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2022 Annual Report of Available Drawdowns for Each Oil Storage Cavern in the Strategic Petroleum Reserve

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ABSTRACT

The Department of Energy maintains an up-to-date documentation of the number of available full drawdowns of each of the caverns owned by the Strategic Petroleum Reserve (SPR). This information is important for assessing the SPR's ability to deliver oil to domestic oil companies expeditiously if national or world events dictate a rapid sale and deployment of the oil reserves. Sandia was directed to develop and implement a process to continuously assess and report the evolution of drawdown capacity, the subject of this report.

A cavern has an available drawdown if after that drawdown, the long-term stability of the cavern, the cavern field, or the oil quality are not compromised. Thus, determining the number of available drawdowns requires the consideration of several factors regarding cavern and wellbore integrity and stability, including stress states caused by cavern geometry and operations, salt damage caused by dilatant and tensile stresses, the effect of enhanced creep on wellbore integrity, and the sympathetic stress effect of operations on neighboring caverns.

A consensus has now been built regarding the assessment of drawdown capabilities and risks for the SPR caverns (Sobolik et al., 2014; Sobolik 2016). The process involves an initial assessment of the pillar-to-diameter (P/D) ratio for each cavern with respect to neighboring caverns. A large pillar thickness between adjacent caverns should be strong enough to withstand the stresses induced by closure of the caverns due to salt creep. The first evaluation of P/D includes a calculation of the evolution of P/D after a number of full cavern drawdowns. The most common storage industry standard is to keep this value greater than 1.0, which should ensure a pillar thick enough to prevent loss of fluids to the surrounding rock mass. However, many of the SPR caverns currently have a P/D less than 1.0 or will likely have a low P/D after one or two full drawdowns. For these caverns, it is important to examine the structural integrity with more detail using geomechanical models. Finite-element geomechanical models have been used to determine the stress states in the pillars following successive drawdowns. By computing the tensile and dilatant stresses in the salt, areas of potential structural instability can be identified that may represent "red flags" for additional drawdowns. These analyses have found that many caverns will maintain structural integrity even when grown via drawdowns to dimensions resulting in a P/D of less than 1.0. The analyses have also confirmed that certain caverns should only be completely drawn down one time.

As the SPR caverns are utilized and partial drawdowns are performed to remove oil from the caverns (e.g., for occasional oil sales, purchases, or exchanges authorized by the Congress or the President), the changes to the cavern caused by these procedures must be tracked and accounted for so that an ongoing assessment of the cavern's drawdown capacity may be continued. A proposed methodology for assessing and tracking the available drawdowns for each cavern was presented in Sobolik et al. (2018). This report is the latest in a series of annual reports, and it includes the baseline available drawdowns for each cavern, and the most recent assessment of the evolution of drawdown expenditure for several caverns.

ACKNOWLEDGEMENTS

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EXECUTIVE SUMMARY

The Department of Energy maintains up-to-date documentation of the number of available full drawdowns of each cavern owned by the Strategic Petroleum Reserve (SPR). A cavern has an available drawdown if after that drawdown, the long-term stability of the cavern, the cavern field, or the oil quality are not compromised. In this report, a full drawdown is defined as the removal of 90% of the oil from a cavern with raw water. This information is important for assessing the SPR's ability to deliver oil to domestic and foreign oil refineries expeditiously if national or world events dictate a rapid sale and deployment of the oil reserves. Sandia was directed to develop and implement a process to continuously assess and report the evolution of drawdown capacity, the subject of this report.

What factors go into assessing available drawdowns? Determining the number of drawdowns requires the consideration of several factors regarding cavern and wellbore integrity and stability, including stress states caused by cavern geometry and operations, salt damage caused by dilatant and tensile stresses, the effect of enhanced creep on wellbore integrity, and the sympathetic stress effect of operations on neighboring caverns.

A consensus has now been built regarding the assessment of drawdown capabilities and risks for the SPR caverns (Sobolik et al., 2014; Sobolik 2016). The process involves an initial assessment of the pillar-to-diameter (P/D) ratio for each cavern with respect to neighboring caverns. Ideally, it is desired to keep this value greater than 1.0, which is in line with most industry design standards and should ensure cavern integrity and prevent loss of fluids to the surrounding rock mass. However, many of the SPR caverns currently have a P/D less than 1.0 or will likely have a low P/D after one or two full drawdowns. For these caverns, it is important to examine the structural integrity with more detail using geomechanical models. Finite-element geomechanical models have been used to determine the stress states in the pillars following successive drawdowns. By computing the tensile and dilatant stresses in the salt, areas of potential structural instability can be identified that may represent "red flags" for additional drawdowns. These analyses have found that many caverns will maintain structural integrity even when grown via drawdowns to dimensions resulting in a P/D of less than 1.0. The analyses have also confirmed that certain caverns should only be completely drawn down one time.

In addition, full drawdowns of caverns are rarely performed. Instead, partial drawdowns are usually performed to remove oil from the caverns (e.g., for occasional oil sales authorized by the Congress or the President); these partial drawdowns leach only the deeper regions of the cavern, depending on the hanging string depth, and cause a much larger change to cavern geometry at depth than in the shallower regions. These geometry changes can have loading effects throughout the cavern, but they tend to be more pronounced in the leached section. As the SPR caverns are utilized and partial drawdowns are performed as needed, the changes to the cavern caused by these procedures must be tracked and accounted for so that an ongoing assessment of the cavern's drawdown capacity may be continued.

All of the SPR caverns have been or are being evaluated for the number of baseline available drawdowns while maintaining cavern structural integrity. Two factors that contribute to a greater number of available drawdowns are homogeneous salt and cavern shapes that resemble candlesticks and have smooth, axisymmetric walls. Both of these factors create conditions where stress concentration points are avoided, and thus caverns can deform uniformly and with low values of differential stress. West Hackberry caverns have these characteristics, and thus its caverns tend to have the most available drawdowns. Big Hill caverns also do very well in this regard, although there

are more surface irregularities than at West Hackberry. Several Bayou Choctaw caverns have irregular shapes, but cavern stability there is aided by slow-creeping salt and lower stresses due to their shallower location within the dome. The stability of the Bryan Mound caverns is shown through analysis to be correlated with many of the irregular features found in these caverns. Almost universally, the Phase 1 caverns (those caverns created prior to DOE ownership of the properties) have limited drawdown capacity due to irregular shapes, large diameters, or salt which is either heterogeneous or contains significant amounts of impurities, all of which create concentration points for large shear stresses and tensile stresses.

The criteria and processes that will be used to track the expenditure of drawdowns for each cavern have been identified. Over the past year, the databases required to initialize and track the volume changes to each cavern, and their effects on cavern integrity and thus to drawdown capacity, have either been constructed or have been initiated.

This report includes an update to the baseline drawdowns for each cavern, and provides an initial assessment of the evolution of drawdown expenditure for several caverns. Based on the assessment of fluid exchanges and the resulting increase of cavern volumes due to leaching, and the changes to cavern shapes from raw water injection operations, the following statements can be made about the available drawdowns for the SPR caverns as of January 2022:

- Six caverns have spent an available drawdown due to the amount of volume created by raw water/leaching operations calculated from 1/1/2010 to January 2022: BH-104, BM-113, and WH-111 were identified in the 2019 report, BM-114 and WH-105 were added in the 2020 report, and BH-101 was added in the 2021 report. No new caverns have been added in this 2022 report. In the case of BM-113, over two drawdowns have been spent due to raw water injection used to grow the cavern from its previous smaller volume. The current status of all the caverns is summarized in Table 8-1.
- The following additional caverns have gained at least 5% additional volume since 2010 due to leaching operations, and thus should be tracked closely as additional leaching occurs: BC-18, BC-20, BH-102, BH-105, BH-106, BH-107, BH-108, BH-109, BH-110, BH-111, BM-102, BM-103, BM-104, BM-108, BM-110, BM-111, BM-115, BM-116, WH-11, WH-102, WH-103, WH-106 (the highest at 13%), WH-109, WH-113, WH-114, WH-115, and WH-117.
- Eight caverns were predicted to have experienced significant changes to their shapes in the bottom portions of the caverns. These caverns were BM-102, BM-103, and BM-110; BH-110 and BH-111; WH-11 and WH-109; and BC-19. The caverns' predicted shapes were compared to the results of the corresponding geomechanical analyses. The following categories of shape changes were flagged as having the potential to alter the number of baseline available drawdowns (that is, available drawdowns defined by the shape of the cavern): an extension of an existing feature where a stress concentration may occur; the creation of a new feature that would create a stress concentration location; or the change in location or magnitude of the maximum diameter of the cavern. In the examination of the eight caverns with notable shape changes, none were found to change the number of baseline available drawdowns. In addition, this report continues the recommendation from last year's report that a sonar be performed on BM-105 as soon as possible so that its true current shapes can be measured and then included in the BM geomechanical model for analysis of its effects.

- In late December 2021, wellhead pressure data indicated that cavern BC-18 was leaking. That cavern itself was being operated in static mode, however, nearby cavern BC-17 had been undergoing significant fluid exchanges since late summer 2021. Caverns BC-15 and BC-17 have been operated as a gallery for many years, and all three of these caverns had been designated as 1-drawdown caverns prior to this incident. At the publication date of this report, it is believed that the wellbore casing in BC-18 is tight, and that a hydraulic connection has occurred between BC-18 and BC-17 that is probably located in the brine sections of the caverns. This incident and its consequences will obviously be a major topic in the 2023 drawdown report that covers 2022 SPR activities.
- One well, BH-105B, has been designated to be temporarily plugged and instrumented for casing evaluation. After evaluation, this well will be permanently plugged and abandoned due to significant casing damage at the salt/caprock interface. This change does not affect the cavern integrity or the drawdown availability of the cavern; however, ongoing casing damage may complicate future utilization of that cavern space.

ACRONYMS AND DEFINITIONS

Abbreviation	Definition
2D	two-dimensional
3D	three-dimensional
bbl	oil barrel (*42 US gallons*)
BC	Bayou Choctaw (*SPR site*)
BH	Big Hill (*SPR site*)
BM	Bryan Mound (*SPR site*)
DD	full drawdown
DOE	U.S. Department of Energy
FFPO	Fluor Federal Petroleum Operations (*SPR M&O contractor*)
GM	geomechanical model
HS	hanging string (*and/or associated end of tubing depth*)
LAS	**L**og **A**SCII **S**tandard (*well log file format*)
M&O	management and operations
MB	thousand barrels
MMB	million barrels
OBI	oil-brine interface (*depth*)
P/D	pillar to diameter (*ratio*)
P2D	**P**illar-**2**-**D**iameter (*software program*)
PD	partial drawdown
psi	pounds-force per square inch
SANSMIC	**San**dia **S**olution **Mi**ning **C**ode (*software program*)
SPR	U.S. Strategic Petroleum Reserve
TD	total depth (*cavern floor depth*)
WH	West Hackberry (*SPR site*)

1. INTRODUCTION

1.1. Background and objective

The U.S. Strategic Petroleum Reserve (SPR), operated by the U.S. Department of Energy (DOE), stores crude oil in solution-mined caverns in the salt dome formations of the Gulf Coast. There is a total of 60 active caverns located at four different sites in Texas (Bryan Mound and Big Hill) and Louisiana (Bayou Choctaw and West Hackberry), as shown in Figure 1. Each cavern is constructed by drilling one or more boreholes into the salt dome and injecting fresh water. The fresh water dissolves the salt and creates brine, which is then pumped out of the cavern. This process, which is known as leaching, creates a brine-filled volume in the salt that is eventually used for the storage of oil. The boreholes (or wells) of the cavern are then lined with steel casings cemented in place from the surface to near the top of the cavern. The long-term safe and effective operation of the storage caverns requires technical issues to be addressed in order to maintain the integrity of the caverns and their wells. In recent years, the SPR has decided to decommission Bayou Choctaw Cavern 20, West Hackberry Cavern 6 and Bryan Mound Cavern 2 by moving remaining oil to other caverns and removing the cavern from active use, reducing the number of active SPR caverns to 60.

Stored oil is removed from a cavern by an operation called a drawdown. For a full drawdown, an entire storage cavern is emptied of oil by replacing it with another fluid, typically either fresh water or partially saturated brine. A drawdown is usually performed when stored oil is required for sale and distribution to refiners, either during an emergency event when national oil supplies have been compromised, or from an oil sale authorized by either Congress or the President. When fresh water is pumped into an existing cavern, it causes salt in the cavern wall to dissolve, which increases the volume of the cavern and decreases the volume of any pillar between the cavern being drawn down and adjacent caverns. A cavern can also be partially drawn down, where only a fraction of the oil is removed. DOE maintains an up-to-date documentation of the number of available full drawdowns of each of the caverns owned by the SPR. The information is important for assessing the SPR's ability to deliver oil to domestic and foreign oil refineries expeditiously if national or world events dictate a rapid sale and deployment of the oil reserves. Sandia was directed to develop and implement a process to continuously assess and report the evolution of drawdown capacity, the subject of this report.

What factors go into assessing available drawdowns? A cavern has an available drawdown if after that drawdown, the long-term stability of the cavern, the cavern field, or the oil quality are not compromised. Thus, determining the number of drawdowns requires the consideration of several factors regarding cavern and wellbore integrity and stability, including stress states caused by cavern geometry and operations, salt damage caused by dilatant and tensile stresses, the effect of enhanced creep on wellbore integrity, and the sympathetic stress effect of operations on neighboring caverns.

A consensus has now been built regarding the assessment of drawdown capabilities and risks for the SPR caverns. This work began in 2014, when the SPR issued an Engineering Change Process (ECP), PM-00449, Baseline Remaining Drawdowns for all SPR Caverns. It described creating a technical baseline for all available drawdowns for each cavern considering pillar-to-diameter (P/D) ratios and other factors. These meetings led to the establishment of baseline values for available drawdowns for each cavern (Sobolik et al., 2014; Sobolik 2016). Then in September 2017, Sandia Labs was directed to update these reports annually to include a process to track the evolution of drawdown capacity for each cavern as operations are performed on them. This request was in response to legislation beginning, in 2015, directing the sale of SPR oil through the year 2028, to reduce the stored oil inventory at SPR from approximately 700 million barrels (MMB) to approximately 400

MMB. As a result, meetings were held between Sandia, DOE/SPR, and Fluor Federal Petroleum Operations (FFPO; the SPR M&O contractor) to define the process that will be used to track volume changes and their impact on drawdown capacity.

The process involves an initial assessment of the pillar-to-diameter (P/D) ratio for each cavern with respect to neighboring caverns. Ideally, it is desirable to keep this value greater than 1.0, which is in line with most industry design standards and should ensure cavern integrity and prevent loss of fluids to the surrounding rock mass. These standards have been developed over several decades based on engineering experience at domal storage sites and are a good general standard to follow. However, many of the SPR caverns currently have a P/D less than 1.0 or will likely have a low P/D after one or two full drawdowns. For these caverns, it is important to examine the structural integrity with more detail using geomechanical models. Finite-element geomechanical models have been used to determine the stress states in the pillars following successive drawdowns. By computing the tensile and dilatant stresses in the salt, areas of potential structural instability can be identified that may represent "red flags" for additional drawdowns. These analyses have found that many caverns will maintain structural integrity even when grown via drawdowns to dimensions resulting in a P/D of less than 1.0. The analyses have also confirmed that certain caverns should only be completely drawn down one time; after a full drawdown to remove all the oil, these caverns will no longer be suitable for oil storage because additional leaching will pose structural integrity problems. As the SPR caverns are utilized and partial drawdowns are performed to remove oil from the caverns (e.g., for occasional oil sales authorized by the Congress or the President), the changes to the cavern caused by these procedures must be tracked and accounted for so that an ongoing assessment of the cavern's drawdown capacity may be continued. The methodology for assessing the available drawdowns and tracking the expenditure drawdowns for each cavern is presented in this report, as is the annual tracking and computation of spent drawdowns.

Figure 1-1. Location of SPR sites.

1.2. Report organization

This report is organized in the following fashion: Sections 2 and 3 describe the analytical process and tabulations of the baseline drawdown capacity for each cavern in its current geometry prior to any new full or partial drawdowns having occurred. Section 4 describes the methodology that will be used to evaluate the evolution of drawdown capacity via the tracking of fluid movements in each cavern and their effect on cavern volume and integrity. Section 5 contains the site database tables that will be used to track to evolution of drawdown expenditure for each cavern. The database includes histories of cavern volume measurements by sonar, fluid exchanges (oil and brine in/out, and raw water in), hanging string and oil-brine interface depths, and cavern depths. Section 6 includes selected predictions of cavern geometry from raw water input operations, created by the SANSMIC (Sandia Solution Mining Code) program (Weber et al., 2014). This section also includes a discussion of how SANSMIC predictions, in conjunction with sonar measurements and site data tracking, are used to evaluate if and when a cavern operation has spent an available drawdown. Section 7 lists the caverns evaluated for this report, and the determination of the status of spent drawdowns. Section 8 summarizes the results and provides concluding remarks.

2. BASELINE ASSESSMENT OF CAVERN DRAWDOWN CAPACITIES - PROCESS

Based on the original meetings held in 2014, a five-step process was developed to determine the baseline number of full drawdowns for each SPR cavern prior to any additional volume changes due to new drawdowns (Sobolik et al., 2014). This process originally included the use of 2D P/D ratios (Sobolik et al., 2019); however, because the 3D P/D ratios are a more meaningful description of the proximity of neighboring caverns, the 2D P/D will no longer be used. Therefore, the assessment of cavern drawdown capacities uses the following process:

1. Using the industry standard of keeping the P/D > 1, the drawdown limit is initially assigned to be the number of drawdowns before the 3D P/D becomes less than 1.0. The 3D P/D ratio defined in Lord, et al. (2009), uses the smallest pillar thickness between caverns as obtained from sonar measurements and wellbore coordinates. This allows for an accurate portrayal of the relative distance between closest points on two caverns.
2. The drawdown limit based on full-scale geomechanical model predictions are also compared to the 3D P/D limit. If the geomechanical analysis additionally fits certain criteria described below, and if its drawdown limit is the highest of the two, then the geomechanical limit is used as the best estimate.
3. If, after all these steps, the drawdown limit is equal to zero, the best estimate is assigned a value of 1, with comments describing the anticipated technical issues during a drawdown of that cavern. This step results from the fact that the oil must at some point be withdrawn from all the caverns.
4. Regardless of P/D or geomechanics calculations, an upper limit of 5 drawdowns has been defined. This number was determined partially from a historical assumption on the SPR of a 5-drawdown maximum limit on drawdowns. It is also the number of layers of leached material surrounding each cavern included in the geomechanical models; each layer included in the finite element mesh adds further complexity and computational time to the calculations, so the understood limit of five drawdowns was used in mesh construction. This number can be updated in the future with increased knowledge and experience to better inform this process.

For all of the SPR sites, large dome-scale geomechanical analyses have been performed including representations for all the caverns. All of these analyses have included drawdown or leach layers for all caverns. In general, when assessing the potential for cavern stability problems, the following events/processes are the most critical:

- Large pressure change, ΔP, events such as workovers; dilatant and tensile stress conditions occur during large values of ΔP but are driven by large values of rate of pressure change dP/dt; these events may cause salt falls and cracking.
- Length of time that the caverns are held in workover; strain rate is a function of ΔP, and most damage occurs during the enhanced creep resulting from a workover.

The overriding observation from the geomechanical analyses is that the drawdown process itself rarely induces stress conditions (i.e., shear stress levels that create dilatant salt damage, tensile normal stresses that create fractures in the salt, or excessive vertical strains on the borehole casings) that cause instability issues. This is because the drawdown process uses fresh water injected at pressures not significantly lower than the normal operating pressures of the cavern; therefore, the large pressure differential that causes increased cavern creep, and that can create the conditions listed above, is not present during drawdown. Therefore, for this reason as well as for ease of numerical computation, drawdown processes are modeled in the geomechanical analyses as instantaneous removal of a specified "onion layer" of material around the cavern.

Stability problems related to a drawdown would be expected to occur during a workover following the drawdown. The wellhead pressure during a workover is zero, creating the maximum pressure differential condition for a cavern. Because the cavern volume expanded and the pillar thickness decreased due to leaching, the potential for undesired stress conditions increases during post-drawdown workovers. The most critical times are immediately after depressurization, when the pressure differential is highest and the transient creep of the salt is greatest, and immediately after repressurization, when the sudden cavern pressure increase may create temporary tensile stress conditions in the salt around a cavern before creep processes can equilibrate toward a compressive state. Nearly all of the Phase 2 and Phase 3 caverns, because of their cylindrical construction and designed spacing, are expected to be capable of having several drawdowns in their lifetime. Many of the Phase 1 caverns, however, have cavern geometry issues which will limit their available drawdowns to one or two.

Step 2 listed above stated that geomechanical analyses may be used as the overriding values for the best estimate for the drawdown limit if they fit certain criteria. The criteria are as follows: if the specific caverns have been meshed according to the sonar geometry (either an axisymmetric representation of the geometry, or the actual sonar-measured geometry), and additional drawdown layers are built into the cavern's mesh and removed in simulated leaching processes. The cavern geometry caveat is important, because the bumps and sharp corners are the locations of stress concentrations, and thus are the most likely places for damage from dilatant or tensile stresses.

The results of the geomechanical analyses are used to establish a limit to available drawdowns. The assessment of whether a drawdown is allowable is based on the examination of two conditions in the salt around the cavern and in the pillar between caverns. These two conditions are the presence of either tensile stress or dilatant stress. Tensile stresses are important because salt has a very low tensile strength (ranging from 1-5 MPa, or 150-750 psi). If tensile stress occurs in the skin immediately surrounding a cavern, one of three things may happen. First, a sufficiently large tensile stress occurring near the top or side of the cavern could cause salt cracking which would result in a salt fall; while salt falls are not necessarily limiting conditions, they could break a hanging string and cause temporary or permanent loss of access to oil. Second, if a radial crack is propagated outward from the cavern, it could cause oil to locate to a region where it may be permanently inaccessible. This is particularly possible for vertically short caverns with large diameters, for which the stresses around the perimeter of the cavern are more susceptible to the generation of radial fractures. Such fractures may also intersect nearby caverns and cause operational issues. Third, if the tensile stress occurs in the pillar between two caverns, or the pillar between a cavern and the edge of salt, such a condition could cause the loss of the structural integrity of the pillar, leading to either cavern communication or cavern failure issues. In assessing whether a tensile stress condition is a limiting factor for a drawdown, such conditions as predicted location, magnitude, and duration of the tensile stress, and potential consequences of the stress, must be considered.

The second important condition used for assessing available drawdowns is the presence of dilatant stress. Dilatancy is considered as the onset of damage to rock resulting in significant increases in permeability. Dilatant damage in salt typically occurs at a stress state where a rock reaches its minimum volume, or dilation limit, at which point microfracturing increases the volume. The salt damage factor (analogous to a safety factor) has been developed from a dilatant damage criterion based on a linear function of the hydrostatic pressure (Van Sambeek et al., 1993). Dilatant criteria typically relate two stress invariants: the mean stress invariant I_1 (equal to three times the average normal stress) and the square root of the stress deviator invariant J_2, or $\sqrt{J_2}$ (a measure of the overall deviatoric or dilatant shear stress). The dilatant criterion chosen here is the equation typically used from Van Sambeek et al. (1993),

$$\sqrt{J_2} = -0.27 I_1. \qquad (1)$$

The Van Sambeek damage criterion defines a linear relationship between I_1 and $\sqrt{J_2}$, and such linear relationships have been established from many suites of laboratory tests on WIPP, SPR, and other salt samples. This criterion was applied during post-processing of the analyses. A damage factor (safety factor, SF) index was created by normalizing I_1 by the given criterion:

$$SF = \frac{-0.27 I_1}{\sqrt{J_2}} \qquad (2)$$

Using Equation 2, when the SF achieve a value less than 1.0, then the salt is in a dilatant condition and microfracturing will begin to occur. This dilatant damage factor criterion is very conservative regarding the dilatant stress condition because achieving a short-term state of dilatant stress is not a distinct threshold for failure. In addition, the failure due to dilatant stress may be merely a salt fall, which is not necessarily a condition that would cause environmental or operational problems. Much as for tensile stresses, in assessing whether a dilatant stress condition is a limiting factor for a drawdown, such conditions as predicted location, magnitude, and duration of the tensile stress, and potential consequences of the stress, must be considered.

The general rule that is implemented when using an assessment of the tensile and dilatant stresses for a cavern is that if it is determined that during a simulated five-year period after a drawdown, which will include one workover, that the maximum principal stress achieves a tensile condition, or the dilatant damage factor achieves a value less than 1.0 for a significant period of time, then that particular drawdown would be disallowed (i.e., if this condition occurs after the 3rd drawdown, then the limit due to geomechanics would be two drawdowns). There are some caveats that have been applied to this rule. In order to better illustrate how these assessments have been made, the assessments for a few selected caverns are described below. These scenarios should give the reader an understanding about how the geomechanical analysis results are used along with knowledge of the caverns and models themselves.

2.1. Example 1 – WH-105

West Hackberry cavern 105 (WH-105) was most recently evaluated by geomechanical analysis in September 2015 (Sobolik, 2015). The model included a rendering of the full dome, axisymmetric caverns meshed using symmetrical representations of the caverns from sonar geometries, and the Multimechanism Deformation, or Munson-Dawson (M-D) creep model (Munson & Dawson, 1979, 1982, & 1984). The West Hackberry caverns are all very nearly axisymmetric, so cavern features can be easily represented using axisymmetric renderings of the sonar data. Therefore, a meshing process using axisymmetric representations of the sonars was used because it is simpler and produces better quality finite elements. The finite element meshes for the full WH model, and for WH-105, are shown in Figures 2-1 and 2-2. Note that there is a cylinder of material surrounding WH-105 in the mesh shown in Figure 2-2; this block is the region of interest for this cavern. The results from the 2015 geomechanical analyses, specifically the predictions of dilatant damage and tensile stress around WH-105, were used to evaluate the number of available drawdowns.

Figure 2-3 is a plot of the minimum value of dilatant safety factor in the cylinder surrounding WH-105 through its pressure history and predicted future drawdowns. A plot of the minimum safety factor surrounding a cavern is useful as a first glance to determine the state of stresses caused by a cavern's operations. Figure 2-3 shows that this cavern never experiences a dilatant safety factor < 1 through 5 leaches. A workover in 2015 created a condition where one location on the skin of the cavern very briefly had a safety factor of about 1, then quickly recovered, meaning no damage occurred. A similar plot of the maximum principal stress around WH-105 shows that no tensile stresses occur in the vicinity of WH-105. Based on these results, it has been determined that WH-105 has at least 5 baseline available drawdowns.

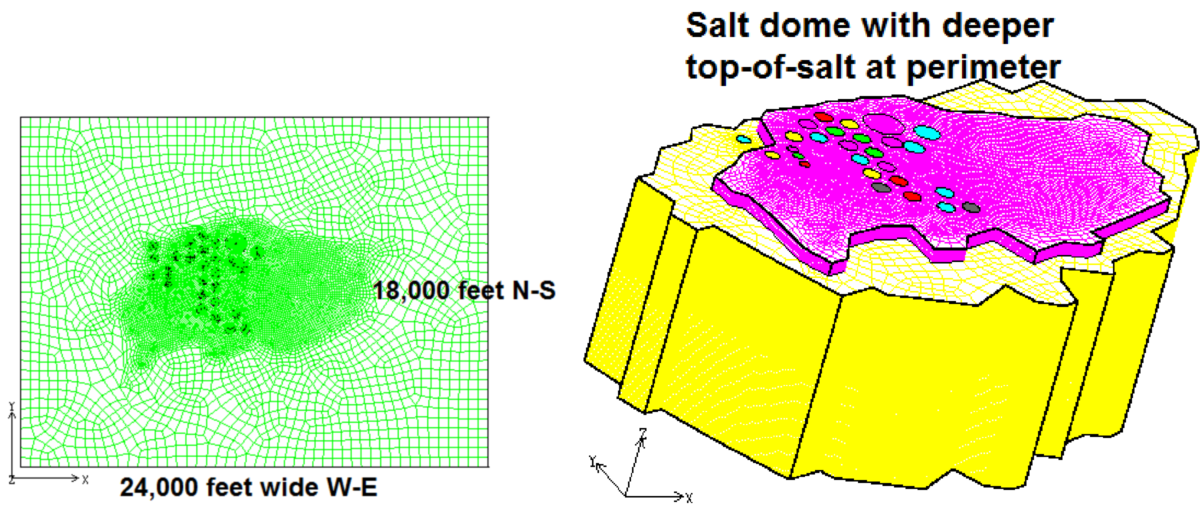

Figure 2-1. Finite element mesh used for West Hackberry geomechanical calculations, showing full mesh domain and salt dome.

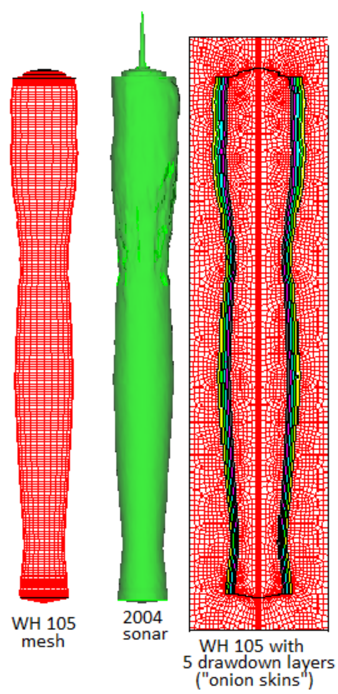

Figure 2-2. Finite element mesh sonar-measured geometry for WH-105.

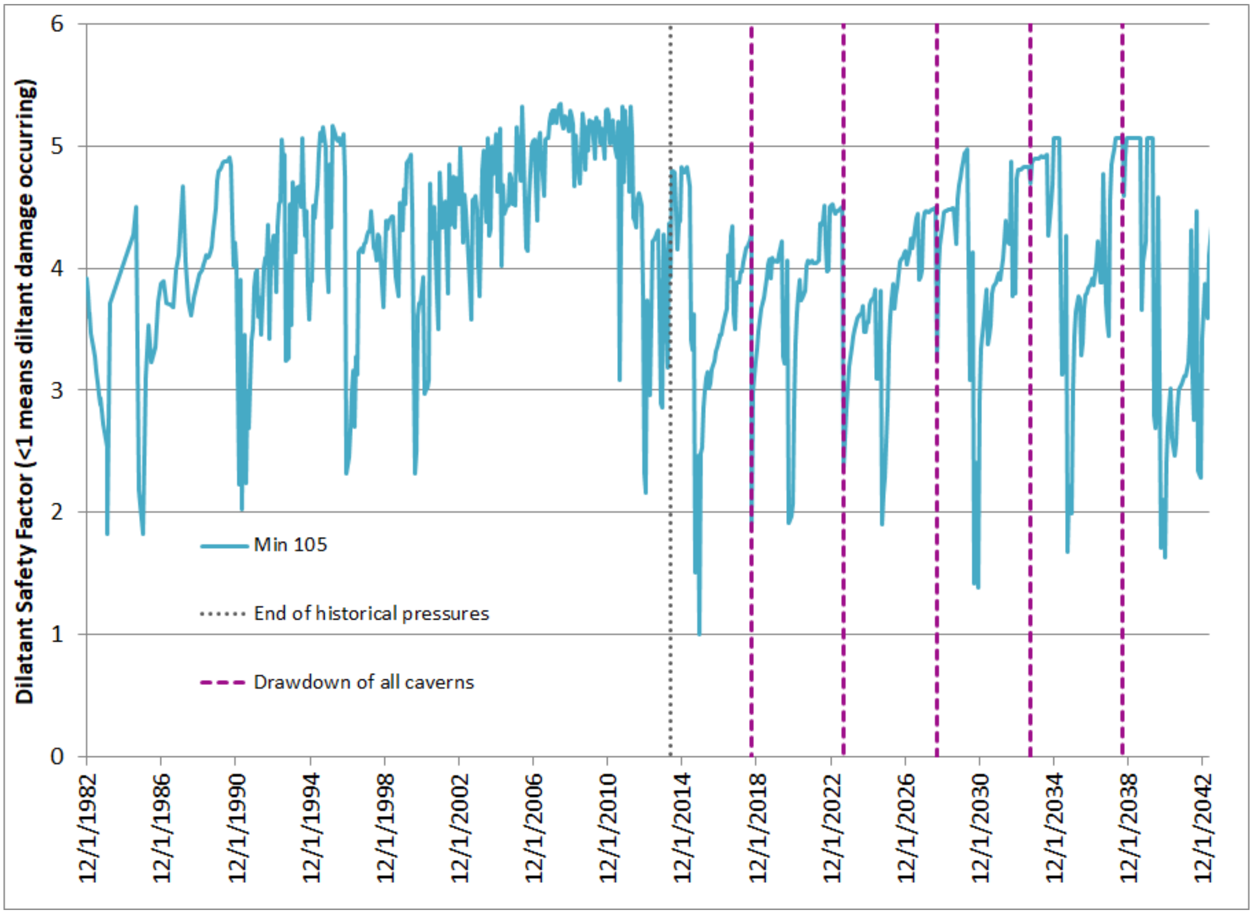

Figure 2-3. Minimum value of dilatant safety factor around WH-105.

2.2. Example 2 – BM-101

Bryan Mound cavern 101 (BM-101) was most recently evaluated by geomechanical analysis in August 2018 (Sobolik, 2018a & 2018b). The model included a rendering of the full dome, caverns meshed to geometries obtained from sonars, and the M-D creep model. The finite element meshes for the Bryan Mound caverns, in their actual spacing in the dome, is shown in Figure 2-4. Figure 2-5 shows the finite element mesh generated for BM-101, five drawdown layers, and a cylinder surrounding the cavern. The results from the 2018 geomechanical analyses, specifically the predictions of dilatant damage and tensile stress around BM-101, were used to evaluate the number of available drawdowns.

Figure 2-6 is a plot of the minimum value of dilatant safety factor in the cylinder surrounding BM-101 through its pressure history and predicted future drawdowns. This cavern has several instances where the dilatant safety factor is < 1 for very short intervals that are coincident with workovers. Figure 2-7 shows a similar plot of maximum principal stress around BM-101, where positive stresses represent tension. Short duration tension events are shown to occur at the same workover times. Because threshold stress events have been identified, the next step is to determine their location and potential consequences. For all of these events, the only location around the cavern exhibiting these stresses are at the bottom of the cavern, at a location with a sharp corner feature (refer to Figure 2-5). This location is not deemed to be a significant cavern stability issue for several reasons: any damage here will not initiate salt falls; the geometry of the bottom of the cavern does not lend itself to generating large radial cracks that would intersect other caverns; and any fluid that might be lost into the salt at this location would be brine, not oil. Therefore, the several "spikes" are not assumed to be cavern integrity problems. There are longer periods after the 4th and 5th drawdowns of dilatant and tensile stresses at the bottom of the cavern. Again, because of the advantageous location and negligible consequences of these stresses, they are not deemed to pose any cavern integrity issues. Therefore, our current strategy says this is acceptable, and BM-101 has been determined to have 5 baseline available drawdowns.

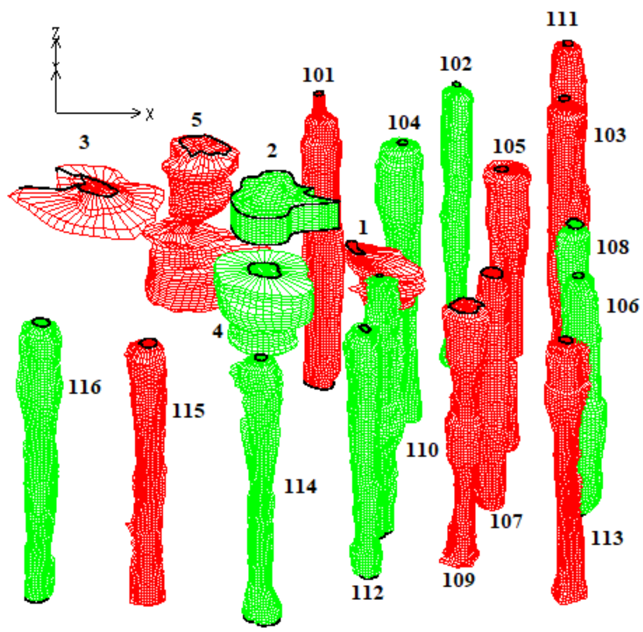

Figure 2-4. Finite element mesh of the Bryan Mound caverns.

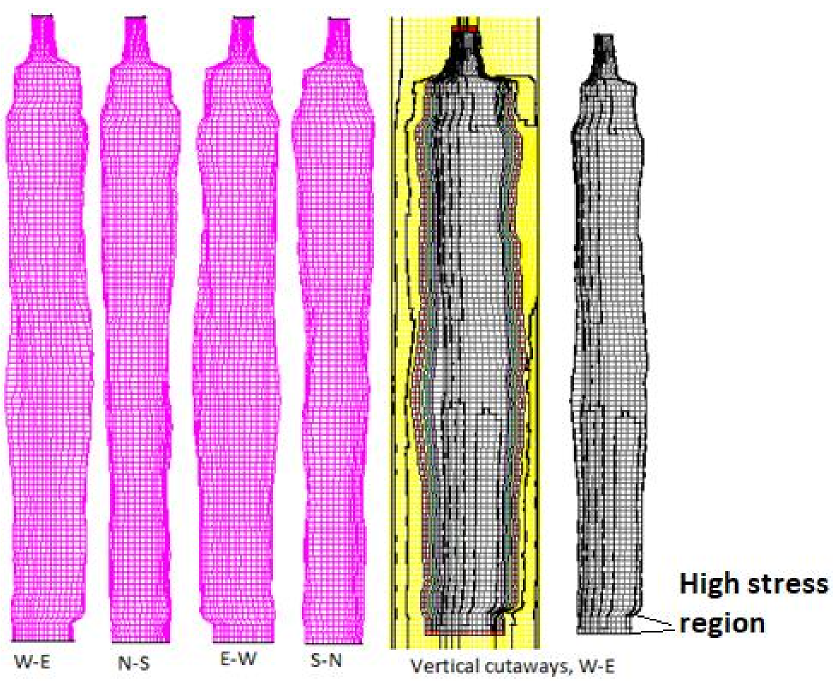

Figure 2-5. Several views of the finite element mesh for BM-101.

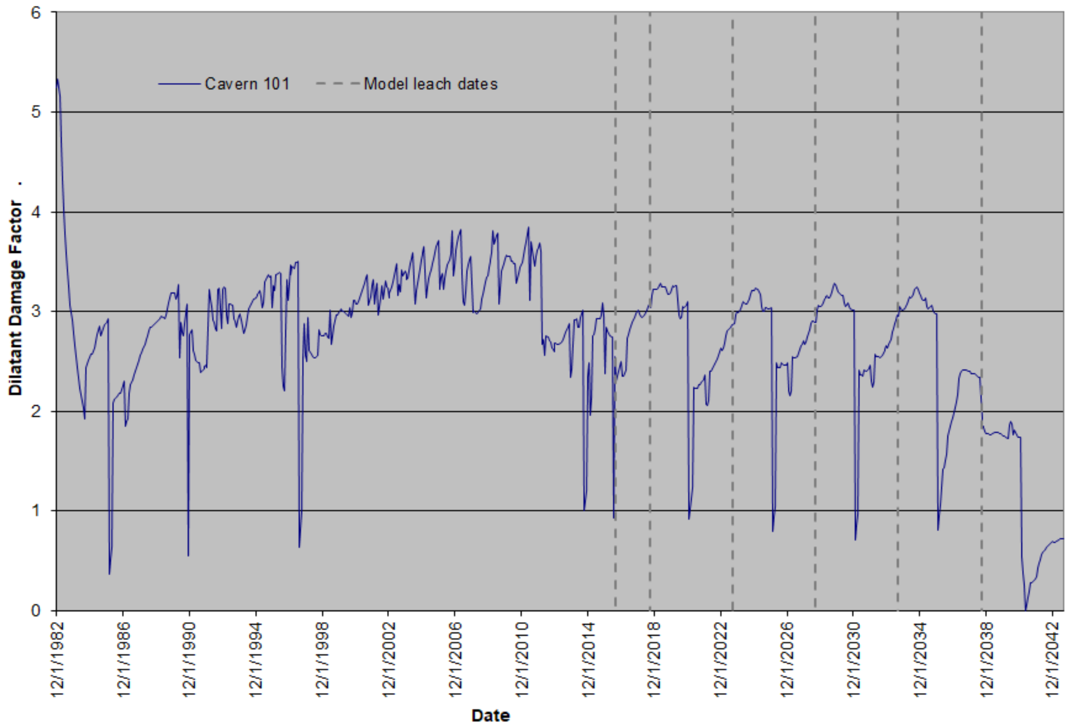

Figure 2-6. Minimum value of dilatant safety factor around BM-101.

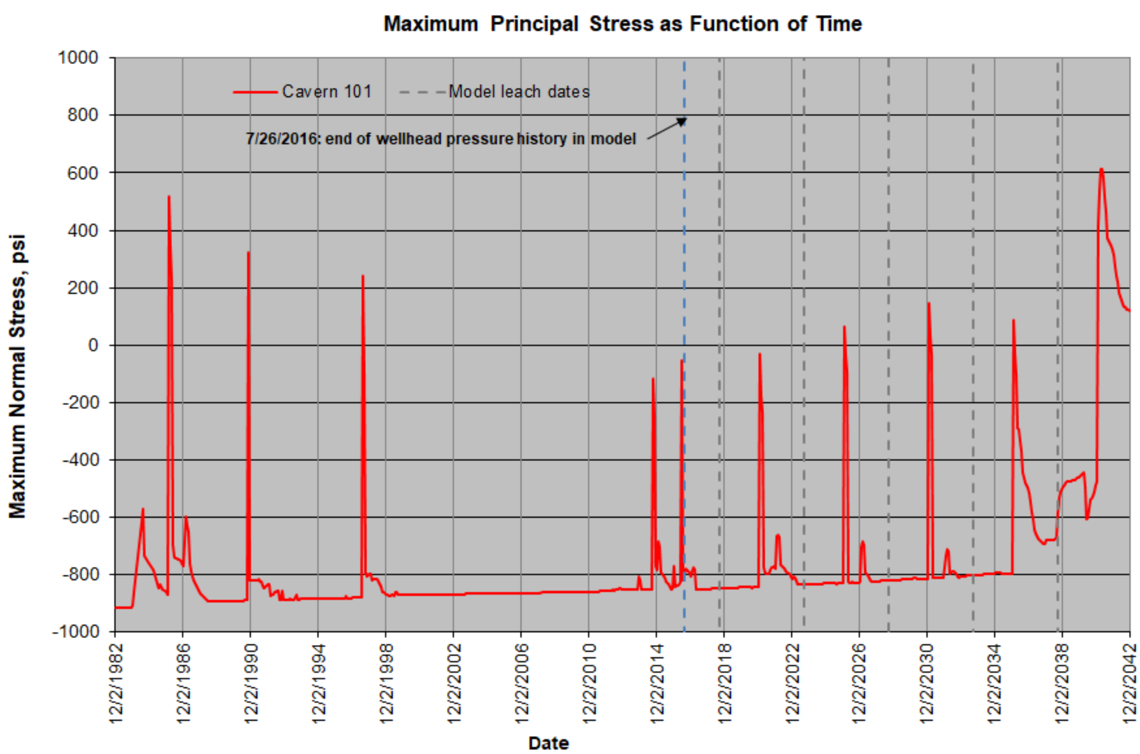

Figure 2-7. Maximum principal stress around BM-101.

2.3. Example 3 – BM-103 and 105 (based on 2014 Geomechanical Model)

The next three examples will show how the assessment of baseline available drawdowns changes over time due to improvements in geomechanical models and understanding of the SPR sites. It is for this reason that the latest annual report should be referenced in any evaluation of cavern activity based on drawdowns. The three examples shown in this and the next two sections deal with how the drawdown assessments for BM-103 and 105 changed over time. In summary, assessments based on earlier (circa 2014) versions of the geomechanical models gave each of these caverns 5 baseline available drawdowns; however, after the model was upgraded in 2018, that number was changed to 2 drawdowns for both caverns. These sections will describe why that change was made.

The geomechanical finite element model used to analyze the Bryan Mound site in 2011-2014 used axisymmetric renderings of the cavern geometries obtained from sonar measurements (Sobolik & Ehgartner, 2012; Sobolik et al., 2014). Figure 2-8 shows how caverns BM-103 and BM-105 appeared in the finite element mesh in the 2014 model. The 2014 BM model also used an earlier version of the creep model. Figure 2-9 plots the minimum dilatant safety factor values for these two caverns using the earlier model. The minimum safety factor never reaches values less than 1, which would indicate that these caverns have 5 baseline available drawdowns. A plot of maximum principal stresses would show that predicted tensile conditions were never reached. The predicted locations for the most extreme stress states were at the top of the cavern for BM-103, and at the skinny section of BM-105. Again, these extremes never exceeded the dilatant or tensile stress thresholds, so at the time these caverns were assessed to have 5 baseline available drawdowns.

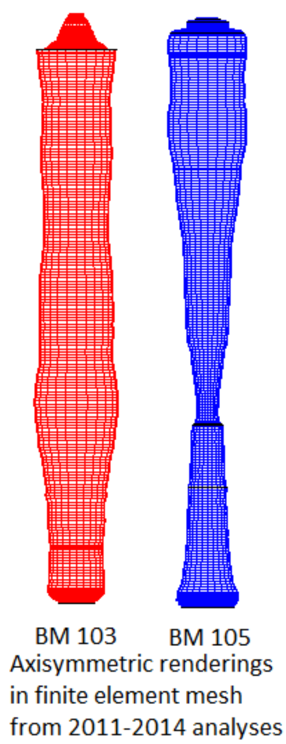

Figure 2-8: Finite element meshes for caverns BM-103 & BM-105 in the 2014 Bryan Mound model.

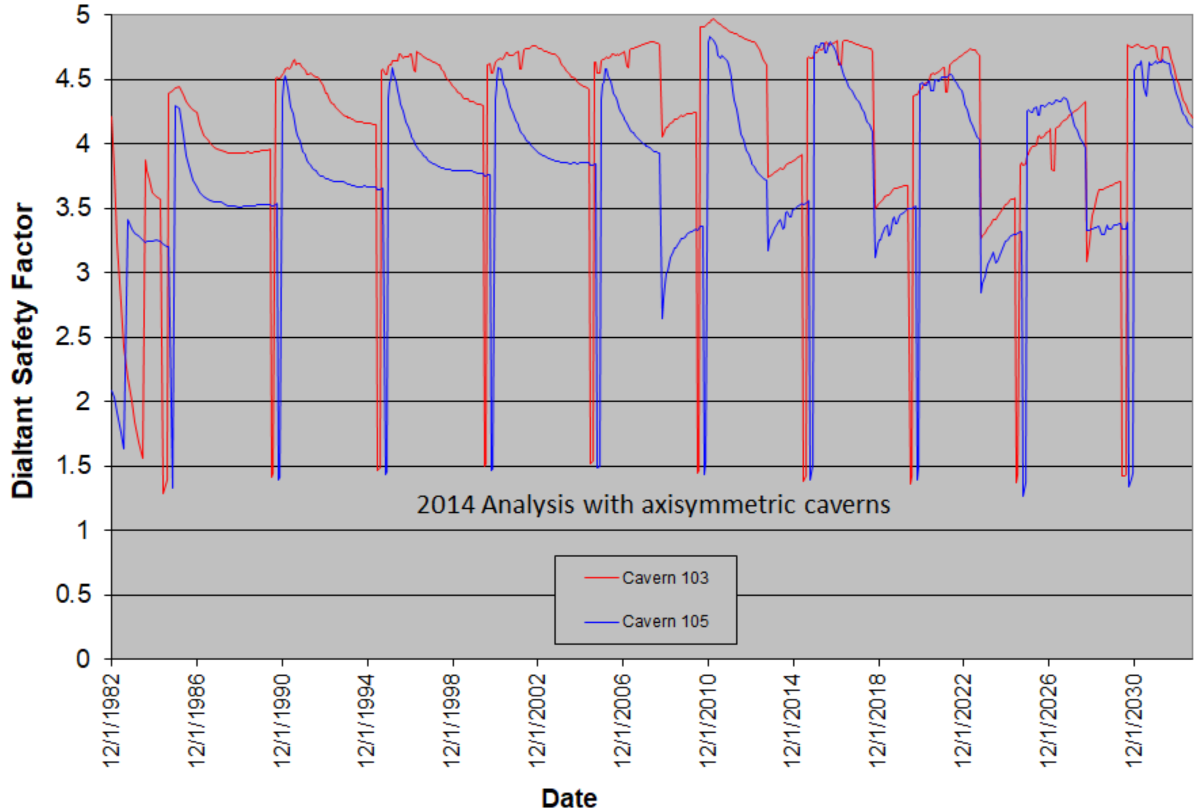

Figure 2-9. Minimum value of dilatant safety factor around BM-103 & BM-105, from the 2014 model.

2.4. Example 4 – BM-103 (based on 2018 Geomechanical Model)

Bryan Mound cavern 103 (BM-103) was most recently evaluated by geomechanical analysis in August 2018 (Sobolik, 2018a & 2018b). The model included a rendering of the full dome, caverns meshed to geometries obtained from sonars, and the M-D creep model. Figure 2-10 shows the finite element mesh generated for BM-103, five drawdown layers, and a cylinder surrounding the cavern. Note the significant asymmetry of the cavern, with the pronounced bulges on the north side. The results from the 2018 geomechanical analyses, specifically the predictions of dilatant damage and tensile stress around BM-103, were used to evaluate the number of available drawdowns.

Figures 2-11 and 2-12 show the historical progression of minimum dilatant safety factor and maximum principal stress around BM-103. With the exception of some short-duration spikes, the stresses are in the acceptable range. However, after the third drawdown, there is an extended period of time when a location near BM-103 undergoes high dilatant stresses (much less than 1) and tensile stresses. After the fourth drawdown, the minimum dilatant safety factor remains at zero, and the tensile stress reaches a very high value. Inspection of the results finds that these damaging stresses are occurring in the salt near the large hump in the cavern at mid-depth and the north side of the cavern. These undesired stresses occur 10-20 feet away from wall, indicating a significant effect on the condition of the salt into the pillar, and a corresponding significant possibility of salt fall and crack formation. There is a gradual degradation with each successive drawdown. For these reasons, the assessed number of baseline available drawdowns for BM-103 was reduced from 5 to 2.

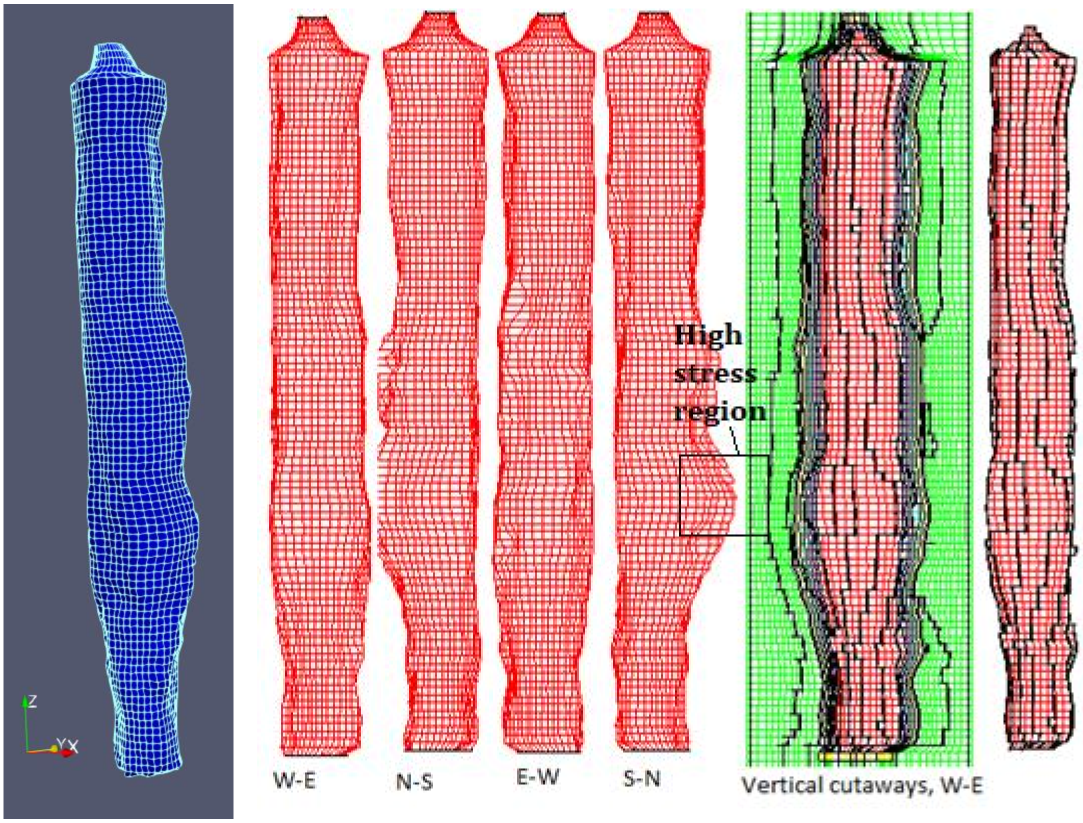

Figure 2-10: Finite element mesh for cavern BM-103 in the 2018 Bryan Mound model.

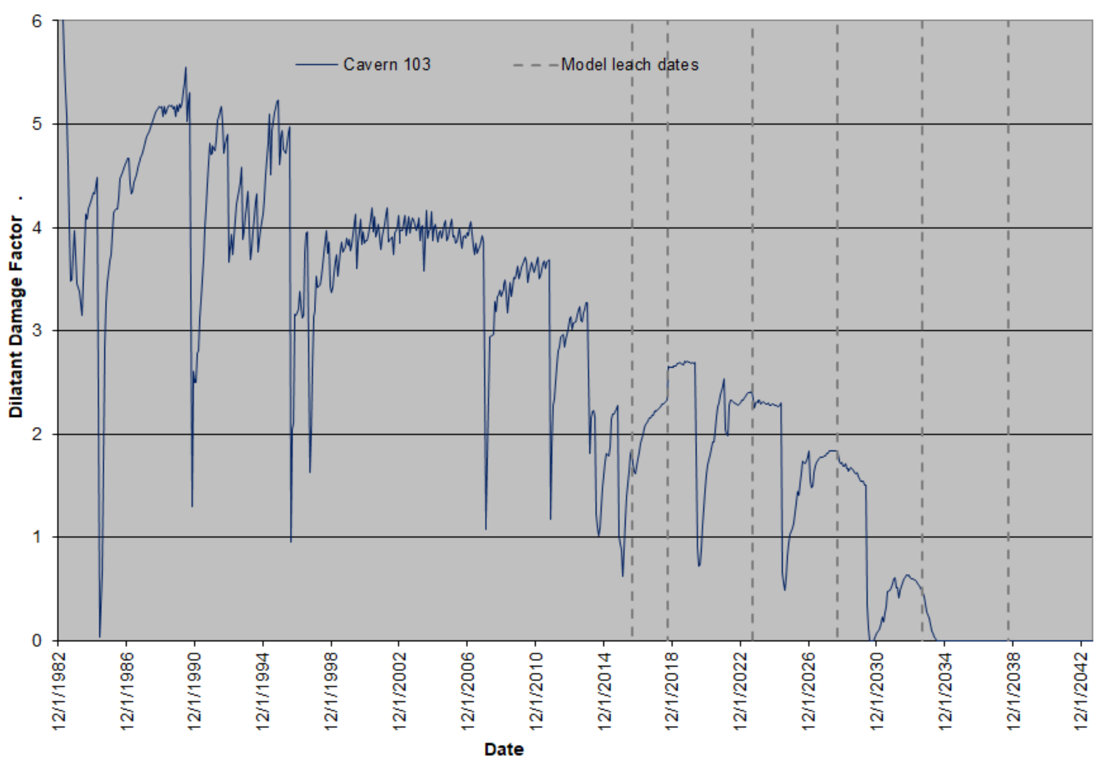

Figure 2-11. Minimum value of dilatant safety factor around BM-103, from the 2018 model.

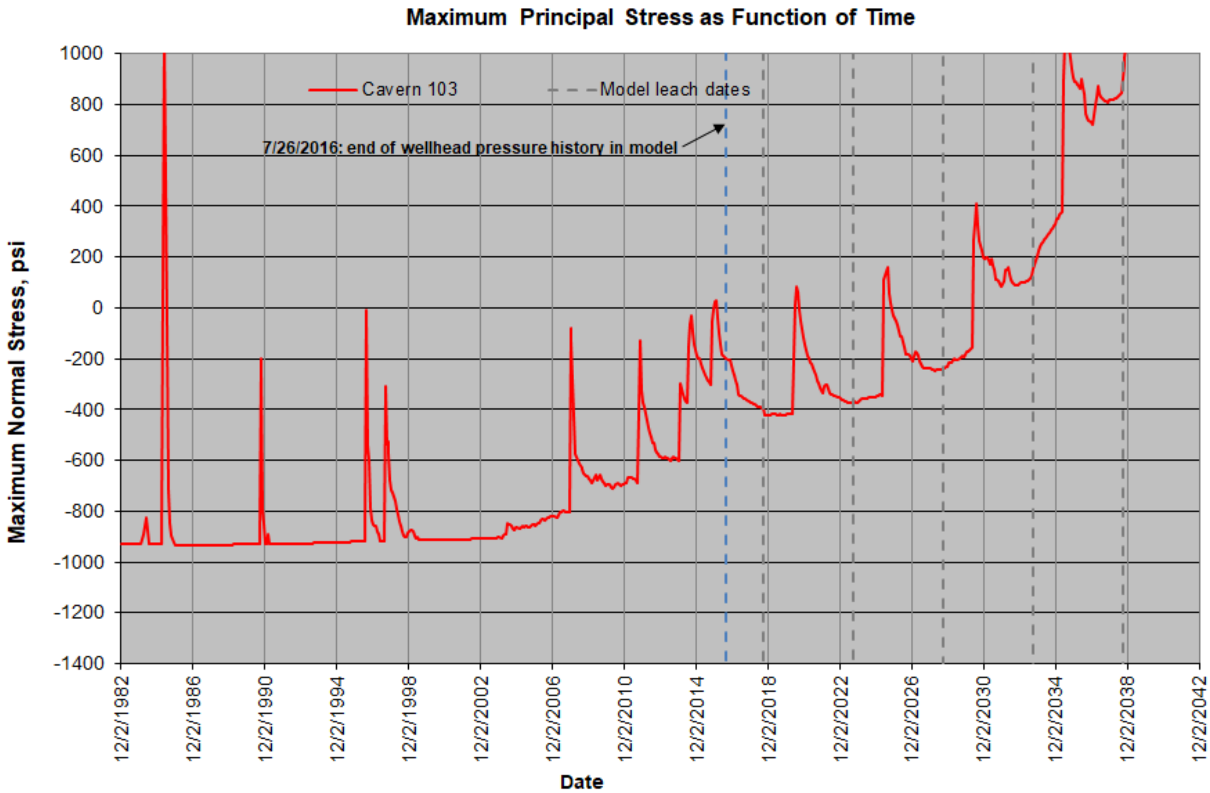

Figure 2-12. Maximum principal stress around BM-103, from the 2018 model.

2.5. Example 5 – BM-105 (based on 2018 Geomechanical Model)

Bryan Mound cavern 105 (BM-105) was most recently evaluated by geomechanical analysis in August 2018 (Sobolik, 2018a & 2018b). The model included a rendering of the full dome, caverns meshed to geometries obtained from sonars, and the M-D creep model. Figure 2-13 shows the finite element mesh generated for BM-105, five drawdown layers, and a cylinder surrounding the cavern. (This geometry is based on the 2010 sonar measurements; a recent discovery about the true geometry of BM-105 will be discussed at the end of Section 2.5). Note the large notch and large dimeter decrease near the bottom of the cavern. These features, if real, would create a stress concentration that would likely lead to a salt fall or crack generation. Additionally, the feature might be mitigated if it could be leached away. The results from the 2018 geomechanical analyses, specifically the predictions of dilatant damage and tensile stress around BM-105, were used to evaluate the number of available drawdowns.

Figures 2-14 shows the historical progression of minimum dilatant safety factor around BM-105. The minimum value is almost always less than 1, indicating a constant state of dilatancy causing microcracking. An inspection of the results shows that these extreme stresses occur only at the notched area pointed out in Figure 2-13. The primary consequence of any cracking here would be a degradation of the presumed salt ledge beneath it, and actually over time might create a shape more conducive to cavern integrity. Detrimental effects do not appear to extend out into the salt pillar. This cavern illustrates difficulty of assessing a drawdown limit: Which is more important for assessing cavern stability – skin effects shown here, or stresses in the pillar? For now, the assessed number of baseline available drawdowns for BM-105 was reduced from 5 to 2.

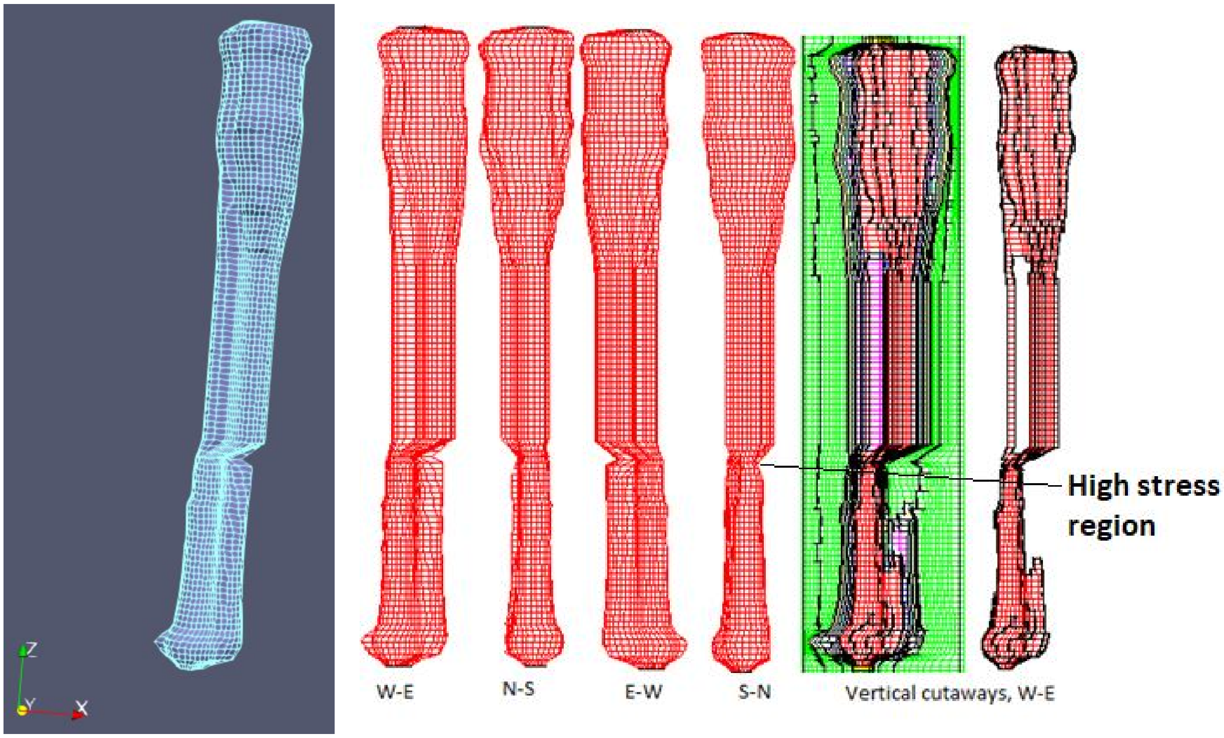

Figure 2-13: Finite element mesh for cavern BM-105 in the 2018 Bryan Mound model.

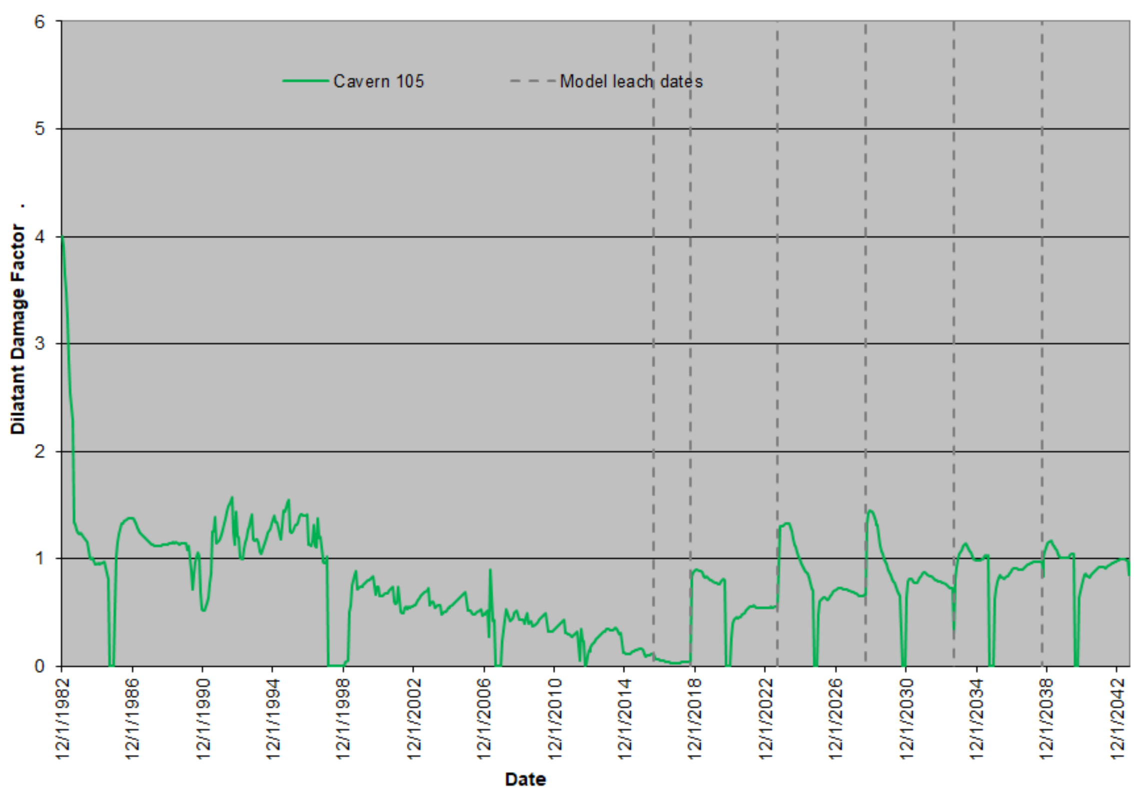

Figure 2-14. Minimum value of dilatant safety factor around BM-105, from the 2018 model.

As an additional complication for BM-105, it has been recently learned that the notch feature in this mesh may not actually be a notch, but rather a sort of salt bridge. An inspection of several sets of sonars taken from two different boreholes in BM-105 indicate that the original leaching process may not have been completed, leaving a salt bridge across the cavern. When a sonar from either one of the boreholes is examined, part of the cavern is hidden from the sonar tool due to the bridge and ledge features that can be best seen from a combination of sonars. Figure 2-15 is a composite geometry of BM-105 based on combining the sonars from the two boreholes. DOE performed new sonars for this cavern from both boreholes recently; those sonars are currently being used to develop a new finite element model for BM-105, and its baseline available drawdowns will be reassessed.

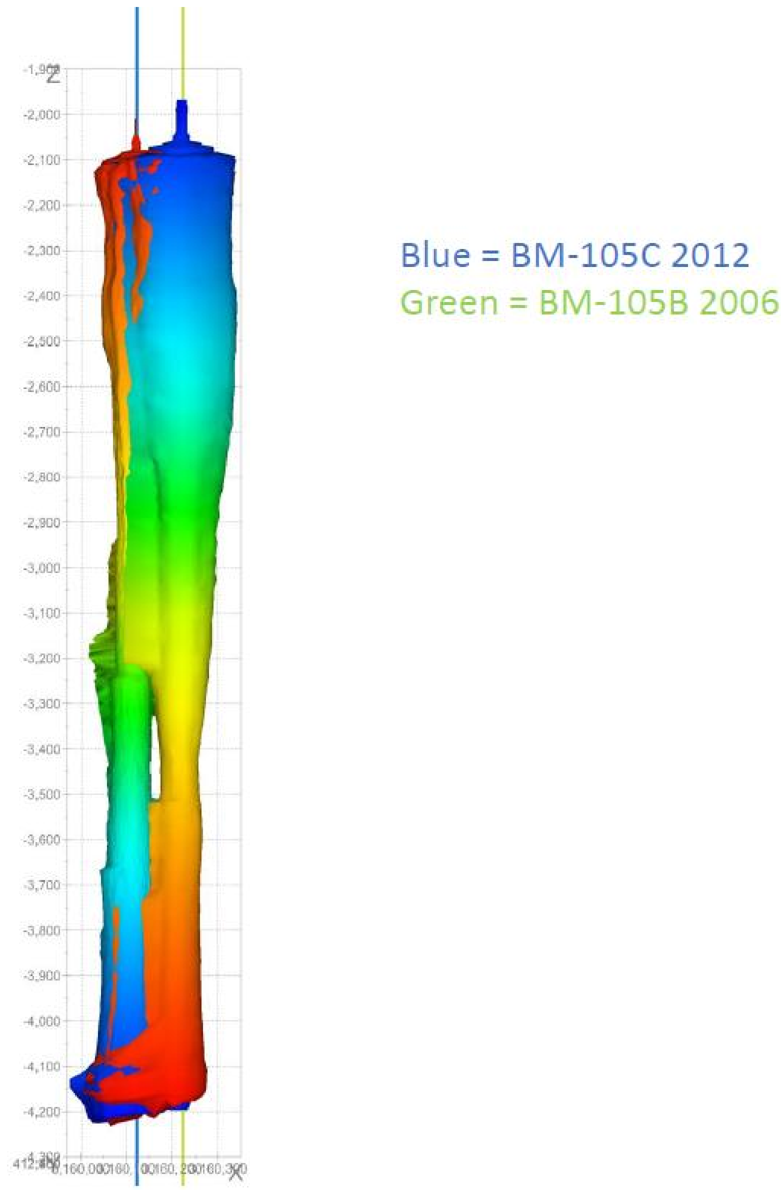

Figure 2-15. BM-105 cavern geometry based on composite sonars from both boreholes.

3. BASELINE ASSESSMENT OF CAVERN DRAWDOWN CAPACITIES - RESULTS

Using the process described in Section 2, a best estimate for the number of baseline available drawdowns currently available for each cavern has been determined. These numbers are considered the starting point from which to assess ongoing impacts (i.e., spent drawdowns) resulting from oil sales. For all four SPR sites, the term "best estimate" refers to the estimate of available drawdowns for each cavern which has the best pedigree in terms of evaluating the effects of the cavern geometry and operating conditions on cavern stability. The first-order estimate is always based on keeping the 3D P/D ratio greater than 1.0. When a geomechanical analysis incorporates sufficient detail in the cavern geometry, spacing, and operating conditions, then the resulting evaluation of geomechanical cavern stability provides the best estimate for the available number of drawdowns. Additionally, the best estimate is pinned to the time of the most recent full-cavern sonar measurement of the cavern geometry.

3.1. Bayou Choctaw

For Bayou Choctaw, until recently the best estimates for the number of baseline available drawdowns wer based on P/D ratios. However, the estimates for the available drawdowns have now been updated based on the recently upgraded Bayou Choctaw geomechanical model (Park, 2017a). The new estimates for Bayou Choctaw are summarized in Table 3-1 (Park, 2017b). BC-19, 101 and 102 are predicted to have five available full drawdowns remaining, but only under certain conditions as described below. BC-15 and 17 have only one remaining drawdown due to proximity to each other. BC-20 has been emptied of oil and will not likely be reutilized for oil storage, and therefore has been updated as "not available". As a follow-up to these recommendations, it is important for the SPR to develop a procedure to document the number and dates of full and partial drawdowns, so that this table may be updated to be a useful tool for planning future operations.

BC-18 has a region of concern near the neck of the cavern, where tensile and dilatant stresses are predicted to occur during each workover. In its current configuration, BC-18 has only one available drawdown because of the concerns about stresses around the neck. The remainder of the cavern has minimal stress concerns, so if the neck region can be smoothed out with designed leaching, then the cavern will have a capacity for five available drawdowns.

The possibility was examined for a loss of integrity of BC-20 in the salt between the dome edge and the cavern. The results from the analysis indicate that if we keep the normal brine operation wellhead pressure, the edge pillar has a risk of structural instability in the form of tensile failure and/or dilatant damage. The normal brine cavern operating pressures are not high enough to reduce the differential stresses in the thin edge pillar; this condition creates tensile and highly dilatant stresses predicted in the model. This structural instability may lead to eventual cavern integrity issues for BC-20. Based on the results, Sandia recommended that the brine-side wellhead pressure in BC-20 immediately be maintained at 654 psi, the maximum pressure allowed under current rules (Park, 2017c). If BC-20 is considered to be stable, the neighboring caverns BC-19, 101 and 102 have five available drawdowns. However, if BC-20 is unstable (brine leaks) or experiences dilatant or tensile stress-related cracking, the structural integrity of those caverns needs to be re-investigated immediately.

In late December 2021, wellhead pressure data indicated that cavern BC-18 was leaking. That cavern itself was being operated in static mode; however, nearby cavern BC-17 had been undergoing significant fluid exchanges since late summer 2021. Caverns BC-15 and BC-17 have been operated as a gallery for many years, and all three of these caverns had been designated as 1-drawdown caverns prior to this incident. At the publication date of this report, it is believed that the wellbore casing in BC-18 is tight, and that a hydraulic connection has occurred between BC-18 and BC-17 that is probably located in the brine sections of the caverns. Furthermore, the connection between BC-17 and BC-18 likely occurred due to several pressure cycling events in BC-17 resulting from the myriad of oil sale withdrawals from that cavern. The frequently changing cavern pressure in BC-17 may have fatigued the salt between the two caverns, causing either microfracturing or cracking to initiate and propagate. If this scenario can be verified, it will have an impact on the decision to use the three caverns BC-15, 17, & 18 for oil storage after the current oil sales withdrawals. This incident and its consequences will obviously be a major topic in the 2023 drawdown report that covers 2022 SPR activities.

Table 3-1. Baseline number of available drawdowns for caverns at Bayou Choctaw.

Cavern	Basis in 2014			2021Best Estimate (GM 2017)	Remarks
	Number of drawdowns until 3D P/D < 1	Geomechanics Model (GM 2014)	2014 Est. (3D P/D)		
BC-15	0	1	1	1	
BC-17	0	1	1	1	Re-examine after 2022 drawdown activities
BC-18	0	5	1	1	Re-examine after 2022 drawdown activities
BC-19	1	5	1	5	Re-investigate if BC-20 is unstable
BC-20				Not available	
BC-101	1	5	1	5	Re-investigate if BC-20 is unstable
BC-102	5	5	5	5	Re-investigate if BC-20 is unstable

3.2. Big Hill

The 3D P/D, geomechanical, and best estimate baseline available drawdown limits for the Big Hill caverns are listed in Table 3-2. The 3D P/D ratios for each of the Big Hill caverns are described in detail in Rudeen and Lord (2013). The Big Hill geomechanical model was recently upgraded, and the new computational results from Park (2019) and Park (2020) were used to determine the geomechanical drawdown limits. The 14 SPR caverns at this site are predicted to be structurally stable up to and perhaps beyond the 5th drawdown leach (Park, 2019 & 2020). The upgraded model reports recommend that BH-101 and BH-105 be reevaluated, using post-drawdown sonar measurements, because of predicted small regions of dilatant and tensile stresses at the bottom of these caverns. The predicted sizes and locations of these high-stress regions currently pose negligible consequences to cavern integrity, but their existence warrants additional observation and evaluation.

Table 3-2. Baseline number of available drawdowns for caverns at Big Hill.

Cavern	Basis in 2021		
	Number of drawdowns until 3D P/D < 1	GM 2019	2021 Best Estimate (GM 2019)
BH-101	3	5	5
BH-102	4	5	5
BH-103	4	5	5
BH-104	3	5	5
BH-105	4	5	5
BH-106	4	5	5
BH-107	4	5	5
BH-108	5	5	5
BH-109	5	5	5
BH-110	5	5	5
BH-111	4	5	5
BH-112	3	5	5
BH-113	3	5	5
BH-114	5	5	5

3.3. Bryan Mound

The current best estimate of baseline available drawdown limits for the Bryan Mound caverns are listed in Table 3-3. These estimates are based on the 3D P/D ratios for each of the Bryan Mound caverns that are described in detail in Rudeen and Lord (2013), and the most recently published geomechanical computational analysis results (Sobolik 2018a and Sobolik 2018b, which supersede Sobolik & Ehgartner, 2009). Several Bryan Mound caverns are currently predicted to exhibit a 3D P/D < 1.0 on the first raw water drawdown. However, the geomechanical model evaluated the stress in the pillars between the caverns and found that the majority of caverns should have as many as five available drawdowns. Only the Phase 1 caverns (BM-1, 2, 4, and 5) are estimated to have only one available drawdown. The geomechanical estimate for BM-5 is currently listed as 1; this is due to the presence of the neck between the upper and lower lobes of the cavern. There have been many rock falls observed from the neck region, some of which have damaged the hanging string in the lower lobe, causing oil extraction problems. A proposal currently under consideration is to permanently remove the oil from the lower lobe, filling it with brine and leaving oil in the upper lobe. If this occurs the number of available drawdowns in the upper lobe will almost certainly increase from the current value of one. Also, the cavern BM-2 was recently emptied of oil and replaced with pressurized brine. The current plan is to maintain and monitor the cavern for brine storage, and to no longer store oil in the cavern. Therefore, the available drawdown listed for BM-2 is included only for completeness, as it is not expected to hold oil in the future. The drawdown availability for the Phase 1 caverns are affected in part by the large roof diameters of the caverns, which create large stresses in the salt back. The general rule for all caverns is that regardless of mechanical stress conditions around the cavern, they have at minimum one remaining drawdown in order to remove the oil.

The cavern shapes at Bryan Mound, even for the Phase 2 and Phase 3 caverns, have many geometric irregularities due to variable impurity content in the salt. These irregularities create stress conditions which can pose problems for long-term cavern stability and drawdown capacity. In particular, BM caverns 103, 104, 105, and 108 have geometric anomalies that create regions of high potential stresses which affect the long-term containment capability of the caverns. That is why the geomechanical analyses for these caverns indicate fewer available drawdowns than the P/D values would show.

The sonars for BM-105 were recently reexamined and found to have internal features not previously included in geomechanical models. BM-105 was leached using two brine strings, as is typical for solution mining operations. However, recent comparisons of sonars taken from each borehole indicate that the leaching was not fully completed, leaving a salt bridge (or a bridge of salt, anhydrite, and/or clay; the exact composition is not known) approximately two-thirds of the way down from the top of cavern. A new sonar is planned for this cavern in the near future, after which BM-105 will be reevaluated when the correct cavern geometry is implemented in the finite element mesh. Previous editions of this drawdown report stated that a similar situation had been found to occur in BM-110; an interpretation of a 2016 sonar indicated that there was a tall ridge jutting into the cavern. However, a revised interpretation of the 2016 sonar, and a partial sonar performed in 2021, both showed that this ridge never existed.

Table 3-3. Baseline number of available drawdowns for caverns at Bryan Mound.

Cavern	Basis		
	# Drawdowns until 3D P/D < 1	GM 2018	2021 Best Estimate (GM 2018)
BM-101	4	5	5
BM-102	5	5	5
BM-103	3	2	2
BM-104	3	3	3
BM-105*	4	2	2
BM-106	2	5	5
BM-107	4	5	5
BM-108	4	2	2
BM-109	2	3	3
BM-110*	2	5	5
BM-111	3	5	5
BM-112	2	5	5
BM-113	4	5	5

Cavern	Basis		
	# Drawdowns until 3D P/D < 1	GM 2018	2021 Best Estimate (GM 2018)
BM-114	5	5	5
BM-115	4	5	5
BM-116	4	5	5
BM-1	0	2	2
BM-2	0	1	1
BM-4	0	2	2
BM-5	0	1	1

* - BM-105 and BM-110 sonars were recently reexamined and found to have internal features not previously included in geomechanical models; these caverns will be reevaluated as soon as correct cavern geometry can be determined and implemented in the finite element mesh.

3.4. West Hackberry

The current best estimate of baseline available drawdown limits for the West Hackberry caverns are listed in Table 3-4. These estimates are based on the 3D P/D ratios for each of the West Hackberry caverns and are described in detail in Rudeen and Lord (2013), and in the most recently published geomechanical computational analysis results (Sobolik, 2015 & 2016). A few West Hackberry caverns, the Phase 1 caverns (WH-6, 7, 8, & 9), are currently at a 3D P/D < 1.0. The geomechanical model evaluated the stress in the pillars between the caverns and found that all the Phase 2 caverns (101-116) and Phase 3 cavern (117) should have as many as five available drawdowns. One of the reasons for this is that the West Hackberry salt is relatively homogeneous, which resulted in caverns that were constructed with very axisymmetric and smooth shapes.

Table 3-4. Baseline number of available drawdowns for caverns at West Hackberry.

Cavern	Basis		
	Number of drawdowns until 3D P/D < 1	GM 2016	2021 Best Estimate (GM 2016)
WH-101	3	5	5
WH-102	3	5	5
WH-103	4	5	5
WH-104	3	5	5
WH-105	2	5	5
WH-106	4	5	5
WH-107	5	5	5
WH-108	4	5	5
WH-109	4	5	5
WH-110	5	5	5

Cavern	Basis		
	Number of drawdowns until 3D P/D < 1	GM 2016	2021 Best Estimate (GM 2016)
WH-111	5	5	5
WH-112	4	5	5
WH-113	4	5	5
WH-114	4	5	5
WH-115	5	5	5
WH-116	5	5	5
WH-117	5	5	5
WH-6	0	1	N/A
WH-7	0	5	5
WH-8	0	2	2
WH-9	0	1	1
WH-11	5	5	5

One exception is WH-11, which has features near the cavern floor in the most current (2018) sonar that were not included in the 2016 geomechanical model used to determine the baseline available drawdowns. This cavern will be reevaluated when the updated cavern geometry is implemented in the finite element mesh.

3.5. Starting date for each cavern

In the previous sections, the baseline numbers of drawdowns for each cavern prior to any drawdowns have been documented. However, the "time zero" point for each cavern, from which time the influence of fluid exchanges will be accounted in that cavern's drawdown capacity, still needs to be established. The geomechanical models typically use the oldest existing complete sonars of the cavern to create the "original" geometry. Generally, these dates are many years after the actual cavern construction and initiation of operations, so there is a fair amount of inconsistency between what the actual original cavern geometries and volumes may have been, and what are used in the model at the starting times. Some of those sonars come from the late 1990s, and we do not have all the fluid exchange records (fluid volumes, hanging string depths, OBIs, etc.) needed to try to track changes to each cavern volume over that length of time. Significant quality assessment and control is needed before using data from 2013 or earlier, and some records do not exist at all prior to 2002. Once the "time zero" for each cavern has been established, then the process for accounting for fluid movements and their effect on cavern volumes will be implemented. The "time zero" for each cavern will be set to the date of the most recent full-cavern sonar, unless other circumstances warrant a different choice.

Table 3-5 lists the pertinent "time zero" dates for the finite element meshes used in the geomechanical (GM) calculations. The table first lists the date at which the cavern is "created" in the GM analyses, and the volume of that cavern as measured in the mesh. The next values listed are the dates of the sonars used to create the geometry of each cavern, and the corresponding volumes from the data or report files from the sonars. Most of the values for volumes have slight discrepancies that can be explained by a combination of two things. One is the ability to match the node points in the finite element meshes to the measured points in the sonars; some modification of the coordinates is sometimes required to smooth out extremely rough edges in the data to produce numerically stable elements. The other is the algorithm used to calculate volume in the finite element plotting software and the sonar generation software. A few caverns have larger discrepancies which are explained by specific geometric issues in the caverns that required additional attention.

Table 3-5. Pertinent dates for cavern geometry in the geomechanical models.

Cavern	Date Cavern Created in GM Model ("Time Zero")	Cavern Volume from GM Mesh at "Time Zero" (MMB)	Date of Sonar used for GM mesh.	Sonar Cavern Volume (MMB)
BC-15	1/1/1990	16.14	4/15/2009	16.49
BC-17	1/1/1990	11.12	4/16/2009	11.40
BC-18	1/1/1990	16.78	1/6/2009	18.32
BC-19	1/1/1990	11.82	4/14/2009	11.99
BC-20	1/1/1990	9.39	12/13/2013	9.42
BC-101	6/1/1991	12.19	2/1/2005	12.45
BC-102	1/1/1990	9.60	2/22/2012	9.68
BH-101	9/19/1990	14.15	9/11/2012	14.24
BH-102	10/20/1990	12.40	8/29/2013	12.53
BH-103	11/29/1990	12.20	4/23/2009	12.42
BH-104	10/21/1990	13.28	5/2/2012	13.41
BH-105	5/14/1990	12.94	7/16/2013	13.10
BH-106	10/17/1990	12.39	2/23/2005	12.55
BH-107	4/25/1990	11.84	8/19/2010	11.97
BH-108	6/14/1990	11.00	3/9/2005	11.16
BH-109	7/25/1990	11.90	3/8/2005	12.04
BH-110	4/20/1990	12.25	3/1/2005	12.28
BH-111	7/15/1991	13.50	3/2/2005	13.70
BH-112	6/19/1991	12.95	4/4/2005	13.18
BH-113	5/2/1991	12.47	2/22/2005	12.43
BH-114	8/29/1991	12.33	10/24/2013	12.57
BM-1	1/1/1947	6.58	6/17/1996	6.54
BM-2	1/1/1947	8.50	12/16/1995	7.02
BM-3	1/1/1947	4.98	1/1/1979	N/A
BM-4	1/1/1947	18.87	9/26/2012	19.05
BM-5	1/1/1957	33.80	9/24/1987	34.45

Cavern	Date Cavern Created in GM Model ("Time Zero")	Cavern Volume from GM Mesh at "Time Zero" (MMB)	Date of Sonar used for GM mesh.	Sonar Cavern Volume (MMB)
BM-101	9/1/1982	13.58	7/18/2006	13.50
BM-102	1/1/1981	11.01	7/22/2013	11.13
BM-103	4/30/1982	12.72	6/28/2006	12.90
BM-104	1/1/1981	11.74	9/7/2011	11.92
BM-105	1/1/1981	11.73	8/22/2012	11.35
BM-106	1/1/1981	13.28	5/2/2006	13.43
BM-107	1/1/1981	12.32	8/28/2006	12.51
BM-108	9/1/1983	11.84	5/3/2006	12.06
BM-109	7/1/1981	12.42	4/10/2006	12.60
BM-110	1/1/1981	10.51	4/11/2006	10.70
BM-111	1/1/1983	12.70	8/15/2006	12.81
BM-112	12/1/1982	11.40	8/29/2006	11.51
BM-113	1/1/1984	9.12	12/13/2011	7.25
BM-114	8/1/1985	9.37	1/18/2012	9.60
BM-115	9/1/1984	10.41	9/13/2011	10.57
BM-116	7/30/1984	11.27	9/14/2011	11.49
WH-6	1/1/1947	7.60	8/12/1982	8.98
WH-7	1/1/1947	12.79	5/7/1999	13.09
WH-8	1/1/1947	11.18	9/16/1977	11.66
WH-9	1/1/1948	9.37	5/26/1977	10.88
WH-011	1/1/1963	9.09	5/28/2003	8.87
WH-101	11/30/1983	10.63	1/16/2000	10.83
WH-102	2/1/1982	6.03	8/22/1983	6.30
WH-103	12/31/1983	10.28	3/20/2004	10.76
WH-104	12/31/1983	10.45	7/11/2000	10.82
WH-105	12/31/1983	9.94	12/8/2004	10.10
WH-106	9/1/1987	10.92	6/28/2000	11.21
WH-107	7/30/1984	11.36	11/26/1999	11.58
WH-108	11/30/1984	11.81	4/22/2003	12.10
WH-109	10/31/1985	11.54	3/14/1997	11.76
WH-110	2/28/1985	11.64	5/19/2003	11.95
WH-111	4/1/1988	9.04	4/24/2006	9.17
WH-112	1/1/1987	11.36	8/15/2000	11.70

Cavern	Date Cavern Created in GM Model ("Time Zero")	Cavern Volume from GM Mesh at "Time Zero" (MMB)	Date of Sonar used for GM mesh.	Sonar Cavern Volume (MMB)
WH-113	6/1/1985	11.44	11/4/2000	11.67
WH-114	9/1/1985	10.94	11/14/2000	original LAS N/A
WH-115	6/1/1987	11.13	8/17/2006	11.25
WH-116	9/1/1985	10.60	4/22/2000	10.87
WH-117	8/31/1988	11.69	3/29/2004	12.05

4. METHODOLOGY FOR TRACKING DRAWDOWN CAPACITY

This section describes the methodology for tabulating the number of drawdowns that an individual cavern has expended, and the process for the development of the information required for that tabulation. There are three essential components of this methodology: the specific data and analysis tools that will be used, the criteria for determining the expenditure of a drawdown, and the process for tracking the information.

4.1. Required data and tools

The data and analysis tools that will be required for tracking the evolution of drawdown capacity of each SPR cavern include the following:

1. The initial state of the cavern, which includes the "time zero" date, its volume at that date (which will come from a full-cavern sonar), and the baseline number of drawdowns (from Section 3 of this report);
2. Every fluid exchange operation in the cavern, including date of event, amount of oil removed, information about replacement water to determine amount of salt leached away (volume, salinity, temperature, etc.), depth of hanging string, and oil-brine interface (OBI);
3. Any full or partial sonar measurements of the cavern geometry;
4. P2D computer program (Rudeen & Lord, 2013), which will be used to calculate the change in the pillar-to-diameter ratio (P/D) for new cavern geometries;
5. The SANSMIC leaching program (Weber et al., 2014), which will be used to estimate the change to the cavern shape after each drawdown/leaching operation;
6. The finite element mesh created for each of the four SPR geomechanical site models, which now include estimated leach layers based on the sonar-measured geometries of each cavern.

The first of these tools (baseline available drawdowns) is developed from the geomechanical models. The next three tools depend on data obtained from site operations – daily wellhead pressure readings and fluid exchange reports, information obtained from sonars and other downhole instrumentation, and evaluation of those data to determine changes in P/D ratios. The final two tools require a more analytical examination of the changes to cavern shapes prior to new sonar measurements, and the potential impact of stress evolution around each cavern.

4.2. Drawdown expenditure criteria

During a meeting of the SNL/DOE/FFPO team in January 2018, the following criteria were established to either signify the expenditure of a drawdown, or to flag a cavern for further investigation as to whether a drawdown has been spent. There was one criterion that was agreed upon that explicitly means that a drawdown has been spent:

1. When it can be determined that a cavern volume has increased by 15% over its previous baseline volume, either through an accumulation of full or partial drawdowns or from a sonar measurement, then that cavern has spent one of its drawdowns. Furthermore, each successive 15% increase in the cavern volume will result in the expenditure of another drawdown.

This criterion is based on the longstanding rule-of-thumb that a full drawdown of a cavern with fresh water removes a volume of salt around the cavern equal to 15% of the original volume (Hoffman and Ehgartner, 1993; Ehgartner and Sobolik, 2002). This standard was used in the geomechanical models to assess the effect on cavern integrity with successive leaching operations. In addition, this standard will be used to estimate the increase of cavern volume following raw water injection events such as removing oil from a cavern for sales. For example, if 1 MMB of oil is removed from a cavern using raw water, then an estimated increase of cavern volume due to salt dissolution will be 150,000 bbl.

Three other criteria were identified to flag a cavern for investigation to determine whether the observed changes constitute a drawdown expenditure:

2. A combination of partial drawdowns causes the radius of the cavern at some point to exceed the projected radius of the cavern at that same location from a full drawdown;

Any time a cavern experiences a full or partial drawdown, Sandia will investigate how that event has changed the cavern shape. Obviously, a sonar measurement immediately after the event is the first order determination of the new geometry. However, sonars will not always be performed after a partial drawdown. In that case, SANSMIC will be used to estimate the change to the cavern geometry that occurred resulting from that drawdown. The new shape will be compared to a similar SANSMIC simulation of a full drawdown of the cavern; if the new geometry exceeds the radius of the simulated full-drawdown geometry a geomechanical analysis of the new shape will be conducted. SANSMIC will be used to create a metric by which the estimated/measured change in shape of cavern will be represented by a change in average radius as function of height, $\frac{\Delta r}{\Delta z}$ (at least for Big Hill & West Hackberry). The new shape will also be compared to the finite element mesh of the geomechanical model to make the same determination. The additional analysis may require only a comparison with the current geomechanical model and an engineering judgment of the effect on drawdown capacity, or it may require a reconstructed or rerun model.

3. The occurrence of one or more salt falls of significant size may make changes to the cavern geometry that can affect cavern integrity.

A sonar measurement of the change in geometry due to the salt fall (if available), SANSMIC and the geomechanical model will be used to evaluate the effect of the salt fall on cavern integrity and drawdown capacity.

4. An event occurring at a nearby cavern (e.g., a significant volume changed due to drawdowns, wellbore or cavern leak) may lead to a change in stress conditions that can impact cavern integrity.

A similar evaluation will occur if a nearby cavern's situation has changed.

4.3. Process for tracking information

The list of required data and tools, and the criteria used to assess drawdown expenditure, demonstrate that a well-designed table of data and information must be created, and a process for near real-time updating of this information be implemented. Such a system would be similar to the system Sandia has already created for compiling and examining wellhead pressure data, which requires coordination of data transmission between the four SPR sites and Sandia. For these annual reports of drawdown capacity, the following databases and processes have been established:

1. The table of initial states of the caverns, which will include the "time zero" date, its volume at that date (which will come from a full-cavern sonar), and the baseline number of drawdowns (this information is presented as Table 3-5 in Section 3);
2. A library of P2D calculations for each cavern (this is described in Section 5);
3. A library of all sonar measurements to date for each cavern, and the mechanism in place to include new sonar measurements as they occur (described in Section 5);

4. A database to track the cumulative volume change for each cavern. This database (described in Section 5) will include the following:
   - Database of all fluid exchanges, including dates, volume, salinity, and temperature of water used for drawdown
   - Hanging string (HS) depth
   - Oil-brine interface (OBI) depth
   - Cavern floor total depth (TD)
   - Algorithm to calculate the expected increase in cavern volume due to the salt dissolved into the water
5. A library of SANSMIC simulations of all the SPR caverns to include their projected shapes after at least one and up to five full-cavern drawdowns; this is described in greater detail in Section 6.

The culmination of the collection of these data will be the calculation and characterization of volumes changes in each cavern, and the resulting expenditure of drawdowns for each cavern since 2014. These tabulations will be detailed in Section 7 and will track the changes to the caverns resulting from cavern operations. The number of spent drawdowns will be subtracted from the baseline available drawdowns listed in Section 3 to obtain the current estimate of available drawdowns for each cavern. It is important to note that the number of baseline available drawdowns may be adjusted based on several factors, primarily refinement of the geomechanical models and assumptions regarding cavern integrity. However, the calculation of spent drawdowns is a more concrete number as it will be based on measured/estimated volume changes to the cavern due to data obtained from cavern operations. It will be the intent of this report, then, to focus on calculating the expenditure of drawdowns first, before translating that to an estimate of available drawdowns. As stated earlier, an accumulated 15% increase in cavern volume (corresponding to an estimated dissolution and removal of an equivalent volume of salt due to leaching) will constitute an automatic expenditure of a drawdown for a cavern. The other information will be used to identify caverns that will be investigated to determine any effect on drawdown capacity.

5. SITE OPERATIONS DATABASES

In order to track the expenditure of drawdowns for each cavern, it is essential to accurately track the various fluid exchanges and operating conditions for each cavern. Specifically, the following cavern attributes must be tracked to assess drawdown availability:

- Creation of new cavern volume due to raw water injection, either for oil removal or for intended leaching;
- Loss of cavern volume due to salt creep;
- Changes in operating characteristics such as depths of the OBI, hanging string, and bottom of cavern;
- Changes in cavern shape and P/D ratios due primarily to leaching, but also to secondary effects such as salt creep, salt falls.

The primary criterion for the expenditure of a drawdown is an increase in the volume of a cavern by 15%. This number comes from the long-observed characteristic of caverns that a volume of raw water (i.e., water with salinity equivalent to ocean water, or less), when injected and removed from a salt formation, will dissolve and remove 15% of its volume in salt from the formation. Therefore, tracking of raw water injections is the primary mechanism for computing cavern volume changes. The accumulated volume of salt removal is considered equivalent to the accumulated cavern volume increase due to raw water injections. This accumulated volume increase is compared to the most recent reliable cavern volume (see discussion below); when the ratio exceeds 15%, an available drawdown will have been spent.

A second phenomenon that affects cavern volume is salt creep, which causes the cavern to slowly close. This value can be tracked on a continuous basis by summing measured fluid exchanges such as brine bleed-offs, and oil/brine and oil/water exchanges. These volume reductions result in a gradual equilibration of the stress states around the cavern, moving it to a better cavern integrity state. Additional data such as hanging string, OBI, and cavern bottom depths can be used to calculate changes in cavern volume due to salt creep. Over the long term, these volume changes can and will be compared with cavern volume measurements from sonars.

The dataset required for these calculations is rather large. Table 5-1 gives a small portion of the detailed table of measurements of cavern volume, and depths of hanging strings, OBIs, and cavern bottoms for a few caverns. Table 5-2 summarizes these data for all the caverns. (Note that well BH-105B has been commissioned to be plugged and abandoned due to significant casing damage.) Table 5-3 lists all the available raw water injection data for BH-109 starting in 2013; the collections of data for the other caverns have similar quantities and frequencies of data. All of these data are used to calculate running totals of volume increase in the caverns due to salt dissolution and removal.

An additional criterion that needs to be considered is the change in cavern shape due to salt removal, which may occur in an asymmetric manner. The change in the shape of a cavern may either create or diminish regions of deviatoric stress concentration around the cavern, which in turn may change the geomechanical behavior of the cavern. The loss of pillar salt due to raw water also reduces the pillar-to-diameter (P/D) ratio of a cavern with respect to its neighbor. As described earlier, the P/D ratio is a useful index for quickly evaluating a cavern's availability for additional drawdowns. The P/D ratio for each cavern combination is derived from sonar data using the program P2D (Rudeen and Lord, 2013). As caverns are modified due to raw water operations, P2D will be used to periodically recalculate the P/D ratios.

Table 5-1. Portion of detail tabulation of sonar, OBI, hanging string, total cavern depth data collected for drawdown analyses.

Cavern	Date of Latest Pre-Sales sonar (Pre-2017)	Date of Latest Post-Sales sonar (2017 forward)	OBI Date	OBI depth (ft)	HS Date	HS depth (ft)	Total Depth Date	Total Depth (ft)
BH-101A	9/11/2012		2/19/2014	4083		N/A	2/19/2014	4116
			9/29/2014	4074		N/A	9/29/2014	4116
			2/10/2015	4070		N/A	9/29/2014	4116
			8/22/2017	4044		N/A	8/22/2017	4105
BH-101B			2/11/2013	4028		4092	2/11/2013	4109
			9/29/2014	4062		4092	9/29/2014	4110
BH-102A	8/29/2013		8/28/2013	3562		N/A	8/28/2013	4060
			2/24/2015	3524		N/A	8/28/2013	4060
			10/1/2015	3526		N/A	10/1/2015	4046
			10/18/2016	3651		N/A	10/18/2016	4046
BH-102B			6/27/2013	3707		3965	6/27/2013	4068
			10/18/2016	3658		3965	6/27/2013	4068
			5/23/2017	3501		3965	6/27/2013	4068
BH-103A	10/4/2011		11/13/2013	3770		N/A	11/13/2013	3797
			4/21/2014	3767		N/A	4/21/2014	3800
			8/18/2015	3743		N/A	4/21/2014	3800
			12/21/2015	3747		N/A	4/21/2014	3800
			6/29/2016	3730		N/A	6/29/2016	3764
BH-103B			2/19/2014	3765		3800	2/19/2014	3820
			4/21/2014	3765		3800	4/16/2014	3820
			4/21/2014	3765		3066	8/11/2014	3820
			4/17/2015	3763		3790	4/17/2015	3815
			4/17/2015	3763		3274	8/9/2017	3808

Table 5-2. Summary of OBI, hanging string, total cavern depth data accumulated for drawdown analyses

Cavern (Well)	Date of Latest Pre-Sales sonar (Pre-2017)	Date of Latest Post-Sales sonar (2017 forward)	Most Recent OBI Date	Most Recent OBI depth (ft)	Most recent Hanging String depth (ft)	Most Recent Total Depth Date	Most Recent Total Depth (ft)
BC-015	8/25/14	8/27/19	11/23/20	3272		8/26/19	3299
BC-015A			11/16/21	3263	3290	11/16/21	3288
BC-017	8/27/14	8/28/19	8/28/19	3941		8/28/19	3997
BC-017A			11/16/21	3785	3954	11/16/21	3985
BC-018	9/3/14	12/29/20	12/29/20	3794	2153	12/29/20	4224
BC-018A			2/10/21	3808	4085	2/10/21	4232
BC-019	10/14/14	9/24/19	4/27/21	4168	4192	5/1/18	4209
BC-019A			6/24/20	4168		6/24/20	4210
BC-020	1/14/14		2/3/14	0	4018	2/3/14	4188
BC-020A		9/25/18	7/15/13	2469		5/1/18	4225
BC-101A	11/10/14		7/30/21	4772	4772	4/15/20	4795
BC-101B		10/7/19	10/7/19	4728		10/7/19	4823
BC-102A	2/2/12	5/4/17	6/3/20	4398	5200	6/18/14	5250
BC-102B			11/23/20	4043		4/14/20	5072
BH-101A	9/11/12	9/11/12	9/1/21	3908		9/1/21	4109
BH-101B			6/18/19	4019	4092	6/13/19	4110
BH-102A	8/29/13	10/12/21	10/11/21	3360		10/11/21	4020
BH-102B			12/16/21	3364	4021	12/16/21	4041
BH-103A	10/4/11	8/3/21	8/3/21	3725		8/3/21	3780
BH-103B			10/10/18	3719	3773	10/10/18	3789
BH-104A	12/19/12	10/27/21	11/4/21	3766		10/27/21	4160

Cavern (Well)	Date of Latest Pre-Sales sonar (Pre-2017)	Date of Latest Post-Sales sonar (2017 forward)	Most Recent OBI Date	Most Recent OBI depth (ft)	Most recent Hanging String depth (ft)	Most Recent Total Depth Date	Most Recent Total Depth (ft)
BH-104B			11/5/21	3765	4155	11/5/21	4172
BH-105A	7/16/13	10/26/20	7/15/21	3689	4022	7/6/21	4028
~~BH-105B~~	*Well BH-105B set for P&A*		~~6/10/20~~	~~3635~~		~~5/7/20~~	~~4019~~
BH-106A	3/31/15	3/31/15	10/14/20	3643		10/19/17	4085
BH-106B			10/15/20	3644	4065	10/15/20	4078
BH-107A	8/19/10	9/18/19	7/13/20	3493		7/13/20	4085
BH-107B			8/6/21	3331	4083	8/26/21	4096
BH-108A	4/24/15	12/18/19	12/17/19	3191		12/17/19	4104
BH-108B			8/26/21	2937	4076	1/12/21	4094
BH-109A	5/5/15	2/10/20	3/9/21	3390		3/9/21	4180
BH-109B			3/10/21	3393	4157	3/10/21	4174
BH-110A	4/8/15	3/23/20	9/5/19	4047		9/5/19	4186
BH-110B			9/2/21	3424	4157	9/2/21	4175
BH-111A	4/9/15	9/8/21	9/8/21	3392		9/8/21	4224
BH-111B			11/3/21	3263	4039	11/1/21	4224
BH-112A	5/7/15		1/7/20	4132		1/7/20	4172
BH-112B			11/30/21	4142	4165	11/30/21	4185
BH-113A	9/24/15		1/20/20	4097		1/21/20	4149
BH-113B			9/7/21	4003	4129	9/7/21	4144
BH-114A	10/24/13	10/13/21	12/28/21	3562		10/12/21	4060
BH-114B			12/29/21	3557	3857	12/29/21	4084
BM-001	6/17/96		7/14/09	2725		7/14/09	2754
BM-001A			7/15/19	2716	2736	7/15/19	2754

Cavern (Well)	Date of Latest Pre-Sales sonar (Pre-2017)	Date of Latest Post-Sales sonar (2017 forward)	Most Recent OBI Date	Most Recent OBI depth (ft)	Most recent Hanging String depth (ft)	Most Recent Total Depth Date	Most Recent Total Depth (ft)
BM-002	5/11/15		6/7/16	1456		6/7/16	1668
BM-002A			5/31/16	1455	1656	5/31/16	1676
BM-003	1/1/79						
BM-004A	9/26/12		10/1/20	2981		2/6/18	3080
BM-004B			11/4/19	3021	3067	11/4/19	3089
BM-004C			6/4/20	3011	3050	6/4/20	3069
BM-005	9/24/87		3/24/20	3204	3221	3/24/20	3243
BM-005A			3/31/21	3211		6/27/18	3268
BM-005C			10/22/07	3226	2098	2/18/16	3234
BM-101A	8/23/16		6/10/21	4060		5/8/18	4128
BM-101C			9/;29/21	4066	4108	9/22/21	4126
BM-102B	7/22/13	3/17/20	10/7/21	3488	4224	12/14/21	4244
BM-102C			12/15/21	3493		3/17/20	4251
BM-103B	6/23/16	8/13/19	5/26/21	3327		5/9/18	3995
BM-103C			7/27/21	3235	3964	7/27/21	3984
BM-104A	9/7/11	7/7/21	7/7/21	3800		7/7/21	4152
BM-104B			7/27/21	3822	4146	7/27/21	4166
BM-104C			12/12/17	4101		12/12/17	4163
BM-105B	8/22/12		3/31/21	4164		5/2/19	4192
BM-105C			10/28/21	4158	4185	10/28/21	4206
BM-106A	5/5/16		12/14/20	3390	3777	12/14/20	3797
BM-106B			7/29/20	3470		5/15/18	3820
BM-106C			1/14/21	3390	3762	1/14/21	3783

Cavern (Well)	Date of Latest Pre-Sales sonar (Pre-2017)	Date of Latest Post-Sales sonar (2017 forward)	Most Recent OBI Date	Most Recent OBI depth (ft)	Most recent Hanging String depth (ft)	Most Recent Total Depth Date	Most Recent Total Depth (ft)
BM-107A	5/10/16	5/10/16	12/2/19	3916	3999	12/2/19	4019
BM-107B			8/17/20	3909		5/10/18	4011
BM-107C			7/26/21	3915		11/20/14	4008
BM-108A	6/20/16	4/9/19	8/10/21	3568		4/9/19	4175
BM-108B			6/14/21	3556	4122	6/14/21	4140
BM-108C			12/14/15	4068		12/14/15	4142
BM-109A	5/2/16		7/12/21	3962	4050	7/12/21	4070
BM-109B			4/16/13	4083		1/25/16	4044
BM-109C			2/11/20	3981		4/18/18	4075
BM-110A	5/4/16	8/25/21 (partial)	9/8/21	3469	4057	9/8/21	4077
BM-110B			7/31/17	3958		7/31/17	4070
BM-110C			7/9/19	3951		7/9/19	4051
BM-111A	8/23/16	3/20/20	7/22/20	3321		3/19/20	4131
BM-111B			8/3/21	3112	4081	8/3/21	4102
BM-112A	8/29/06	5/11/17	8/6/19	3917		5/6/19	3924
BM-112C			8/17/17	3920	3818	8/17/17	3952
BM-113A	8/21/12		3/25/21	3532		5/19/20	4066
BM-113B			2/2/21	3519	4044	2/2/21	4066
BM-114A	1/18/12	12/27/21	12/27/21	3012		12/27/21	4103
BM-114B			9/30/20	4004	4076	9/30/20	4098
BM-115A	9/13/11	4/6/21	11/9/21	4034		7/8/19	4092
BM-115B			3/30/21	4034	4074	11/8/21	4092
BM-116A	9/14/11	4/5/21	4/12/21	3695		4/7/21	4220

Cavern (Well)	Date of Latest Pre-Sales sonar (Pre-2017)	Date of Latest Post-Sales sonar (2017 forward)	Most Recent OBI Date	Most Recent OBI depth (ft)	Most recent Hanging String depth (ft)	Most Recent Total Depth Date	Most Recent Total Depth (ft)
BM-116B			11/19/20	3706	4216	11/19/20	4236
WH-006	10/19/14		1/8/91	3346		1/8/91	3390
WH-006B		8/14/20	5/4/16	2609	3276	8/18/20	3388
WH-006C			1/4/06	3361		1/7/06	3365
WH-007A	5/19/15	6/10/20	6/30/20	3453	3470	11/30/21	3486
WH-007B			12/6/21	3451		6/10/20	3497
WH-008	12/17/14	12/5/19		3426		12/16/14	3446
WH-008A			4/15/21	3387	3438	4/15/21	3456
WH-008B			12/5/19	3422		12/5/19	3450
WH-009	2/25/15	3/27/20	3/8/21	3526		5/4/05	3549
WH-009A			3/27/20	3537		3/27/20	3593
WH-009B				3529	3554	4/15/14	3568
WH-011	10/19/13	3/25/20		3518		6/30/20	3743
WH-011A			9/16/21	3482	3632	11/15/18	3743
WH-011B				3433		3/25/20	3749
WH-101	9/23/16		12/7/21	4358	4388	12/11/19	4404
WH-102	8/11/15		10/11/21	4396	4437	6/14/17	4455
WH-103	10/8/14	3/7/19	5/27/21	4086	4304	5/27/21	4316
WH-104	10/20/11	4/2/19	6/11/20	4441	4484	4/15/19	4505
WH-105	2/7/15	1/16/20	11/19/21	4490	4523	11/15/21	4543
WH-106A	10/23/12	1/27/18	11/18/20	4088	4249	6/17/20	4267
WH-107	5/1/14	2/8/19	1/5/21	4423	4496	1/5/21	4515
WH-108	2/24/11	4/27/21	5/4/21	4211	4354	5/4/21	4351

Cavern (Well)	Date of Latest Pre-Sales sonar (Pre-2017)	Date of Latest Post-Sales sonar (2017 forward)	Most Recent OBI Date	Most Recent OBI depth (ft)	Most recent Hanging String depth (ft)	Most Recent Total Depth Date	Most Recent Total Depth (ft)
WH-109	10/21/16	5/23/19	8/9/21	3674	4546	8/9/21	4563
WH-110	5/19/03	3/4/20	3/23/20	4432	4498	3/23/20	4516
WH-111	9/8/15	6/8/21	6/8/21	3066	4440	6/8/21	4521
WH-112	2/15/13	2/21/18	9/16/21	4063	4479	2/24/18	4500
WH-113	3/14/14	1/9/19	2/3/20	4288	4598	1/17/19	4615
WH-114	5/14/15	3/31/20	8/10/21	3284	4489	8/10/21	4503
WH-115	12/17/12	3/26/20 (partial)	8/10/21	3437	3836	8/10/21	4580
WH-116	12/8/04	4/4/18	12/17/21	4563	4668	12/15/21	4684
WH-117A	9/18/13	10/21/21	10/25/21	4094		10/25/21	4555
WH-117B			9/17/21	4086	4545	6/29/20	4558

Table 5-3. Raw water injection events for Cavern BH-109 (condensed).

Date	Volume (bbls)
10/5/2013	24,165
10/6/2013	34,022
4/2/2014	1,360
4/3/2014	17,914
4/12/2014	34,322
4/16/2014	35,961
4/30/2014	13,780
5/1/2014	558
5/2/2014	87,875
5/3/2014	10,230
5/5/2014	92,905
5/6/2014	14,346
5/7/2014	22,037
5/8/2014	33,160
5/11/2014	22,599
5/12/2014	32,725
5/17/2014	88,044
5/18/2014	23,156
5/23/2014	1,114
11/11/2014	3,032
3/11/2015	601
3/8/2017	998
4/30/2017	21,208
5/1/2017	14,210
5/9/2017	27,961
5/12/2017	2,778
5/13/2017	72,928
5/14/2017	62,839
5/16/2017	32,129
5/17/2017	14,334
5/18/2017	74,195
5/19/2017	4,530
5/20/2017	54,252
5/21/2017	76,830
5/22/2017	76,059
5/23/2017	68,256
5/26/2017	75,117
5/27/2017	23,302
6/8/2017	3,645
11/5/2017	2,076
11/7/2017	40,119
11/8/2017	9,908
11/21/2017	63,388
11/22/2017	25,589
11/22/2017	37,068
11/26/2017	67,517
11/27/2017	125,221
11/28/2017	17,804
11/29/2017	19,688
12/1/2017	-3,006
5/30/2018	16,768
5/31/2018	25,072
6/1/2018	5,507
6/7/2018	4,046
9/15/2018	7,986
9/16/2018	3,946
10/2/2018	52,625
10/5/2018	34,473
10/6/2018	51,321
10/7/2018	24,778
10/11/2018	26,834
10/12/2018	50,765
10/13/2018	22,166
10/14/2018	28,027
10/16/2018	39,253
10/19/2018	55,512
10/23/2018	48,290
10/24/2018	9,189
10/25/2018	49,146
10/26/2018	63,116
10/27/2018	37,853
10/29/2018	25,905
11/8/2018	45,714
11/9/2018	21,038
11/13/2018	47,594
11/14/2018	43,577
11/14/2018	43,577
11/20/2018	47,591
11/21/2018	28,108
11/24/2018	49,528
11/25/2018	69,334
11/26/2018	4,881
11/28/2018	34,110
11/29/2018	49,037
11/30/2018	3,223
12/14/2018	6,146
12/15/2018	3,202
12/16/2018	1,806
5/11/2019	36,879
10/3/2019	48,658
10/6/2019	44,618
10/13/2019	25,265
10/30/2019	11,259
10/31/2019	49,488
11/2/2019	69,065
11/4/2019	48,974
11/5/2019	63,554
11/6/2019	68,132
11/10/2019	47,537
11/14/2019	80,039
11/15/2019	2,856
11/16/2019	40,467
11/18/2019	65,003
11/21/2019	46,370
11/23/2019	62,288
11/24/2019	30,992
11/25/2019	44,971
9/4/2020	66,612
9/5/2020	45,214

6. CAVERN SHAPE DATABASE

The first measure for tracking the expenditure of drawdowns for a cavern is the computation of cavern volume gained due to dissolution of salt; when a volume of salt equal to 15% of the prior cavern volume has been added, then a drawdown has been spent. However, other factors relating to the change in cavern shape and its effect of the stress conditions in the surrounding salt may cause the loss of an available drawdown. The most reliable determination of the change in cavern geometry is a sonar measurement, which can detect detailed changes to cavern geometry, and allow for comparisons between it and the results of geomechanical analyses for an assessment of the effect of that change. Often however, sonar measurements are not available after a significant influx of raw water into a cavern. In these circumstances, an analytical tool (SANSMIC) is needed to predict the change to cavern geometry. The SANSMIC model (Weber et al., 2014) is being used to calculate the expected evolution of each sale cavern geometry as a result of leaching due to the injected fresh water used to withdraw the sale oil. This kind of analysis is useful for tracking the potential impact of sales on the cavern geometry without the cost associated with measuring the new geometry with sonar surveys. This analysis will also be used to estimate the volume changes of the caverns as a result of sales.

In 2021, there was a significant amount of activity at SPR due first to a national program to sell substantial amounts of oil for inventory reduction, followed by a program to lease storage space for excess oil supplies created by the 2020 COVID pandemic and its resulting economic impact. As a result, 25 caverns were identified in CAVEMAN to have had more than 10,000 bbls of raw water injected; this is Sandia's current criterion for modeling the leaching of these caverns with SANSMIC. Among these caverns, four had sonars performed. Table 6-1 has the raw water totals for 2021 for the 25 caverns that were modeled for leaching (sorted by injected volume). Because of the lack of post-injection sonars for 2021, Sandia chose to use SANMIC analyses to estimate the changes in cavern shapes and evaluate for any potential impact to drawdown availability.

Table 6-1. List of SPR caverns with over 10,000 bbls raw water injection in 2021.

Cavern	Barrels of Raw Water Injection (CAVEMAN)	2021 Sonar	Sonar Date	First Water Injection	Volume Water Injected Prior to Sonar (bbls)
BH110	3,702,557				
WH109	3,314,679				
WH114	3,133,393				
BM111	3,120,849				
WH115	2,894,850				
BH111	2,765,449	x	9/8/2021	4/7/2021	1,066,519
BM110	2,750,194	x	8/25/2021	4/2/2021	1,518,323
BH106	2,262,584				
BH107	2,209,892				
BM103	2,032,528				
WH011	1,917,039				
BC017	1,838,930				

Cavern	Barrels of Raw Water Injection (CAVEMAN)	2021 Sonar	Sonar Date	First Water Injection	Volume Water Injected Prior to Sonar (bbls)
BC101	1,836,795				
BM109	1,338,477				
BM104	1,296,760				
BM102	1,233,699				
BH108	1,086,411				
WH117	802,682	x	10/21/2021	5/20/2021	802,682
WH112	751,237				
BC019	645,218				
BH109	430,555				
WH111	142,035	x	6/8/2021	4/22/2021	134,887
BH112	99,292				
BH113	61,419				
BC018	13,492				
Total	41,686,733				

Among the caverns in Table 6-1 that were analyzed using SANSMIC, eight caverns in particular were predicted to have experienced significant changes to their shapes in the bottom portions of the caverns. These caverns were BM-102, BM-103, and BM-110; BH-110 and BH-111; WH-11 and WH-109; and BC-19. The caverns' predicted shapes were compared to the results of the corresponding geomechanical analyses. The following categories of shape changes were flagged as having the potential to alter the number of baseline available drawdowns (that is, available drawdowns defined by the shape of the cavern): an extension of an existing feature where a stress concentration may occur; the creation of a new feature that would create a stress concentration location; or the change in location or magnitude of the maximum diameter of the cavern. In the following examination of the eight caverns with notable shape changes, none were found to change the number of baseline available drawdowns. However, it is important to evaluate these shape changes and their potential effects on drawdown availability, so that mitigating actions may be taken during future drawdowns.

Because the Bryan Mound site has a large amount of anhydrite and clay impurities in its salt, it naturally has unusual and often very irregular and asymmetrical cavern shapes. SANSMIC uses axisymmetric representations of cavern geometries, which smooths over the asymmetries, but not necessarily the vertical distribution of irregular geometry. Figure 6-1 shows the predicted changes to caverns BM-102 and BM-103. The 2020 sonar measurement of BM-102 confirmed the presence of a flare near the floor of the cavern. Because of this, the string was perforated prior to the 2021 drawdown activities. The analyses predict the creation of a shelf at the EOT depth of 4045 feet. The predicted radial extent of the shelf is approximately 5 feet. Because the shelf diameter is significantly less than the cavern's maximum diameter, and it occurs in the brine-filled portion of the cavern, there is no expected effect on the overall cavern integrity.

For BM-103, leaching has extended the largest diameter of the cavern, at the original OBI depth near the mid-height of the cavern. The radius is predicted to have grown 4-5 feet in that location. For a full bottom-to-top drawdown of the cavern, the cavern volume is expected to increase by 15%; if this growth is uniform across the entire height, that would result in a radial growth of 7.2%. At the location of maximum cavern diameter, the average cavern radius was recorded by the 2019 sonar to be about 136 feet; a 7.2% increase in radius would be nearly 10 feet. The radial growth predicted by SANSMIC is less than that, so the growth is less than would be expected for a full drawdown. Therefore, there are no expected effects on the drawdown availability for BM-103.

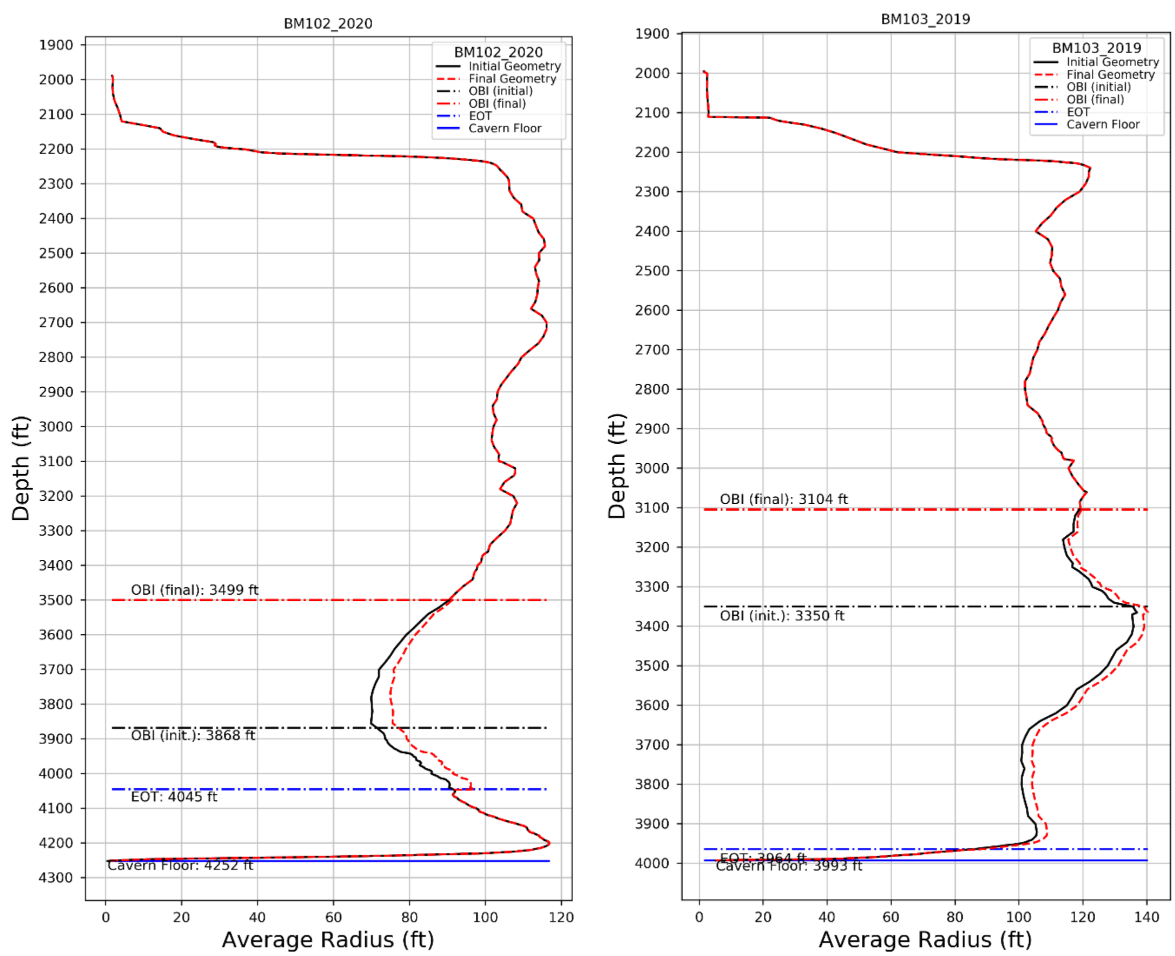

Figure 6-1. Predicted changes to geometry of BM-102 and BM-103 from recent leaching activities, from SANSMIC calculations.

Figure 6-2 shows the predicted growth in BM-110 in comparison to pre- and post-drawdown sonars. The 2016 sonar showed a nearly vertical cavern wall from the floor to ~3,500 ft. Leaching between the 2016 and 2021 sonars (red dashed line on left figure) was predicted to grow the cavern radius up to ~3,500 ft, with more growth near the EOT. The 2021 sonar (black line on right figure) confirmed the expected growth. The small amount of leaching that has occurred since the 2021 sonar is predicted to result in only minimal cavern growth. The overall resulting cavern shape between the EOT and OBI does not present a concern with respect to the number of available drawdowns.

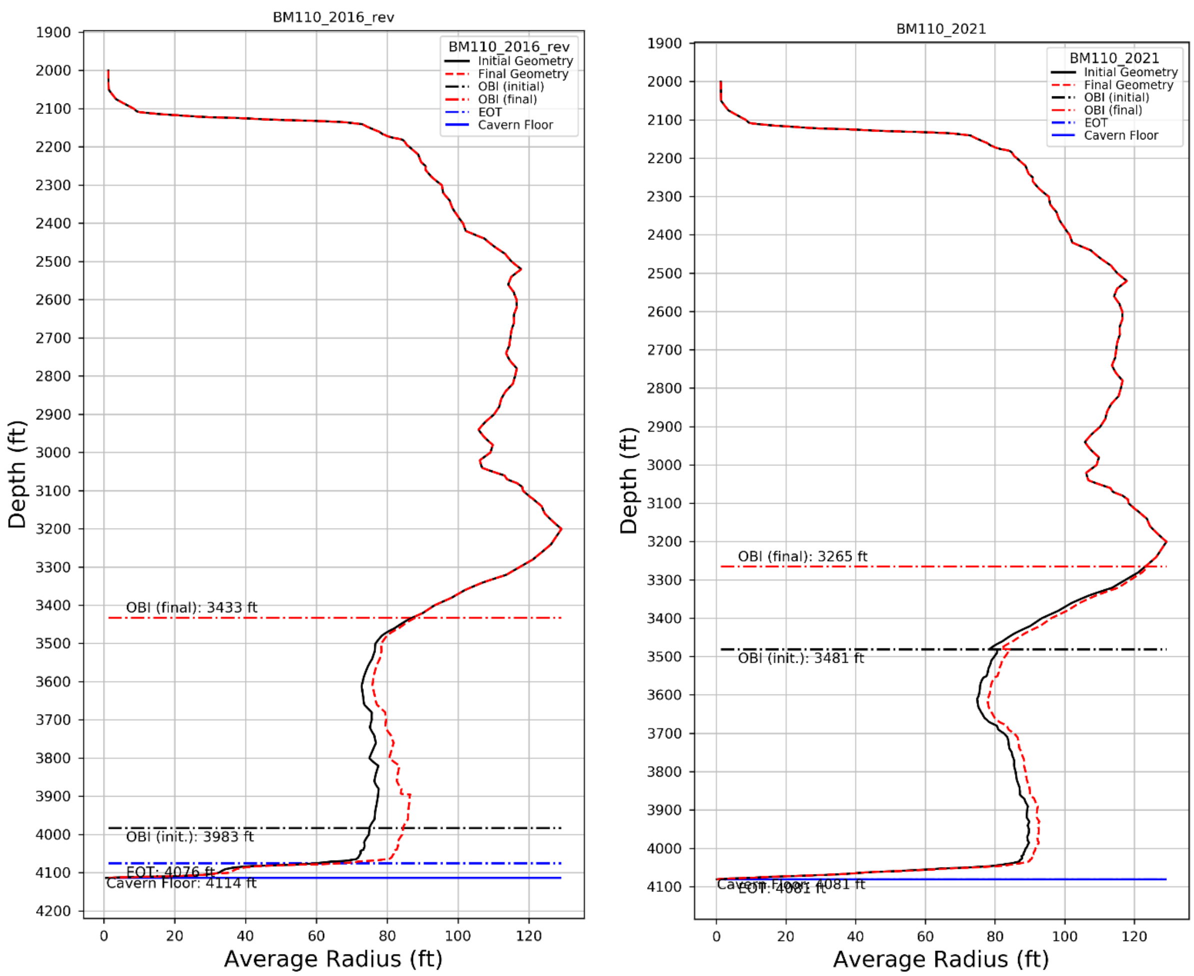

Figure 6-2. Predicted changes to geometry of BM-110 from recent leaching activities, from SANSMIC calculations, in comparison to 2016 (left) and 2021 (right) sonars.

Figure 6-3 shows the predicted growth in caverns BH-110 and BH-111 as compared to earlier sonars. Both caverns had pre-existing flares at the bottom, and the EOT was also close to the bottom, so it would be expected that there would be some growth in those flares. Figure 6-3 shows that SANSMIC predicts such growth, but also substantial growth up to the final OBI locations in both caverns. The overall characteristics of the predicted cavern shapes did not change, nor did the maximum cavern diameters, so there is no expected effect of drawdown availability.

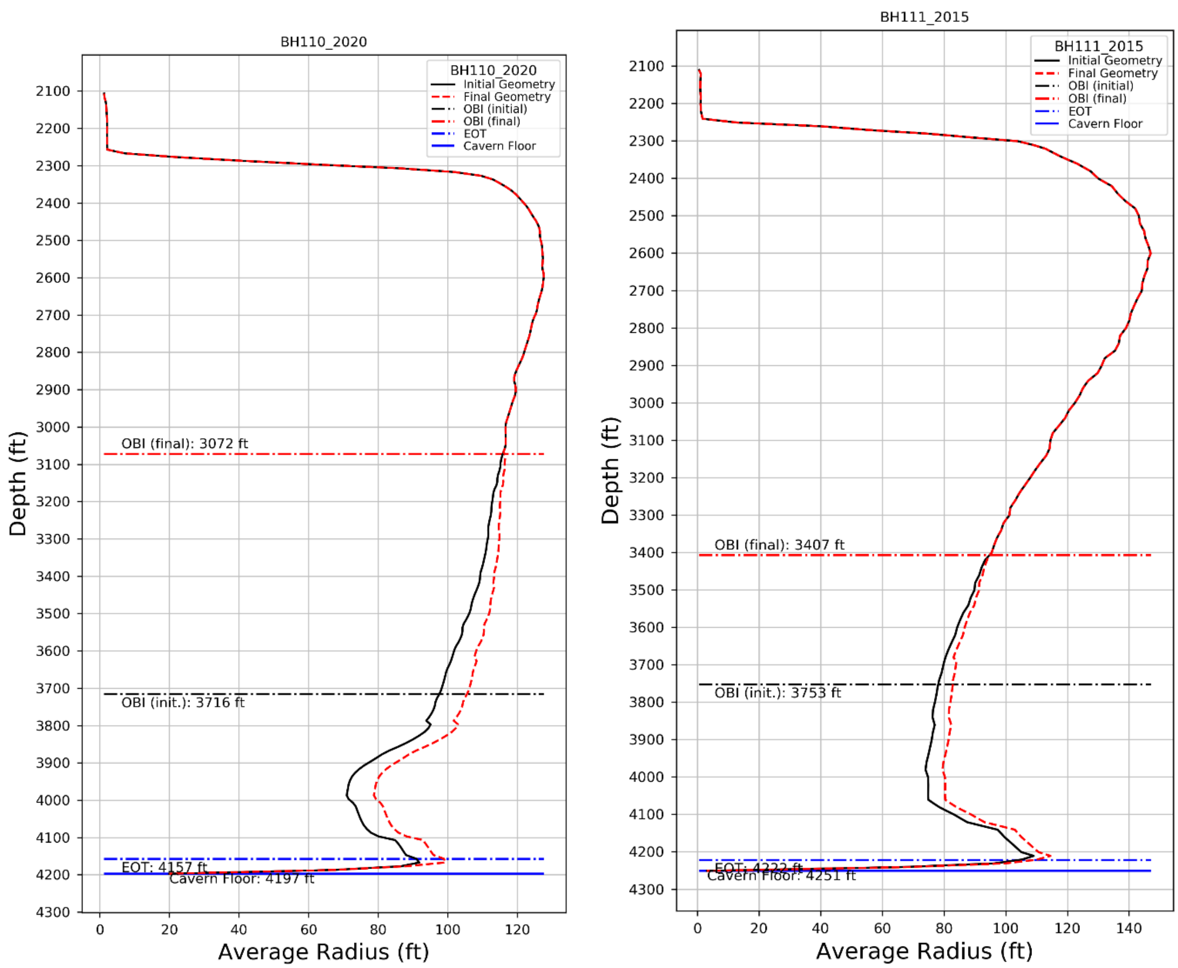

Figure 6-3. Predicted changes to geometry of BH-110 and BH-111 from recent leaching activities, from SANSMIC calculations.

Figure 6-4 shows the predicted changes to caverns WH-109 and WH-11. The caverns at West Hackberry are naturally nearly axisymmetric, so SANSMIC approximations using prescribed axial symmetry are very close to field conditions. The 2019 sonar measurements of WH-109 present a cavern with a slightly larger diameter at the top than at the bottom. The predicted changes to WH-109 make the cavern more cylindrical. There are no geometric features of concern, so there is no effect on drawdown availability. On the other hand, cavern WH-11 developed a significant flair from drawdown activities in 2018-19. The effects of the flare were analyzed with Sandia's West Hackberry geomechanical model, and it was determined that the flare posed no cavern integrity concerns. For the 2021 drawdown activities in WH-11, the EOT was moved higher to avoid growing the flare at the floor. SANSMIC predicts that the flare remained unchanged but raising the EOT caused a shelf to develop above the flare. The primary concern about such a shelf would be the creation of stress conditions leading to a salt fall. The location of this shelf is below the current EOT, so there would be no impact to a hanging string from a salt fall there. For the same reasons cited in earlier drawdown reports – the location of the shelf and flare in the brine section of the cavern, its long distance from other caverns – there is no cavern shape effect on drawdown availability for WH-11.

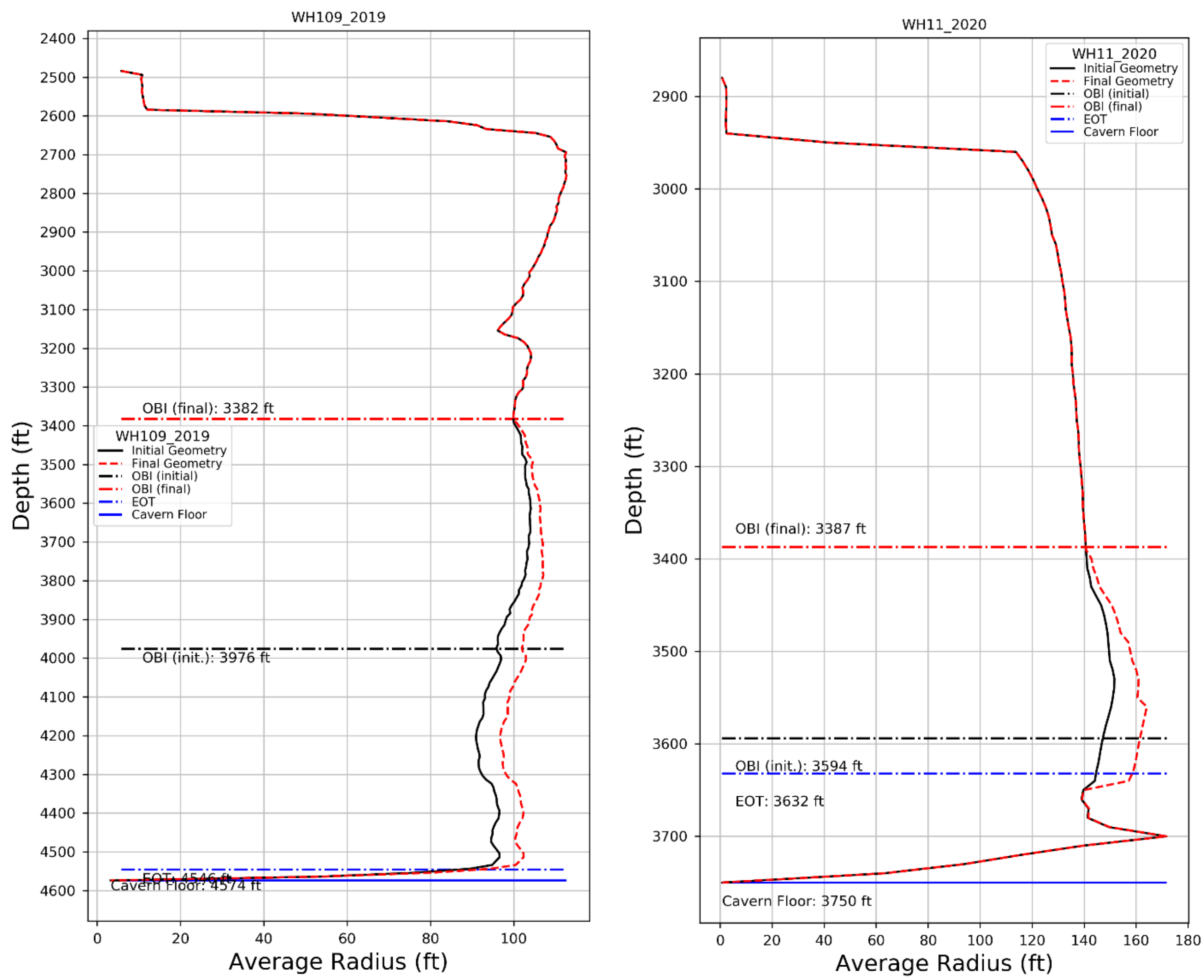

Figure 6-4. Predicted changes to geometry of WH-109 and WH-11 from recent leaching activities, from SANSMIC calculations.

Figure 6-5 shows the predicted changes to cavern BC-19. The 2019 sonar found an extended feature at the bottom of the cavern, and a shelf approximately 200 feet above that. The EOT was very close to the floor in 2021, and fresh water injected from this location would be expected to grow the flare on the floor. That is indeed what was predicted by SANSMIC – cavern growth was limited to the flare in the foot. This extended feature will increase the likelihood of a fracture forming there. However, much like for WH-11, the location of the feature in the brine-filled portion of the cavern, coupled with its location far from other caverns, keeps the feature from affecting the drawdown availability of BC-19.

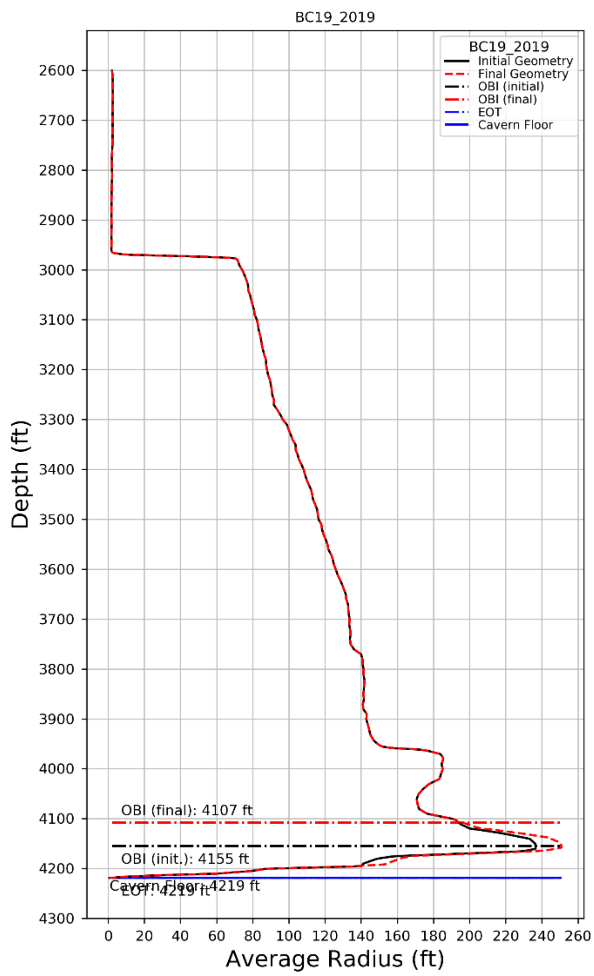

Figure 6-5. Predicted changes to geometry of BC-19 from recent leaching activities, from SANSMIC calculations.

7. EVALUATION OF EXPENDITURE OF AVAILABLE DRAWDOWNS

The primary measure for determining the expenditure of available drawdowns is tracking and calculating the accumulated volume change due to raw water injection activities. For the annual assessments of spent drawdowns, it was decided to use an estimate of cavern volume as of 1/1/2010 as the starting value from which to determine the percentage of volume change due to raw water injection and thus compute spent drawdowns. This value was determined from the most recent sonar-measured volume of the cavern prior to 1/1/2010, and then calculating changes to the cavern volume from between those dates based on fluid exchanges and salt removal. The various fluid exchange values were obtained from the daily site reports (the "DSR" database). Beginning with 1/1/2010, raw water injection volumes were used to calculate a running total of volume of salt removed from each cavern. The volume of salt removed from each cavern was calculated to be 15% of the volume of raw water injected into the cavern.

The several types of data used to calculate the number of spent drawdowns for each cavern have varying degrees of reliability. The values taken from the DSR database for raw water exchanges are the most reliable dataset, in terms of both accurate measurements and consistent reporting. The cavern volumes measured from sonars have varying degrees of uncertainty based on measurement technique (for example, assumed values of fluid temperature used to calculate speed of sound), data processing methods, and point density. In addition, several sonars used to estimate cavern volumes only measured a portion of the cavern. Estimates of cavern closure due to creep comes from closure estimates based on CAVEMAN calculations with wellhead pressure, and records (often incomplete) of bleed-off volumes during normal operations. Therefore, the numbers in the tables in this section of the report may be modified in the future as additional quality assurance and quality control are applied to the existing data.

Table 7-1 and 7-2 present the current estimated volume of each cavern, the amount of volume increased due to raw water injections, and the resulting number of drawdowns spent and the resulting available drawdowns; volumes are given in units of one thousand barrels (MB). The first two columns in Table 7-1 identify each cavern's last sonar, which was used to establish the final volume for each cavern; using the most recent sonar to calculate the final volume limits the chance of data errors propagating through the calculation. The next two columns in Table 7-1 show the calculated volume of raw water injected into each cavern since the date of its last sonar, and the resulting estimated current (1/1/2022) cavern volume based on the amount of salt removed. The first four columns of Table 7-2 list the estimated current (1/1/2022) cavern volume, the estimated cavern volume as of 1/1/2010, the raw water added to the cavern since 2010, and calculated percentage growth of the volume of the cavern due to leaching based on the raw water volume. The final three columns list the baseline available drawdowns from each cavern (from Table 3-1 through Table 3-4 in Section 3), the number of spent drawdowns in decimal form, and the current available drawdowns. The current available drawdowns are the difference between the baseline drawdowns and the truncated value of the spent drawdowns.

Using 15% cavern growth as the threshold for the expenditure of an available drawdown, three caverns were identified in 2019 as having spent an available drawdown due to the amount of volume created by raw water/leaching operations calculated from 1/1/2010 to the present: BH-104, BM-113, and WH-111. In 2020, two additional caverns have been added to this list: BM-114 and WH-105. In the 2021 report, one more cavern was been added: BH-101. For this year's report, which includes fluid exchanges during 2021, no new caverns have exceeded 15% cavern growth. These rows for these six caverns are highlighted in **bold** in Table 7-2.

For the five caverns that have spent one available drawdown due to leaching-induced volume increases (and resulting pillar thickness decreases), the baseline volume for determining the next spent drawdown will be based on the cavern volume due to the first drawdown. The calculation follows the following method.

The change in the number of drawdowns is calculated iteratively from the 2010 cavern volume. Given the original cavern volume, V_0, a volume of raw water injected since 2010 of V_w, and the volume of dissolution, V_d, then

$$V_d = V_w \times 0.15$$
$$V_1 = V_0 \times 1.15$$
$$V_d^{(1)} = V_1 - V_0$$

where V_1 is the total cavern volume after the first expended drawdown, and $V_d^{(1)}$ is the change in volume needed to achieve that drawdown. There are two cases to consider. In the first case, not enough water has been injected to dissolve enough salt to equal a change in cavern volume equivalent to one full drawdown. For that case $V_d^{(1)} > V_d$ and the number of spent drawdowns is

$$N_{spent} = \frac{V_d}{V_d^{(1)}}.$$

The value of N_{spent} will always be less than 1 for this case. The definitions of V_d and $V_d^{(1)}$can be used to simplify the criteria for this case to be when

$$V_0 > V_w$$

then a drawdown has not been spent and the expression for N_{spent} becomes

$$N_{spent} = \frac{V_w}{V_0}.$$

In the second case, enough water has been injected to dissolve enough salt to equal a change in cavern volume equivalent to at least one drawdown. For that case, $V_d^{(1)} \leq V_d$, or

$$V_0 \leq V_w$$

and

$$V_2 = V_1 \times 1.15$$
$$V_d^{(2)} = V_2 - V_1$$
$$N_{spent} = 1 + \frac{V_d - V_d^{(1)}}{V_d^{(2)}}.$$

This can be generalized, by calculating the integer number of drawdowns spent, n, using the optimization formulation as follows.

$$\max n \quad \text{s.t.} \quad 0.15\, V_w > (1.15^n - 1)\, V_0$$
$$n \in \{1,2,3, \dots\}$$

The total number of drawdowns spent is then calculated as

$$N_{spent} = n + \frac{0.15\,V_w - (1.15^n - 1)\,V_0}{1.15^{n+1}\,V_0}.$$

For example, in Table 7-2, the following values are given for BH-104: volume of cavern on 1/1/2010, 12,519 MB = V_0; raw water volume since 1/1/2010, 15,629 MB = V_w. For BH-104 $V_0 < V_w$, which places it in the second case where enough water has been injected to dissolve enough salt to equal a change in cavern volume equivalent to at least one drawdown. The number of spent drawdowns can then be calculated assuming a value of $n = 1$

$$N_{spent} = 1 + \frac{0.15(15{,}624MB) - (1.15^1 - 1)\,12{,}519MB}{1.15^{1+1}12{,}519MB} = 1 + 0.21.$$

The expenditure of the first drawdown was based on adding 15% volume to the cavern due to leaching based on the volume of 1/1/2010, 12,519 MB. To achieve this, an equivalent amount of fresh water would have to be added to the cavern. The value of 15,629 MB clearly exceeds that, and the corresponding value for spent drawdowns in Table 7-2 is 1 + 0.21. Therefore, as a first approximation, the next spent drawdown will not occur until a new 15% volume increase occurs based on the new baseline volume of 12,519*1.15 = 14,397 MB. The choice of this baseline does not take account for the additional cavern closure due to salt creep. If a cavern volume is calculated based on the 1/1/2010 volume and the added volume due to salt water, the current volume of BH-104 would be calculated to be 12,519 + (15%)*15,629 = 14,862 MB. However, the estimated volume as of 1/1/2020, which includes tracking additional fluid exchanges from the cavern, is listed as 14,531 MB. The smaller value for cavern volume reflects closure due to salt creep. In addition, there is some uncertainty in these volume estimates.

In the case of BM-113, over two drawdowns have been spent due to raw water injection used to grow the cavern through remedial leaching. The baseline volume for determining the next spent drawdown due to leaching-induced volume increase will be based on 2 equivalent drawdowns, or (Volume of 1/1/2010)*$(1.15)^2$. Because of this situation, BM-113 will be targeted for more specific evaluation in future geomechanical analyses to determine the long-term effect on future available drawdowns. The last three columns of Table 7-2 are summarized in Table 8-1 in the conclusions section.

In addition to the caverns that have at least one spent drawdown, the following caverns have gained at least 5% additional volume since 2010 due to leaching operations, and thus should be tracked closely as additional leaching occurs: BC-18, BC-20, BH-102, BH-105, BH-106, BH-107, BH-108, BH-109, BH-110, BH-111, BM-102, BM-103, BM-104, BM-108, BM-110, BM-111, BM-115, BM-116, WH-11, WH-102, WH-103, WH-106 (the highest at 13%), WH-109, WH-113, WH-114, WH-115, and WH-117.

Table 7-1. Estimated cavern volumes on 1/1/2022 for each cavern.

Cavern	Last full cav. sonar, date	Last sonar, cav. vol. (MB)	Raw Water since Last Sonar (MB)	Est. cav. vol. 1/1/2022 (MB)
BC015	8/26/19	16,395	-	16,395
BC017	8/28/19	11,198	1,839	11,474
BC018	12/29/20	20,001	13	20,003
BC019	9/24/19	12,001	645	12,098
BC020	9/25/18	9,147	-	9,147
BC101	10/7/19	11,973	1,837	12,249
BC102	5/2/17	9,468	1,957	9,762
BH101	9/11/12	14,244	1,194	14,423
BH102	8/29/13	12,530	4,226	13,164
BH103	10/4/11	12,583	177	12,610
BH104	4/17/18	14,352	3,302	14,847
BH105	10/26/20	12,944	-	12,944
BH106	3/31/15	12,652	4,097	13,267
BH107	9/17/19	12,190	2,661	12,589
BH108	12/17/19	10,994	1,875	11,275
BH109	2/10/20	12,446	515	12,523
BH110	3/23/20	12,225	4,241	12,861
BH111	4/9/15	13,355	3,747	13,917
BH112	5/7/15	12,639	278	12,681
BH113	9/14/15	11,921	376	11,977
BH114	**10/13/21**	12,739	0	12,739
BM001	6/17/96	6,538	439	6,604
BM002	5/11/15	6,902	5,859	7,781

Cavern	Last full cav. sonar, date	Last sonar, cav. vol. (MB)	Raw Water since Last Sonar (MB)	Est. cav. vol. 1/1/2022 (MB)
BM004	9/26/12	19,051	2,366	19,406
BM005	6/26/18	33,555	5	33,556
BM101	8/23/16	13,311	-	13,311
BM102	3/17/20	11,237	1,234	11,422
BM103	8/12/19	12,782	2,033	13,087
BM104	9/7/11	11,896	1,339	12,097
BM105	8/22/12	11,345	125	11,364
BM106	5/5/16	13,148	3,000	13,598
BM107	5/10/16	12,246	301	12,291
BM108	4/9/19	13,033	2	13,033
BM109	5/2/16	12,221	1,996	12,520
BM110	5/4/16**	10,902	-	10,902
BM111	3/19/20	12,979	3,121	13,447
BM112	5/10/17	11,046	-	11,046
BM113	8/21/12	8,993	874	9,124
BM114	**12/27/21**	9,773	-	9,773
BM115	**4/5/21**	10,533	-	10,533
BM116	**4/5/21**	11,891	-	11,891
WH006	10/19/14	7,357	-	7,357
WH007	6/8/20	12,727	0	12,727
WH008	12/3/19	9,910	-	9,910
WH009	3/27/20	8,814	-	8,814
WH011	3/25/20	8,499	2,593	8,888

Cavern	Last full cav. sonar, date	Last sonar, cav. vol. (MB)	Raw Water since Last Sonar (MB)	Est. cav. vol. 1/1/2022 (MB)
WH101	9/23/16	10,429	51	10,437
WH102	8/11/15	10,330	658	10,429
WH103	3/6/19	10,681	-	10,681
WH104	4/2/19	10,314	-	10,314
WH105	1/15/20	12,025	-	12,025
WH106	10/23/12**	11,945	-	11,945
WH107	2/8/19	11,296	44	11,303
WH108	**4/27/21**	10,628	-	10,628
WH109	5/23/19	11,149	3,553	11,682
WH110	3/16/20	11,548	-	11,548
WH111	9/8/15**	10,186	-	10,186
WH112	2/21/18	10,790	1,860	11,069
WH113	1/9/19	10,721	269	10,761
WH114	3/31/20	11,067	3,752	11,630
WH115	3/26/20	11,254	3,547	11,786
WH116	4/4/18	10,446	267	10,486
WH117	**10/21/21**	11,841	-	11,841

* BM113 underwent remedial leaching between 2011-2013. A full cavern sonar has not been performed, and cavern volume is assumed to be accurate only to ±5% at this point.

** Partial sonar only taken since the specified date

Table 7-2. Calculations of volume increases due to leaching and the resulting spent and available drawdowns for each cavern. Please note that some volumes may not exactly match the 2020 report, as this table is now automatically calculated from CAVEMAN data. Greyed cavern entries indicate decommissioned caverns.

Cavern	Est. cav. vol. 1/1/2022 (MB)	Est. cav. Vol. 1/1/2010 (MB)	Raw Water since 1/1/2010 (MB)	Current normalizing cavern volume	Leaching since 1/1/10 (% cav)	Baseline Available DD 2019 (Section 3)	DD spent due to leaching since 1/1/10	Available DD (Baseline – Spent)
BC015	16,446	16,576	169		0%	1	0.01	1
BC017	11,192	11,423	1,847		2%	1	0.16	1
BC018	20,001	18,441	9,710		8%	1	0.53	1
BC019	11,998	11,990	854		1%	5	0.07	5
BC020	*9,141*	*9,537*	*3,416*		*5%*	*0*	*0.36*	*0*
BC101	11,891	12,559	2,117		3%	5	0.17	5
BC102	9,625	9,895	2,014		3%	5	0.20	5
BH101	14,156	12,703	12,874	14,608	15%	5	1 + 0.00	4
BH102	12,788	12,047	8,061		10%	5	0.67	5
BH103	11,944	12,482	1,555		2%	5	0.12	5
BH104	14,660	12,569	18,295	14,455	22%	5	1 + 0.06	4
BH105	12,636	12,137	8,975		11%	5	0.74	5
BH106	12,919	12,530	4,168		5%	5	0.33	5
BH107	12,097	12,649	5,719		7%	5	0.45	5
BH108	10,869	11,033	6,124		8%	5	0.56	5
BH109	12,318	11,826	4,658		6%	5	0.39	5
BH110	12,080	12,218	6,140		8%	5	0.50	5
BH111	13,312	13,765	5,587		6%	5	0.41	5
BH112	12,479	13,031	439		1%	5	0.03	5

Cavern	Est. cav. vol. 1/1/2022 (MB)	Est. cav. Vol. 1/1/2010 (MB)	Raw Water since 1/1/2010 (MB)	Current normalizing cavern volume	Leaching since 1/1/10 (% cav)	Baseline Available DD 2019 (Section 3)	DD spent due to leaching since 1/1/10	Available DD (Baseline – Spent)
BH113	11,716	12,518	537		1%	5	0.04	5
BH114	12,877	12,650	3,794		4%	5	0.30	5
BM001	6,776	6,718	117		0%	2	0.02	2
BM002	*7,672*	*7,060*	*7,175*	*8,119*	*15%*	*0*	*1 + 0.00*	*0*
BM004	19,329	17,540	3,378		3%	2	0.19	2
BM005	33,532	34,293	462		0%	1	0.01	1
BM101	13,302	13,474	2,802		3%	5	0.21	5
BM102	11,237	11,481	5,290		7%	5	0.46	5
BM103	12,770	14,914	6,142		6%	2	0.41	2
BM104	11,943	11,495	3,486		5%	3	0.30	3
BM105	11,359	10,976	126		0%	2	0.01	2
BM106	13,411	13,290	3,058		3%	5	0.23	5
BM107	12,222	12,186	3,008		4%	5	0.25	5
BM108	13,026	12,068	4,809		6%	2	0.40	2
BM109	12,277	12,606	2,203		3%	3	0.17	3
BM110	10,920	10,683	4,195		6%	5	0.39	5
BM111	12,977	12,725	7,474		9%	5	0.59	5
BM112	11,004	12,131	191		0%	5	0.02	5
BM113	8,854	6,745	15,015	8,920	33%	5	2 + 0.06	3
BM114	9,513	8,552	9,175	9,834	16%	5	1 + 0.01	4
BM115	10,584	10,203	5,762		8%	5	0.56	5
BM116	11,613	12,067	7,539		9%	5	0.62	5

Cavern	Est. cav. vol. 1/1/2022 (MB)	Est. cav. Vol. 1/1/2010 (MB)	Raw Water since 1/1/2010 (MB)	Current normalizing cavern volume	Leaching since 1/1/10 (% cav)	Baseline Available DD 2019 (Section 3)	DD spent due to leaching since 1/1/10	Available DD (Baseline – Spent)
WH006	*7,259*	*17,365*	*5,872*		*5%*	*0*	*0.34*	*0*
WH007	12,860	14,037	215		0%	5	0.02	5
WH008	9,903	10,097	70		0%	2	0.01	2
WH009	8,955	8,874	254		0%	1	0.03	1
WH011	8,611	8,880	6,174		10%	5	0.70	5
WH101	10,348	11,098	308		0%	5	0.03	5
WH102	10,336	7,056	2,667		6%	5	0.38	5
WH103	10,661	11,877	4,418		6%	5	0.37	5
WH104	10,330	11,225	2,175		3%	5	0.19	5
WH105	12,016	10,769	14,141	12,384	20%	5	1 + 0.04	4
WH106	12,040	11,103	9,666		13%	5	0.87	5
WH107	11,292	11,886	1,082		1%	5	0.09	5
WH108	10,838	12,355	675		1%	5	0.05	5
WH109	11,162	11,361	6,355		8%	5	0.56	5
WH110	11,599	12,633	2,706		3%	5	0.21	5
WH111	10,921	9,253	11,967	10,641	19%	5	1 + 0.04	4
WH112	10,564	11,229	2,119		3%	5	0.19	5
WH113	10,807	11,793	3,649		5%	5	0.31	5
WH114	11,209	10,837	8,854		12%	5	0.82	5
WH115	11,348	10,969	6,895		9%	5	0.63	5
WH116	10,486	11,000	441		1%	5	0.04	5
WH117	11,710	11,738	3,811		5%	5	0.32	5

* BM113 underwent remedial leaching between 2011-2013. A full cavern sonar has not been performed, and cavern volume is assumed to be accurate only to ±5% at this point.

8. CONCLUSIONS

All of the SPR caverns have been or are being evaluated for the number of baseline available drawdowns while maintaining cavern structural integrity. Two factors that contribute to a greater number of available drawdowns are homogeneous salt and cavern shapes resembling candlesticks with smooth, axisymmetric surfaces. West Hackberry caverns have these characteristics, and thus its caverns tend to have the most available drawdowns. Big Hill caverns also do very well in this regard, although there are more surface irregularities than at West Hackberry; an updated analysis of these caverns is currently underway. Several Bayou Choctaw caverns have irregular shapes, but cavern stability is aided by slow-creeping salt and lower stresses due to their shallower location in the dome. The stability of the Bryan Mound cavern field is currently undergoing an updated analysis that includes a detailed examination of many of the irregular features found in these caverns. Almost universally, the Phase 1 caverns (those caverns created prior to DOE ownership of the properties) have limited drawdown capacity.

The criteria and processes that will be used to track the expenditure of drawdowns for each cavern have been identified. Over the past year, the databases required to initialize and track the volume changes to each cavern, and their effects on cavern integrity and thus to drawdown capacity, have either been constructed or have been initiated.

Based on the assessment of fluid exchanges and the resulting increase of cavern volumes due to leaching, and the changes to cavern shapes from raw water injection operations, the following statements can be made about the available drawdowns for the SPR caverns as of January 2022:

- Six caverns have spent an available drawdown due to the amount of volume created by raw water/leaching operations calculated from 1/1/2010 to the present: BH-104, BM-113, and WH-111 were identified in the 2019 report, BM-114 and WH-105 were added in the 2020 report, and BH-101 was added in the 2021 report. No new caverns have been added in this 2022 report. In the case of BM-113, over two drawdowns have been spent due to raw water injection used to grow the cavern from its previous smaller volume. Because of this situation, BM-113 will be targeted for more specific evaluation in future geomechanical analyses to determine the long-term effect on future available drawdowns. The current status of all the caverns is summarized in Table 8-1.
- The following additional caverns have gained at least 5% additional volume since 2010 due to leaching operations, and thus should be tracked closely as additional leaching occurs: BC-18, BC-20, BH-102, BH-105, BH-106, BH-107, BH-108, BH-109, BH-110, BH-111, BM-102, BM-103, BM-104, BM-108, BM-110, BM-111, BM-115, BM-116, WH-11, WH-102, WH-103, WH-106 (the highest at 13%), WH-109, WH-113, WH-114, WH-115, and WH-117.
- Eight caverns were predicted to have experienced significant changes to their shapes in the bottom portions of the caverns. These caverns were BM-102, BM-103, and BM-110; BH-110 and BH-111; WH-11 and WH-109; and BC-19. The caverns' predicted shapes were compared to the results of the corresponding geomechanical analyses. The following categories of shape changes were flagged as having the potential to alter the number of baseline available drawdowns (that is, available drawdowns defined by the shape of the cavern): an extension of an existing feature where a stress concentration may occur; the creation of a new feature that would create a stress concentration location; or the change in location or magnitude of the maximum diameter of the cavern. In the examination of the

eight caverns with notable shape changes, none were found to change the number of baseline available drawdowns. In addition, this report continues the recommendation from last year's report that a sonar be performed on BM-105 as soon as possible so that its true current shapes can be measured and then included in the BM geomechanical model for analysis of its effects.

- In late December 2021, wellhead pressure data indicated that cavern BC-18 was leaking. That cavern itself was being operated in static mode; however, nearby cavern BC-17 had been undergoing significant fluid exchanges since late summer 2021. Caverns BC-15 and BC-17 have been operated as a gallery for many years, and all three of these caverns had been designated as 1-drawdown caverns prior to this incident. At the publication date of this report, it is believed that the wellbore casing in BC-18 is tight, and that a hydraulic connection has occurred between BC-18 and BC-17 that is probably located in the brine sections of the caverns. This incident and its consequences will obviously be a major topic in the 2023 drawdown report that covers 2022 SPR activities.
- One well, BH-105B, has been designated to be temporarily plugged and instrumented for casing evaluation. After evaluation, this well will be permanently plugged and abandoned due to significant casing damage at the salt/caprock interface. This change does not affect the cavern integrity or the drawdown availability of the cavern; however, ongoing casing damage may complicate future utilization of that cavern space.

Table 8-1. Summary of baseline, spent and available drawdowns.

Cavern	Baseline Available DD 2022 (Section 3)	DD spent due to leaching since 1/1/10	Available DD = Baseline - Spent
BC015	1	0.01	1
BC017	1	0.16	1
BC018	1	0.53	1
BC019	5	0.07	5
BC101	5	0.17	5
BC102	5	0.20	5
BH101	5	1 + 0.00	4
BH102	5	0.67	5
BH103	5	0.12	5
BH104	5	1 + 0.06	4
BH105	5	0.74	5
BH106	5	0.33	5
BH107	5	0.45	5
BH108	5	0.56	5
BH109	5	0.39	5
BH110	5	0.50	5
BH111	5	0.41	5
BH112	5	0.03	5
BH113	5	0.04	5
BH114	5	0.30	5
BM001	2	0.02	2
BM004	2	0.19	2
BM005	1	0.01	1
BM101	5	0.21	5
BM102	5	0.46	5
BM103	2	0.41	2
BM104	3	0.30	3
BM105	2	0.01	2
BM106	5	0.23	5
BM107	5	0.25	5
BM108	2	0.40	2
BM109	3	0.17	3
BM110	5	0.39	5
BM111	5	0.59	5
BM112	5	0.02	5
BM113	5	2 + 0.06	3
BM114	5	1 + 0.01	4
BM115	5	0.56	5
BM116	5	0.62	5
WH007	5	0.02	5
WH008	2	0.01	2
WH009	1	0.03	1
WH011	5	0.70	5
WH101	5	0.03	5
WH102	5	0.38	5
WH103	5	0.37	5
WH104	5	0.19	5
WH105	5	1 + 0.04	4
WH106	5	0.87	5
WH107	5	0.09	5
WH108	5	0.05	5
WH109	5	0.56	5
WH110	5	0.21	5
WH111	5	1 + 0.04	4
WH112	5	0.19	5
WH113	5	0.31	5
WH114	5	0.82	5
WH115	5	0.63	5
WH116	5	0.04	5
WH117	5	0.32	5

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