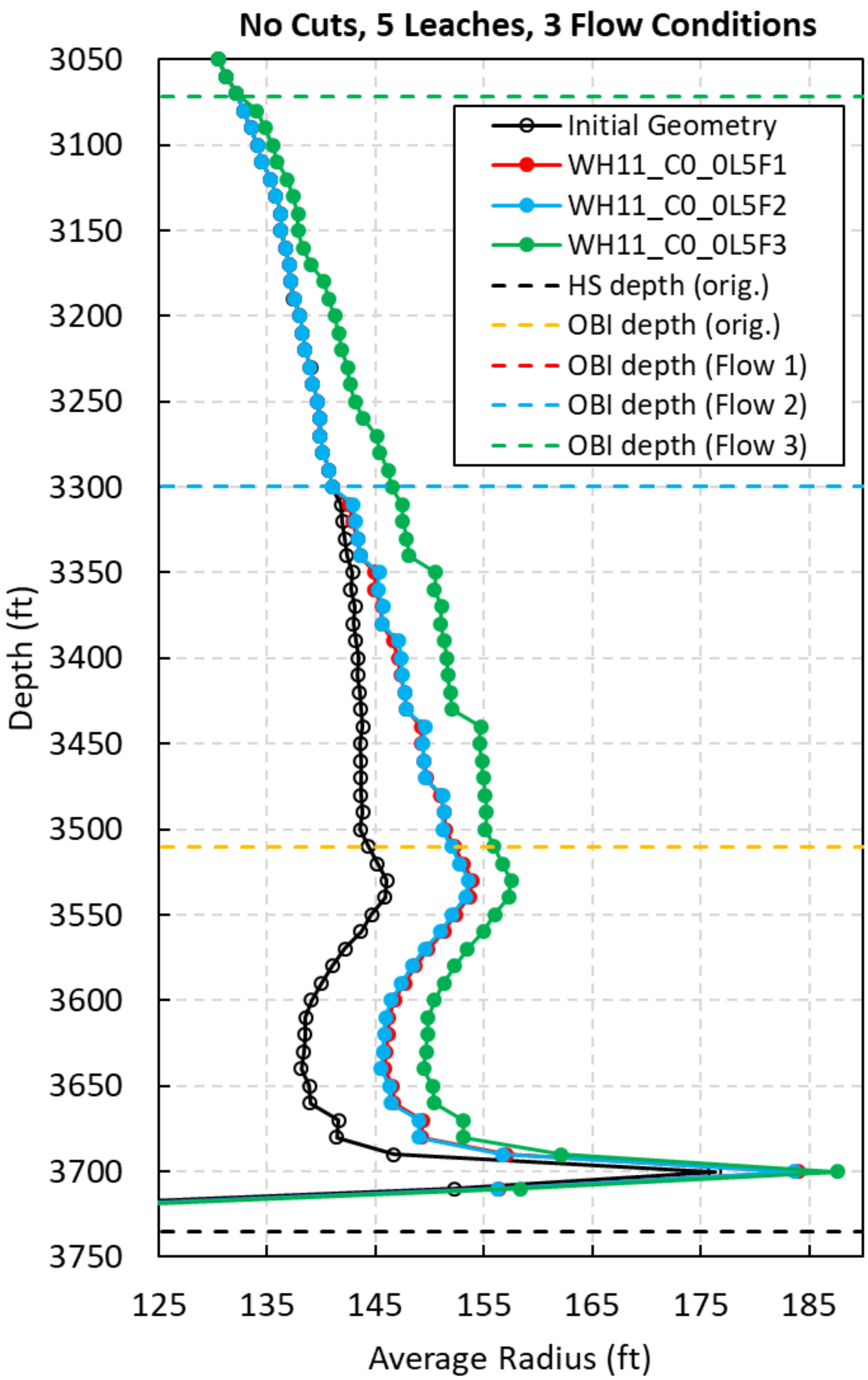

Figure 4-3. **Predicted WH11 geometries for no string cuts and five leaches with flow condition 1 (red), 2 (blue) and 3 (green) compared with the starting geometry (black).**

Cumulatively, the almost identical final geometries for flow conditions 1 and 2 shown in Figure 4-2 and Figure 4-3 indicate that flow rate is not a dominant variable in determining leaching outcomes given the same total volume injected (as a result, final OBI depths for flow conditions 1 and 2 are almost identical for each cut/leach pair). Similarly, the substantial difference in final geometries between flow conditions 2 and 3 in Figure 4-2 and Figure 4-3 indicates the impact of total volume injected on determining leaching outcomes.

4.1.2. Mitigation Results 1 – Cut the String Once

Results are described below for the case of a single string cut prior to sales for one or five sales. Cut lengths of 20, 60, and 100 ft were investigated.

4.1.2.1. One Sale

Figure 4-4 shows the cases of a single cut, a single leach, and three flow conditions (9 total cases) for cuts of 20, 60, and 100 ft, respectively; these scenarios examine the leaching that may happen after one sale if the string is cut once prior to leaching. This figure shows the impact of the three flow conditions for a single leach and a single brine string cut of 20, 60, or 100 ft. For cuts of 20 ftFigure 4-4), there is some increase in radius of the feature at 3700 ft. In the cases of 60 and 100-ft cuts, leaching does not result in an appreciable increase in radius of the feature at 3700 ft; rather, the leaching only goes down to a depth of 3690 ft for 60-ft cuts and 3650 ft for 100-ft cuts. These results imply that a minimum cut length of 60 ft is necessary in this cavern to stop leaching of the feature at 3700’. Similarly, the string cut at 100 ft starts to form a secondary feature starting at 3650’ depth and, thus, to avoid forming that secondary feature, the string should be cut no higher than 100 ft. Based on these results, Zeitler and Chojnicki (2020) recommended that an 80 ft cut be made to the hanging string in WH11.

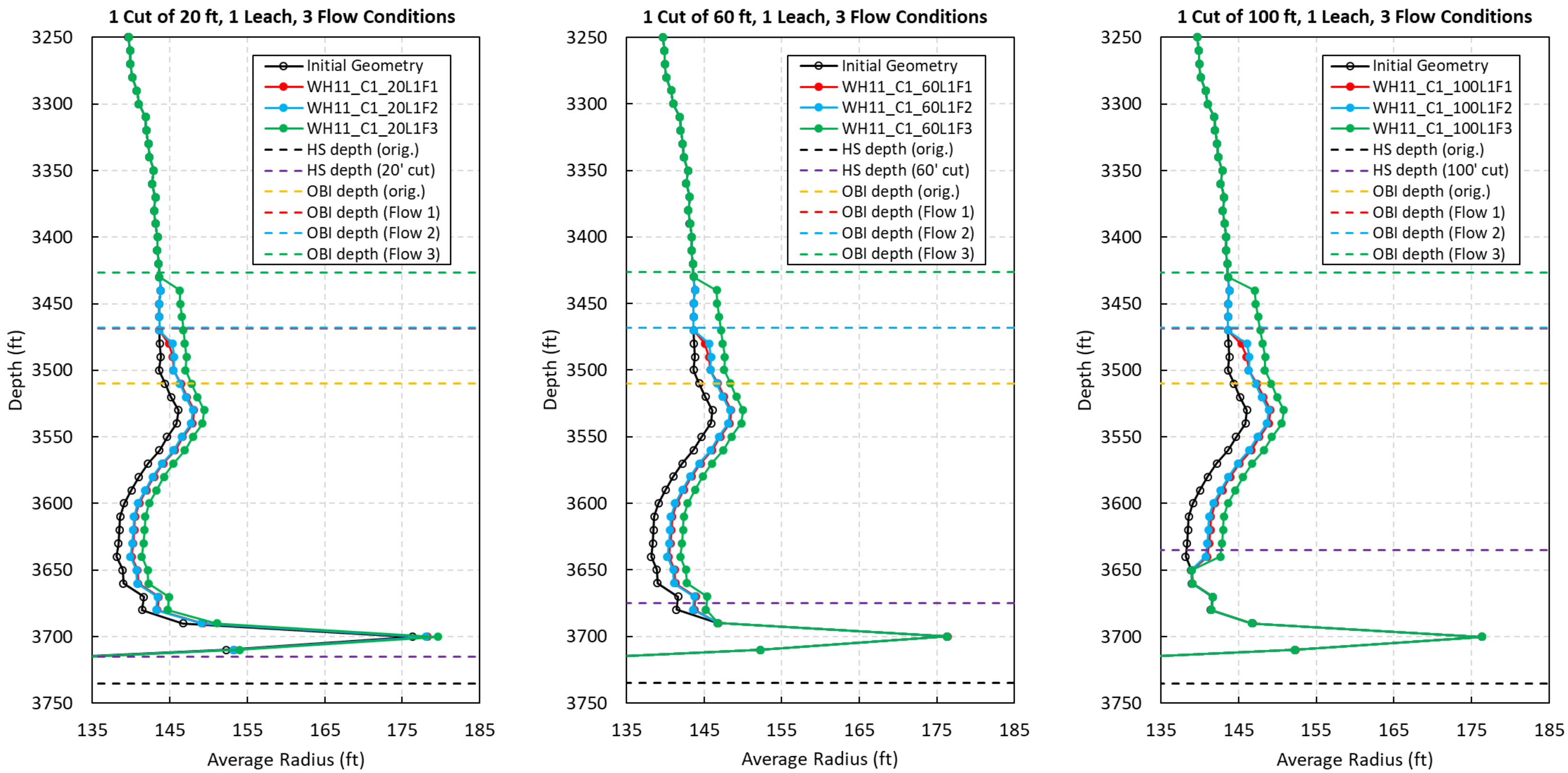

Figure 4-4. **Predicted WH11 geometries for a single leach and a single string cut of (left) 20 ft, (middle) 60ft, and (right) 100 ft (three flow conditions).**

For clarity, a subset of the runs shown in Figure 4-4 are plotted in Figure 4-5 for the three cut length runs associated only with flow condition 3. Since this condition has the greatest total amount of water injected and greatest leaching effect, it is easiest to see the relative effects of the string cut lengths for this condition.

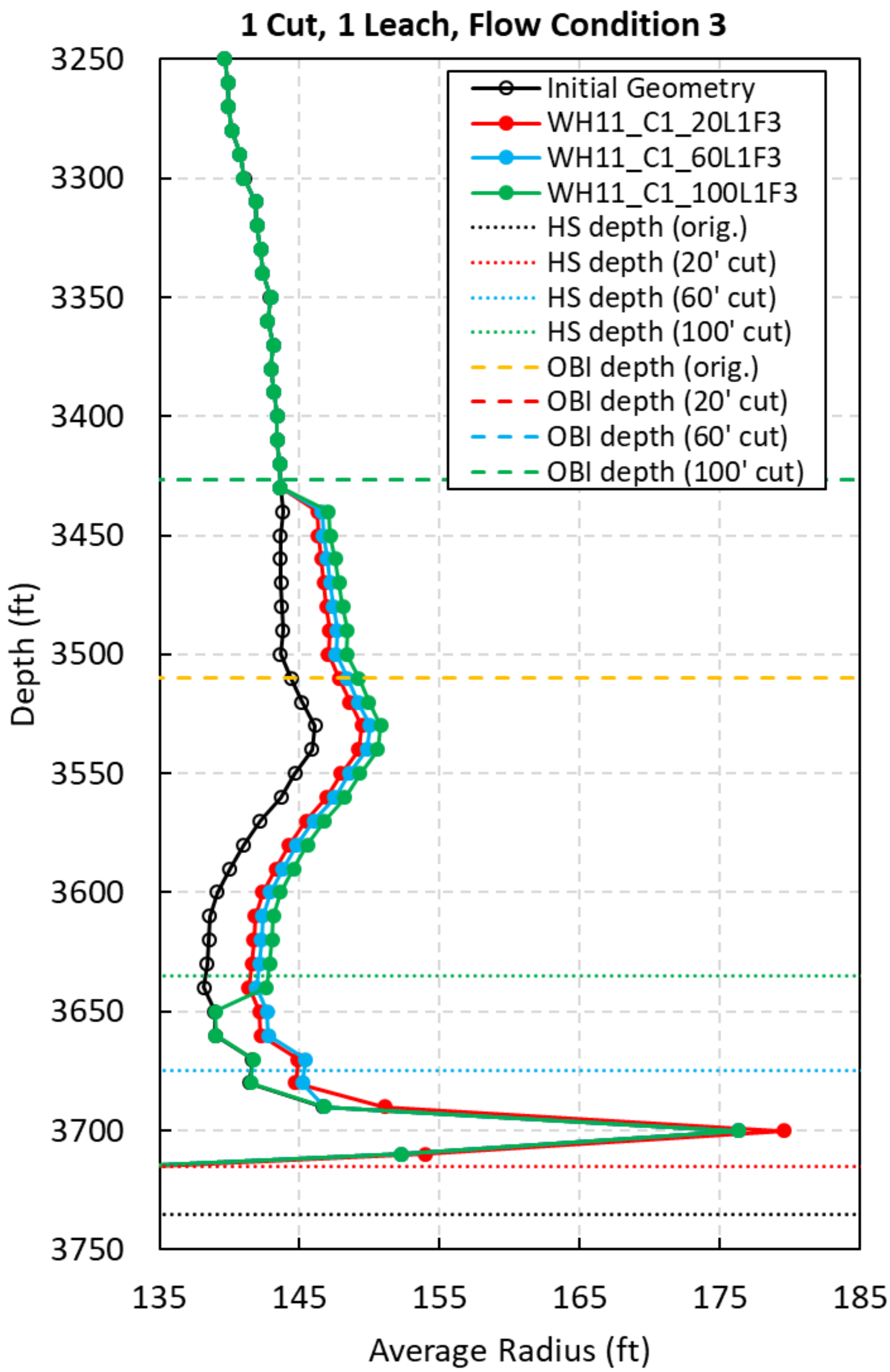

Figure 4-5. Predicted WH11 geometries for a single string cut and a single leach (flow condition 3).

4.1.2.2. Multiple Sales

Figure 4-6 shows the cases of a single cut, five leaches, and three flow conditions (9 total cases) for cuts of 20, 60, and 100 ft, respectively; these scenarios examine the leaching that may happen after five sales if the string is cut once prior to any leaching. This figure shows the impact of the three flow conditions for five consecutive leaches following a single brine string cut of 20, 60, or 100 ft. Compared to the single leach cases (Figure 4-4), the cavern radius increases in the leaching zone, as expected due to the five-fold increase in injected water volume. Similar to the single leach cases, growth of the feature at 3700 ft is avoided for runs with cuts of 60 or 100 ft. The development of the secondary feature above 3650 ft for cuts of 100 ft is more prominent in Figure 4-6 and underscores the importance of considering the effects of multiple leaches as well as single leaches on the outcome of a string length change in these sales caverns.

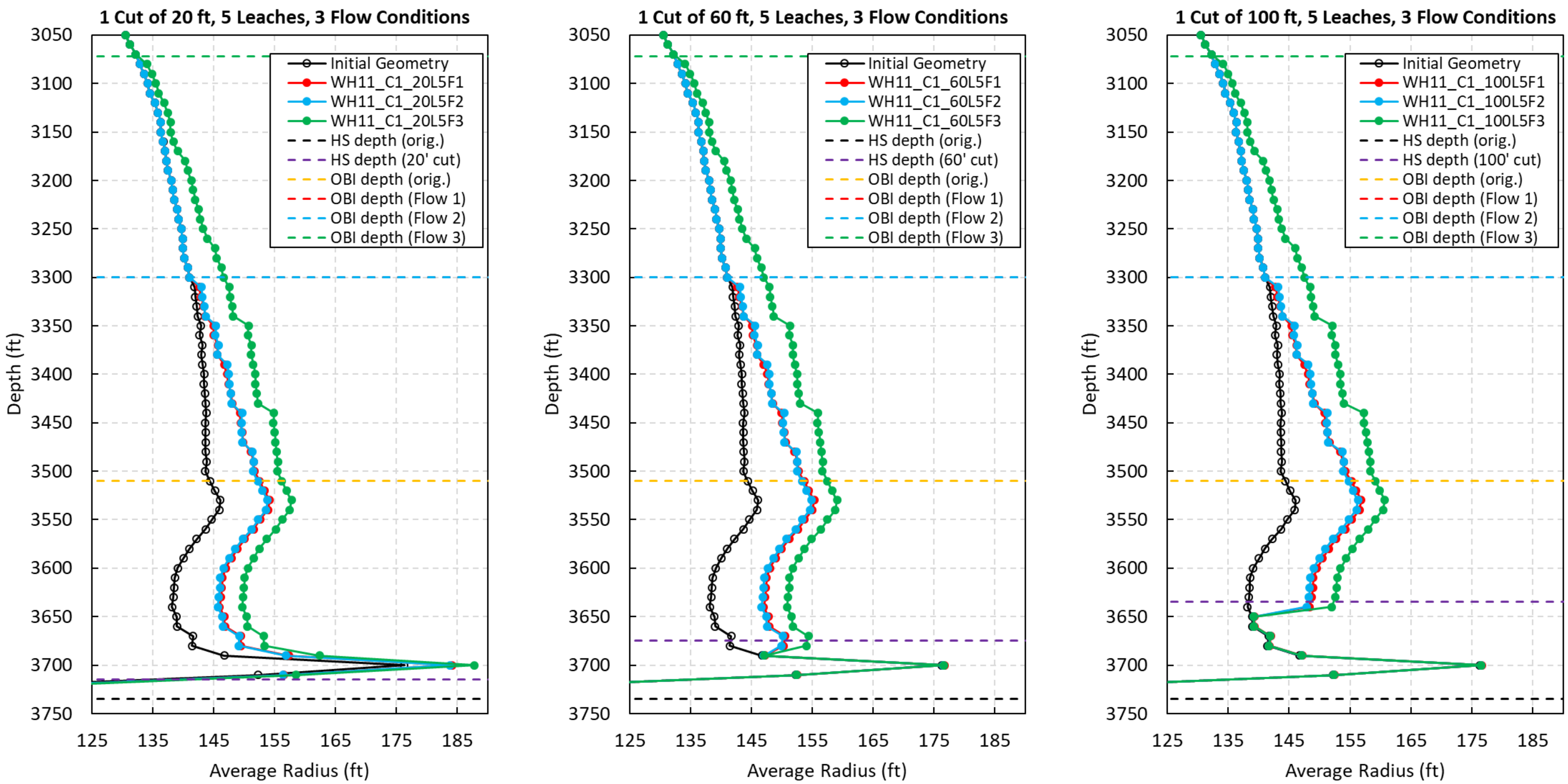

Figure 4-6. **Predicted WH11 geometries for five leaches and a single string cut of (left) 20 ft, (middle) 60 ft, and (right) 100 ft (three flow conditions).**

4.1.3. Mitigation Results 2 – Cut the String Prior to Each of Five Sales

Results are described below for the case of string cuts prior to each of five sales.

4.1.3.1. Multiple Sales

Figure 4-7 show the cases of five cuts, five leaches, and three flow conditions (9 total cases) for cuts of 20, 60, and 100 ft, respectively; these scenarios examine the leaching that may happen after five sales if the string is cut prior to each sale. This figure shows the multiple cut cases with total cut lengths of 20, 60, and 100 ft. In contrast to the multiple leach, single cut cases (Figure 4-6), growth of the feature at 3700 ft is observed for all cut lengths. This can be attributed to leaching taking place in the depths near the feature for the first few leaches, as the first leaches take place at string cuts of only 4, 12, and 20 ft for total cut lengths of 20, 60, and 100 ft, respectively. Although these are unlikely cut lengths for cavern operations, they are considered in this study as an exercise in learning the impact of these variables on leaching outcomes.

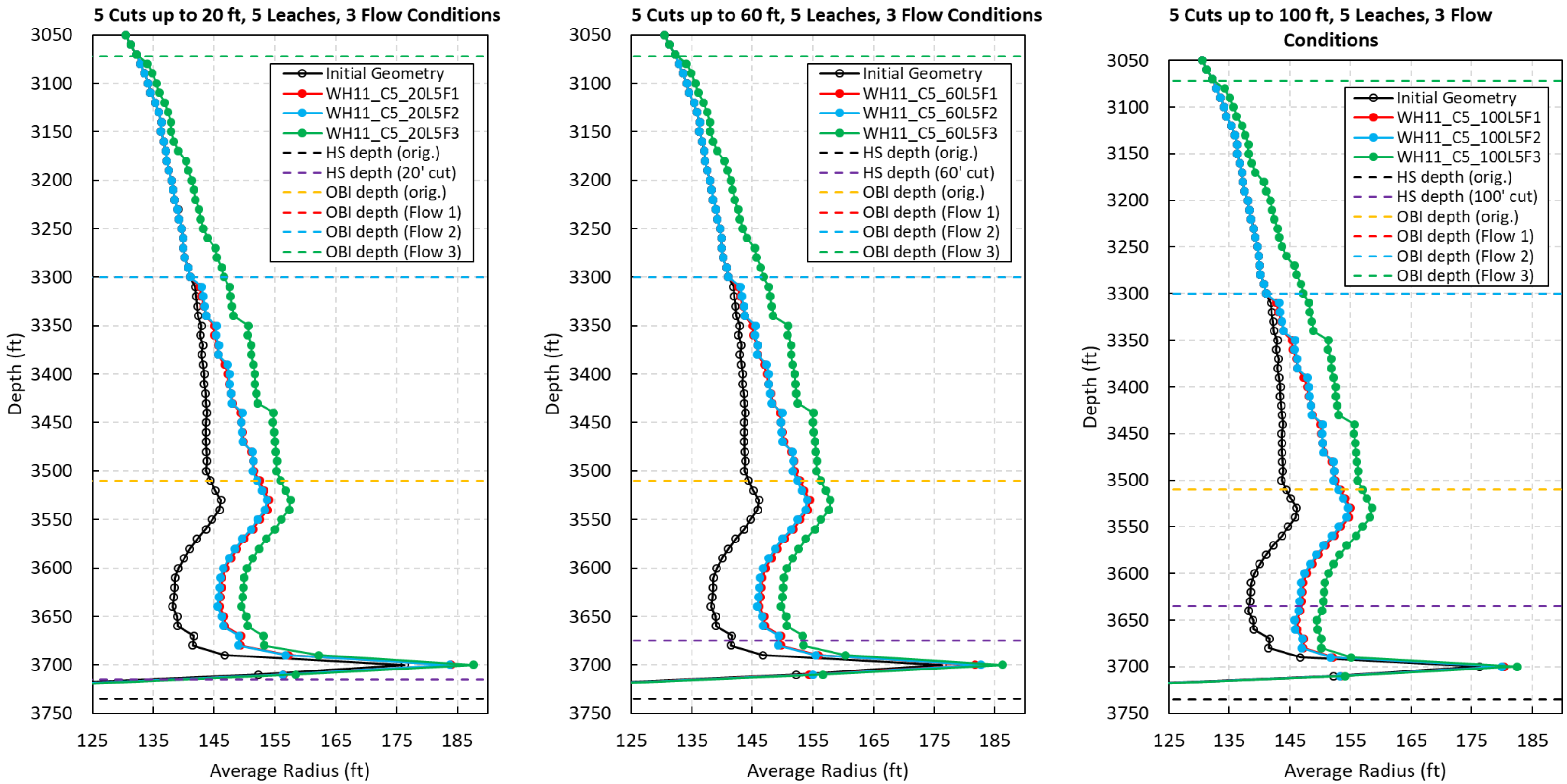

Figure 4-7. Predicted WH11 geometries for five leaches and five string cuts, total of (left) 20 ft, (middle) 60 ft, and (right) 100 ft (three flow conditions).

4.1.4. Comparison of Sonar Measurements and Modeling Results Following Operational String Cut

As described in Zeitler and Chojnicki (2020) and Section 4.1.2.1 above, a recommendation was made by SNL for a string cut to be made in WH11. Modeling results indicated that a string cut of between 60 and 100 ft would be ultimately beneficial to the leaching pattern in the cavern—because hanging strings are in 40-ft sections, a recommendation of an 80-ft cut was made. Prior to 2019 oil sales (10/7-12/1/2019), the lowest approximately 90 ft of hanging string was cut in WH11 on 9/23/2019. A sonar was then taken on 3/25/2020 that provided an updated cavern geometry since the previous sonar taken on 2/28/2018. In this section, comparisons are made among the 2018 and 2020 sonar results along with SANSMIC modeling predictions.

4.1.4.1. Comparison of 2018 and 2020 Sonars

Figure 4-8 shows a comparison of axisymmetric WH11 cavern geometries derived from the 2018 and 2020 sonars with depth measured from a common reference point at the surface.[1] Hanging string depths were determined to be 3710 ft in 2018 and 3620 ft in 2020, indicating that 90 ft of hanging string were removed in the 2019 cut. The differences in cavern geometry between the two sonars can be attributed to the injection of raw water at different depths, creep closure of the cavern, and the string cut. The injection of raw water serves to increase cavern radius as salt is removed from cavern walls, while creep closure results in a decrease in cavern radius. The extent of the observed changes in cavern geometry varies with cavern depth.

Between the 2018 and 2020 sonars, approximately 1.3 MMbbls of raw water were injected into WH11 during two time periods. In 2018, approximately 85 Mbbls were injected over two days (9/12-9/13; prior to string cut). In 2019, approximately 1.25 MMbbls were injected on 31 days over a 56-day period (10/7-12/1; subsequent to string cut).

The comparison of sonar geometries shows cavern shrinkage above the OBI, as expected due to creep closure. Floor rise is also observed and may also be attributed to creep closure. Leaching appears to have occurred in the region from just below the EOT (depth of 3435 ft) to just below the OBI (depth of 3650 ft) subsequent to the string cut. The preexisting flare has decreased slightly in terms of the maximum radius (for an axisymmetric representation). The flare has maintained roughly the same shape and size subsequent to the string cut, indicating that no substantial leaching occurred there. The string cut mitigation appears to have been successful for WH11; by moving the EOT away from the flare, additional leaching of the flare has been avoided.

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[1] Note that the 2020 sonar was taken down the B well (WH11B), while the 2018 sonar was taken a different well. Both geometry representations shown in Figure 4-14 were taken using five degree increments, but the geometry representation shown in Figure 3-1 was not.

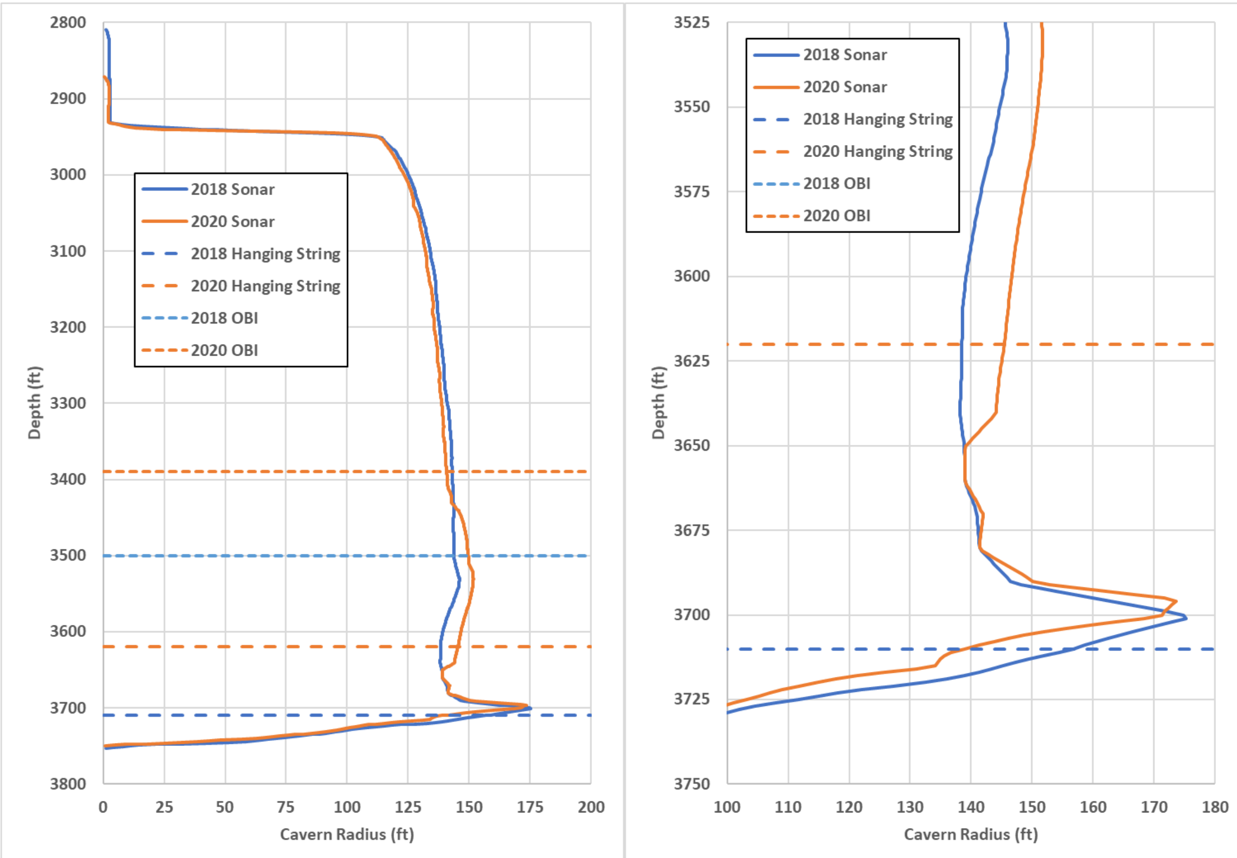

Figure 4-8. Axisymmetric cavern geometry based on sonar results for WH11 in 2018 and 2020; (left) full cavern and (right) near flare.

4.1.4.2. Comparison of 2020 Sonar with SANSMIC Prediction

An additional run of the SANSMIC code ("WH11_2018") was performed which incorporated two leaching stages in attempt to match the actual raw water injections of WH11 and provide a predicted cavern geometry to compare with the 2020 WH11 sonar. Stage 1 simulated 85 Mbbls of raw water injected over two days (42591 bbls/day) plus a 60-day workover period. The injection point (i.e., EOT) was at a depth of 3720 ft (30 ft above the cavern floor depth of 3750). This was followed by Stage 2, which simulated 1.25 MMbbls of raw water injected over 31 days (40222 bbls/day) plus an additional 60-day workover period. The injection point/EOT was at a depth of 3631 ft (119 ft above the cavern floor) representing an 89 ft cut prior to the raw water injection.

The starting geometry for the WH11_2018 SANSMIC run was taken from a higher-resolution dataset (i.e., including additional angled measurements) from the 2018 sonar than was used in the other WH11 SANSMIC runs described in the first part of this report. The higher-resolution dataset was converted to an axisymmetric representation with 10-ft vertical cell heights, the same as was done to produce the initial geometry for the other WH11 SANSMIC runs. A comparison of the initial geometries used for the WH11 SANSMIC runs is shown in Figure 4-9. A comparison of the 2020 sonar geometry to the predicted SANSMIC geometry is shown in Figure 4-10.

Excellent agreement is found between the SANSMIC-predicted geometry and 2020 sonar following the 2019 string cut, particularly in the region of leaching. Some discrepancy is found in the regions outside of the leaching region where creep closure dominates cavern geometry changes—this is expected, as SANSMIC does not include a creep closure process model.

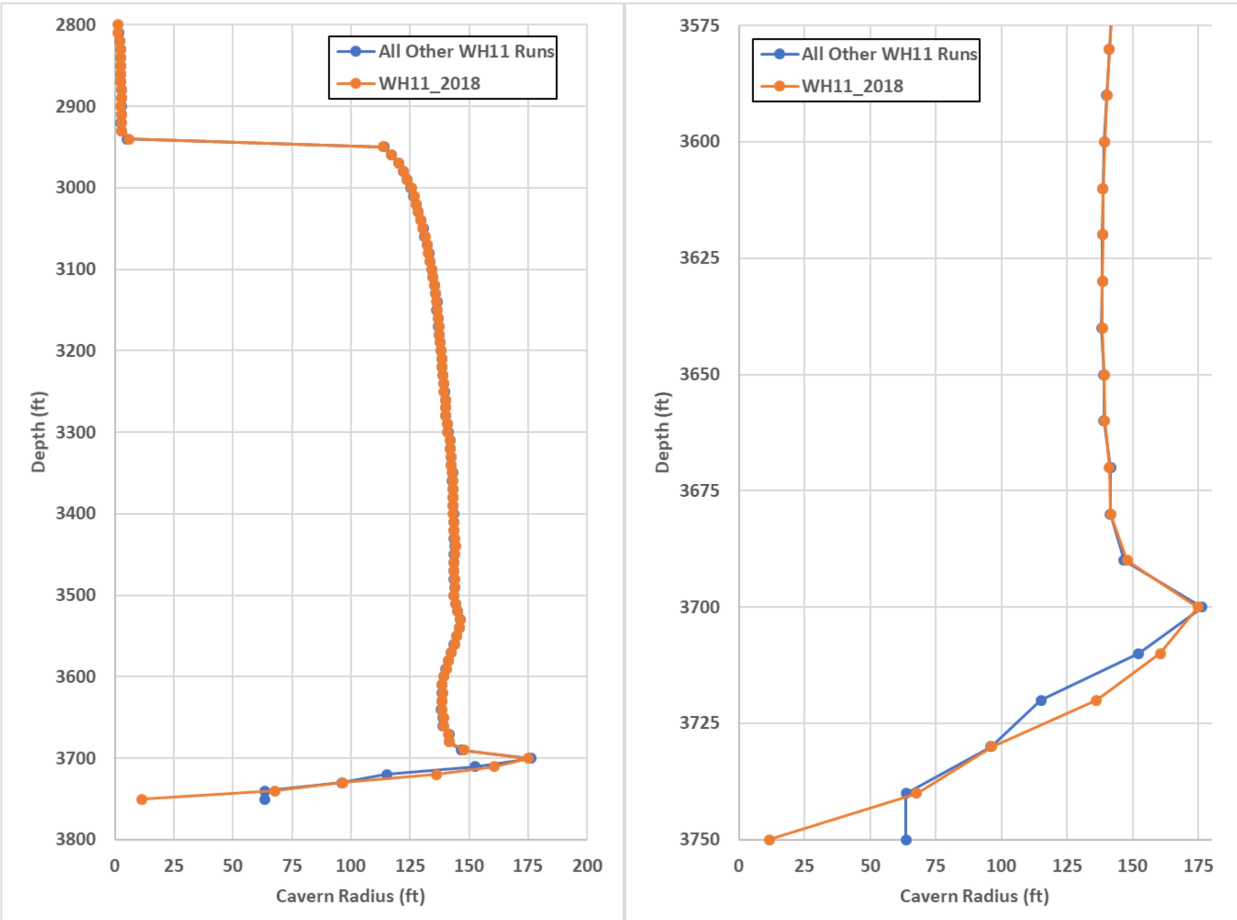

Figure 4-9. Comparison of axisymmetric cavern geometries used for SANSMIC runs in the report, the "WH11_2018" run (orange) and all other WH11 runs (blue); (left) full cavern and (right) near flare.

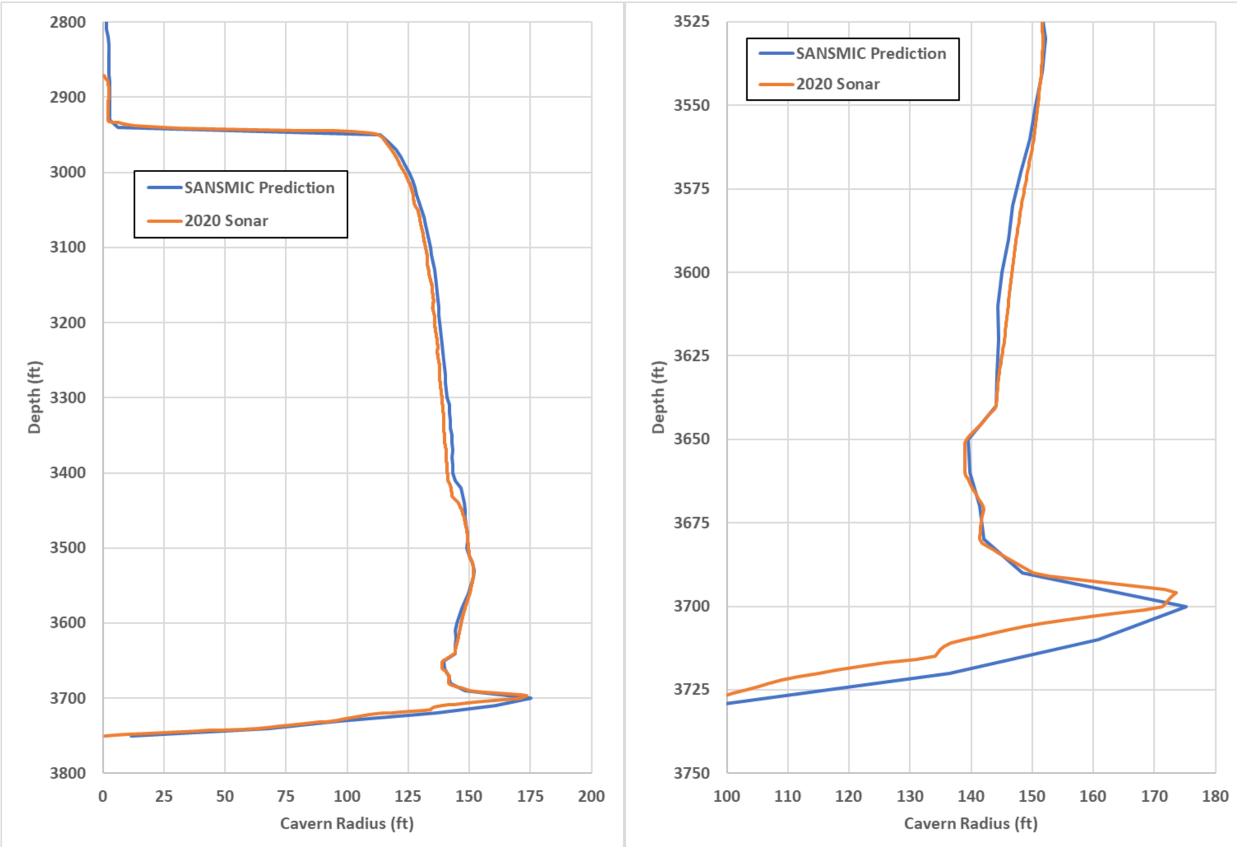

Figure 4-10. Comparison of axisymmetric cavern geometries from 2020 sonar and SANSMIC prediction following string cut; (left) full cavern and (right) near flare.

4.2. West Hackberry 113 (WH113)

Comparisons of the cavern geometries output from the 33 SANSMIC runs with the initial cavern geometry for WH113 are presented in Figure 4-11 to Figure 4-15. Note that the scales for radius and depth are not the same in these figures. Based on these results, there is a recommendation of no string cut for WH113.

4.2.1. Baseline – No Change (No Cuts of the String)

Results are described below for the baseline case of no string cuts for one or five sales.

4.2.1.1. One Sale

Figure 4-11 shows the cases of "no cut," a single leach, and three flow conditions (3 total cases); these scenarios examine the leaching that may happen after one sale if there are no changes to string length. The use of flow conditions 1 and 2 (which have an identical total number of injected bbls) results in almost identical final geometries with leaching up to a depth of 4270 ft, while the use of flow condition 3 (twice the total number of injected bbls) results in increased leaching, including leaching up to a depth of 4180 ft. All cases show an increased radius of the feature in the lowest part of the cavern, but no sharp feature exists or is predicted to develop.

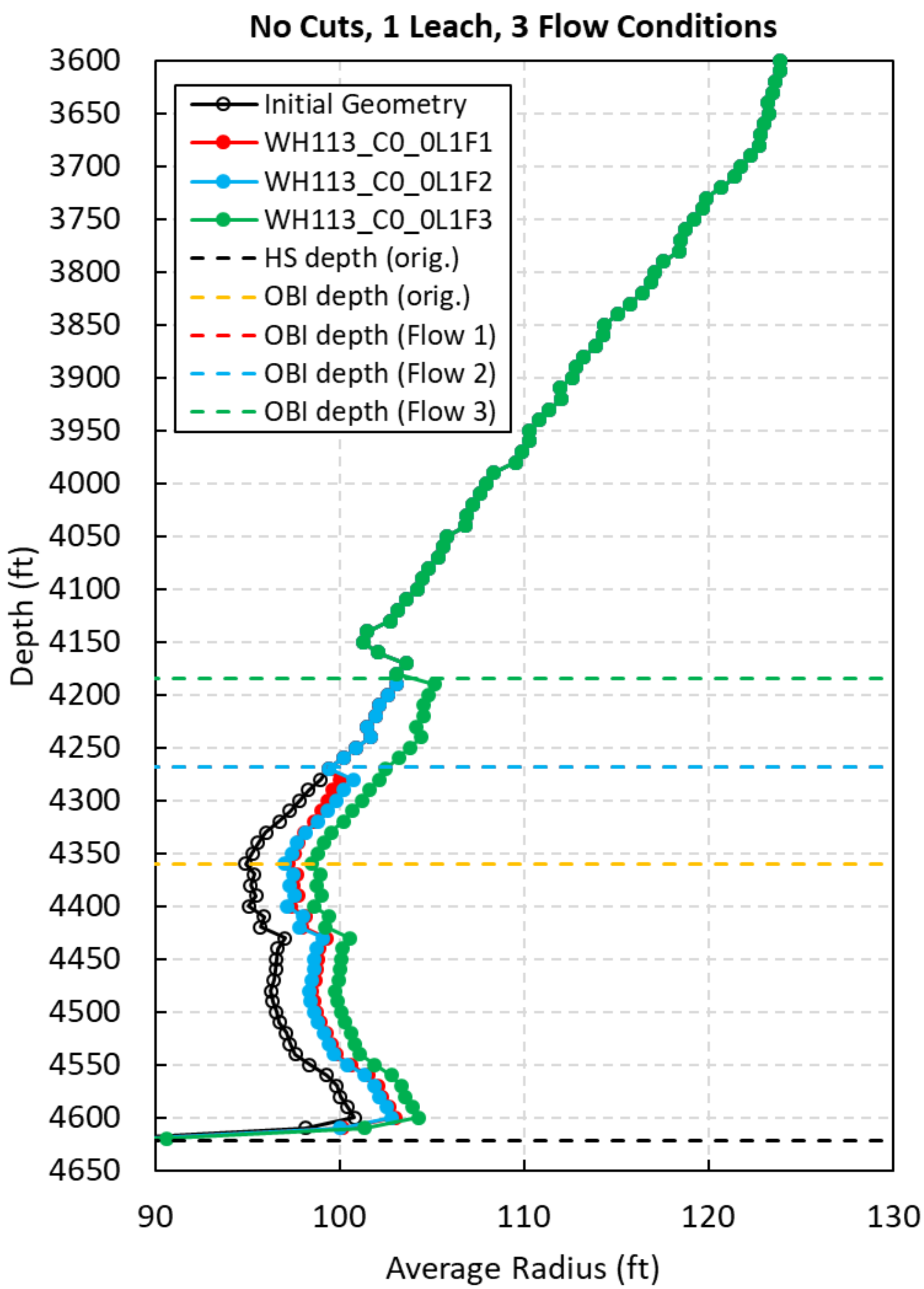

Figure 4-11. Predicted WH113 geometries for no string cuts and a single leach with flow condition 1 (red), 2 (blue) and 3 (green) compared with the starting geometry (black).

4.2.1.2. Multiple Sales

Figure 4-12 shows the cases of "no cut," five leaches, and three flow conditions (3 total cases); these scenarios examine the leaching that may happen after five sales if there are no changes to the string length. Similar to the single leach cases shown in Figure 4-11, the use of flow conditions 1 and 2 (which have an identical total number of injected bbls) results in almost identical final geometries

with leaching up to a depth of 3950 ft, while the use of flow condition 3 (twice the total number of injected bbls) results in increased leaching, including leaching up to a depth of 3640 ft. All cases show an increased radius of the feature in the lowest part of the cavern, but no sharp feature exists or is predicted to develop.

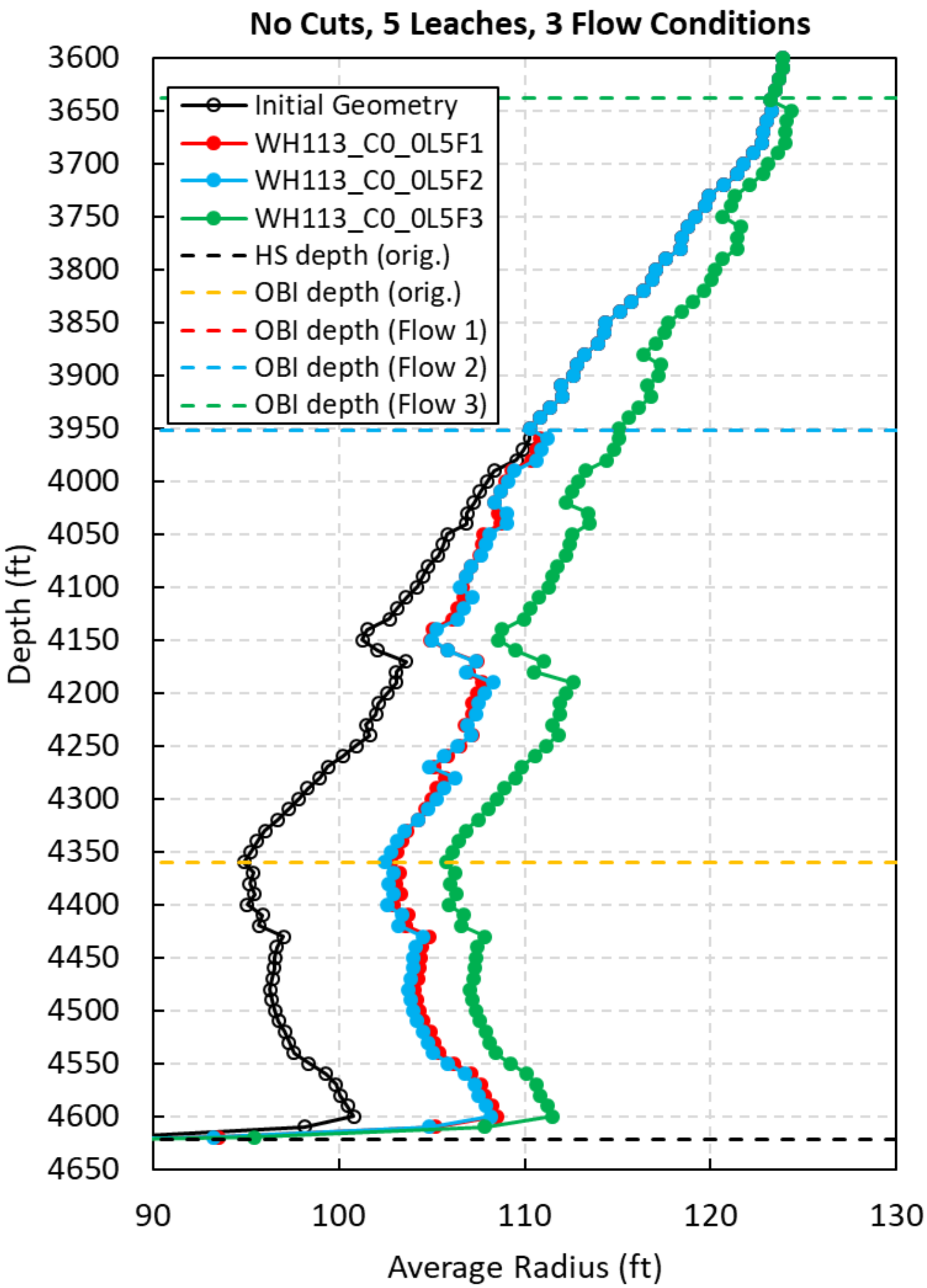

Figure 4-12. Predicted WH113 geometries for no string cuts and five leaches with flow condition 1 (red), 2 (blue) and 3 (green) compared with the starting geometry (black).

Cumulatively, the almost identical final geometries for flow conditions 1 and 2 shown in Figure 4-11 and Figure 4-12 indicate that flow rate is not a dominant variable in determining leaching outcomes given the same total volume injected (as a result, final OBI depths for flow conditions 1 and 2 are almost identical for each cut/leach pair). Similarly, the substantial difference in final geometries between flow conditions 2 and 3 in Figure 4-11 and Figure 4-12 indicates the impact of total volume injected on determining leaching outcomes.

4.2.2. Mitigation Results 1 – Cut the String Once

Results are described below for the case of a single string cut prior to sales for one or five sales. Cut lengths of 20, 60, and 100 ft were investigated.

4.2.2.1. One Sale

Figure 4-13 show the cases of a single cut, a single leach, and three flow conditions (9 total cases) for cuts of 20, 60, and 100 ft, respectively; these scenarios examine the leaching that may happen after one sale if the string is cut once prior to leaching. This figure shows the impact of the three flow conditions for a single leach and a single brine string cut of 20, 60, or 100 ft. For cuts of 20 ft, there is some increase in radius at the bottom of the cavern, but it is not substantially different from the "no cut" case. In the cases of 60 and 100-ft cuts, leaching does not result in an appreciable increase in radius at the bottom of the cavern; rather, the leaching only goes down to a depth of 4570 ft for 60-ft cuts and 4530 ft for 100-ft cuts. However, these results show that the string cuts at 60 or 100 ft result in the beginning of a secondary feature at the bottom of the leached region. To avoid forming that secondary feature, the string should not be cut at 60 or 100 ft. In contrast to the case of WH11, there appears to be no benefit to making a string cut in WH113.

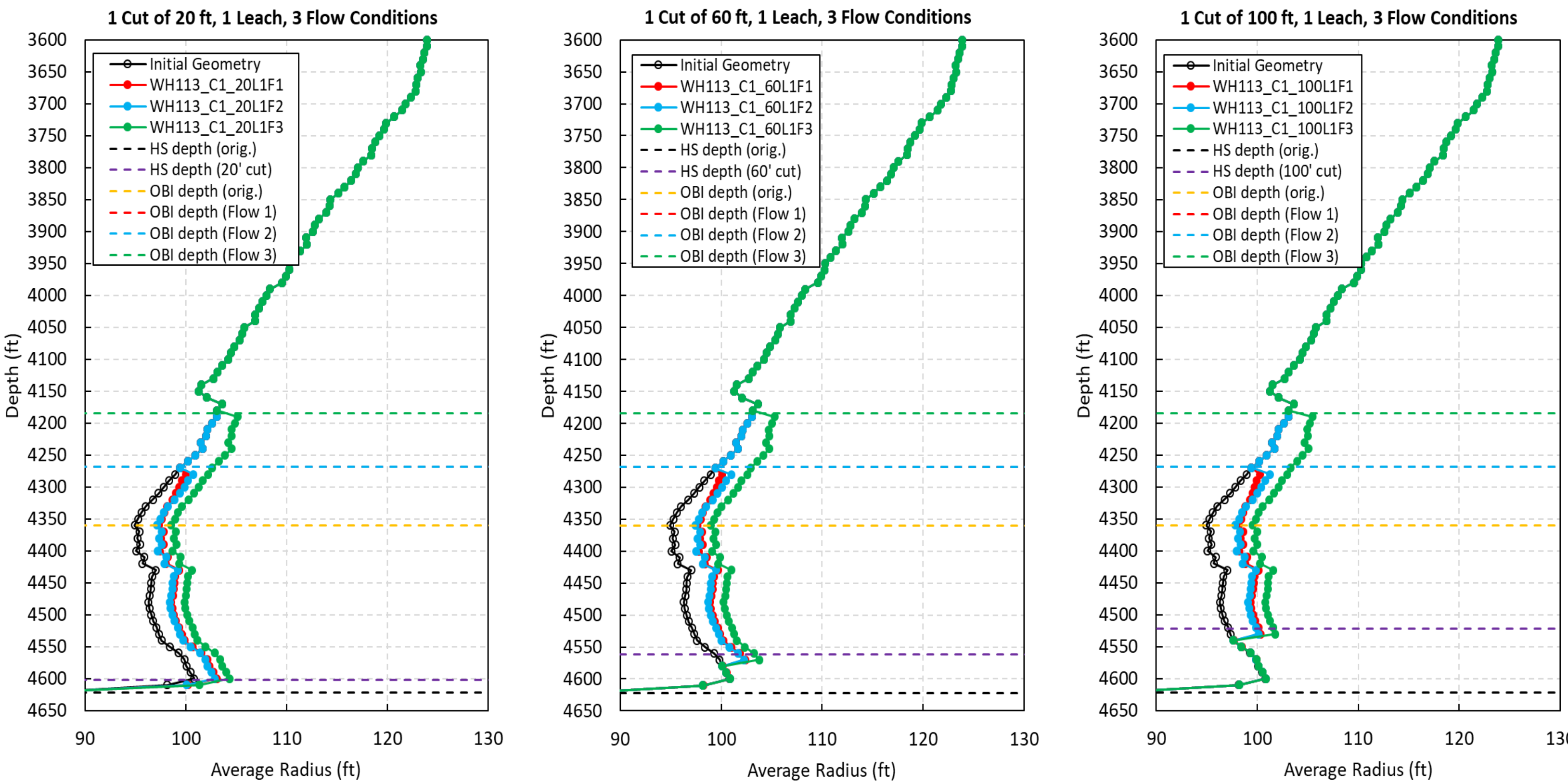

Figure 4-13. **Predicted WH113 geometries for a single leach and a single string cut of (left) 20 ft, (middle) 60 ft, and (right) 100 ft (three flow conditions).**

4.2.2.2. Multiple Sales

Figure 4-14 show the cases of a single cut, five leaches, and three flow conditions (9 total cases) for cuts of 20, 60, and 100 ft, respectively; these scenarios examine the leaching that may happen after five sales if the string is cut once prior to any leaching. This figure shows the impact of the three flow conditions for five consecutive leaches following a single brine string cut of 20, 60, or 100 ft. Compared to the single leach cases (Figure 4-13), the cavern radius increases in the leaching zone, as expected due to the five-fold increase in injected water volume. Similar to the single leach cases, growth in the lower part of the cavern is consistent for a cut of 20 ft, while a secondary feature develops at the lower end of the leaching zone for cuts of 60 ft (depth of 4570 ft) or 100 ft (depth of 4530 ft).

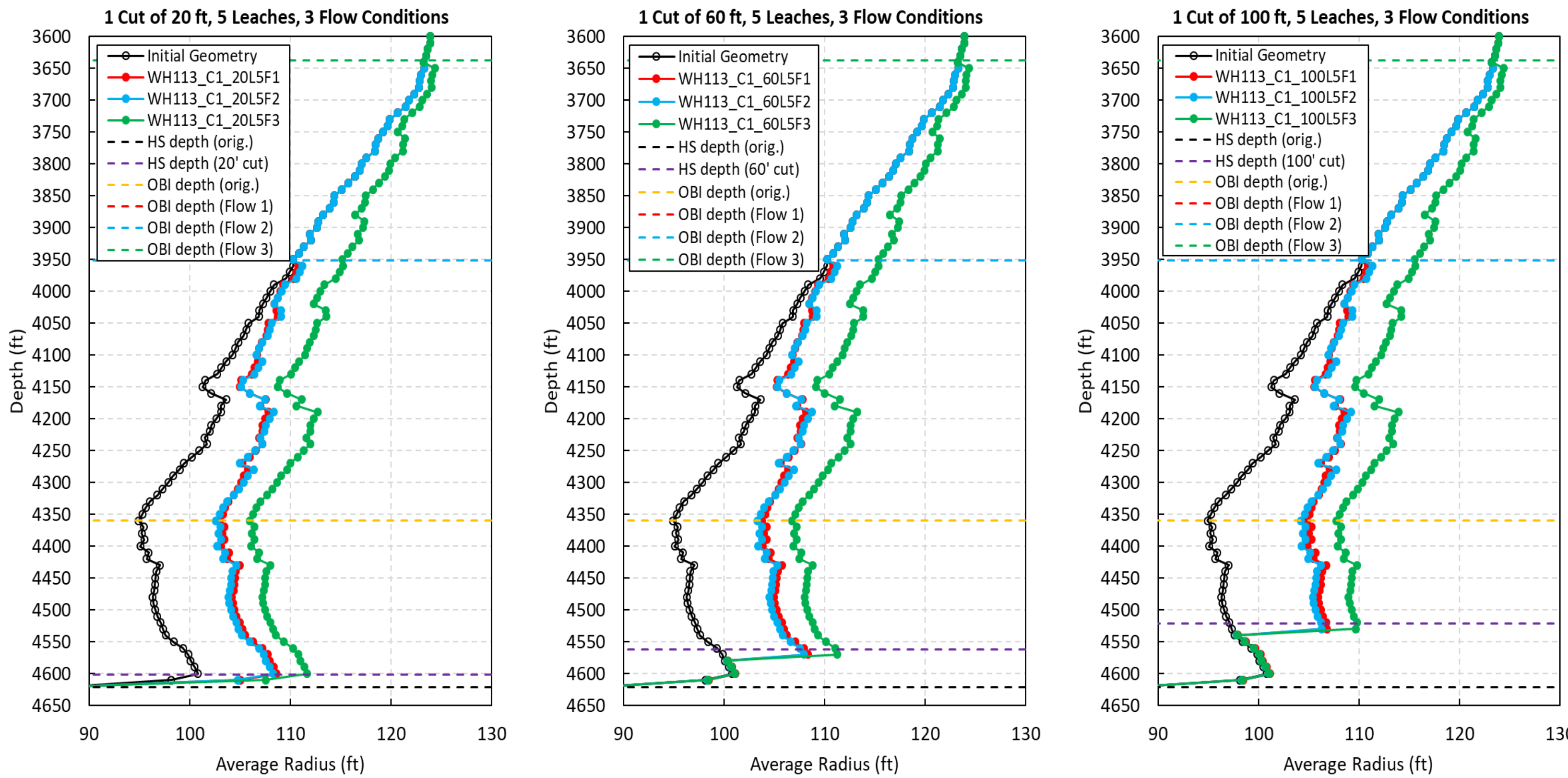

Figure 4-14. **Predicted WH113 geometries for five leaches and a single string cut of (left) 20 ft, (middle) 60 ft, and (right) 100 ft (three flow conditions).**

4.2.3. *Mitigation Results 2 – Cut the String Prior to Each of Five Sales*

Results are described below for the case of string cuts prior to each of five sales.

4.2.3.1. Multiple Sales

Figure 4-15 show the cases of five cuts, five leaches, and three flow conditions (9 total cases) for cuts of 20, 60, and 100 ft, respectively; these scenarios examine the leaching that may happen after five sales if the string is cut prior to each sale. This figure shows the multiple cut cases with total cut lengths of 20, 60, and 100 ft. Similar to the multiple leach, single cut cases (Figure 4-14), there is no adverse growth for a cut of 20 ft. For a cut of 60 ft, there is a development of a secondary feature, but rather than being a ledge, a smoother profile is developed, which may be attributed to the incremental changes in hanging string depth introduced by multiple cuts. For a cut of 100 ft, a relatively odd profile develops due to the multiple, small cuts and the ability of SANSMIC to resolve small changes in depth (vertical cell size is 10 ft). Although these small string cuts are unlikely cut lengths for cavern operations, they are considered in this study as an exercise in learning the impact of these variables on leaching outcomes.

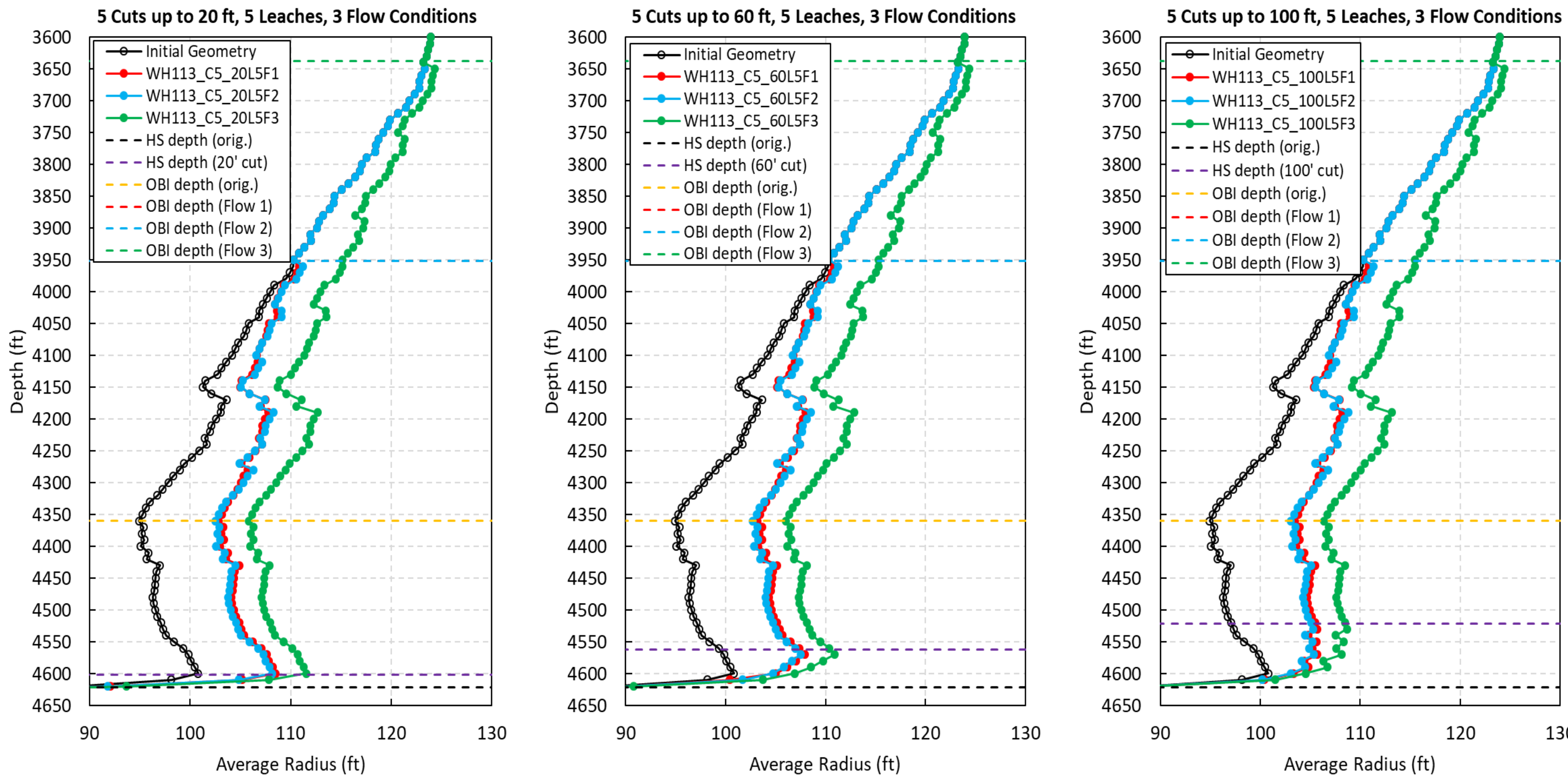

Figure 4-15. Predicted WH113 geometries for five leaches and five string cuts, total of (left) 20 ft, (middle) 60 ft, and (right) 100 ft (three flow conditions).

4.3. Big Hill 104 (BH104)

Comparisons of the cavern geometries output from the 33 SANSMIC runs with the initial cavern geometry for BH104 are presented in Figure 4-16 to Figure 4-20. Note that the scales for radius and depth are not the same in these figures. Based on these results, there is a recommendation of no string cut for BH104.

4.3.1. Baseline – No Change (No Cuts of the String)

Results are described below for the baseline case of no string cuts for one or five sales.

4.3.1.1. One Sale

Figure 4-16 shows the cases of “no cut,” a single leach, and three flow conditions (3 total cases); these scenarios examine the leaching that may happen after one sale if there are no changes to string length. The use of flow conditions 1 and 2 (which have an identical total number of injected bbls) results in almost identical final geometries with leaching up to a depth of 3770 ft, while the use of flow condition 3 (twice the total number of injected bbls) results in increased leaching, including leaching up to a depth of 3710 ft. All cases show an increased radius in the lowest part of the cavern, with the potential for the development of features (“ledges”) at the OBI.

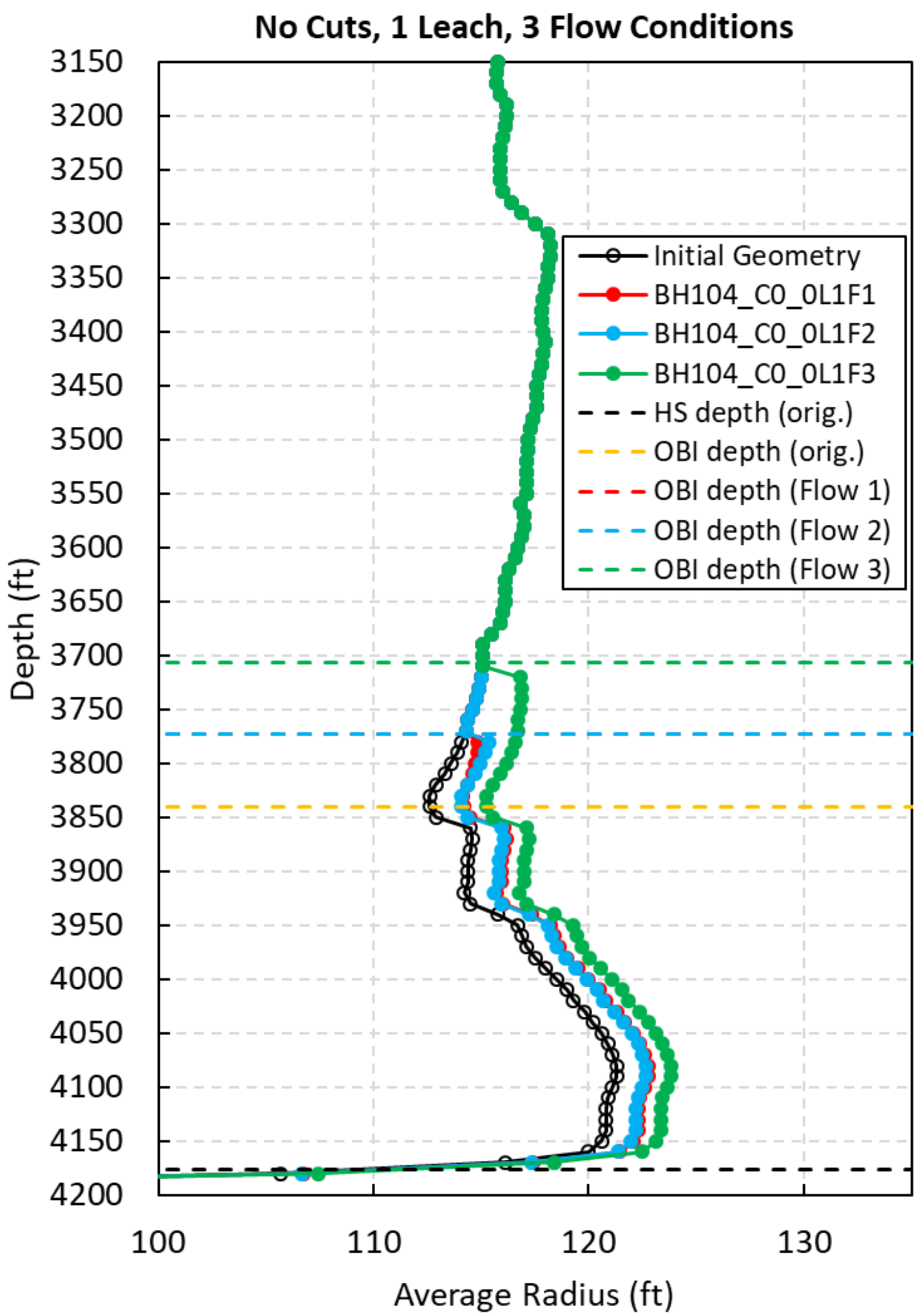

Figure 4-16. **Predicted BH104 geometries for no string cuts and a single leach with flow condition 1 (red), 2 (blue) and 3 (green) compared with the starting geometry (black).**

4.3.1.2. Multiple Sales

Figure 4-17 shows the cases of "no cut," five leaches, and three flow conditions (3 total cases); these scenarios examine the leaching that may happen after five sales if there are no changes to the string length. Similar to the single leach cases shown in Figure 4-2, the use of flow conditions 1 and 2 (which have an identical total number of injected bbls) results in almost identical final geometries

with leaching up to a depth of 3520 ft, while the use of flow condition 3 (twice the total number of injected bbls) results in increased leaching, including leaching up to a depth of 3200 ft. Even without hanging string cuts, additional ledges may be formed after multiple partial leaches. All cases show an increased radius in the lowest part of the cavern.

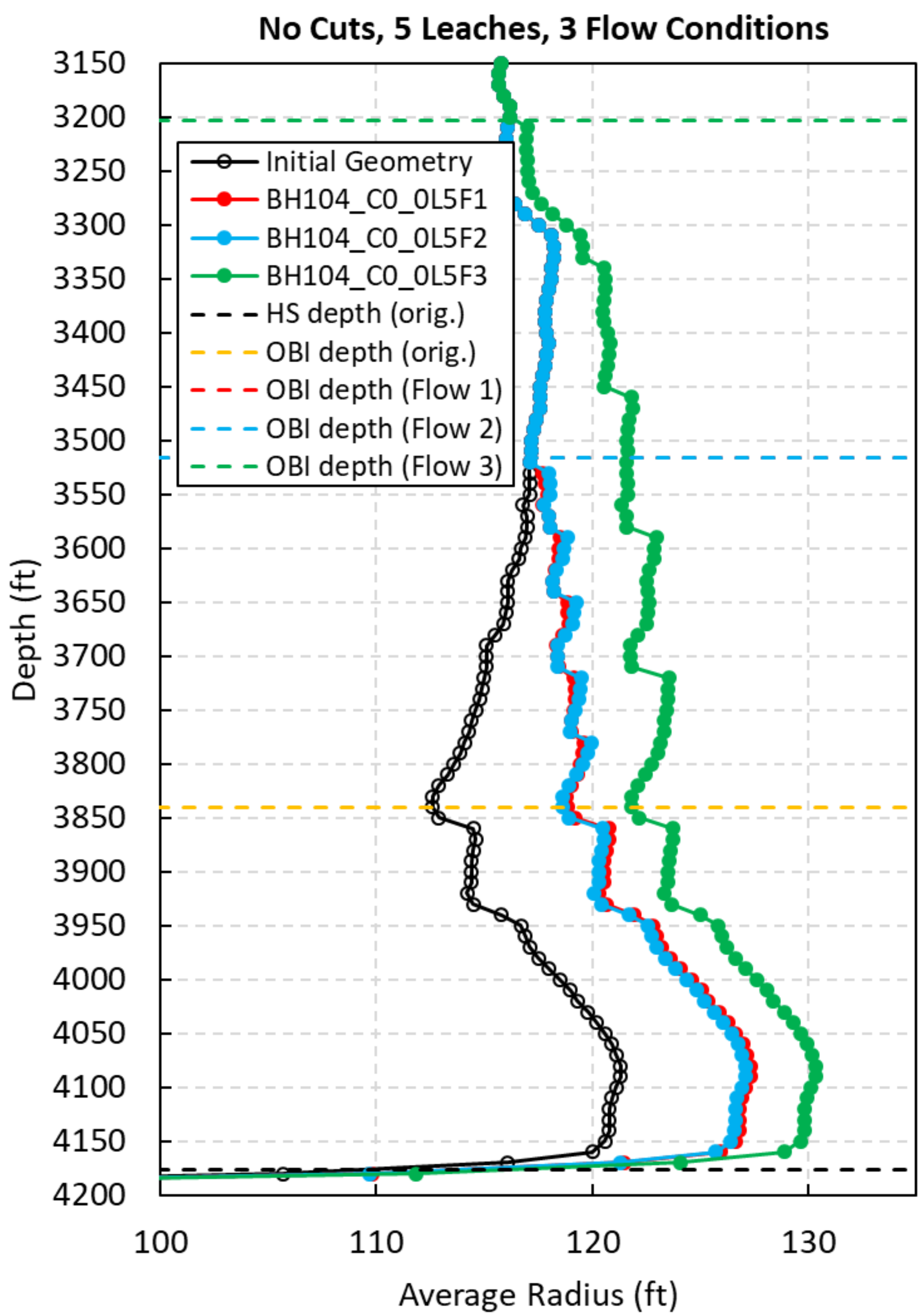

Figure 4-17. **Predicted BH104 geometries for no string cuts and five leaches with flow condition 1 (red), 2 (blue) and 3 (green) compared with the starting geometry (black).**

Cumulatively, the almost identical final geometries for flow conditions 1 and 2 shown in Figure 4-16 and Figure 4-17 indicate that flow rate is not a dominant variable in determining leaching outcomes given the same total volume injected (as a result, final OBI depths for flow conditions 1 and 2 are almost identical for each cut/leach pair). Similarly, the substantial difference in final geometries between flow conditions 2 and 3 in Figure 4-16 and Figure 4-17 indicates the impact of total volume injected on determining leaching outcomes.

4.3.2. Mitigation Results 1 – Cut the String Once

Results are described below for the case of a single string cut prior to sales for one or five sales. Cut lengths of 20, 60, and 100 ft were investigated.

4.3.2.1. One Sale

Figure 4-18 shows the cases of a single cut, a single leach, and three flow conditions (9 total cases) for cuts of 20, 60, and 100 ft, respectively; these scenarios examine the leaching that may happen after one sale if the string is cut once prior to leaching. This figure shows the impact of the three flow conditions for a single leach and a single brine string cut of 20, 60, or 100 ft. For cuts of 20 ft, there is no creation of an adverse feature and leaching occurs relatively uniformly from the hanging string depth to the OBI depth. In the cases of 60 and 100-ft cuts, leaching results in an appreciable increase in radius, such that ledges are created at the OBI and hanging string depths. In contrast to the case of WH11, and similar to the case of WH113, there appears to be no benefit to making a string cut in BH104.

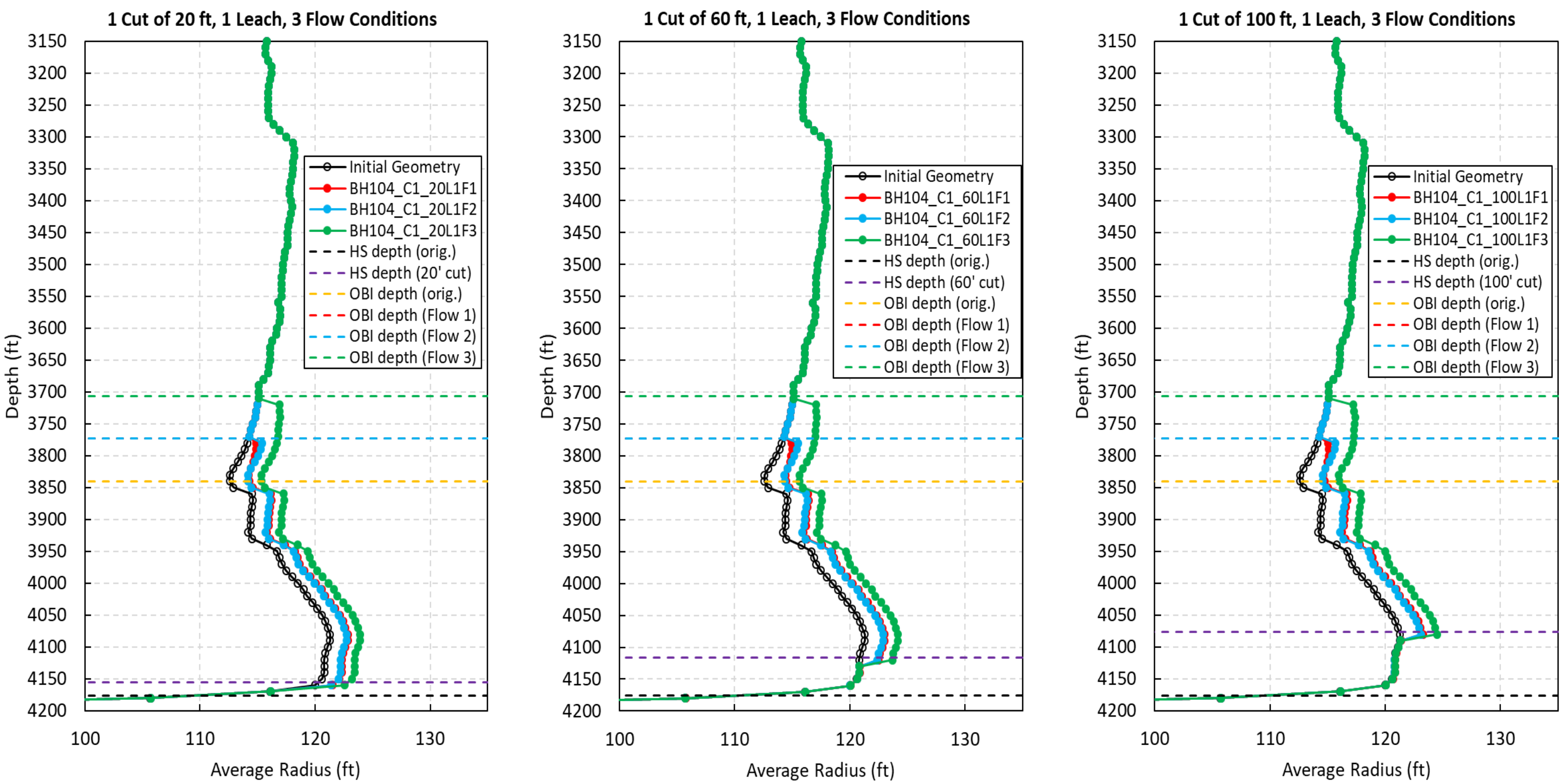

Figure 4-18. Predicted BH104 geometries for a single leach and a single string cut of (left) 20 ft, (middle) 60 ft, and (right) 100 ft (three flow conditions).

4.3.2.2. Multiple Sales

Figure 4-19 shows the cases of a single cut, five leaches, and three flow conditions (9 total cases) for cuts of 20, 60, and 100 ft, respectively; these scenarios examine the leaching that may happen after five sales if the string is cut once prior to any leaching. This figure shows the impact of the three flow conditions for five consecutive leaches following a single brine string cut of 20, 60, or 100 ft. Compared to the single leach cases (Figure 4-18), the cavern radius increases in the leaching zone, as expected due to the five-fold increase in injected water volume. Similar to the single leach cases, no adverse leaching is observed for 20 ft cuts, while cuts of 60 or 100 ft lead to the development of ledges at the OBI and hanging string depths, as well as at depths between them, presumably due to the series of leaches.

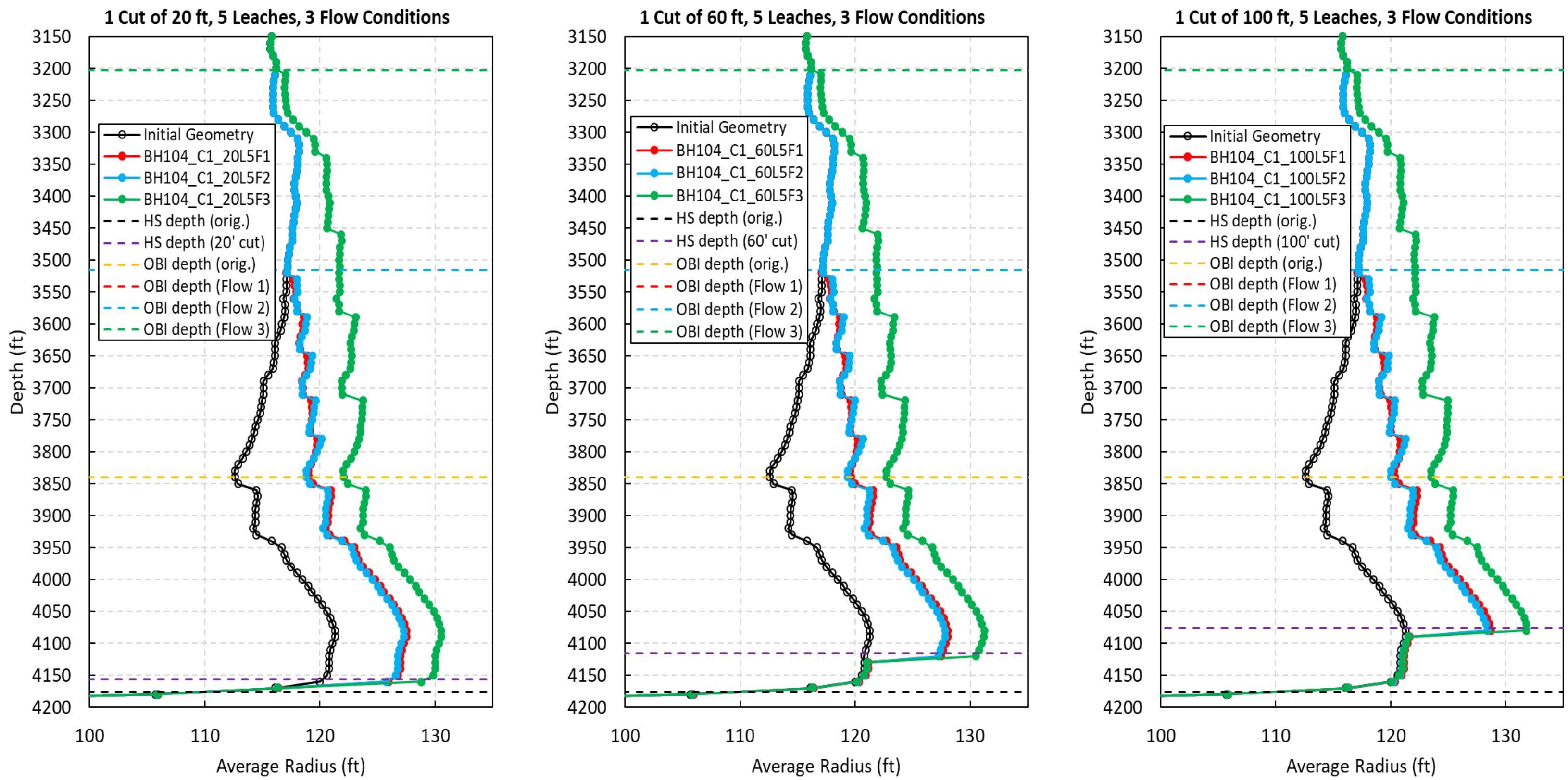

Figure 4-19. Predicted BH104 geometries for five leaches and a single string cut of (left) 20 ft, (middle) 60 ft, and 100 ft (three flow conditions).

4.3.3. Mitigation Results 2 – Cut the String Prior to Each of Five Sales

Results are described below for the case of string cuts prior to each of five sales.

4.3.3.1. Multiple Sales

Figure 4-20 shows the cases of five cuts, five leaches, and three flow conditions (9 total cases) for cuts of 20, 60, and 100 ft, respectively; these scenarios examine the leaching that may happen after five sales if the string is cut prior to each sale. This figure shows the multiple cut cases with total cut lengths of 20, 60, and 100 ft. In contrast to the multiple leach, single cut cases (Figure 4-19), growth in the bottom part of the cavern does not lead to the creation of a ledge, but rather a smoother, stepped transition from the bottom of the cavern to the depth of maximum radius. This can be attributed to leaching taking place in the depths near the feature for the first few leaches, as the first leaches take place at string cuts of only 4, 12, and 20 ft for total cut lengths of 20, 60, and 100 ft, respectively. Although these are unlikely cut lengths for cavern operations, they are considered in this study as an exercise in learning the impact of these variables on leaching outcomes. For this cavern, it appears that in order to avoid the creation of ledges under high flow conditions, either no cuts or multiple small cuts are appropriate. A single cut followed by multiple leaches appears to lead to the creation of ledges.

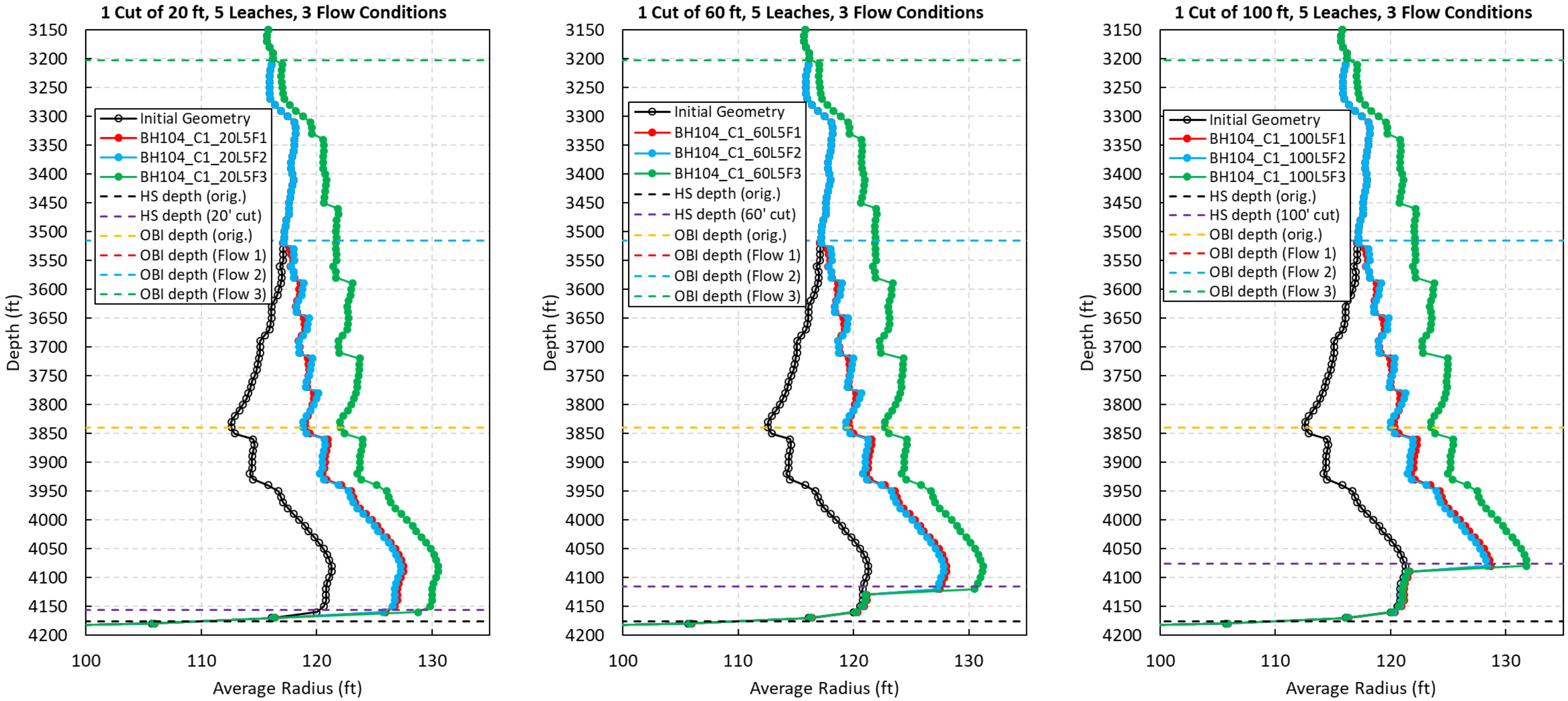

Figure 4-20. Predicted BH104 geometries for a single string cut of (left) 20 ft, (middle) 60 ft, and (right) 100 ft and five leaches (three flow conditions).

4.4. Big Hill 114 (BH114)

Comparisons of the cavern geometries output from the 33 SANSMIC runs with the initial cavern geometry for BH114 are presented in Figure 4-21 to Figure 4-25. Note that the scales for radius and depth are not the same in these figures. Based on these results, there is a recommendation of no string cut for BH114.

4.4.1. Baseline – No Change (No Cuts of the String)

Results are described below for the baseline case of no string cuts for one or five sales.

4.4.1.1. One Sale

Figure 4-21 shows the cases of "no cut," a single leach, and three flow conditions (3 total cases); these scenarios examine the leaching that may happen after one sale if there are no changes to string length. The use of flow conditions 1 and 2 (which have an identical total number of injected bbls) results in almost identical final geometries with leaching up to a depth of 3560 ft, while the use of flow condition 3 (twice the total number of injected bbls) results in increased leaching, including leaching up to a depth of 3470 ft. All cases show no appreciable increase in the radius of the feature at 4100 ft.

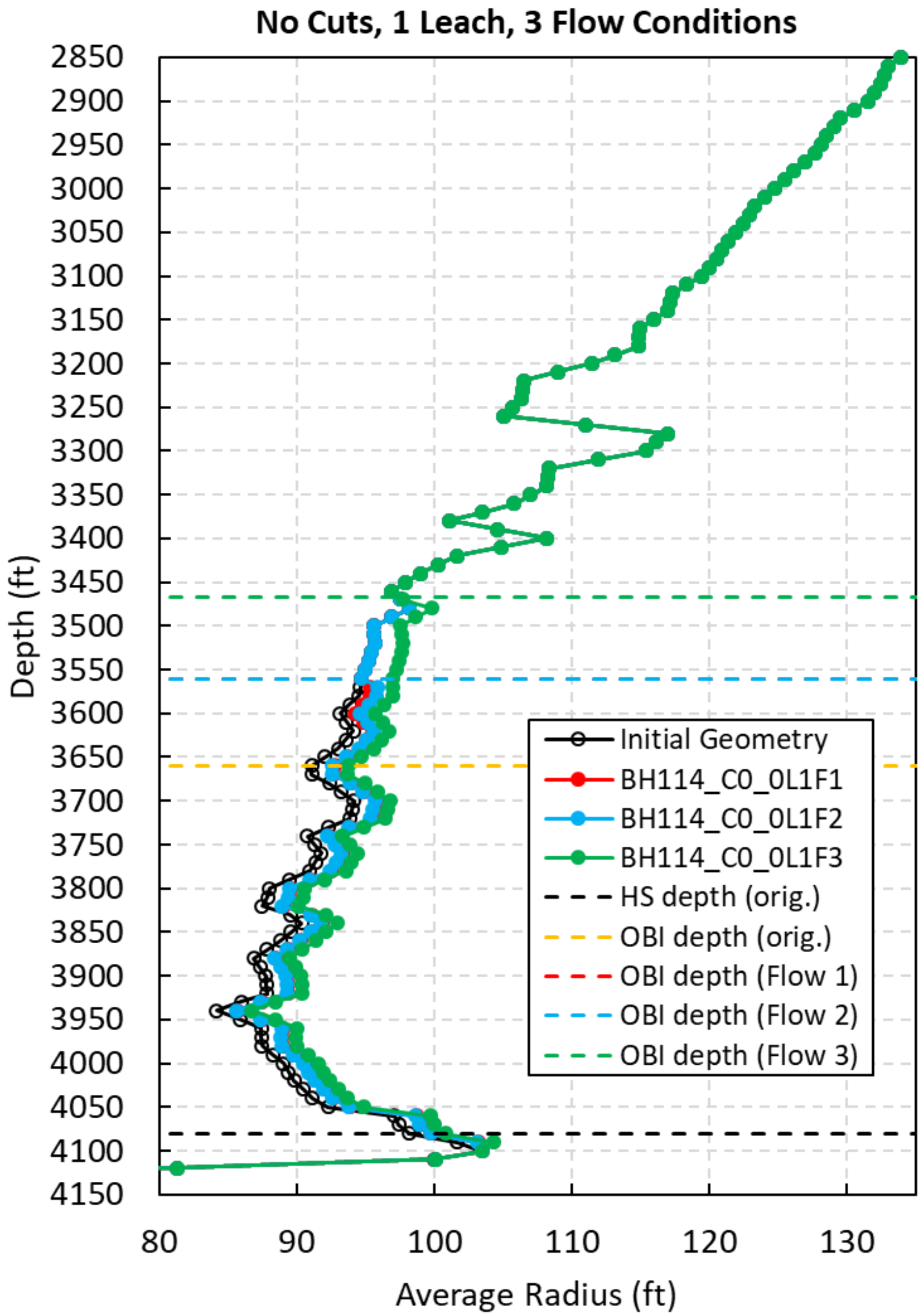

Figure 4-21. Predicted BH114 geometries for no string cuts and a single leach with flow condition 1 (red), 2 (blue) and 3 (green) compared with the starting geometry (black).

4.4.1.2. Multiple Sales

Figure 4-22 shows the cases of "no cut," five leaches, and three flow conditions (3 total cases); these scenarios examine the leaching that may happen after five sales if there are no changes to the string length. Similar to the single leach cases shown in Figure 4-21, the use of flow conditions 1 and 2 (which have an identical total number of injected bbls) results in almost identical final geometries

with leaching up to a depth of 3240 ft, while the use of flow condition 3 (twice the total number of injected bbls) results in increased leaching, including leaching up to a depth of 2930 ft. All cases show a small increase in radius of the feature at 4100 ft.

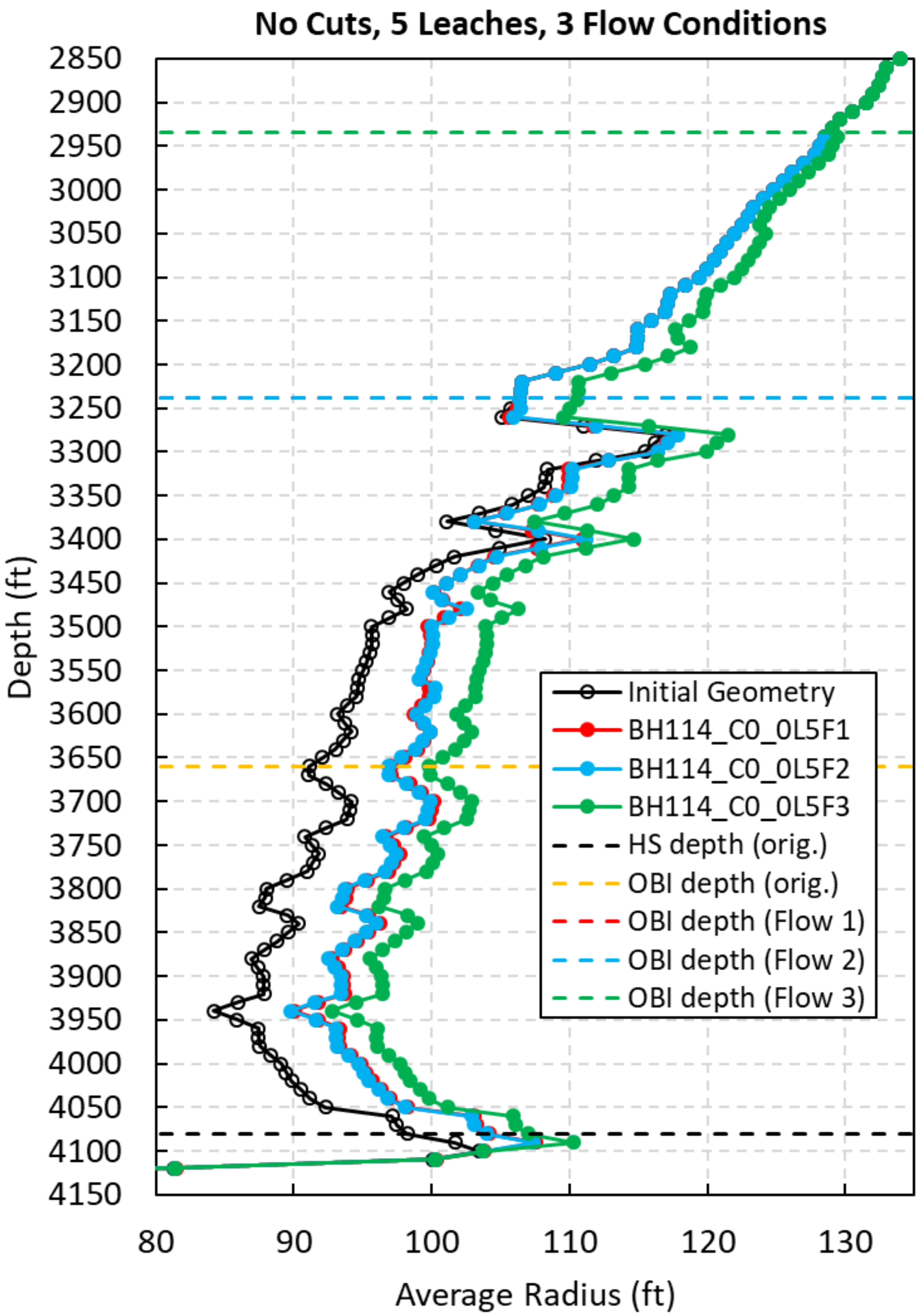

Figure 4-22. Predicted BH114 geometries for no string cuts and five leaches with flow condition 1 (red), 2 (blue) and 3 (green) compared with the starting geometry (black).

Cumulatively, the almost identical final geometries for flow conditions 1 and 2 shown in Figure 4-21 and Figure 4-22 indicate that flow rate is not a dominant variable in determining leaching outcomes given the same total volume injected (as a result, final OBI depths for flow conditions 1 and 2 are almost identical for each cut/leach pair). Similarly, the substantial difference in final geometries between flow conditions 2 and 3 in Figure 4-21 and Figure 4-22 indicates the impact of total volume injected on determining leaching outcomes.

4.4.2. Mitigation Results 1 – Cut the String Once

Results are described below for the case of a single string cut prior to sales for one or five sales. Cut lengths of 20, 60, and 100 ft were investigated.

4.4.2.1. One Sale

Figure 4-23 shows the cases of a single cut, a single leach, and three flow conditions (9 total cases) for cuts of 20, 60, and 100 ft, respectively; these scenarios examine the leaching that may happen after one sale if the string is cut once prior to leaching. This figure shows the impact of the three flow conditions for a single leach and a single brine string cut of 20, 60, or 100 ft. For cuts of 20 ft, 60 ft, and 100 ft, there is no increase in radius of the feature at 4100 ft, but a small ledge is formed at the respective hanging string depth. In contrast to the case of WH11, and similar to the cases of WH113 and BH104, there appears to be no benefit to making a string cut in BH114.

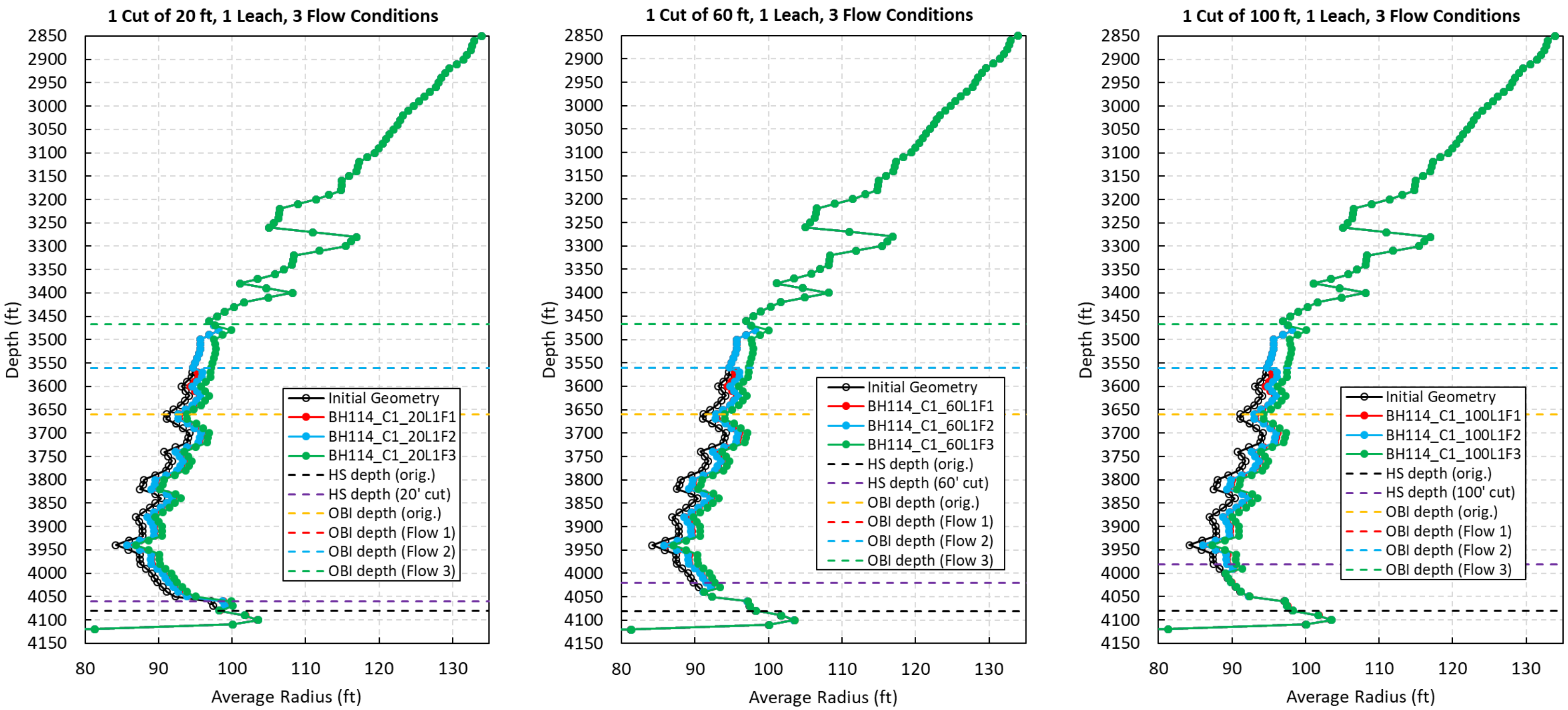

Figure 4-23. **Predicted BH114 geometries for a single leach and a single string cut of (left) 20 ft, (middle) 60 ft, and (right) 100 ft (three flow conditions).**

4.4.2.2. Multiple Sales

Figure 4-24 show the cases of a single cut, five leaches, and three flow conditions (9 total cases) for cuts of 20, 60, and 100 ft, respectively; these scenarios examine the leaching that may happen after five sales if the string is cut once prior to any leaching. This figure shows the impact of the three flow conditions for five consecutive leaches following a single brine string cut of 20, 60, or 100 ft. Compared to the single leach cases (Figure 4-23), the cavern radius increases in the leaching zone, as expected due to the five-fold increase in injected water volume. Similar to the single leach cases, growth of the feature at 4100 ft is minimal for runs with cuts of 20, 60, or 100 ft, but even more pronounced ledges are developed due to the increased leaching volume across five leaches.

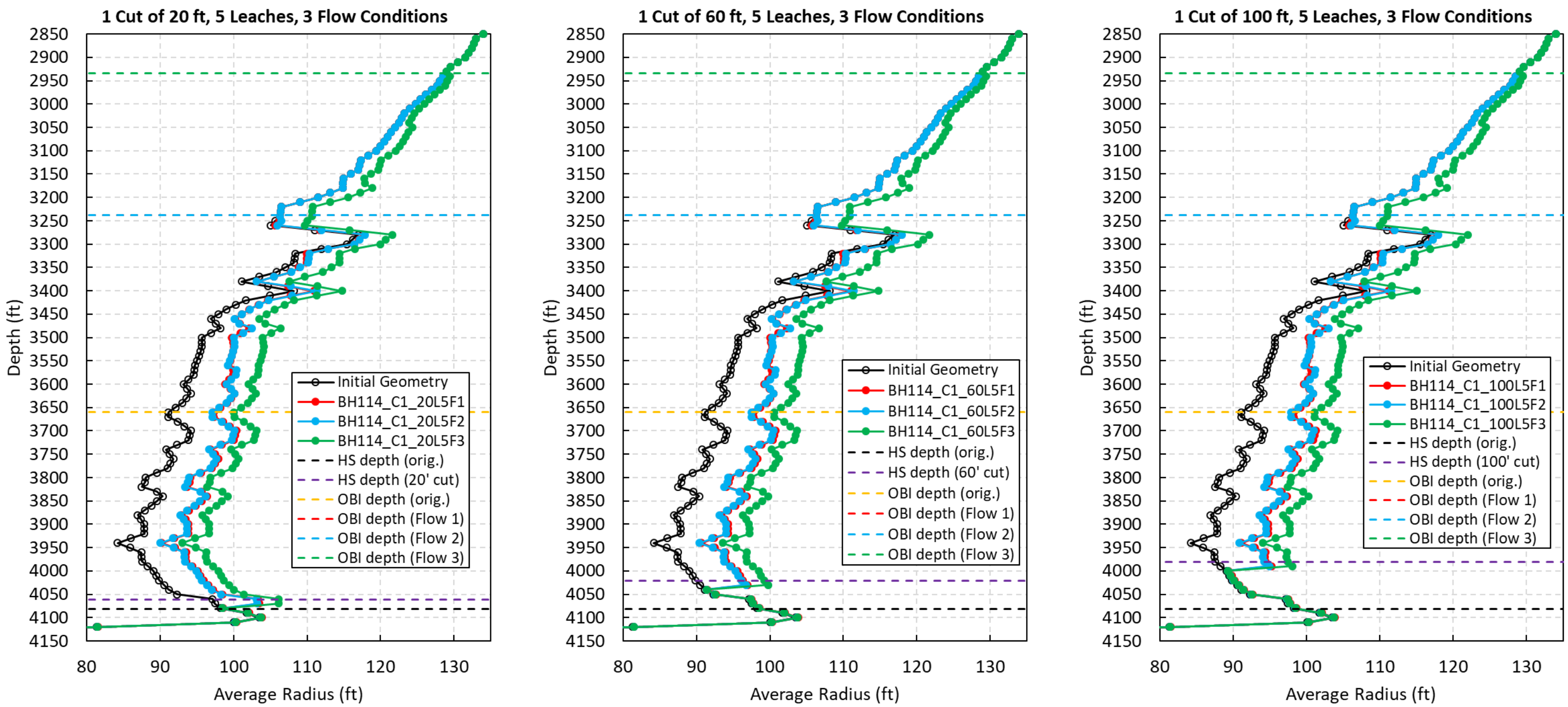

Figure 4-24. Predicted BH114 geometries for a single string cut of 20 ft and five leaches (three flow conditions).

4.4.3. Mitigation Results 2 – Cut the String Prior to Each of Five Sales

Results are described below for the case of string cuts prior to each of five sales.

4.4.3.1. Multiple Sales

Figure 4-25 shows the cases of five cuts, five leaches, and three flow conditions (9 total cases) for cuts of 20, 60, and 100 ft, respectively; these scenarios examine the leaching that may happen after five sales if the string is cut prior to each sale. This figure shows the multiple cut cases with total cut lengths of 20, 60, and 100 ft. Similar to the multiple leach, single cut cases (Figure 4-24), only minimal growth of the feature at 4100 ft is observed for all cut lengths. Although these are unlikely cut lengths for cavern operations, they are considered in this study as an exercise in learning the impact of these variables on leaching outcomes.

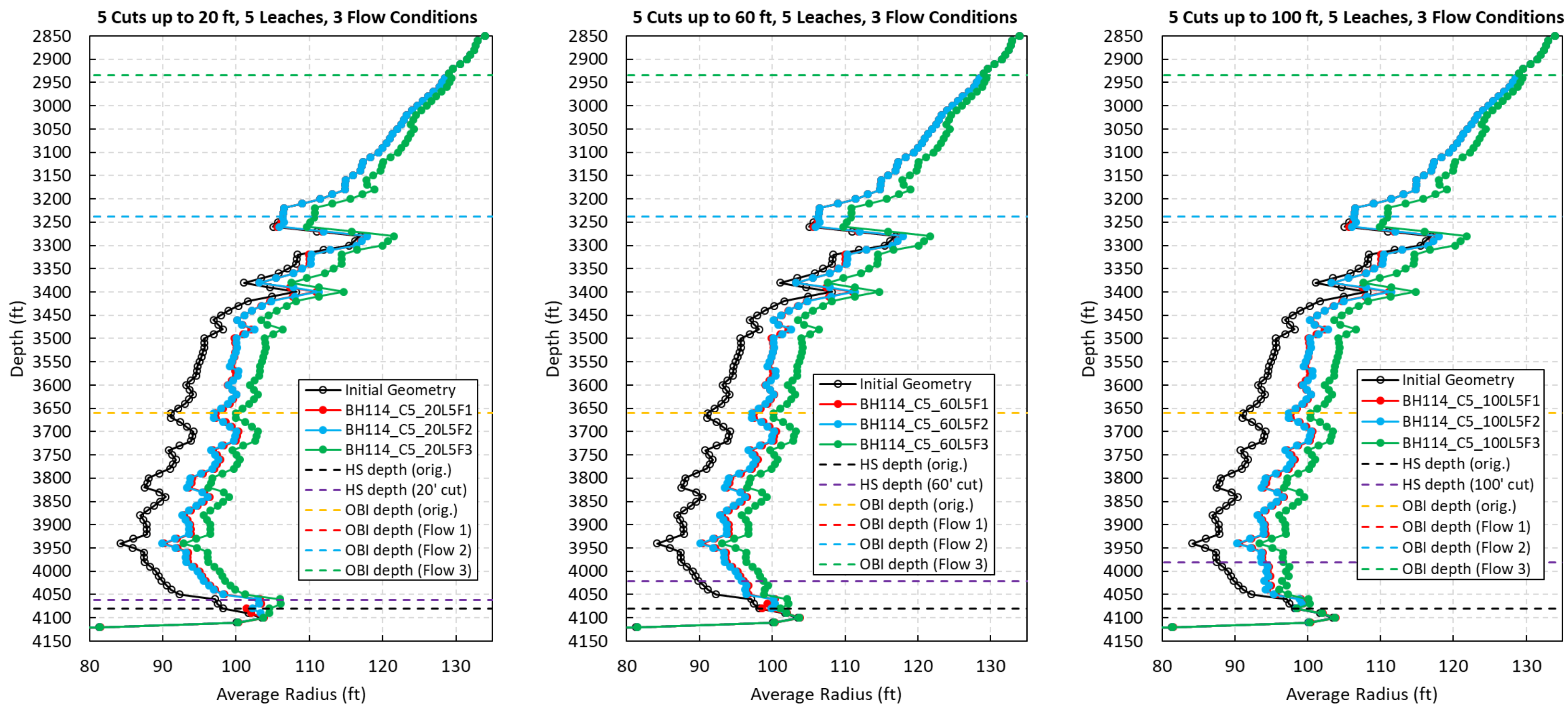

Figure 4-25. **Predicted BH114 geometries for five leaches and five string cuts, total of (left) 20 ft, (middle) 60 ft, and (right) 100 ft (three flow conditions).**

5. CONCLUSIONS

A methodology and workflow have been developed and tested in which the SANSMIC code is used to predict future cavern leaching behavior with a focus on understanding the impact of cutting brine strings on cavern geometry. The methodology and workflow used here could be incorporated into an overall mitigation strategy designed to reduce adverse future cavern growth.

Leaching simulations on the West Hackberry 11 (WH11), West Hackberry 113 (WH113), Big Hill 104 (BH104), and Big Hill 114 (BH114) caverns show the impact on cavern geometry due to varying the following input parameters: length of brine string cuts, number of brine string cuts, number of leaches, and flow conditions for each leach. Some combinations of input parameters result in a reduction of adverse leaching.

An important conclusion from this study is that the growth of adverse cavern geometry features appears to be avoidable by cutting the end of the brine string in some instances. The general principle behind this behavior seems to be that leaching during water injection primarily takes place between the EOT and OBI. Additionally, the longer that leaching takes place with the hanging string near a large radius feature, the more it grows. Cutting of the string is shown to move the zone of leaching away from preexisting, problematic cavern geometry features. However, the development of additional (undesired) secondary features is also possible with the flow volumes associated with partial drawdowns. Another finding is that flow rate is not a dominant variable in determining leaching outcomes given the same total volume injected, but there is an impact of total volume injected on determining leaching outcomes.

This work has resulted in the conclusion that a hanging string cut of 80 ft in WH11 could be beneficial to future cavern geometry, while there would be little to no benefit to string cuts in the other three caverns investigated here. A summary of recommendation actions for string cuts is found in Table 5-1. The WH11 recommendation was followed in 2019, resulting in an operational string cut. A sonar performed after the string cut showed no adverse leaching in the area of the preexisting flare, as expected from the results of the preliminary SANSMIC runs described in this report. Additional SANSMIC modeling of the actual amount of injected raw water resulted in good agreement with the post-cut sonar.

Table 5-1. Summary of Recommended Actions for String Cuts

Cavern Name	Recommended Action for String Cut
BH104	No string cut
BH114	No string cut
WH11	80 ft string cut
WH113	No string cut

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APPENDIX A. SUMMARIZED SANSMIC INPUT AND RESULTS

This Appendix contains tables that summarize input parameters and output data for the 33 SANSMIC runs for each of the WH11, WH113, BH104, BH114 caverns. Input parameters include: the number of cuts, total cut length, number of leaches, and flow condition number (see Table 3-3 in the main text for explanation of the three flow conditions tested here). Output data include: final hanging string depth (HS), final OBI, difference between HS and OBI, maximum cavern radius observed (the maximum was always in the zone of leaching for WH11), initial cavern volume, final cavern volume, volume of raw water injected, and leach efficiency (defined as the difference between initial and final cavern volumes divided by the volume of raw water injected).

A distinct run name was developed to identify each run of the SANSMIC code with the cavern name, number of cuts, total cut length, number of leaches, and flow conditions making up part of the name. The "key" to run names is the following: [Cavern Name]_C[Number of Cuts]_[Total Cut Length]L[Number of Leaches]F[Flow Condition Identifier]. For example, WH11_C1_100L1F1 is a run of the West Hackberry 11 cavern with a single cut of 100 ft and a single leach under flow condition 1. As another example, WH11_C1_60L5F3 is a run of the West Hackberry 11 cavern with a single cut of 60 ft and five leaches under flow condition 3

Table A-1. Input Parameters and Output Data for 33 Runs of SANSMIC for WH11

Run Number	Run Name	Number of Cuts	Total Cut Length (ft)	Number of Leaches	Flow Condition	Final HS Depth (ft)	Final OBI (ft)	(HS - OBI) (ft)	Max. Cavern Radius (ft)	Initial Cavern Volume (bbls)	Final Cavern Volume (bbls)	Volume Injected (bbls)	Leach Efficiency
1	WH11_C0_0L1F1	0	0	1	1	3735	3468	267	178.18	8.48E+06	8.56E+06	500000	0.144
2	WH11_C0_0L1F2	0	0	1	2	3735	3468	267	178.04	8.48E+06	8.55E+06	500000	0.136
3	WH11_C0_0L1F3	0	0	1	3	3735	3426	309	179.49	8.48E+06	8.63E+06	1000000	0.142
4	WH11_C0_0L5F1	0	0	5	1	3735	3300	435	183.99	8.48E+06	8.88E+06	2500000	0.158
5	WH11_C0_0L5F2	0	0	5	2	3735	3300	435	183.70	8.48E+06	8.87E+06	2500000	0.155
6	WH11_C0_0L5F3	0	0	5	3	3735	3072	663	187.65	8.48E+06	9.27E+06	5000000	0.157
7	WH11_C1_20L1F1	1	20	1	1	3715	3468	247	178.23	8.48E+06	8.56E+06	500000	0.144
8	WH11_C1_20L1F2	1	20	1	2	3715	3468	247	178.09	8.48E+06	8.55E+06	500000	0.136
9	WH11_C1_20L1F3	1	20	1	3	3715	3426	289	179.56	8.48E+06	8.63E+06	1000000	0.143
10	WH11_C1_60L1F1	1	60	1	1	3675	3468	207	176.37	8.48E+06	8.56E+06	500000	0.147
11	WH11_C1_60L1F2	1	60	1	2	3675	3468	207	176.35	8.48E+06	8.55E+06	500000	0.139
12	WH11_C1_60L1F3	1	60	1	3	3675	3426	249	176.35	8.48E+06	8.63E+06	1000000	0.145
13	WH11_C1_100L1F1	1	100	1	1	3635	3468	167	176.37	8.48E+06	8.56E+06	500000	0.148
14	WH11_C1_100L1F2	1	100	1	2	3635	3468	167	176.35	8.48E+06	8.55E+06	500000	0.141
15	WH11_C1_100L1F3	1	100	1	3	3635	3427	209	176.35	8.48E+06	8.63E+06	1000000	0.145
16	WH11_C1_20L5F1	1	20	5	1	3715	3300	415	184.12	8.48E+06	8.88E+06	2500000	0.158
17	WH11_C1_20L5F2	1	20	5	2	3715	3300	415	183.82	8.48E+06	8.87E+06	2500000	0.155
18	WH11_C1_20L5F3	1	20	5	3	3715	3072	643	187.78	8.48E+06	9.27E+06	5000000	0.157
19	WH11_C1_60L5F1	1	60	5	1	3675	3300	375	176.66	8.48E+06	8.88E+06	2500000	0.159
20	WH11_C1_60L5F2	1	60	5	2	3675	3300	375	176.53	8.48E+06	8.87E+06	2500000	0.156
21	WH11_C1_60L5F3	1	60	5	3	3675	3072	603	176.56	8.48E+06	9.27E+06	5000000	0.157
22	WH11_C1_100L5F1	1	100	5	1	3635	3300	335	176.66	8.48E+06	8.88E+06	2500000	0.159
23	WH11_C1_100L5F2	1	100	5	2	3635	3300	335	176.53	8.48E+06	8.87E+06	2500000	0.156
24	WH11_C1_100L5F3	1	100	5	3	3635	3072	563	176.56	8.48E+06	9.27E+06	5000000	0.157
25	WH11_C5_20L5F1	5	20	5	1	3715	3300	415	184.04	8.48E+06	8.88E+06	2500000	0.158

Run Number	Run Name	Number of Cuts	Total Cut Length (ft)	Number of Leaches	Flow Condition	Final HS Depth (ft)	Final OBI (ft)	(HS - OBI) (ft)	Max. Cavern Radius (ft)	Initial Cavern Volume (bbls)	Final Cavern Volume (bbls)	Volume Injected (bbls)	Leach Efficiency
26	WH11_C5_20L5F2	5	20	5	2	3715	3300	415	183.73	8.48E+06	8.87E+06	2500000	0.155
27	WH11_C5_20L5F3	5	20	5	3	3715	3072	643	187.67	8.48E+06	9.27E+06	5000000	0.157
28	WH11_C5_60L5F1	5	60	5	1	3675	3300	375	181.75	8.48E+06	8.88E+06	2500000	0.158
29	WH11_C5_60L5F2	5	60	5	2	3675	3300	375	182.73	8.48E+06	8.87E+06	2500000	0.156
30	WH11_C5_60L5F3	5	60	5	3	3675	3072	603	186.30	8.48E+06	9.27E+06	5000000	0.157
31	WH11_C5_100L5F1	5	100	5	1	3635	3300	335	180.33	8.48E+06	8.88E+06	2500000	0.159
32	WH11_C5_100L5F2	5	100	5	2	3635	3300	335	180.05	8.48E+06	8.87E+06	2500000	0.156
33	WH11_C5_100L5F3	5	100	5	3	3635	3072	563	182.50	8.48E+06	9.27E+06	5000000	0.157

Table A-2. Input Parameters and Output Data for 33 Runs of SANSMIC for WH113

Run Number	Run Name	Number of Cuts	Total Cut Length (ft)	Number of Leaches	Flow Condition	Final HS Depth (ft)	Final OBI (ft)	(HS - OBI) (ft)	Max. Cavern Radius (ft)	Initial Cavern Volume (bbls)	Final Cavern Volume (bbls)	Volume Injected (bbls)	Leach Efficiency
1	WH113_C0_0L1F1	0	0	1	1	4622	4268	354	103.01	1.13E+07	1.13E+07	500000	0.086
2	WH113_C0_0L1F2	0	0	1	2	4622	4268	354	102.86	1.13E+07	1.13E+07	500000	0.082
3	WH113_C0_0L1F3	0	0	1	3	4622	4184	438	104.28	1.13E+07	1.14E+07	1000000	0.120
4	WH113_C0_0L5F1	0	0	5	1	4622	3952	670	108.53	1.13E+07	1.17E+07	2500000	0.147
5	WH113_C0_0L5F2	0	0	5	2	4622	3952	670	108.20	1.13E+07	1.17E+07	2500000	0.145
6	WH113_C0_0L5F3	0	0	5	3	4622	3638	984	111.51	1.13E+07	1.21E+07	5000000	0.152
7	WH113_C1_20L1F1	1	20	1	1	4602	4268	334	103.05	1.13E+07	1.13E+07	500000	0.088
8	WH113_C1_20L1F2	1	20	1	2	4602	4268	334	102.90	1.13E+07	1.13E+07	500000	0.084
9	WH113_C1_20L1F3	1	20	1	3	4602	4184	418	104.33	1.13E+07	1.14E+07	1000000	0.121
10	WH113_C1_60L1F1	1	60	1	1	4562	4268	294	102.42	1.13E+07	1.13E+07	500000	0.088
11	WH113_C1_60L1F2	1	60	1	2	4562	4268	294	102.24	1.13E+07	1.13E+07	500000	0.084
12	WH113_C1_60L1F3	1	60	1	3	4562	4184	378	103.78	1.13E+07	1.14E+07	1000000	0.121
13	WH113_C1_100L1F1	1	100	1	1	4522	4268	254	100.88	1.13E+07	1.13E+07	500000	0.088

Run Number	Run Name	Number of Cuts	Total Cut Length (ft)	Number of Leaches	Flow Condition	Final HS Depth (ft)	Final OBI (ft)	(HS - OBI) (ft)	Max. Cavern Radius (ft)	Initial Cavern Volume (bbls)	Final Cavern Volume (bbls)	Volume Injected (bbls)	Leach Efficiency
14	WH113_C1_100L1F2	1	100	1	2	4522	4268	254	100.85	1.13E+07	1.13E+07	500000	0.084
15	WH113_C1_100L1F3	1	100	1	3	4522	4184	338	101.78	1.13E+07	1.14E+07	1000000	0.121
16	WH113_C1_20L5F1	1	20	5	1	4602	3952	650	108.60	1.13E+07	1.17E+07	2500000	0.147
17	WH113_C1_20L5F2	1	20	5	2	4602	3952	650	108.26	1.13E+07	1.17E+07	2500000	0.145
18	WH113_C1_20L5F3	1	20	5	3	4602	3638	964	111.62	1.13E+07	1.21E+07	5000000	0.152
19	WH113_C1_60L5F1	1	60	5	1	4562	3952	610	108.36	1.13E+07	1.17E+07	2500000	0.147
20	WH113_C1_60L5F2	1	60	5	2	4562	3952	610	107.96	1.13E+07	1.17E+07	2500000	0.145
21	WH113_C1_60L5F3	1	60	5	3	4562	3638	924	111.28	1.13E+07	1.21E+07	5000000	0.152
22	WH113_C1_100L5F1	1	100	5	1	4522	3952	570	106.79	1.13E+07	1.17E+07	2500000	0.148
23	WH113_C1_100L5F2	1	100	5	2	4522	3952	570	106.29	1.13E+07	1.17E+07	2500000	0.145
24	WH113_C1_100L5F3	1	100	5	3	4522	3638	884	109.79	1.13E+07	1.21E+07	5000000	0.152
25	WH113_C5_20L5F1	5	20	5	1	4602	3952	650	108.53	1.13E+07	1.17E+07	2500000	0.147
26	WH113_C5_20L5F2	5	20	5	2	4602	3952	650	108.20	1.13E+07	1.17E+07	2500000	0.145
27	WH113_C5_20L5F3	5	20	5	3	4602	3638	964	111.54	1.13E+07	1.21E+07	5000000	0.152
28	WH113_C5_60L5F1	5	60	5	1	4562	3952	610	107.90	1.13E+07	1.17E+07	2500000	0.147
29	WH113_C5_60L5F2	5	60	5	2	4562	3952	610	107.51	1.13E+07	1.17E+07	2500000	0.145
30	WH113_C5_60L5F3	5	60	5	3	4562	3638	924	110.87	1.13E+07	1.21E+07	5000000	0.152
31	WH113_C5_100L5F1	5	100	5	1	4522	3952	570	105.72	1.13E+07	1.17E+07	2500000	0.147
32	WH113_C5_100L5F2	5	100	5	2	4522	3952	570	105.38	1.13E+07	1.17E+07	2500000	0.145
33	WH113_C5_100L5F3	5	100	5	3	4522	3638	884	108.67	1.13E+07	1.21E+07	5000000	0.152

Table A-3. Input Parameters and Output Data for 33 Runs of SANSMIC for BH104

Run Number	Run Name	Number of Cuts	Total Cut Length (ft)	Number of Leaches	Flow Condition	Final HS Depth (ft)	Final OBI (ft)	(HS - OBI) (ft)	Max. Cavern Radius (ft)	Initial Cavern Volume (bbls)	Final Cavern Volume (bbls)	Volume Injected (bbls)	Leach Efficiency*
1	BH104_C0_0L1F1	0	0	1	1	4176	3773	403	122.78	1.43E+07	1.44E+07	500000	0.150
2	BH104_C0_0L1F2	0	0	1	2	4176	3773	403	122.68	1.43E+07	1.44E+07	500000	0.144
3	BH104_C0_0L1F3	0	0	1	3	4176	3707	469	123.83	1.43E+07	1.45E+07	1000000	0.149
4	BH104_C0_0L5F1	0	0	5	1	4176	3516	660	127.33	1.43E+07	1.47E+07	2500000	0.160
5	BH104_C0_0L5F2	0	0	5	2	4176	3516	660	127.12	1.43E+07	1.47E+07	2500000	0.158
6	BH104_C0_0L5F3	0	0	5	3	4176	3203	973	130.34	1.43E+07	1.51E+07	5000000	0.159
7	BH104_C1_20L1F1	1	20	1	1	4156	3773	383	122.84	1.43E+07	1.44E+07	500000	0.152
8	BH104_C1_20L1F2	1	20	1	2	4156	3773	383	122.74	1.43E+07	1.44E+07	500000	0.144
9	BH104_C1_20L1F3	1	20	1	3	4156	3707	449	123.93	1.43E+07	1.45E+07	1000000	0.149
10	BH104_C1_60L1F1	1	60	1	1	4116	3773	343	123.03	1.43E+07	1.44E+07	500000	0.152
11	BH104_C1_60L1F2	1	60	1	2	4116	3773	343	122.91	1.43E+07	1.44E+07	500000	0.146
12	BH104_C1_60L1F3	1	60	1	3	4116	3707	409	124.20	1.43E+07	1.45E+07	1000000	0.150
13	BH104_C1_100L1F1	1	100	1	1	4076	3773	303	123.27	1.43E+07	1.44E+07	500000	0.154
14	BH104_C1_100L1F2	1	100	1	2	4076	3773	303	123.13	1.43E+07	1.44E+07	500000	0.148
15	BH104_C1_100L1F3	1	100	1	3	4076	3707	369	124.53	1.43E+07	1.45E+07	1000000	0.150
16	BH104_C1_20L5F1	1	20	5	1	4156	3516	640	127.51	1.43E+07	1.47E+07	2500000	0.160
17	BH104_C1_20L5F2	1	20	5	2	4156	3516	640	127.29	1.43E+07	1.47E+07	2500000	0.158
18	BH104_C1_20L5F3	1	20	5	3	4156	3203	953	130.56	1.43E+07	1.51E+07	5000000	0.159
19	BH104_C1_60L5F1	1	60	5	1	4116	3516	600	128.07	1.43E+07	1.47E+07	2500000	0.161
20	BH104_C1_60L5F2	1	60	5	2	4116	3516	600	127.82	1.43E+07	1.47E+07	2500000	0.158
21	BH104_C1_60L5F3	1	60	5	3	4116	3203	913	131.22	1.43E+07	1.51E+07	5000000	0.159
22	BH104_C1_100L5F1	1	100	5	1	4076	3516	560	128.68	1.43E+07	1.47E+07	2500000	0.161
23	BH104_C1_100L5F2	1	100	5	2	4076	3516	560	128.39	1.43E+07	1.47E+07	2500000	0.158
24	BH104_C1_100L5F3	1	100	5	3	4076	3203	873	131.81	1.43E+07	1.51E+07	5000000	0.159
25	BH104_C5_20L5F1	5	20	5	1	4156	3516	640	127.39	1.43E+07	1.47E+07	2500000	0.160
26	BH104_C5_20L5F2	5	20	5	2	4156	3516	640	127.17	1.43E+07	1.47E+07	2500000	0.158

Run Number	Run Name	Number of Cuts	Total Cut Length (ft)	Number of Leaches	Flow Condition	Final HS Depth (ft)	Final OBI (ft)	(HS - OBI) (ft)	Max. Cavern Radius (ft)	Initial Cavern Volume (bbls)	Final Cavern Volume (bbls)	Volume Injected (bbls)	Leach Efficiency*
27	BH104_C5_20L5F3	5	20	5	3	4156	3203	953	130.39	1.43E+07	1.51E+07	5000000	0.159
28	BH104_C5_60L5F1	5	60	5	1	4116	3516	600	127.62	1.43E+07	1.47E+07	2500000	0.160
29	BH104_C5_60L5F2	5	60	5	2	4116	3516	600	127.39	1.43E+07	1.47E+07	2500000	0.158
30	BH104_C5_60L5F3	5	60	5	3	4116	3203	913	130.63	1.43E+07	1.51E+07	5000000	0.159
31	BH104_C5_100L5F1	5	100	5	1	4076	3516	560	127.94	1.43E+07	1.47E+07	2500000	0.161
32	BH104_C5_100L5F2	5	100	5	2	4076	3516	560	127.71	1.43E+07	1.47E+07	2500000	0.158
33	BH104_C5_100L5F3	5	100	5	3	4076	3203	873	130.99	1.43E+07	1.51E+07	5000000	0.159

Table A-4. Input Parameters and Output Data for 33 Runs of SANSMIC for BH114

Run Number	Run Name	Number of Cuts	Total Cut Length (ft)	Number of Leaches	Flow Condition	Final HS Depth (ft)	Final OBI (ft)	(HS - OBI) (ft)	Max. Cavern Radius (ft)	Initial Cavern Volume (bbls)	Final Cavern Volume (bbls)	Volume Injected (bbls)	Leach Efficiency
1	BH114_C0_0L1F1	0	0	1	1	4081	3561	520	103.55	1.28E+07	1.29E+07	500000	0.156
2	BH114_C0_0L1F2	0	0	1	2	4081	3561	520	103.52	1.28E+07	1.29E+07	500000	0.152
3	BH114_C0_0L1F3	0	0	1	3	4081	3467	614	104.32	1.28E+07	1.30E+07	1000000	0.155
4	BH114_C0_0L5F1	0	0	5	1	4081	3238	843	107.58	1.28E+07	1.32E+07	2500000	0.161
5	BH114_C0_0L5F2	0	0	5	2	4081	3238	843	107.38	1.28E+07	1.32E+07	2500000	0.160
6	BH114_C0_0L5F3	0	0	5	3	4081	2934	1147	110.32	1.28E+07	1.36E+07	5000000	0.160
7	BH114_C1_20L1F1	1	20	1	1	4061	3561	500	103.55	1.28E+07	1.29E+07	500000	0.156
8	BH114_C1_20L1F2	1	20	1	2	4061	3561	500	103.52	1.28E+07	1.29E+07	500000	0.152
9	BH114_C1_20L1F3	1	20	1	3	4061	3467	594	103.53	1.28E+07	1.30E+07	1000000	0.155
10	BH114_C1_60L1F1	1	60	1	1	4021	3561	460	103.55	1.28E+07	1.29E+07	500000	0.158
11	BH114_C1_60L1F2	1	60	1	2	4021	3561	460	103.52	1.28E+07	1.29E+07	500000	0.154
12	BH114_C1_60L1F3	1	60	1	3	4021	3467	554	103.53	1.28E+07	1.30E+07	1000000	0.155
13	BH114_C1_100L1F1	1	100	1	1	3981	3561	420	103.55	1.28E+07	1.29E+07	500000	0.158
14	BH114_C1_100L1F2	1	100	1	2	3981	3561	420	103.52	1.28E+07	1.29E+07	500000	0.154

Run Number	Run Name	Number of Cuts	Total Cut Length (ft)	Number of Leaches	Flow Condition	Final HS Depth (ft)	Final OBI (ft)	(HS - OBI) (ft)	Max. Cavern Radius (ft)	Initial Cavern Volume (bbls)	Final Cavern Volume (bbls)	Volume Injected (bbls)	Leach Efficiency
15	BH114_C1_100L1F3	1	100	1	3	3981	3467	514	103.53	1.28E+07	1.30E+07	1000000	0.155
16	BH114_C1_20L5F1	1	20	5	1	4061	3238	823	103.83	1.28E+07	1.32E+07	2500000	0.162
17	BH114_C1_20L5F2	1	20	5	2	4061	3238	823	103.70	1.28E+07	1.32E+07	2500000	0.160
18	BH114_C1_20L5F3	1	20	5	3	4061	2934	1127	106.15	1.28E+07	1.36E+07	5000000	0.160
19	BH114_C1_60L5F1	1	60	5	1	4021	3238	784	103.83	1.28E+07	1.32E+07	2500000	0.162
20	BH114_C1_60L5F2	1	60	5	2	4021	3238	783	103.70	1.28E+07	1.32E+07	2500000	0.160
21	BH114_C1_60L5F3	1	60	5	3	4021	2934	1087	103.73	1.28E+07	1.36E+07	5000000	0.160
22	BH114_C1_100L5F1	1	100	5	1	3981	3237	744	103.83	1.28E+07	1.32E+07	2500000	0.162
23	BH114_C1_100L5F2	1	100	5	2	3981	3238	743	103.70	1.28E+07	1.32E+07	2500000	0.160
24	BH114_C1_100L5F3	1	100	5	3	3981	2934	1047	104.18	1.28E+07	1.36E+07	5000000	0.160
25	BH114_C5_20L5F1	5	20	5	1	4061	3238	823	103.83	1.28E+07	1.32E+07	2500000	0.162
26	BH114_C5_20L5F2	5	20	5	2	4061	3238	823	103.70	1.28E+07	1.32E+07	2500000	0.160
27	BH114_C5_20L5F3	5	20	5	3	4061	2934	1127	106.12	1.28E+07	1.36E+07	5000000	0.160
28	BH114_C5_60L5F1	5	60	5	1	4021	3238	783	103.83	1.28E+07	1.32E+07	2500000	0.162
29	BH114_C5_60L5F2	5	60	5	2	4021	3238	783	103.70	1.28E+07	1.32E+07	2500000	0.160
30	BH114_C5_60L5F3	5	60	5	3	4021	2934	1087	103.73	1.28E+07	1.36E+07	5000000	0.160
31	BH114_C5_100L5F1	5	100	5	1	3981	3238	744	103.83	1.28E+07	1.32E+07	2500000	0.162
32	BH114_C5_100L5F2	5	100	5	2	3981	3238	743	103.70	1.28E+07	1.32E+07	2500000	0.160
33	BH114_C5_100L5F3	5	100	5	3	3981	2934	1047	103.73	1.28E+07	1.36E+07	5000000	0.160

APPENDIX B. ZEITLER AND CHOJNICKI (2020) MEMO

This Appendix replicates Zeitler and Chojnicki (2020).

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March 18, 2020

US DOE SPR PMO, New Orleans LA

To: Diane Willard, DOE-SPR

Subject: ***Recommendation for Cut of Hanging String in West Hackberry 11 (WH11) Cavern***

Studies monitoring the leaching effects in sales caverns suggest that the partial drawdowns used for oil sales in some SPR caverns may induce adverse cavern leaching by generating features such as a flare near the cavern floor (see Chojnicki (2019) for a more detailed background). The modeling study documented here investigates a potential mitigation approach in order to minimize leaching at the depth of the anomalous feature observed for WH11 (a flare at a depth of 3700') and yet not create additional anomalous features in the process. The study examines the impact of cutting the hanging string in WH11, utilizing the SANSMIC code to predict cavern growth over a range of flow conditions and lengths of string cuts (Russo 1983, Weber et al. 2014). The results suggest that a minimum cut length of 60 ft is necessary in this cavern to stop leaching of the feature at 3700'. However, a string cut at 100 ft is predicted to form a secondary feature starting at 3650' depth, and to avoid forming that secondary feature, the string should be cut no higher than 100 ft. As a result of the modeling work, we have made a **recommendation for a hanging string cut of 80 ft in WH11**.

1. INTRODUCTION

Investigation of leaching for oil sales includes looking closely at cavern geometries (Chojnicki 2019). Anomalous cavern “features” have been observed near the foot of some caverns subsequent to partial drawdowns. The features include localized zones of increased cavern diameter and may be exacerbated by continued leaching of the cavern in the zone near the end of the brine string (i.e., hanging string) (Eldredge et al. 2013). The existence of anomalous features may lead to geomechanical instabilities that could eventually result in salt falls and ensuing brine string damage.

One potential mitigation approach to reducing further growth of preexisting features is based on the hypothesis that reducing the brine string length via a “string cut” would serve to move the zone associated with additional leaching to a location higher up in the cavern and thus away from the preexisting feature. Cutting of the hanging string is expected to provide a control of leaching depth that could be used to “smooth” existing features and thus reduce geomechanical instability in that region of the cavern. Partial drawdowns impact cavern geometry differently than full drawdowns (e.g., via preferential leaching at the cavern bottom) as leaching primarily occurs in the depths of a cavern between the end of the brine string (end of tubing; EOT) (bottom of the zone) to the oil-brine interface (OBI) (top of the zone) (Weber et al. 2014).

Anomalous cavern growth (e.g., flaring of cavern floor) has been observed in WH11 and may lead to geomechanical instabilities via the “sharp” feature observed near the cavern floor as shown in Figure 26 (Chojnicki, 2019). Because leaching during water injection is known to take place between the end of the brine string and the OBI, it is hypothesized that moving the end of the brine string up in the cavern would also move the leaching zone further up in the cavern, avoiding further development of the flared feature and instead creating a less sharp cavern profile (Figure 27).

The work described here focuses on the development of a methodology and workflow to facilitate mediation of further anomalous cavern growth by considering brine string cuts under variable conditions in a single cavern of known initial geometry. Ultimately, this approach could be used to answer the following questions in anticipation of making recommendations for ensuring stable cavern growth:

4. Can cutting brine strings reduce flaring of cavern floors in sales caverns?
5. What specific recommendation can be made for ensuring a stable cavern geometry over time?
6. How does the initial cavern geometry impact the potential for geometry change?

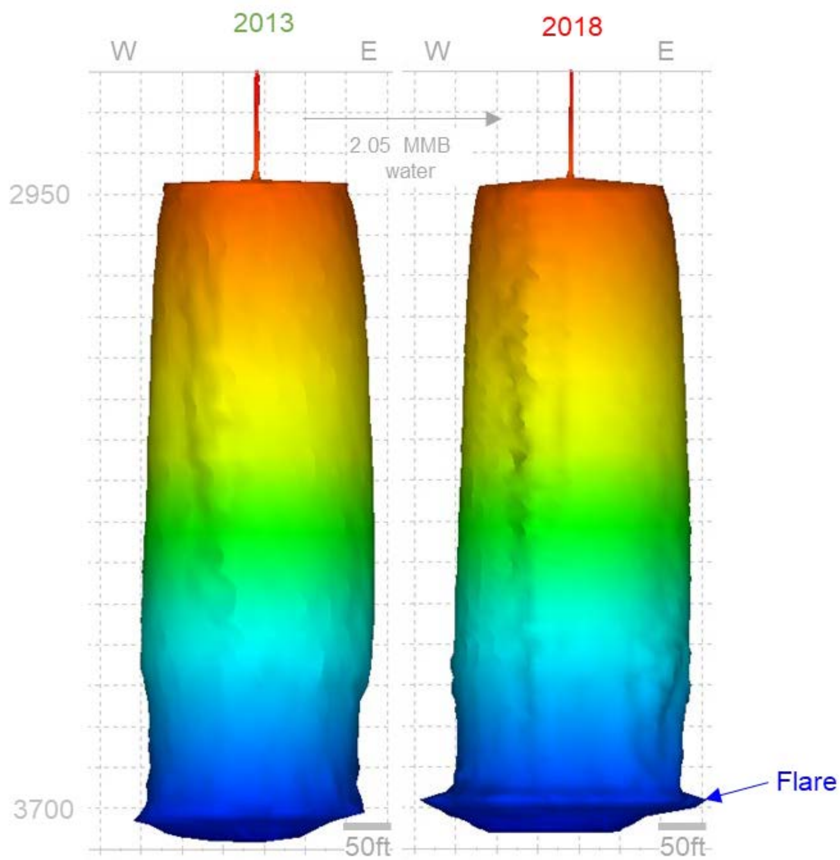

Figure 26 (left) Pre- and (right) Post-sale sonars of WH11 showing the formation of a flare feature after 2.05 MMB of water was injected for oil withdrawal in 2014 (0.1MMB) and 2017 (1.9MMB).

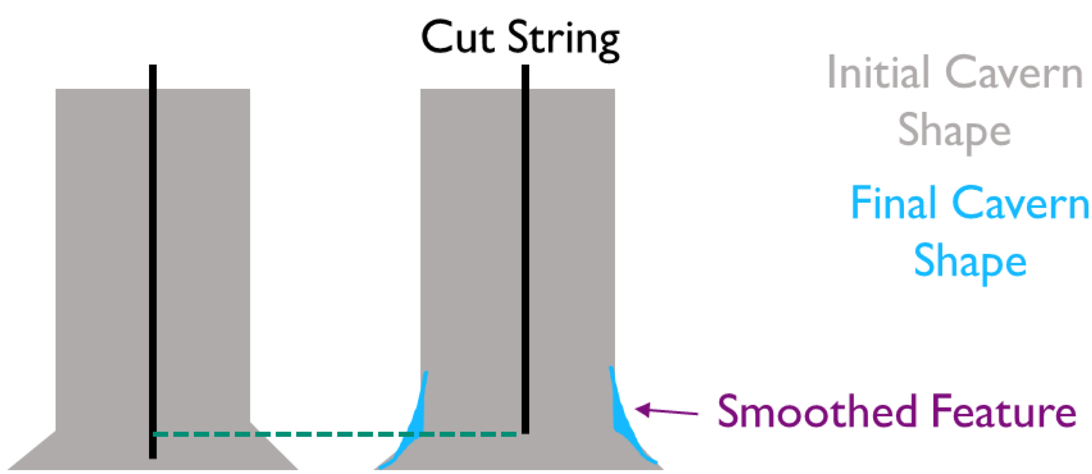

Figure 27 Schematic representation of cavern WH11, showing potential for cut string to lead to smoothing of cavern floor feature. The flare at the floor (or wing) in the initial cavern shape was primarily caused by partial leaching during the 2017 sales (see Chojnicki, 2019 for more information).

2. APPROACH

The SANSMIC code was developed at Sandia National Laboratories (SNL) for modeling leaching during cavern creation and has since been used to track leaching during other transfer operations (i.e., fills and withdrawals) in SPR caverns (Russo 1983, Weber et al. 2014). Various leaching modes have been incorporated in the code, including leaching during water injection/oil extraction. The impact of leaching on cavern geometry can be measured by comparing the pre- and post-leach cavern geometries. Typically, the code has been used to check cavern growth following oil sales wherein a cavern geometry is computed given the pre-sales cavern geometry (obtained from cavern sonars) and known injection data during sales (Weber et al. 2013, Chojnicki 2019). However, the code can also be used in a predictive manner to anticipate changes to an initial cavern geometry under given injection assumptions. In either case, a one-dimensional, axisymmetric representation of the cavern geometry is the model input and output.

In the approach outlined here, the SANSMIC code is used to predict cavern geometry changes (i.e., the extent of cavern growth with depth) based on variable input parameters. By comparing the initial sonar geometry with resultant geometries calculated by the SANSMIC code, conclusions may be drawn about the potential impact of these variables on future cavern growth. Ultimately, these conclusions could be used to assess possible mitigation strategies such as the potential advantage of cutting versus not cutting a brine string.

Input for the SANSMIC code may be broadly categorized as cavern-dependent (i.e., those parameters that vary across caverns) or operations-dependent (i.e., those parameters that may be changed from a caverns operation standpoint). Examples of cavern-dependent input are initial cavern geometry and the initial location of the OBI. Examples of operations-dependent parameters are hanging string length (i.e., location of the end of the brine string) and the flow conditions (i.e., rate and duration) for brine or raw water entering the cavern during a drawdown.

3. METHODOLOGY

The methodology for analyzing string cuts for the WH11 cavern consisted of 33 runs of the SANSMIC code. For all 33 runs of WH11, the initial geometry (including a flare that maximizes at a depth of 3700 ft and a cavern bottom depth of 3750 ft) was based on an axisymmetric representation of the 2018 sonar shown in Figure 28 and an OBI location of 3510 ft, which was the SANSMIC-estimated OBI position for WH11 after the CY2018 sales.[2] Each of the 33 runs consisted of independent combinations of the following input parameters: length of brine string cuts, number of brine string cuts, and number of leaches (Table 2). Eleven combinations of string cut lengths/number of string cuts/number of leaches were used, with each of three flow conditions applied to each combination.

As a baseline, simulations were performed for the case where the string was not cut (0 cuts) to determine the extent of leaching without mitigation and compare it with the extent of leaching which included mitigation from a single cut (1 cut) in a single sale (1 leach) or multiple sales (5 leaches) or multiple cuts (5 cuts) in multiple sales (5 leaches) with one cut after each sale.

For WH11, total cut lengths of zero, 20 ft, 60 ft, and 100 ft were examined. These distances were chosen based on the dimensions of the feature observed in the most recent WH11 sonar. For cases with five cuts, each cut was 1/5th of the total cut length (e.g., for a total cut length of 100 ft, there was first a cut of 20 ft and a leach, then a second cut of 20 ft and a leach, then a third cut of 20 ft and a leach, then a fourth cut of 20 ft and a leach, and finally a fifth cut and a leach). The initial brine string depth (end of string) was 3735 ft (15 ft from the cavern bottom); a cut of 100 ft would result in a string depth of 3635 ft.

For WH11, three flow conditions were examined which were based on the range of values observed for water injection rates and durations in the 2017 sales. Flow condition 1 has a low flowrate for a long duration and flow condition 2 has a high flow rate for a short duration with an equivalent volume of injected water as flow condition 1. Thus, a comparison of results from flow conditions 1 and 2 reveals the effects of flow rate and duration on leaching outcomes. Flow condition 3 has the same rate as flow condition 2 and a longer duration to reach twice the total volume as flow conditions 1 and 2. Thus a comparison of results from flow conditions 2 and 3 reveal the effect of the total volume of water injected. The exact values used for each condition are summarized in Table 3.

[2] The authorized capacity of WH11 is 8.0 MMbbls, while the current cavern volume is approximately 8.5 MMbbls. The volume of oil in the cavern at the time of the 2018 sonar was approximately 6.0 MMbbls.

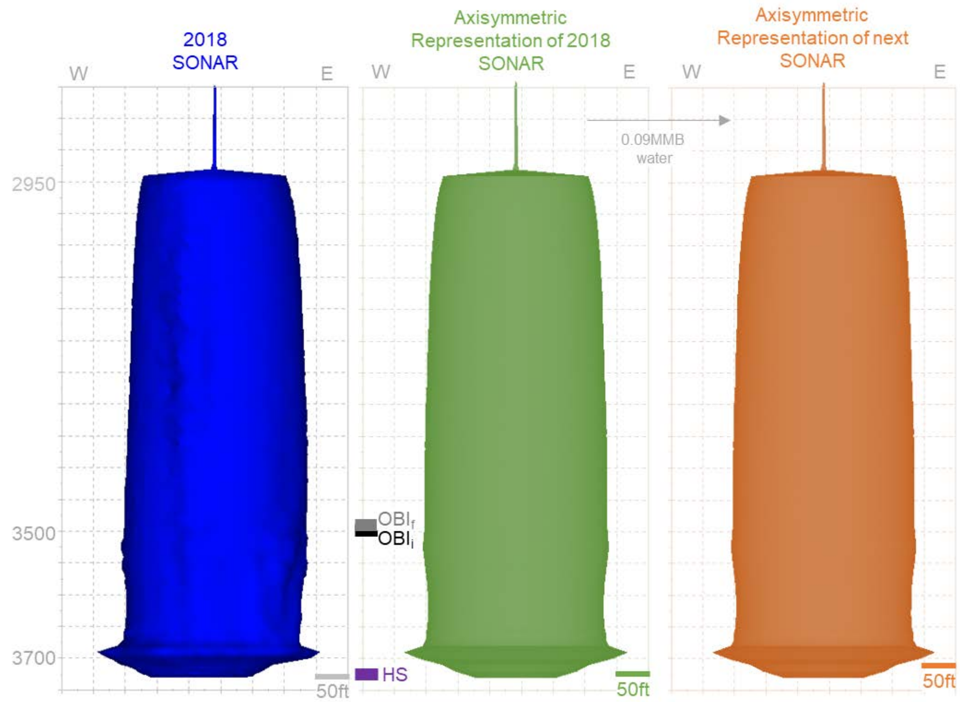

Figure 28 (left) The WH11 2018 sonar, (middle) the axisymmetric representation of that sonar used as an input for modeling the effects of the 0.09 MMB of water injected in WH11 during 2018, and (right) the final cavern geometry after CY2018 sales which was the starting geometry for this study.

Table 2. Lengths of hanging string cuts considered for each combination of number of cuts and leaches.

Number of Cuts	Number of Leaches	
	1	5
0	0 ft	0 ft
1	20 ft, 60 ft, 100 ft	20 ft, 60 ft, 100 ft
5	-	20 ft (5 x 4 ft), 60 ft (5 x 12 ft), 100 ft (5 x 20 ft)

Table 3. Flow conditions on a per leach basis.

Flow Condition	Flow Rate (bbls/day)	Flow Duration per Leach (days)	Volume per Leach (bbls)
1	10000	50	500000
2	50000	10	500000
3	50000	20	1000000

A distinct run name was developed to identify each run of the SANSMIC code with the cavern name, number of cuts, total cut length, number of leaches, and flow conditions making up part of the name. The "key" to run names is the following: [*Cavern Name*]_C[*Number of Cuts*]_[*Total Cut Length*]L[*Number of Leaches*]F[*Flow Condition Identifier*]. For example, WH11_C1_100L1F1 is a run of the West Hackberry 11 cavern with a single cut of 100 ft. and a single leach under flow condition 1. As another example, WH11_C1_60L5F3 is a run of the West Hackberry 11 cavern with a single cut of 60 ft. and five leaches under flow condition 3.

A Windows executable of the SANSMIC code was used. Preprocessing and postprocessing tools were developed to aid in the workflow, reducing manual steps in the process and the potential for user errors.

On the preprocessing side, the *SANSMICsetup.sh* shell script was developed to assemble a SANSMIC input file from two other files, a cavern geometry file (which contains initial geometry information for the cavern of interest) and a SANSMIC input file template (which contains a general framework for the SANSMIC input file). With a run of the *SANSMICsetup.sh* script, the template is populated by command line input, which provides the cavern name, initial brine string height, OBI height, injection rate, injection duration, total cut length, number of cuts, and number of leaches and then combined with the cavern geometry file to produce a SANSMIC input file suitable for running.

When SANSMIC is run, a number of output files are produced including a .out file that includes the final cavern geometry. The *postSANSMIC.py* script was developed in Python to extract final cavern geometry information from the .out file and produce three files: 1) a *.tbl* file (which contains columnar data on a nodal basis); 2) a *.stats* file (which contains a single line of input and output data useful for run verification); and 3) a *.png* file (a graphics file containing a plot of initial and final cavern geometries, as well as initial and final OBI locations). Please see the table in the Appendix for a summary of input parameters and output data for the 33 SANSMIC runs.

4. RESULTS

An example of SANSMIC output is presented in Figure 29. This figure shows what SANSMIC predicts will happen after the next sale in WH11 without a string cut if the flow conditions are like those in condition 1 (red line; WH11_C0_0L1F1) and the initial geometry (i.e., the output geometry from SANSMIC modeling of the 2018 leaching, denoted "Initial Geometry"). In this case, the cavern radius has increased for depths below 3470 ft, including the feature at 3700 ft. This output demonstrates that without mitigation, that feature will continue to grow in this cavern.

Comparisons of the cavern geometries output from the 33 SANSMIC runs with the initial cavern geometry for WH11 are presented in Figure 29 to Figure 41.

Baseline – no change (no cuts of the string)

One sale: Figure 36 shows the cases of "no cut," a single leach, and three flow conditions (3 total cases); these scenarios examine the leaching that may happen after one sale if there are no changes to string length. The use of flow conditions 1 and 2 (which have an identical total number of injected bbls) results in almost identical final geometries with leaching up to a depth of 3480 ft, while the use of flow condition 3 (twice the total number of injected bbls) results in increased leaching, including leaching up to a depth of 3430 ft. All cases show an increased radius of the feature at 3700 ft.

Multiple sales: Figure 37 shows the cases of "no cut," five leaches, and three flow conditions (3 total cases); these scenarios examine the leaching that may happen after 5 sales if there are no changes to the string length. Similar to the single leach cases shown in Figure 36, the use of flow conditions 1 and 2 (which have an identical total number of injected bbls) results in almost identical final geometries with leaching up to a depth of 3310 ft, while the use of flow condition 3 (twice the total number of injected bbls) results in increased leaching, including leaching up to a depth of 3080 ft. All cases show an increased radius of the feature at 3700 ft.

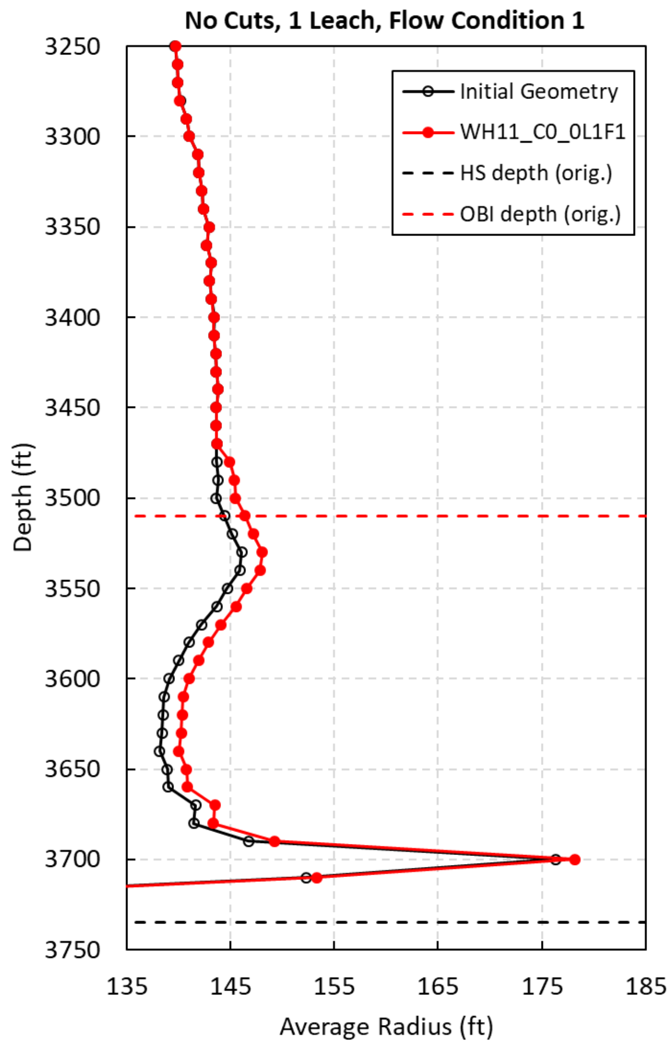

Figure 29. Comparison of (red) predicted WH11 geometry for no string cut, single leach, flow condition 1 (WH11_C0_0L1F1) case with (black) the SANSMIC-generated, axisymmetric representation of the cavern geometry after the CY2018 sales

Cumulatively, the almost identical final geometries for flow conditions 1 and 2 shown in Figure 36 and Figure 37 indicate that flow rate is not a dominant variable in determining leaching outcomes given the same total volume injected (as a result, final OBI depths for flow conditions 1 and 2 are almost identical for each cut/leach pair). Similarly, the substantial difference in final geometries between flow conditions 2 and 3 in Figure 36 and Figure 37 indicates the impact of total volume injected on determining leaching outcomes.

Mitigation Results 1 – Cut the string once

One Sale: Figure 38 through Figure 40 show the cases of a single cut, a single leach, and three flow conditions (9 total cases) for cuts of 20, 60, and 100 ft, respectively; these scenarios examine the leaching that may happen after one sale if the string is cut once prior to leaching. These figures show the impact of the three flow conditions for a single leach and a single brine string cut of 20, 60, or 100 ft. For cuts of 20 ft (Figure 38), there is some increase in radius of the feature at 3700 ft. In the cases of 60 and 100-ft cuts (Figure 39 and Figure 40), leaching does not result in an appreciable increase in radius of the feature at 3700 ft; rather, the leaching only goes down to a depth of 3690 ft for 60-ft cuts and 3650 ft for 100-ft cuts. ***These results imply that a minimum cut length of 60 ft is necessary in this cavern to stop leaching***

of the feature at 3700'. Similarly, the string cut at 100 ft starts to form a secondary feature starting at 3650' depth and, thus, to avoid forming that secondary feature, the string should be cut no higher than 100 ft. Our recommendation is that an 80 ft cut be made to the hangings string in WH11.

For clarity, a subset of the runs shown in Figure 38 through Figure 40 are plotted in Figure 41 for the three cut length runs associated only with flow condition 3. Since this condition has the greatest total amount of water injected and greatest leaching effect, it is easiest to see the relative effects of the string cut lengths for this condition.

Multiple Sales: Figure 42 through Figure 44 show the cases of a single cut, five leaches, and three flow conditions (9 total cases) for cuts of 20, 60, and 100 ft, respectively; these scenarios examine the leaching that may happen after five sales if the string is cut once prior to any leaching. These figures show the impact of the three flow conditions for five consecutive leaches following a single brine string cut of 20, 60, or 100 ft. Compared to the single leach cases (Figure 38 through Figure 40), the cavern radius increases in the leaching zone, as expected due to the five-fold increase in injected water volume. Similar to the single leach cases, growth of the feature at 3700 ft is avoided for runs with cuts of 60 or 100 ft. The development of the secondary feature above 3650' for cuts of 100 ft is more prominent in Figure 44 and underscores the importance of considering the effects of multiple leaches as well as single leaches on the outcome of a string length change in these sales caverns.

Mitigation Results 2 – Cut the string after each sale

Multiple Sales: Figure 45 through Figure 41 show the cases of five cuts, five leaches, and three flow conditions (9 total cases) for cuts of 20, 60, and 100 ft, respectively; these scenarios examine the leaching that may happen after five sales if the string is cut prior to each sale. These figures show the multiple cut cases with total cut lengths of 20, 60, and 100 ft. In contrast to the multiple leach, single cut cases (Figure 42 through Figure 44), growth of the feature at 3700 ft is observed for all cut lengths. This can be attributed to leaching taking place in the depths near the feature for the first few leaches, as the first leaches take place at string cuts of only 4, 12, and 20 ft for total cut lengths of 20, 60, and 100 ft, respectively. Although these are unlikely cut lengths for cavern operations, they are considered in this study as an exercise in learning the impact of these variables on leaching outcomes.

5. CONCLUSIONS

A methodology and workflow have been developed and tested in which the SANSMIC code is used to predict future cavern leaching behavior with a focus on understanding the impact of cutting brine strings on cavern geometry. The methodology and workflow used here could be incorporated into an overall mitigation strategy designed to reduce adverse future cavern growth. Proof-of-concept simulations on the West Hackberry 11 (WH11) cavern show the impact on cavern geometry due to varying the following input parameters: length of brine string cuts, number of brine string cuts, number of leaches, and flow conditions for each leach. Some combinations of input parameters result in a reduction of adverse leaching. An important conclusion from this study is that the growth of adverse cavern geometry features appears to be avoidable by cutting the end of the brine string. The general principle behind this behavior seems to be that leaching during water injection primarily takes place between the EOT and OBI. As a result of this work, we have made a recommendation for a hanging string cut of 80 ft in WH11. The general applicability of this methodology will be tested later when additional caverns are considered. It is anticipated that a SAND report will follow that details the results for a study of additional caverns.

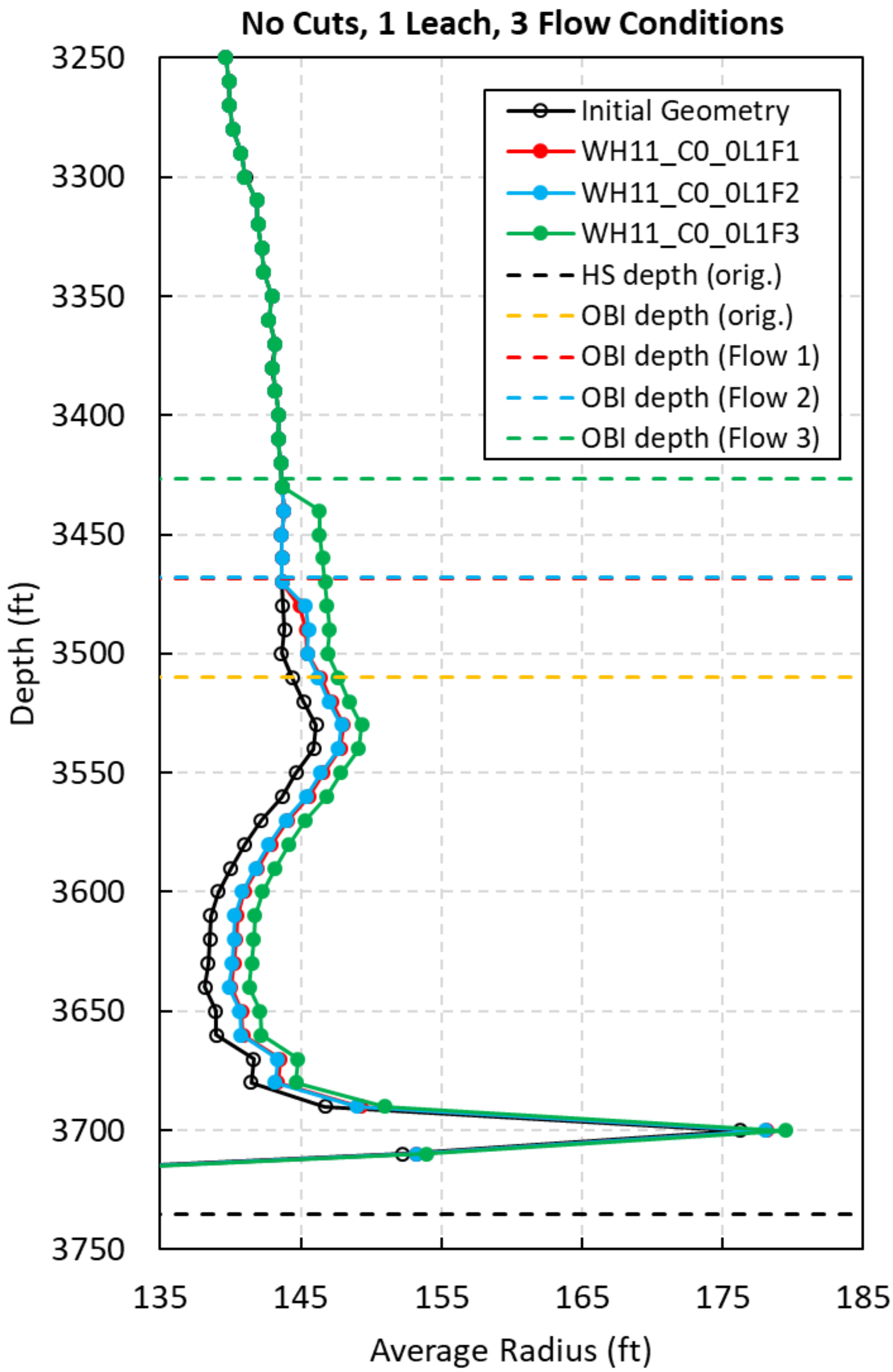

Figure 30. Predicted WH11 geometries for no string cuts and a single leach with flow condition 1 (red), 2 (blue) and 3 (green) compared with the starting geometry (black).

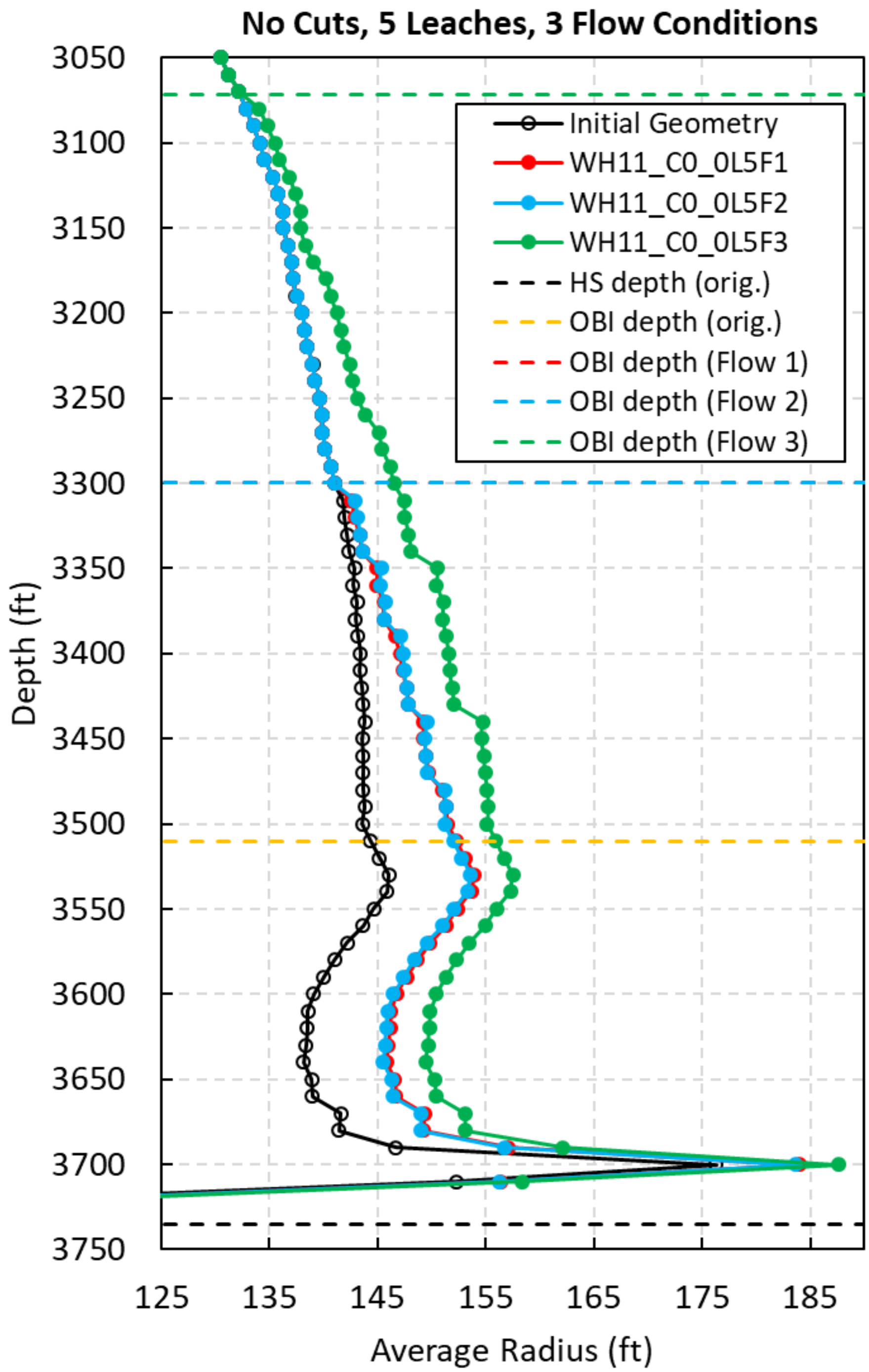

Figure 31. Predicted WH11 geometries for no string cuts and five leaches with flow condition 1 (red), 2 (blue) and 3 (green) compared with the starting geometry (black).

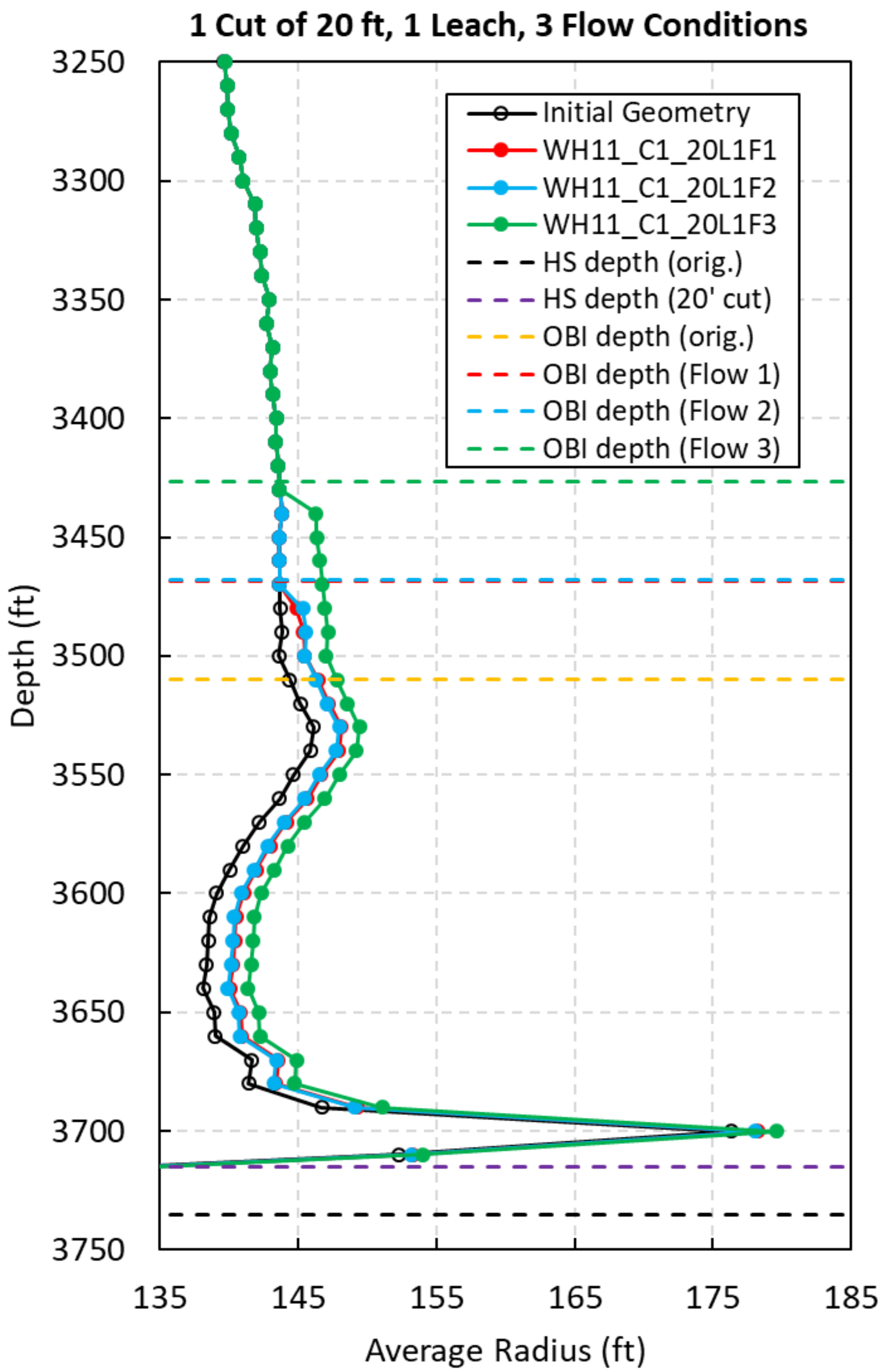

Figure 32. Predicted WH11 geometries for a single string cut of 20 ft and a single leach (three flow conditions).

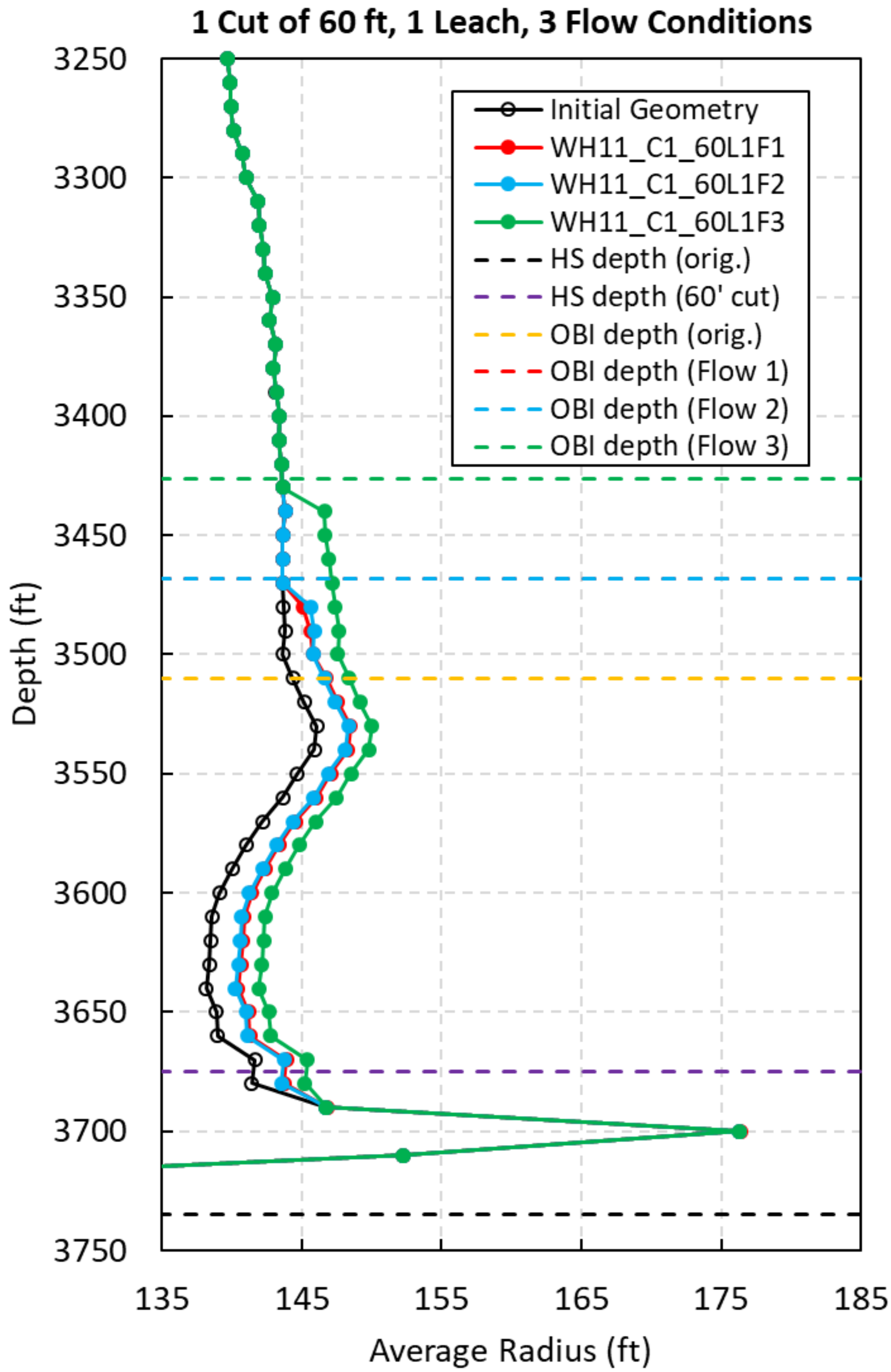

Figure 33. Predicted WH11 geometries for a single string cut of 60 ft and a single leach (three flow conditions).

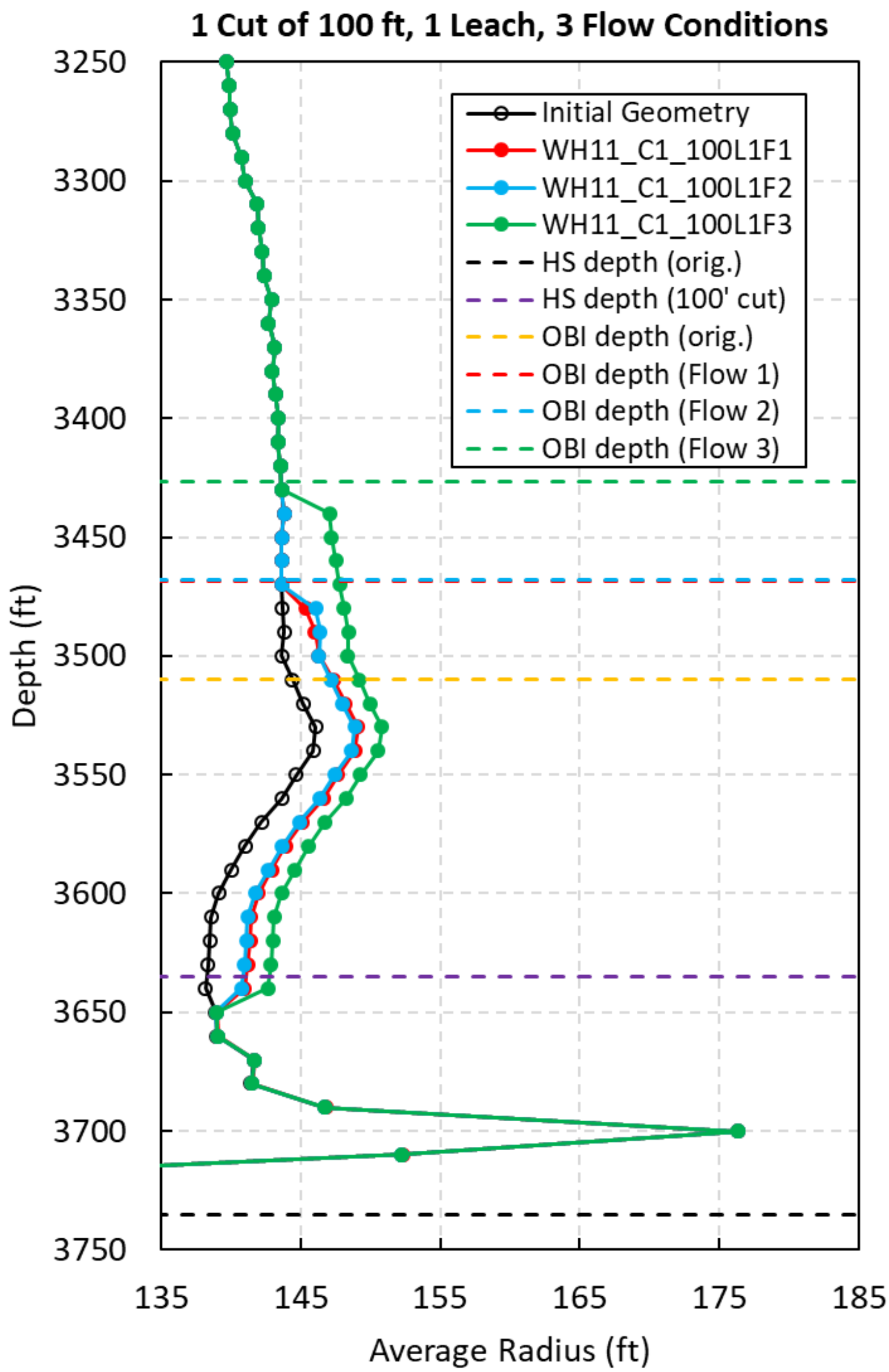

Figure 34. Predicted WH11 geometries for a single string cut of 100 ft and a single leach (three flow conditions).

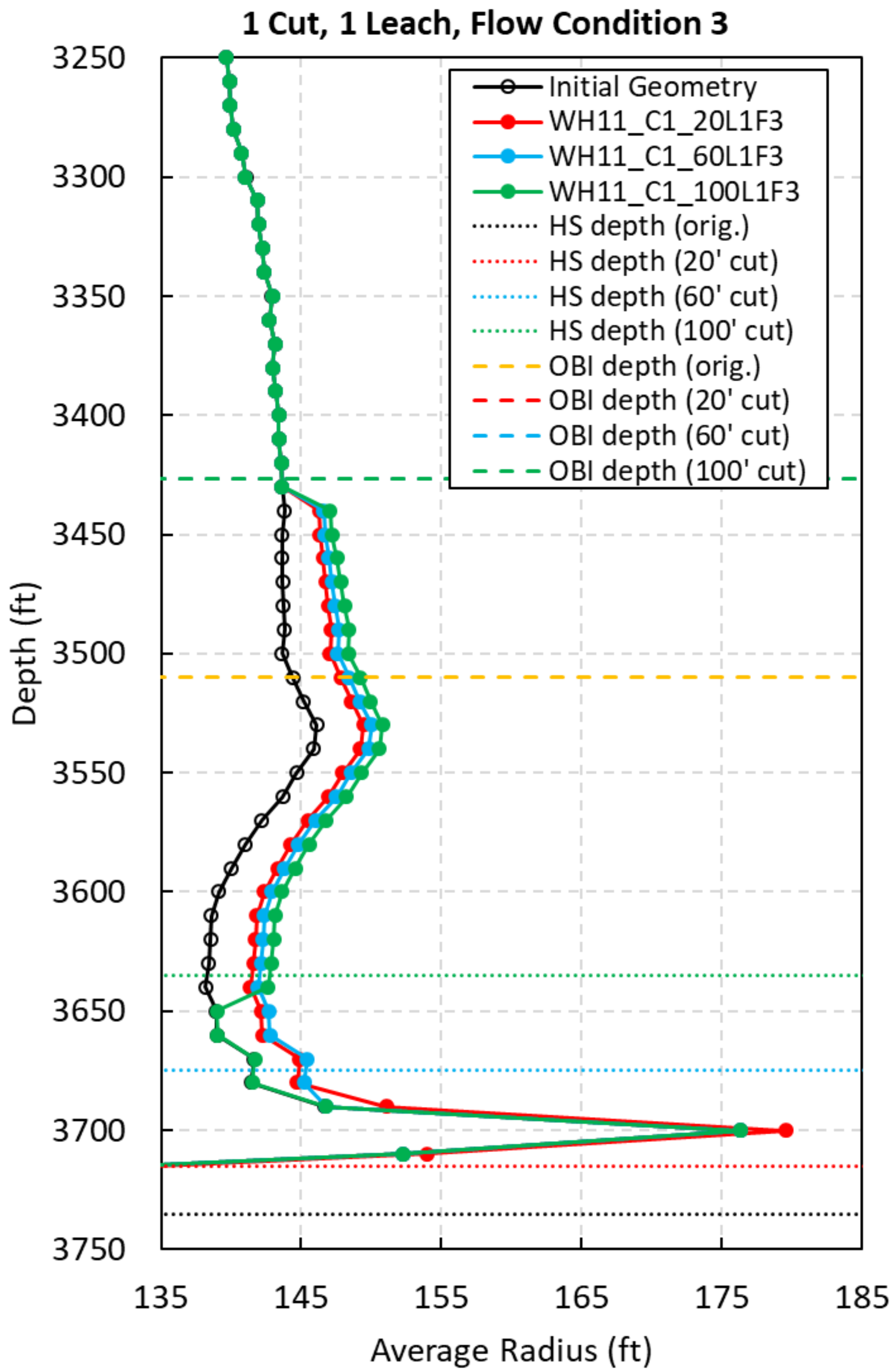

Figure 35. Predicted WH11 geometries for a single string cut and a single leach (flow condition 3).

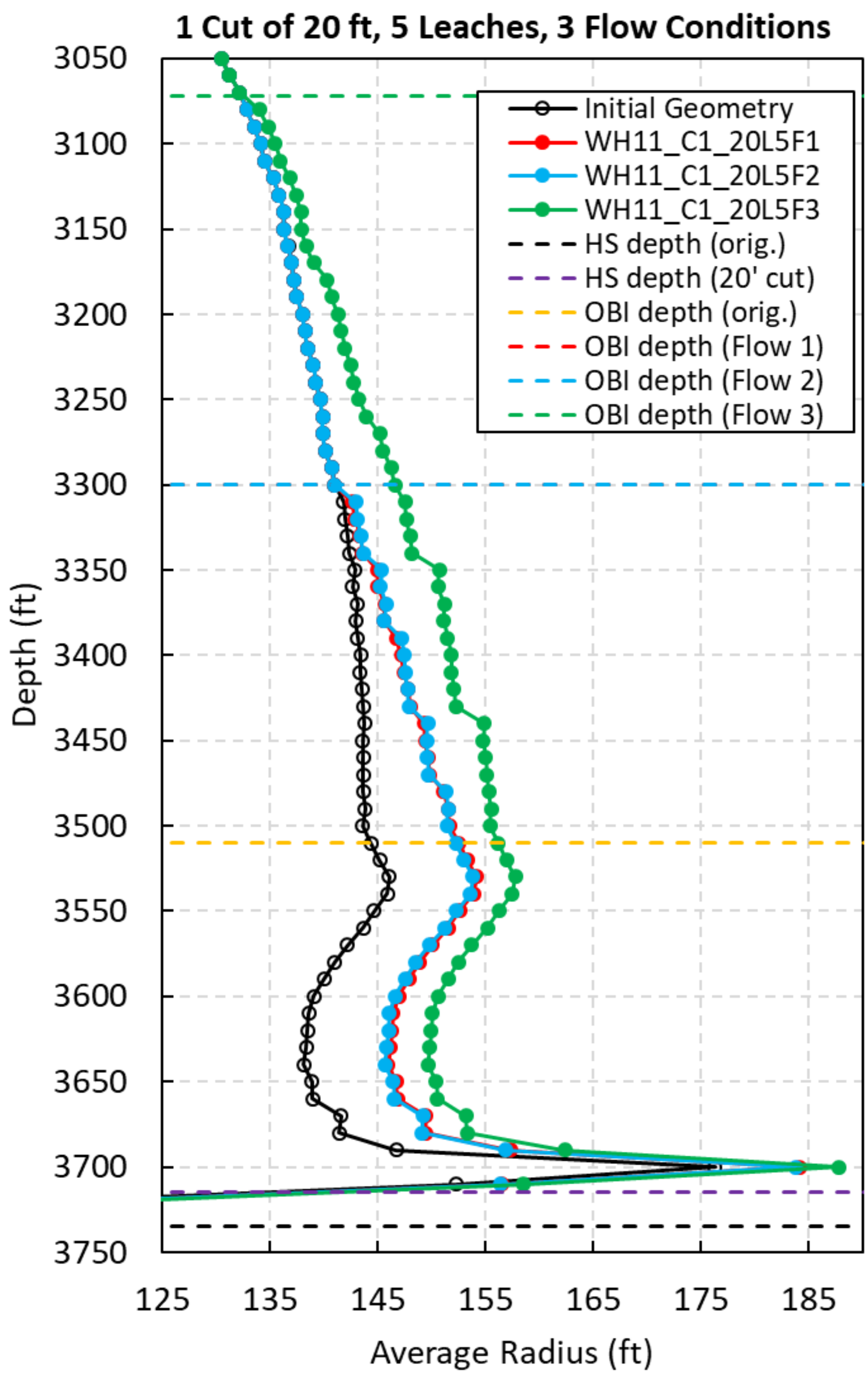

Figure 36. Predicted WH11 geometries for a single string cut of 20 ft and five leaches (three flow conditions).

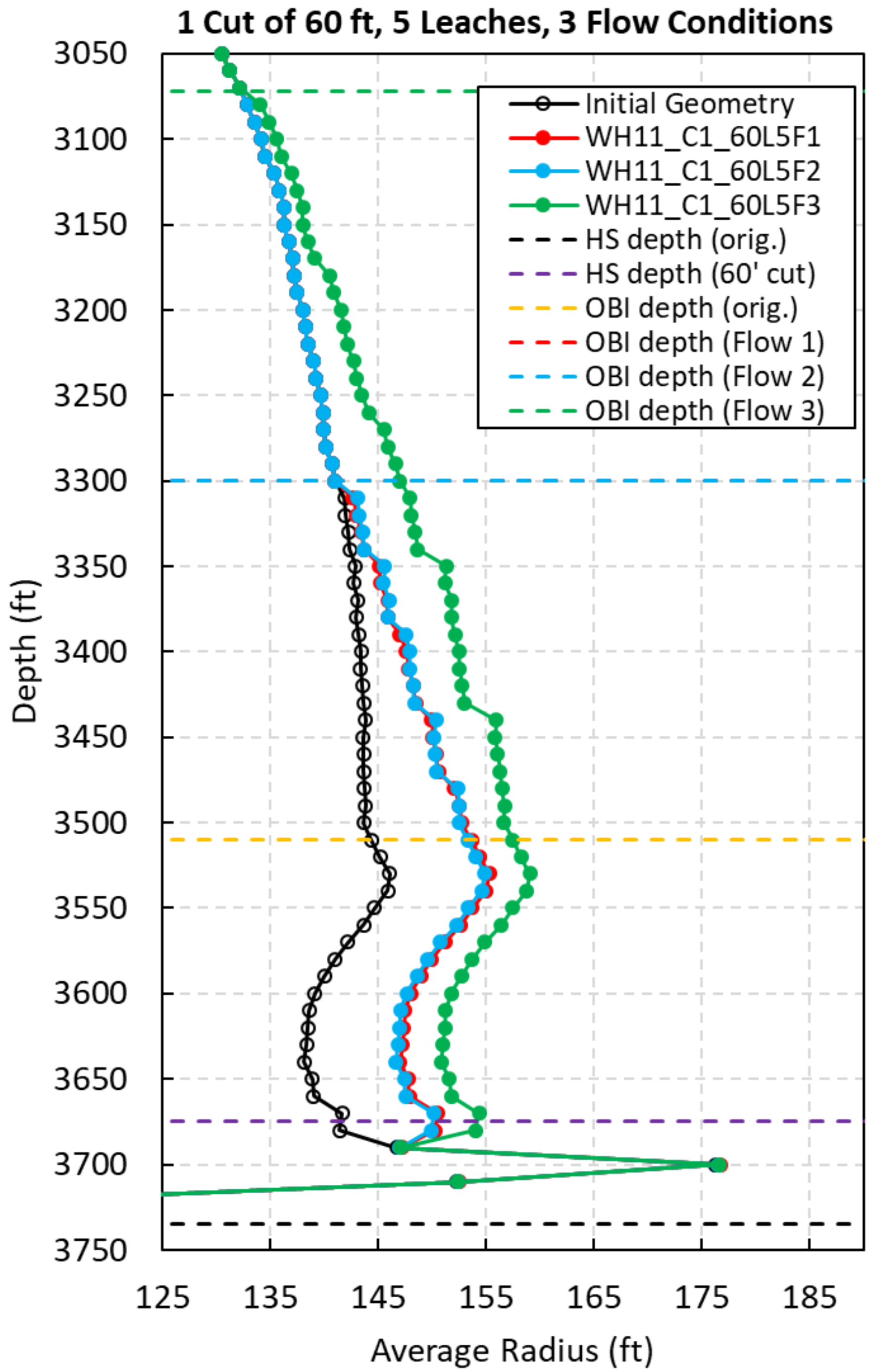

Figure 37. Predicted WH11 geometries for a single string cut of 60 ft and five leaches (three flow conditions).

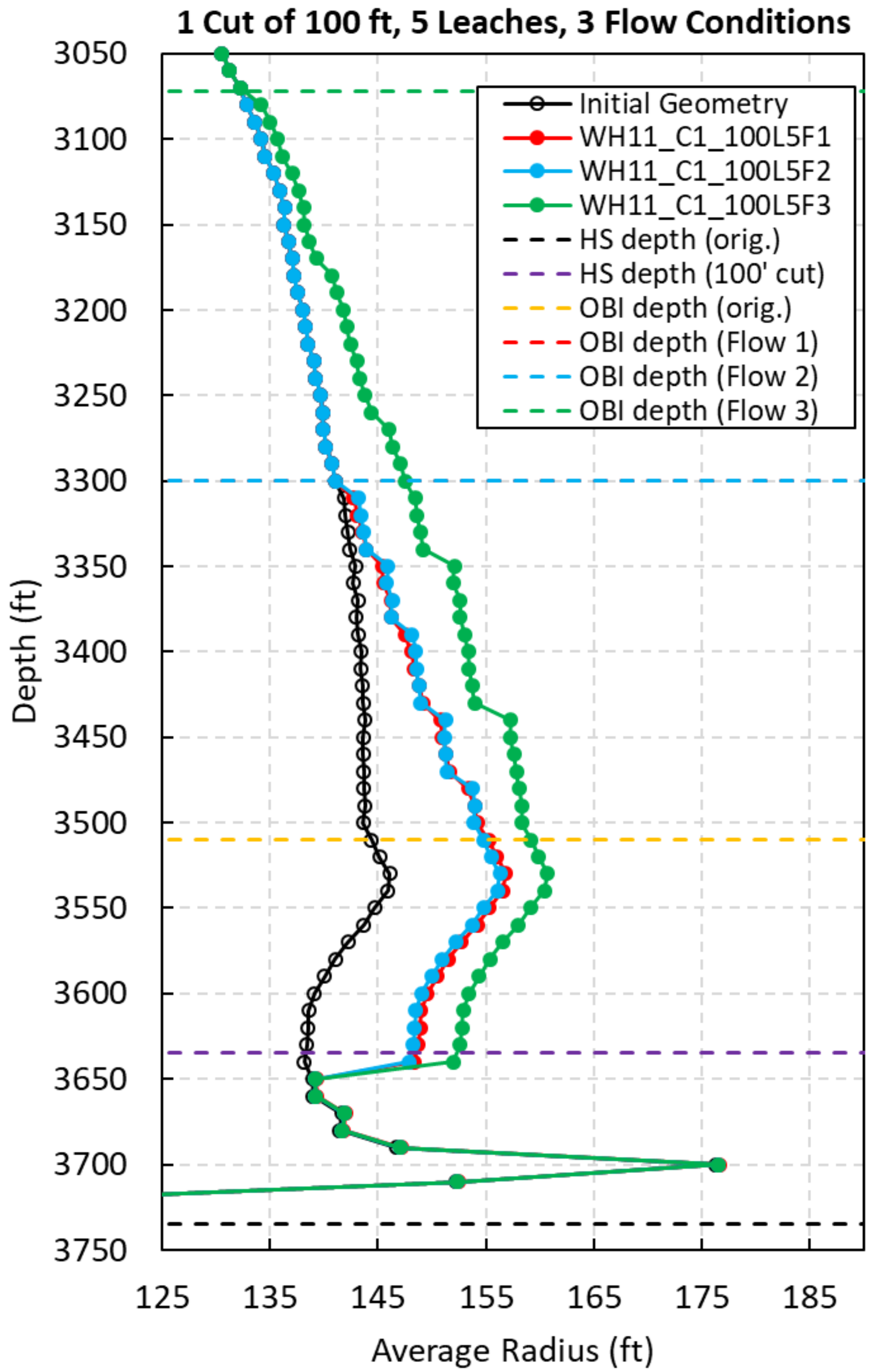

Figure 38. Predicted WH11 geometries for a single string cut of 100 ft and five leaches (three flow conditions).

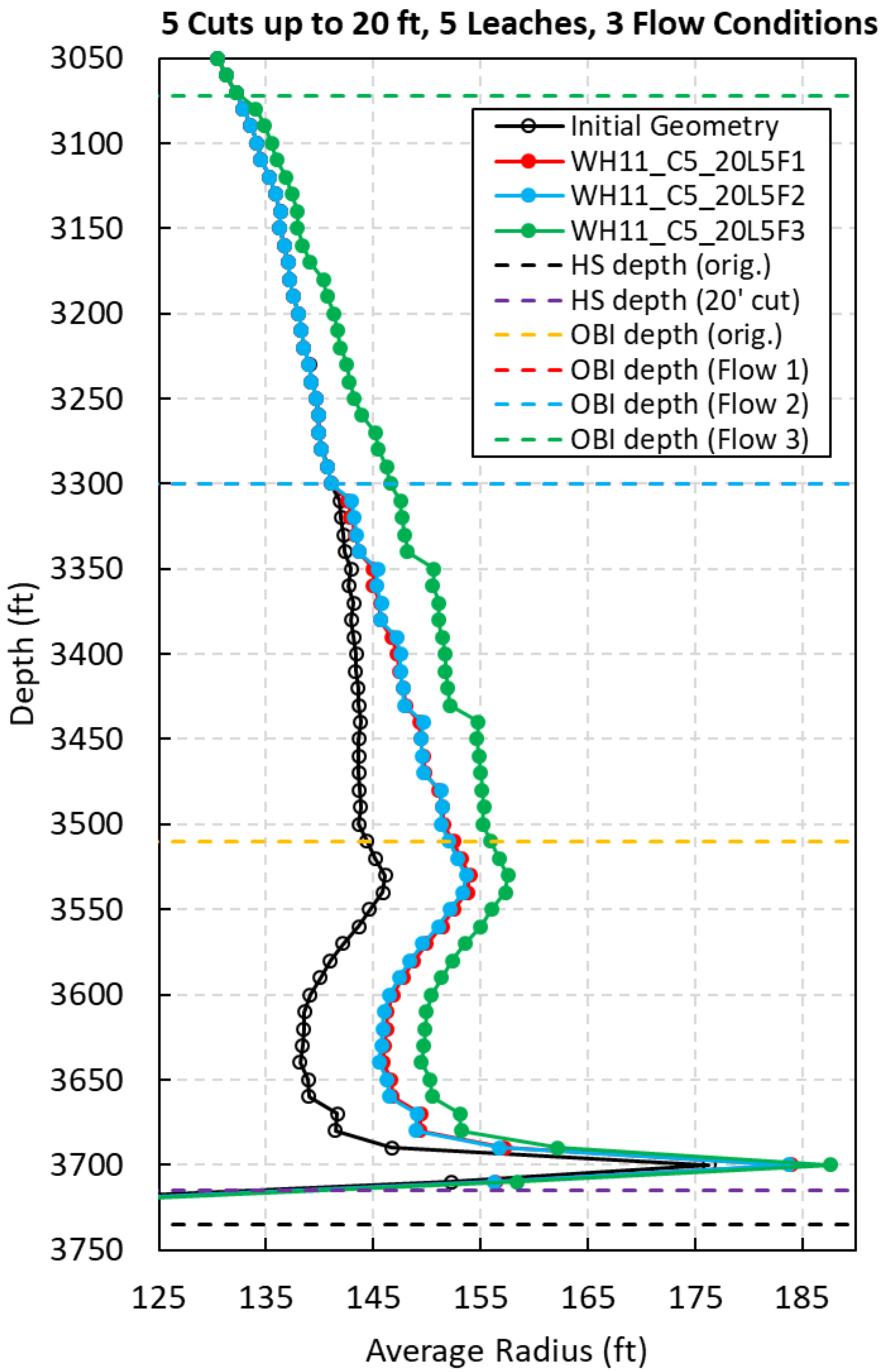

Figure 39. Predicted WH11 geometries for five string cuts (total of 20 ft cut) and five leaches (three flow conditions).

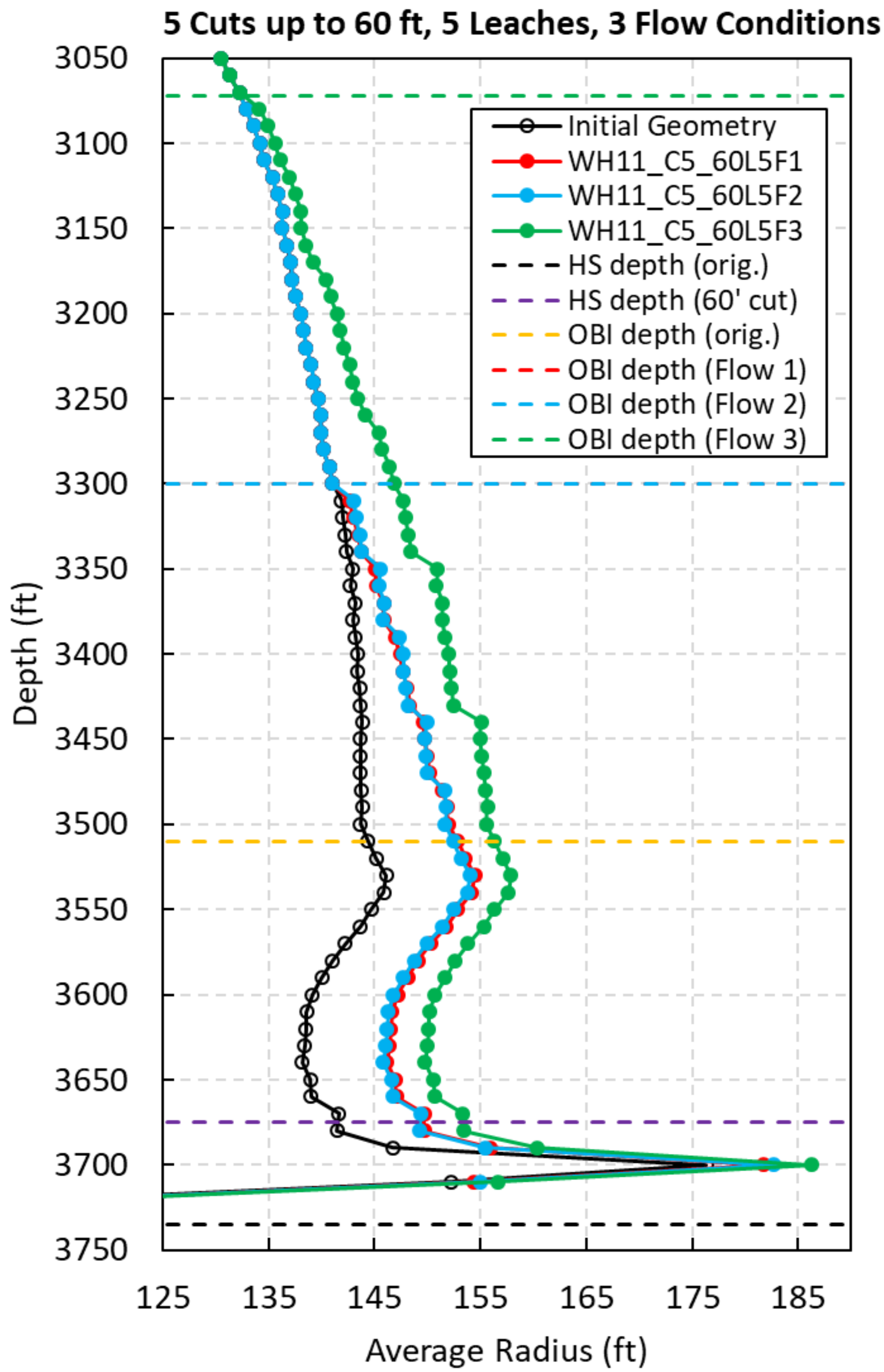

Figure 40. Predicted WH11 geometries for five string cuts (total of 60 ft cut) and five leaches (three flow conditions).

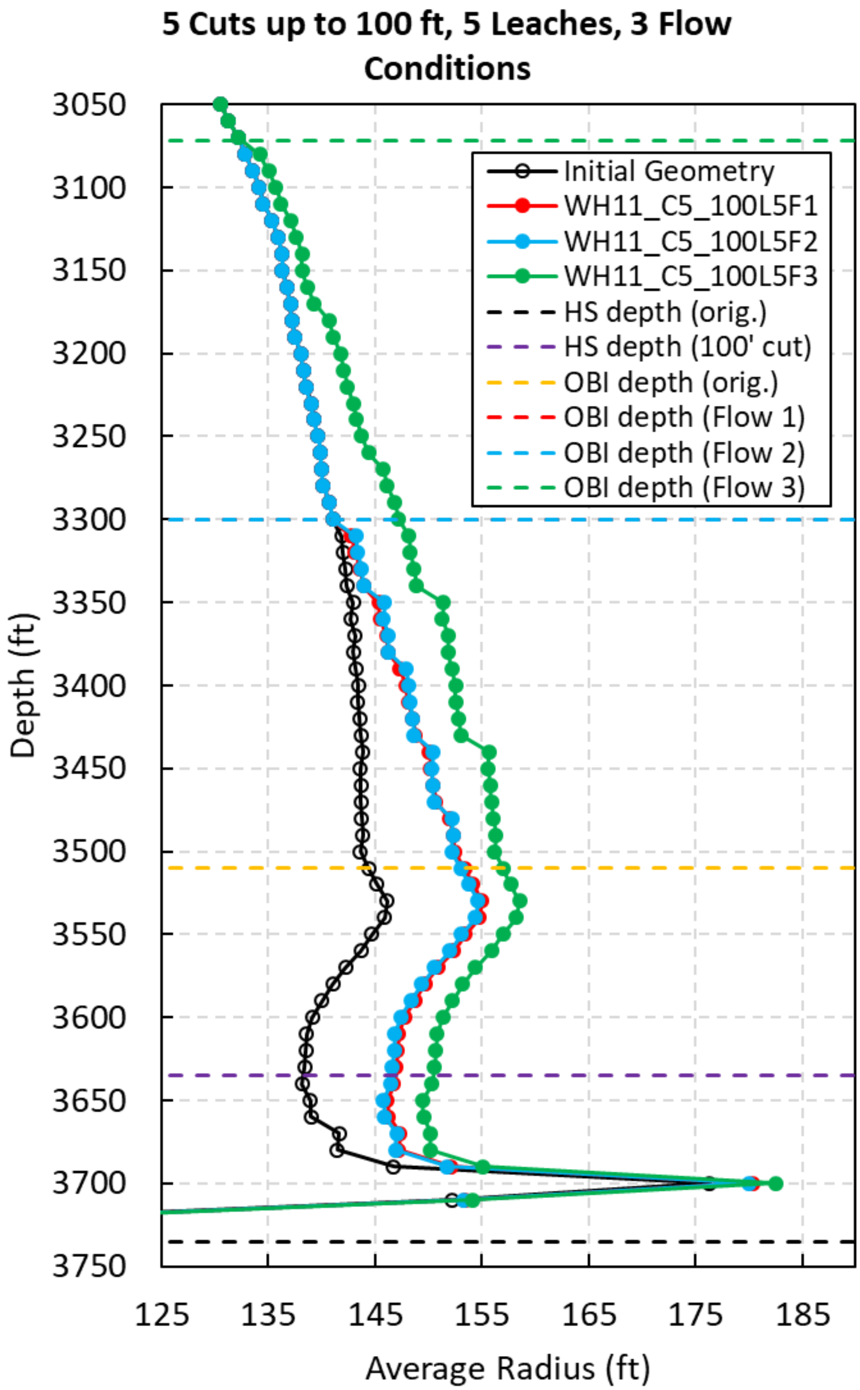

Figure 41. Predicted WH11 geometries for five string cuts (total of 100 ft cut) and five leaches (three flow conditions).

6. REFERENCES

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7. APPENDIX

This Appendix contains a table that summarizes input parameters and output data for the 33 SANSMIC runs for the WH11 cavern. Input parameters include: the number of cuts, total cut length, number of leaches, and flow condition number (see text for description of the three flow conditions tested here). Output data include: final hanging string depth (HS), final OBI, difference between HS and OBI, maximum cavern radius observed (the maximum was always in the zone of leaching for WH11), initial cavern volume (8,484,100 bbls), final cavern volume, volume of raw water injected, and leach efficiency (defined as the difference between initial and final cavern volumes divided by the volume of raw water injected).

A distinct run name was developed to identify each run of the SANSMIC code with the cavern name, number of cuts, total cut length, number of leaches, and flow conditions making up part of the name. The "key" to run names is the following: [*Cavern Name*]_C[*Number of Cuts*]_[*Total Cut Length*]L[*Number of Leaches*]F[*Flow Condition Identifier*]. For example, WH11_C1_100L1F1 is a run of the West Hackberry 11 cavern with a single cut of 100 ft. and a single leach under flow condition 1. As another example, WH11_C1_60L5F3 is a run of the West Hackberry 11 cavern with a single cut of 60 ft. and five leaches under flow condition 3.

8. Table of input parameters and output data for 33 runs of SANSMIC for WH11.

Run Number	Run Name	Number of Cuts	Total Cut Length (ft)	Number of Leaches	Flow Condition	Final HS Depth (ft)	Final OBI (ft)	(HS - OBI) (ft)	Max. Cavern Radius (ft)	Initial Cavern Volume (bbls)	Final Cavern Volume (bbls)	Volume Injected (bbls)	Leach Efficiency
1	WH11_C0_0L1F1	0	0	1	1	3735	3468.3	266.7	178.18	8.48E+06	8.56E+06	500000	0.144
2	WH11_C0_0L1F2	0	0	1	2	3735	3468.2	266.8	178.04	8.48E+06	8.55E+06	500000	0.136
3	WH11_C0_0L1F3	0	0	1	3	3735	3426.4	308.6	179.49	8.48E+06	8.63E+06	1000000	0.142
4	WH11_C0_0L5F1	0	0	5	1	3735	3299.9	435.1	183.99	8.48E+06	8.88E+06	2500000	0.158
5	WH11_C0_0L5F2	0	0	5	2	3735	3299.9	435.1	183.7	8.48E+06	8.87E+06	2500000	0.155
6	WH11_C0_0L5F3	0	0	5	3	3735	3071.9	663.1	187.65	8.48E+06	9.27E+06	5000000	0.157
7	WH11_C1_20L1F1	1	20	1	1	3715	3468.3	246.7	178.23	8.48E+06	8.56E+06	500000	0.144
8	WH11_C1_20L1F2	1	20	1	2	3715	3468.2	246.8	178.09	8.48E+06	8.55E+06	500000	0.136
9	WH11_C1_20L1F3	1	20	1	3	3715	3426.4	288.6	179.56	8.48E+06	8.63E+06	1000000	0.143
10	WH11_C1_60L1F1	1	60	1	1	3675	3468.3	206.7	176.37	8.48E+06	8.56E+06	500000	0.147
11	WH11_C1_60L1F2	1	60	1	2	3675	3468.2	206.8	176.35	8.48E+06	8.55E+06	500000	0.139
12	WH11_C1_60L1F3	1	60	1	3	3675	3426.4	248.6	176.35	8.48E+06	8.63E+06	1000000	0.145
13	WH11_C1_100L1F1	1	100	1	1	3635	3468.3	166.7	176.37	8.48E+06	8.56E+06	500000	0.148
14	WH11_C1_100L1F2	1	100	1	2	3635	3468.2	166.8	176.35	8.48E+06	8.55E+06	500000	0.141
15	WH11_C1_100L1F3	1	100	1	3	3635	3426.5	208.5	176.35	8.48E+06	8.63E+06	1000000	0.145
16	WH11_C1_20L5F1	1	20	5	1	3715	3299.9	415.1	184.12	8.48E+06	8.88E+06	2500000	0.158
17	WH11_C1_20L5F2	1	20	5	2	3715	3299.9	415.1	183.82	8.48E+06	8.87E+06	2500000	0.155
18	WH11_C1_20L5F3	1	20	5	3	3715	3071.9	643.1	187.78	8.48E+06	9.27E+06	5000000	0.157
19	WH11_C1_60L5F1	1	60	5	1	3675	3299.8	375.2	176.66	8.48E+06	8.88E+06	2500000	0.159
20	WH11_C1_60L5F2	1	60	5	2	3675	3299.9	375.1	176.53	8.48E+06	8.87E+06	2500000	0.156
21	WH11_C1_60L5F3	1	60	5	3	3675	3071.9	603.1	176.56	8.48E+06	9.27E+06	5000000	0.157
22	WH11_C1_100L5F1	1	100	5	1	3635	3299.7	335.3	176.66	8.48E+06	8.88E+06	2500000	0.159
23	WH11_C1_100L5F2	1	100	5	2	3635	3299.9	335.1	176.53	8.48E+06	8.87E+06	2500000	0.156
24	WH11_C1_100L5F3	1	100	5	3	3635	3071.9	563.1	176.56	8.48E+06	9.27E+06	5000000	0.157
25	WH11_C5_20L5F1	5	20	5	1	3715	3299.9	415.1	184.04	8.48E+06	8.88E+06	2500000	0.158

Run Number	Run Name	Number of Cuts	Total Cut Length (ft)	Number of Leaches	Flow Condition	Final HS Depth (ft)	Final OBI (ft)	(HS - OBI) (ft)	Max. Cavern Radius (ft)	Initial Cavern Volume (bbls)	Final Cavern Volume (bbls)	Volume Injected (bbls)	Leach Efficiency
26	WH11_C5_20L5F2	5	20	5	2	3715	3299.9	415.1	183.73	8.48E+06	8.87E+06	2500000	0.155
27	WH11_C5_20L5F3	5	20	5	3	3715	3071.9	643.1	187.67	8.48E+06	9.27E+06	5000000	0.157
28	WH11_C5_60L5F1	5	60	5	1	3675	3299.8	375.2	181.75	8.48E+06	8.88E+06	2500000	0.158
29	WH11_C5_60L5F2	5	60	5	2	3675	3299.9	375.1	182.73	8.48E+06	8.87E+06	2500000	0.156
30	WH11_C5_60L5F3	5	60	5	3	3675	3071.9	603.1	186.3	8.48E+06	9.27E+06	5000000	0.157
31	WH11_C5_100L5F1	5	100	5	1	3635	3299.8	335.2	180.33	8.48E+06	8.88E+06	2500000	0.159
32	WH11_C5_100L5F2	5	100	5	2	3635	3299.9	335.1	180.05	8.48E+06	8.87E+06	2500000	0.156
33	WH11_C5_100L5F3	5	100	5	3	3635	3071.9	563.1	182.5	8.48E+06	9.27E+06	5000000	0.157

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