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2020 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 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 includes an update to the baseline drawdowns for each cavern, and provides an initial assessment of the evolution of drawdown expenditure for several caverns

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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 2020:

- Five 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, and BM-114 and WH-105 are added in this 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 9-1.
- 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: BH-101 (the largest increase, 14%), BH-102, BH-105, BH-108, BH-109, BM-108, BM-111, BM-115, BM-116, WH-11, WH-103, WH-106, WH-114, and WH-115.
- The following caverns have had significant changes to their geometry from raw water/leaching operations: BH-104, BM-111, and WH-11. A preliminary analysis indicates no effect on drawdown availability (and in the case of BH-104, no additional effect), but operating conditions on these caverns may need to be modified to prevent additional growth of the base of the cavern
- An important change from the 2019 report is that the baseline available drawdowns have been updated to 5 for all the Big Hill caverns. This is due to the recent upgrade and analysis of the Big Hill geomechanical model (Park, 2019 and 2020). Because of this, all Big Hill caverns except BH-104 have 5 available drawdowns; as stated earlier, BH-104 has spent a drawdown due to fluid exchanges and now has only four available drawdowns.
- BM-105 and BM-110 sonars were recently reexamined, and the caverns were 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 meshes for the models.

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 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: Section 2 describes the criteria used to assess the drawdown capacity for each cavern. Sections 3 and 4 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 5 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 6 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 7 includes selected predictions of cavern geometry from raw water input operations, created by the SANSMIC program. 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 8 lists the caverns evaluated for this report, and the determination of the status of spent drawdowns. Section 9 summarizes the results and provides concluding remarks.

2. DEVELOPMENT OF DRAWDOWN CRITERIA

For a long time SPR management has wanted to know how many full drawdowns are available for current SPR caverns while maintaining system integrity. The number of drawdowns for a particular cavern has been characterized by the pillar-to-diameter ratio (P/D) of adjacent caverns. Two recent studies (Rudeen and Lord, 2013; Lord et al., 2013) calculated the P/D ratios for all adjacent cavern pairs throughout the SPR using several different formulas based on specific geometric properties of the caverns. In addition, the collection of SPR geomechanical analyses of the past several years has further instructed the evaluation of available drawdowns by investigating potentially hazardous stress conditions in the salt surrounding each cavern. Several meetings were held in 2014 between Sandia, DOE/SPR, and DynMcDermott (the M&O operator at that time; they were later replaced by FFPO) to develop a technical baseline to calculate the number of drawdowns for each cavern (Sobolik et al., 2014). From those meetings, several definitions and criteria were established:

1. What is an available drawdown? In these annual drawdown reports, the following definitions will be used:
   - Full Drawdown (DD) = all of the oil removed from a full cavern with raw water (full=assuming cavern volume is ~90% oil). An equivalent definition is an increase of cavern volume by 15% due to leaching. 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).
   - Partial Drawdown (PD) is defined by a raw water injection resulting in <15% increase in cavern volume; several partial drawdowns can add up to or exceed a full drawdown.
   - Available Drawdown: 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.
2. What criteria limit drawdowns? To answer this question, the team defined three ways that a cavern may "fail":
   - Loss of cavern integrity such that oil escapes to another cavern, oil escapes to caprock or an anhydrite conduit to the environment, or a cavern collapses creating a sinkhole above (BC-7, in 1954) or at the side of a salt dome (Bayou Corne, in 2012).
   - Loss of access to stored oil due to irreparable damage to casing, irreparable damage to hanging strings, or sufficient sagging of the roof to below the oil/brine interface.
3. What does it mean to have no remaining drawdowns?
   - To have no remaining drawdowns means that from a geomechanical integrity standpoint, this cavern should not be grown any further (i.e., through raw water injection). Currently, the only caverns with zero drawdowns are caverns that have been decommissioned and oil has been removed.
   - When a cavern has only one drawdown remaining, the oil may be removed with a full raw water injection. Afterwards, any future use of this cavern needs to be reassessed for geomechanical integrity concerns.

The team also discussed the ways that field observations and measurements, and geomechanical analyses, can be used to determine the current status of a cavern and to predict future behavior. After these discussions, a table of criteria was created, shown in Table 2-1, that may be used to limit drawdowns. The table includes example caverns, a technical basis for each criterion and a description of how the example cavern illustrates it.

Table 2-1. Criteria that may be used to limit drawdowns (from 2014 meeting).

Criterion to Limit Drawdowns	Example Cavern	Technical Basis for Criterion
Sinkhole formation	BM-2	Geomechanics (GM) considerations such as predicted tensile stresses above cavern roof; literature on other similar caverns and sinkholes; based on literature, large diameter, proximity to thin caprock, BM-2 is the operational SPR cavern with highest potential for sinkhole formation, along with abandoned pre-DOE caverns BM-3, BC-4.
Cavern coalescence (probable, not absolute)	WH-6 & -9, BC-15 & -17	GM prediction of tensile stresses that could cause coalescence; also, operator judgment. Coalescence of WH-6, 9 would render them inoperable because of casing, GM considerations. Whereas BC-15, 17 are operated as a gallery now, so coalescence might be acceptable.
Oil leaking outside cavern system (casing issue)	BH (example of problem, not DD-based)	GM predictions of strains, shear and collapse stresses on casings. Emphasis on how drawdown would change existing strain, stress accumulation rates. In addition, other definitions would have to be established: What is a leak (operationally, legally)? How do we factor in casing repair? How does this affect 1-DD caverns, which may require long-term post-oil monitoring and maintenance?
Emulsions	BM-5	Not discussed, except that loss of a hanging string in BM-5 would present emulsion issues for removing the oil according to oil quality regulations.
Oil is unrecoverable outside of drastic action (e.g., new borehole)	WH-6, BM-5	Not discussed.
Fluid removal rate not worth drawdown	WH-6, BM-2	Does the difficulty of removing the oil based on allowable removal rates make this cavern worth additional drawdowns?
Edge of dome/property line	BC-20	Regulations, literature, future GM analyses.

In response to the 2015 legislation to sell approximately 200 MMB of SPR oil by 2025, Sandia was directed to develop and implement a process to continuously assess and report the evolution of drawdown capacity. To begin this process, there are two significant components to this work:

1. Complete the establishment of the baseline drawdown capacity for each cavern prior to any drawdowns. This baseline is derived from the initial cavern geometry and conditions of the salt surrounding the cavern, and is the best estimate for the most drawdowns a cavern can experience starting from its initial time of operation. This baseline estimate process is documented in Section 3 and results are documented in Section 4.
2. Determine how SPR (DOE/FFPO/Sandia) will track and account each fluid exchange (past and future) in each individual cavern and from that determine what effect that has on drawdown capacity. This process is detailed in Sections 5 – 7 with results documented in Section 8

3. 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 three, 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.

3.1. 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 3-1 and 3-2. Note that there is a cylinder of material surrounding WH 105 in the mesh shown in Figure 3-2; 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 3-3 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 3-3 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.

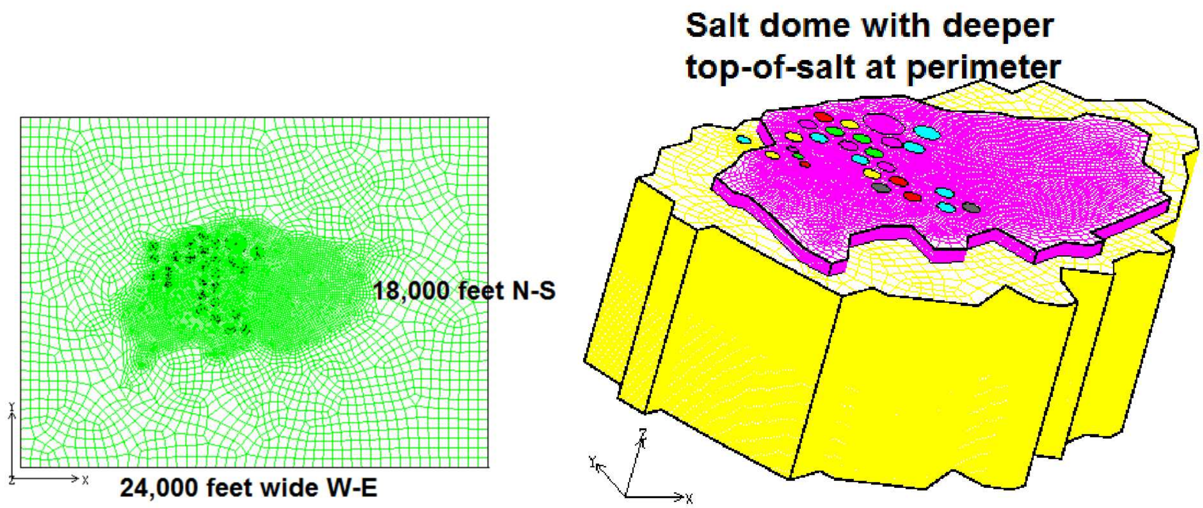

Figure 3-1. Finite mesh used for West Hackberry geomechanical calculations, showing full mesh domain and salt dome.

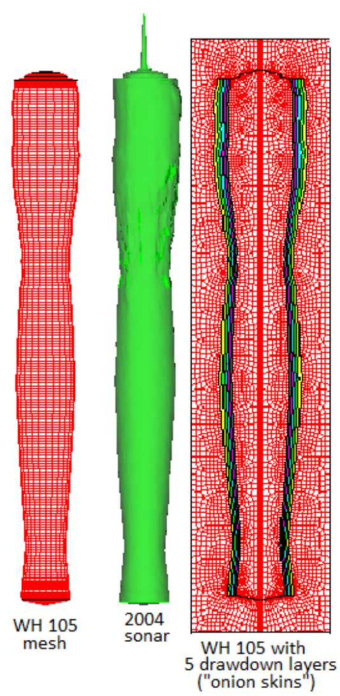

Figure 3-2. Finite element mesh sonar-measured geometry for WH 105.

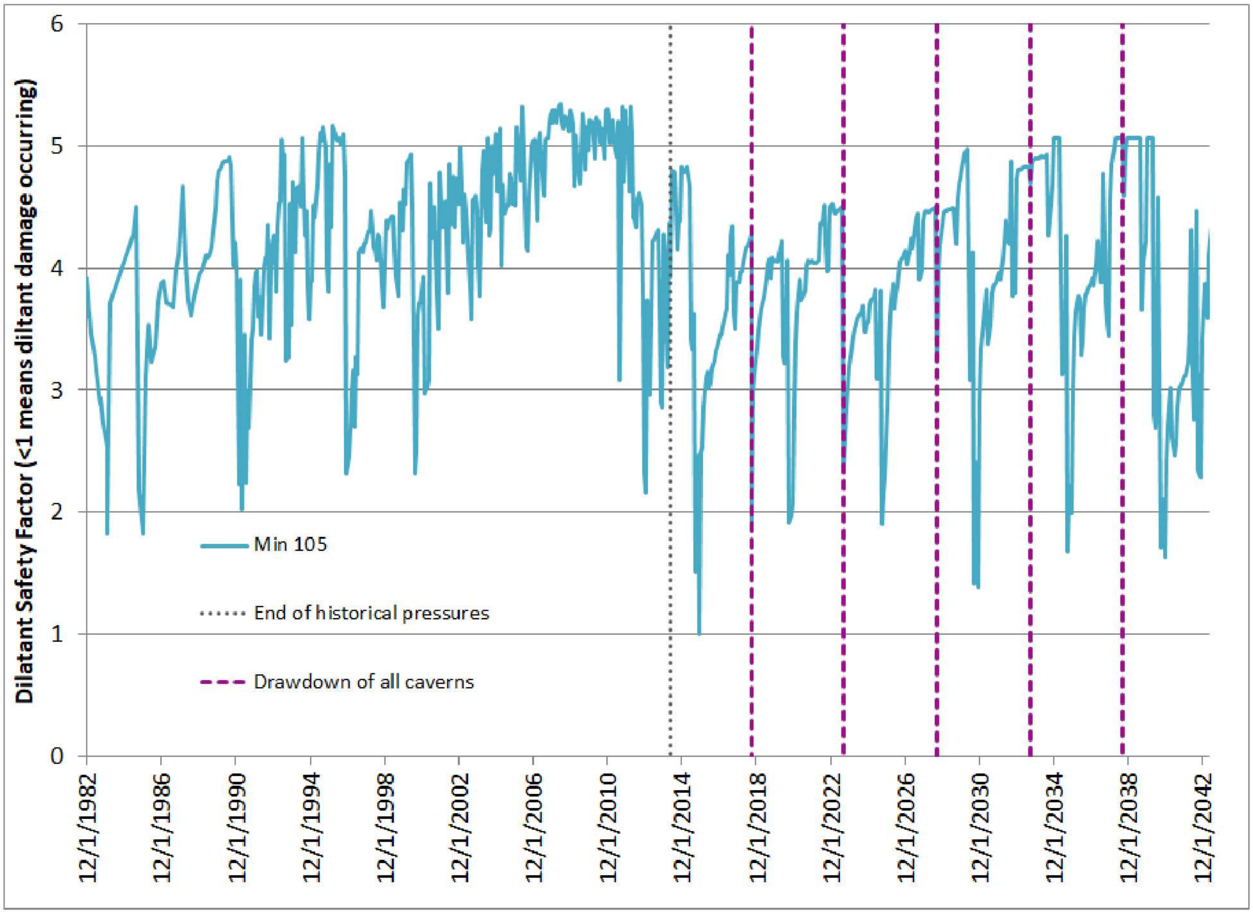

Figure 3-3. Minimum value of dilatant safety factor around WH 105.

3.2. 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 3-4. Figure 3-5 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 3-6 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 3-7 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 3-5). 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.

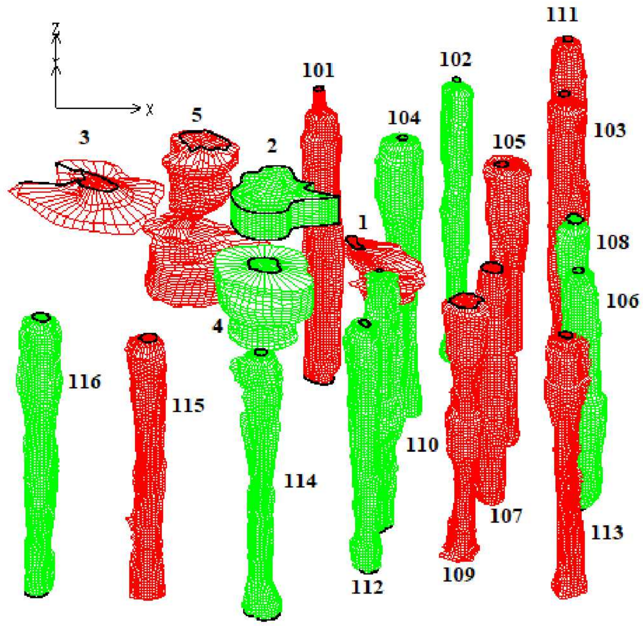

Figure 3-4. Finite element mesh of the Bryan Mound caverns.

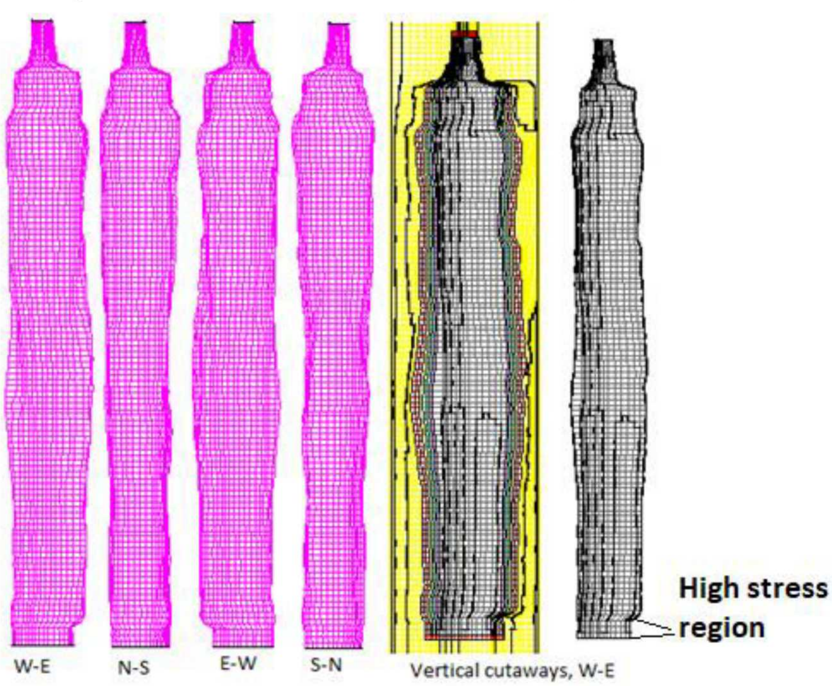

Figure 3-5. Several views of the finite element mesh for BM 101.

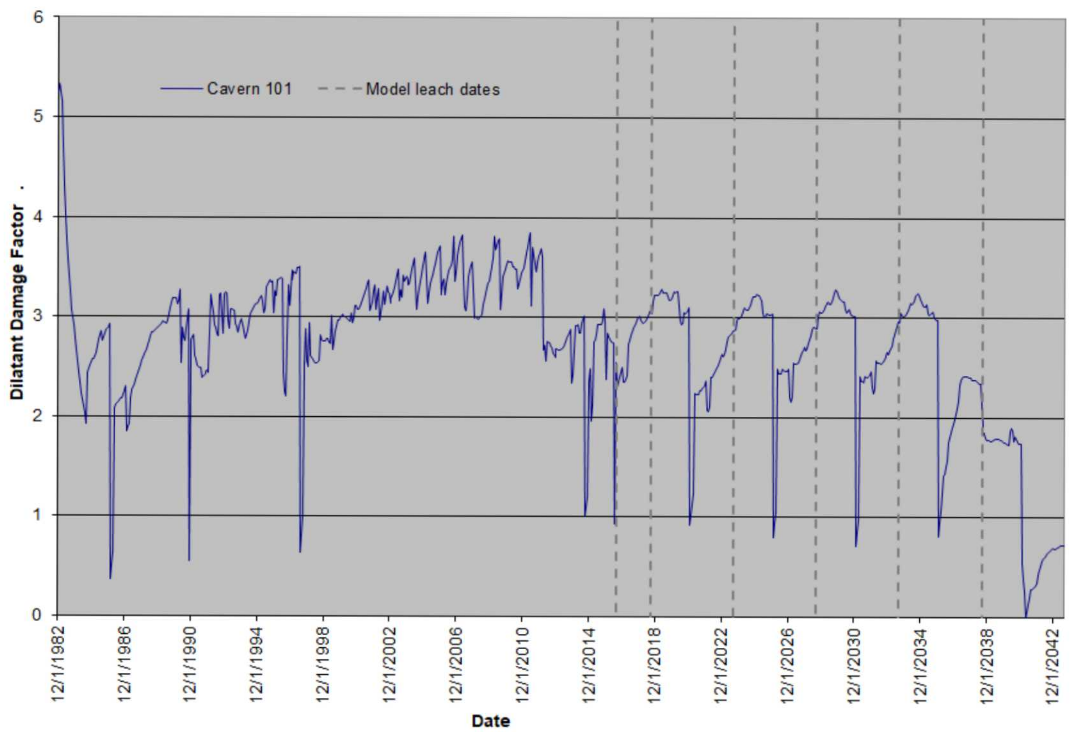

Figure 3-6. Minimum value of dilatant safety factor around BM 101.

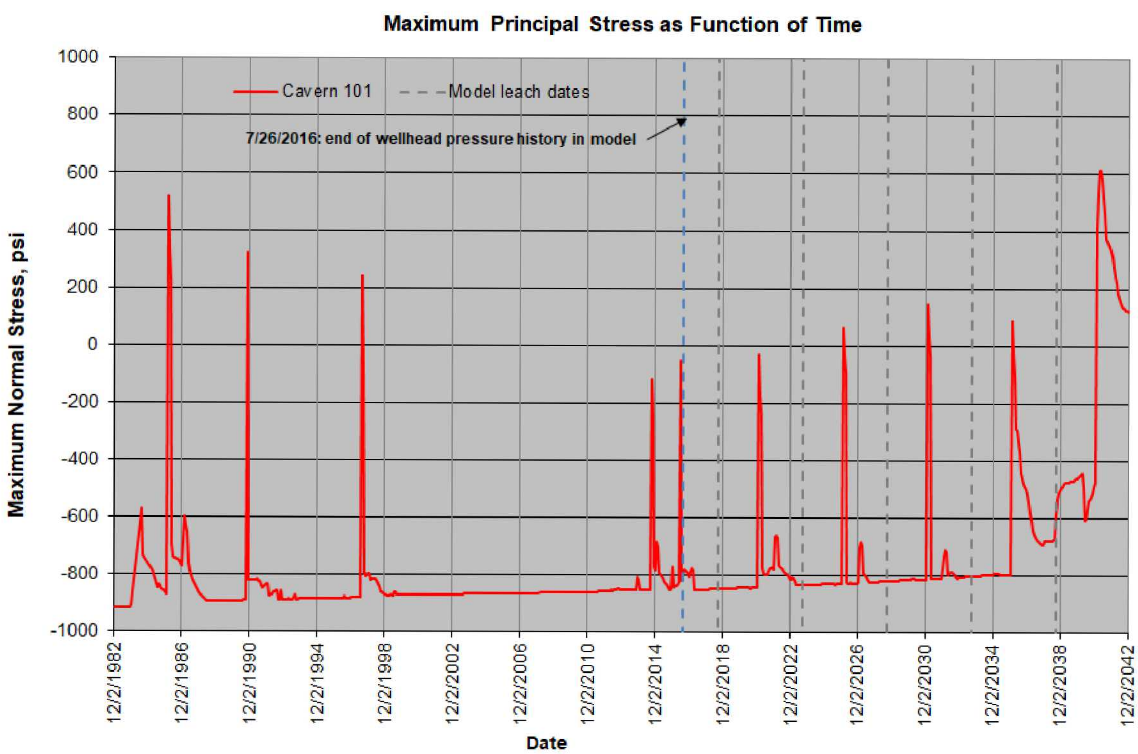

Figure 3-7. Maximum principal stress around BM 101.

3.3. 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 3-8 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 3-9 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.

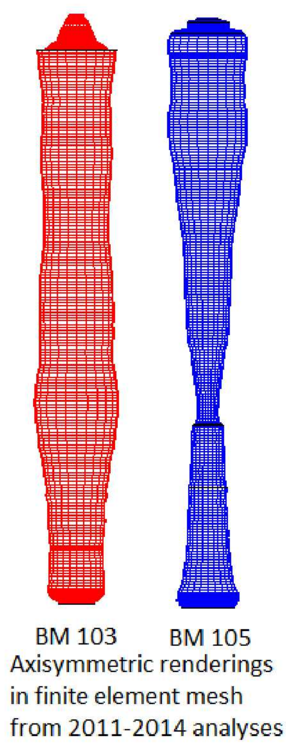

Figure 3-8: Finite element meshes for caverns BM 103 & BM 105 in the 2014 Bryan Mound model.

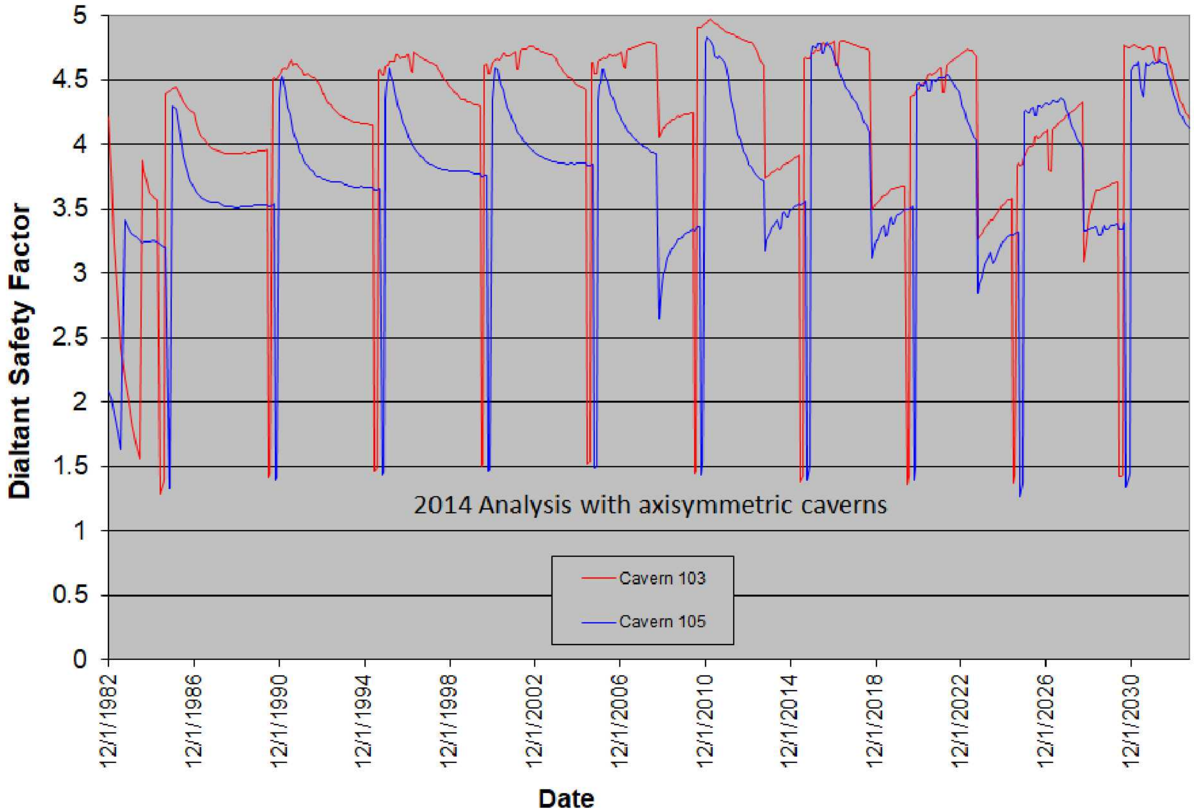

Figure 3-9. Minimum value of dilatant safety factor around BM 103 & BM 105, from the 2014 model.

3.4. 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 3-10 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 3-11 and 3-12 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.

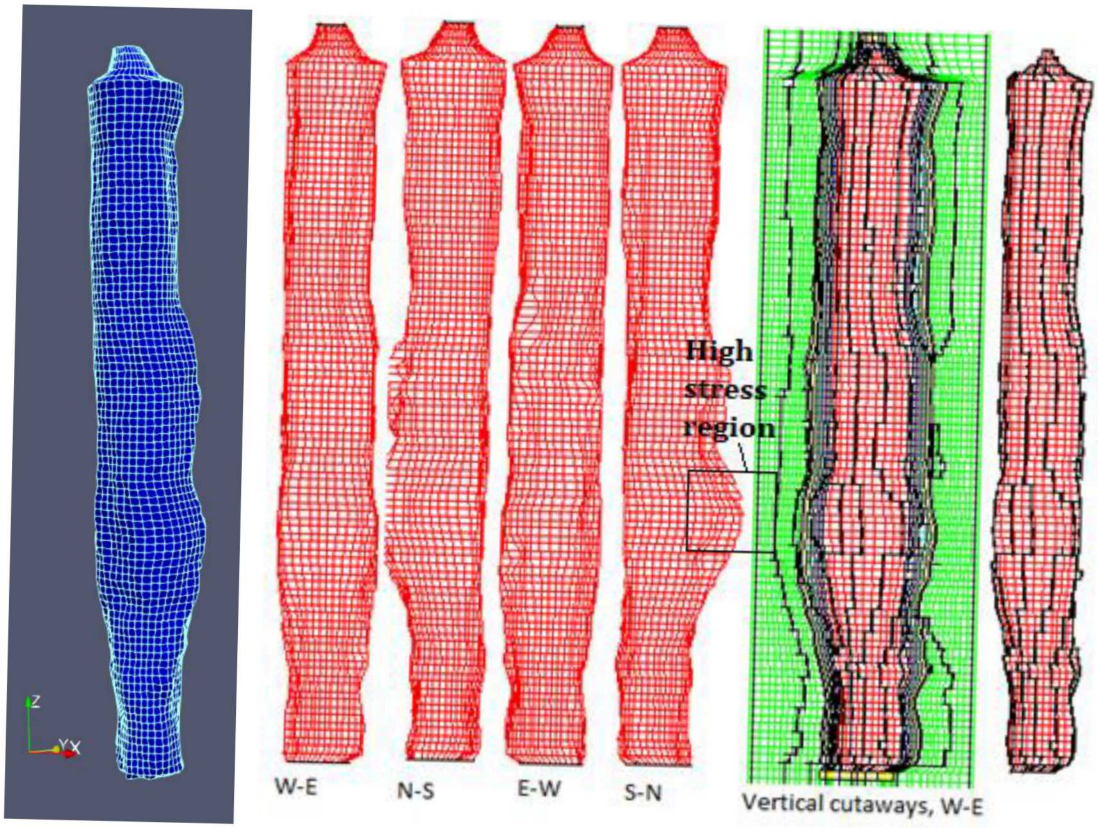

Figure 3-10: Finite element mesh for cavern BM 103 in the 2018 Bryan Mound model.

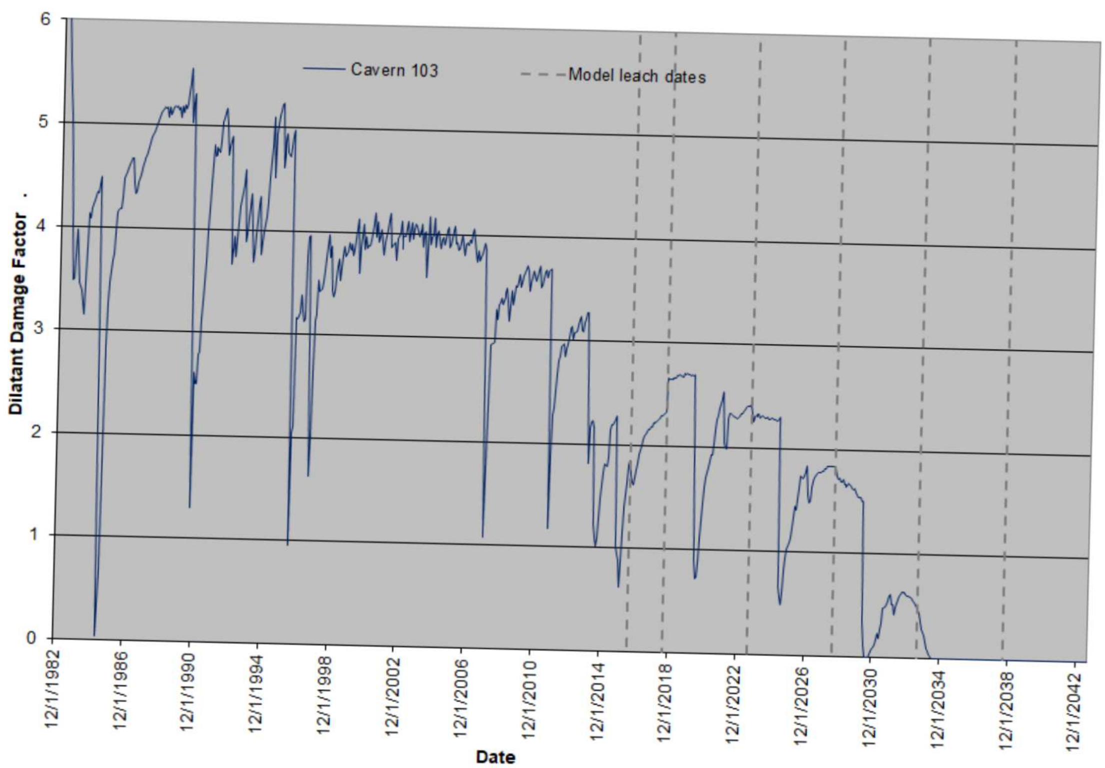

Figure 3-11. Minimum value of dilatant safety factor around BM 103, from the 2018 model.

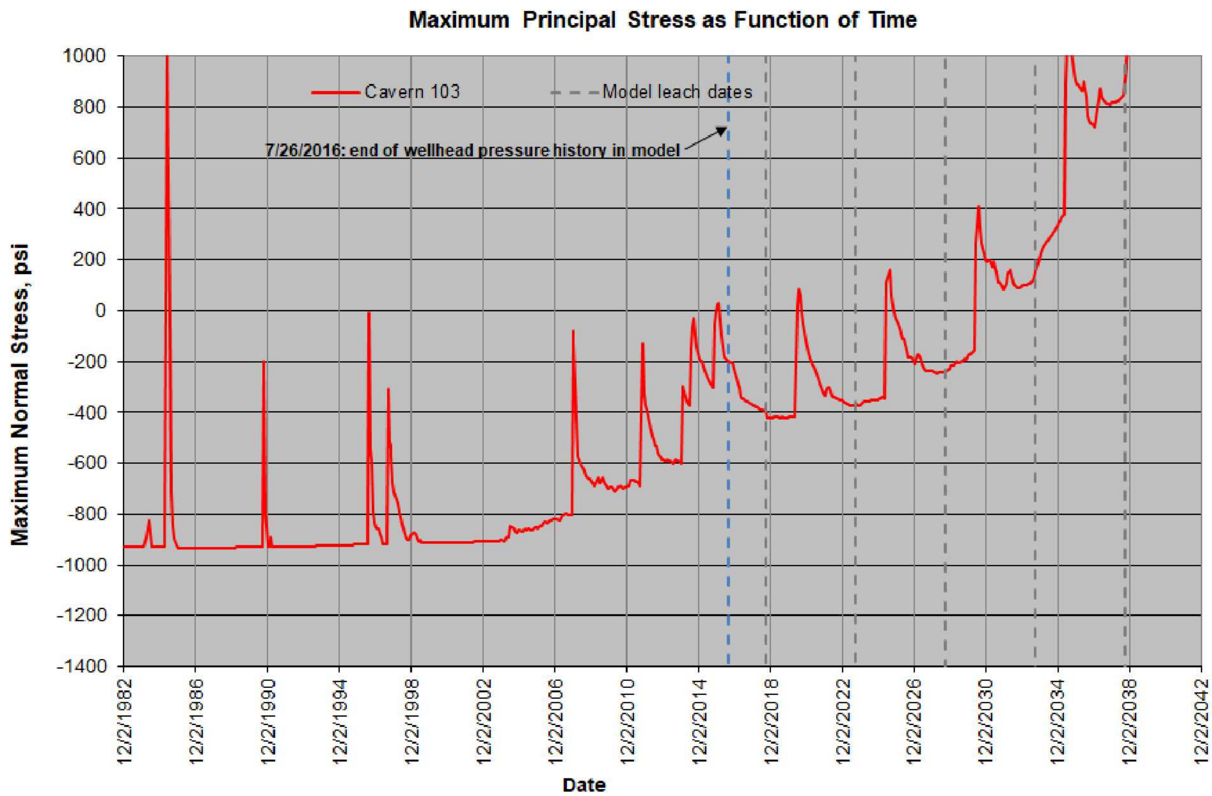

Figure 3-12. Maximum principal stress around BM 103, from the 2018 model.

3.5. 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 3-13 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 3.5). 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 3-14 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 3-13. 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.

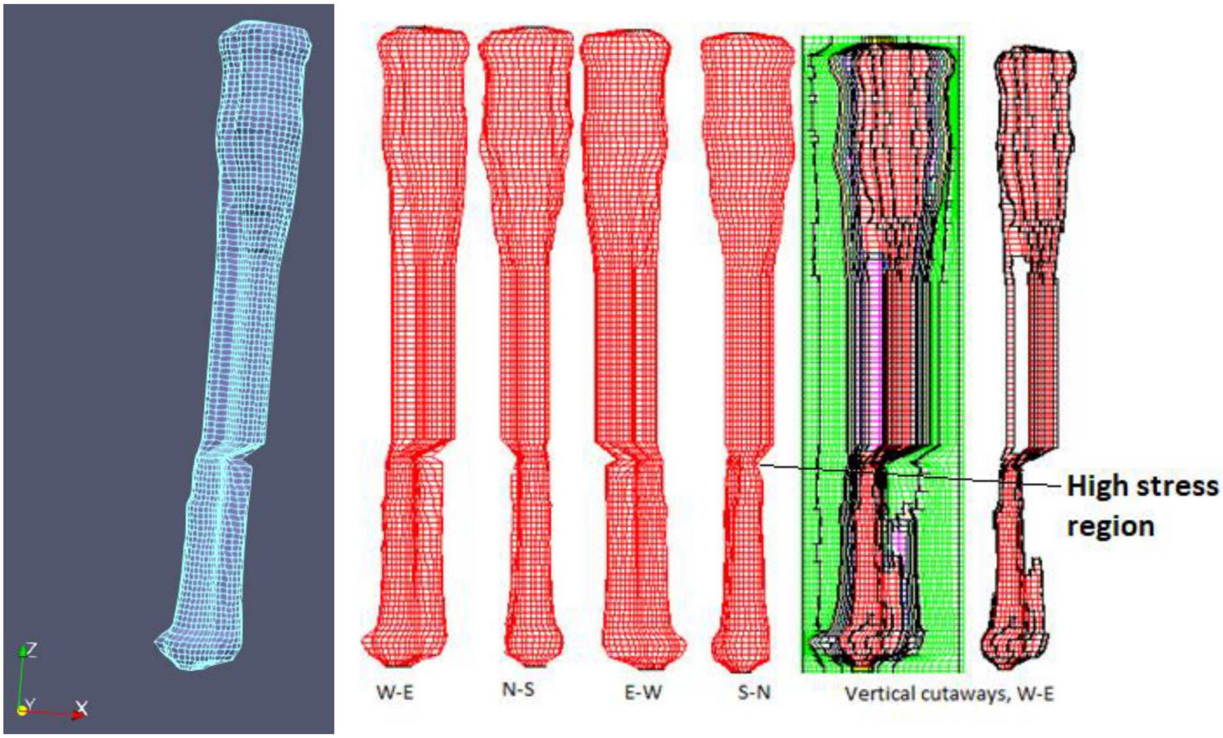

Figure 3-13: Finite element mesh for cavern BM 105 in the 2018 Bryan Mound model.

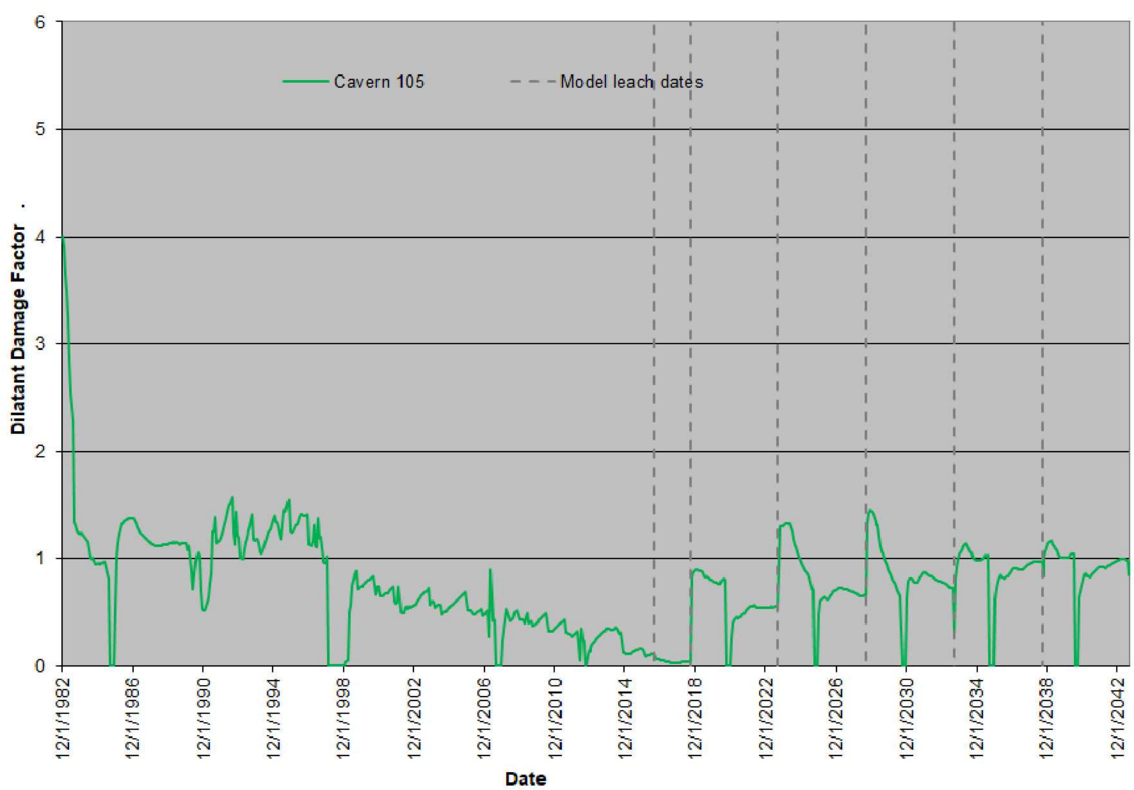

Figure 3-14. Minimum value of dilatant safety factor around BM 105, from the 2018 model.

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 3-15 is a composite geometry of BM-105 based on combining the sonars from the two boreholes. DOE has already planned for new sonars for this cavern from both boreholes in the near future; when those sonars have been obtained, a new finite element model for BM 105 will be developed, and its baseline available drawdowns reassessed.

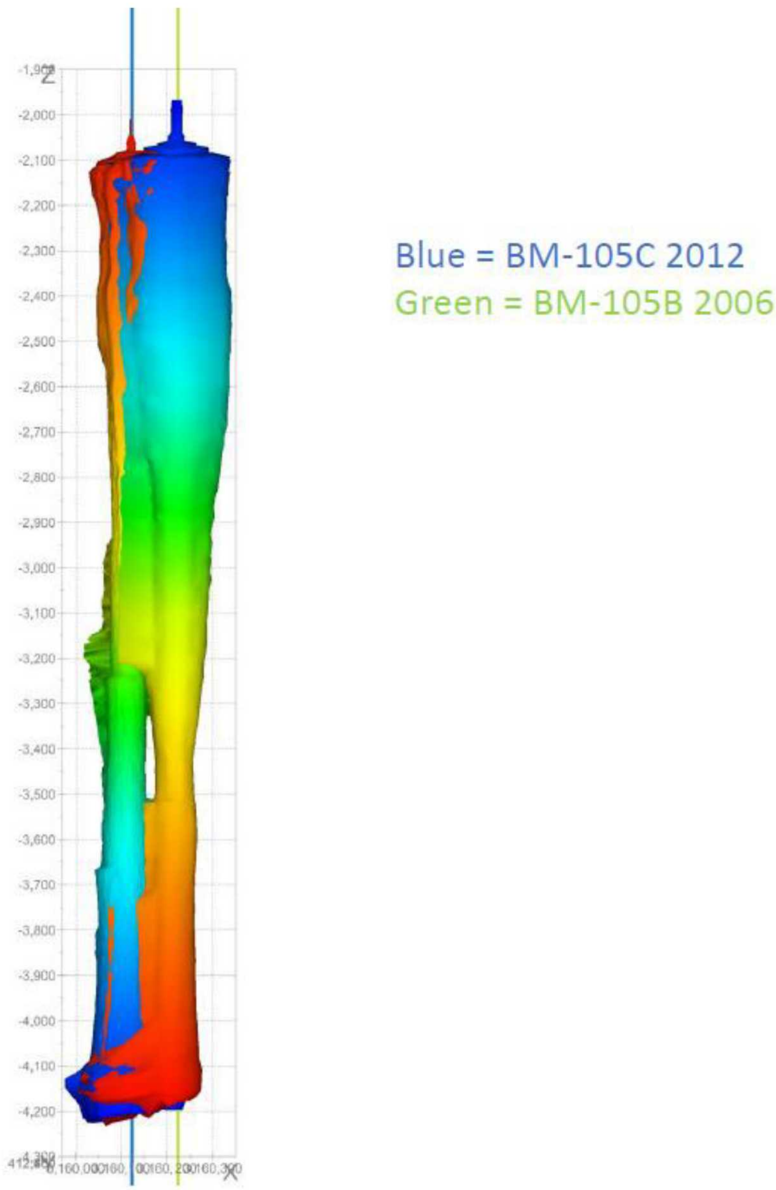

Figure 3-15. BM-105 cavern geometry based on composite sonars from both boreholes.

4. BASELINE ASSESSMENT OF CAVERN DRAWDOWN CAPACITIES - RESULTS

Using the process described in Section 3, a best estimate for the number of baseline available drawdowns currently available for each cavern has been determined. These numbers are considered the stating 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.

4.1. Bayou Choctaw

For Bayou Choctaw, until recently the best estimates for the number of baseline available drawdowns was 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 4-1 (Park, 2017b). BC19, 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 promised 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.

Table 4-1. Baseline number of available drawdowns for caverns at Bayou Choctaw.

Cavern	Basis in 2014			2020 Best 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	
BC-18	0	5	1	1	Re-examine after 1st drawdown
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

4.2. Big Hill

The 3D P/D, geomechanical, and best estimate baseline available drawdown limits for the Big Hill caverns are listed in Table 4-2. 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 BM 101 and BM 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 4-2. Baseline number of available drawdowns for caverns at Big Hill.

Cavern	Basis in 2020		
	Number of drawdowns until 3D P/D < 1	GM 2019	2020 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

Cavern	Basis in 2020		
	Number of drawdowns until 3D P/D < 1	GM 2019	2020 Best Estimate (GM 2019)
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

4.3. Bryan Mound

The current best estimate of baseline available drawdown limits for the Bryan Mound caverns are listed in Table 4-3. 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.

BM-105 and BM-110 sonars 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 similar situation has been found to occur in BM-110; however, it is suspected that instead of a bridge, there is a tall ridge jutting into the cavern. Neither of these features are currently included in the geomechanical models for these caverns. New sonars are planned for both these caverns to determine the current true internal shapes, after which these caverns will be reevaluated when the correct cavern geometries are implemented in the finite element mesh.

Table 4-3. Baseline number of available drawdowns for caverns at Bryan Mound.

Cavern	Basis		
	# Drawdowns until 3D P/D < 1	GM 2018	2020 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
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.

4.4. West Hackberry

The current best estimate of baseline available drawdown limits for the West Hackberry caverns are listed in Table 4-4. 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 4-4. Baseline number of available drawdowns for caverns at West Hackberry.

Cavern	Basis		
	Number of drawdowns until 3D P/D < 1	GM 2016	2020 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
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

Cavern	Basis		
	Number of drawdowns until 3D P/D < 1	GM 2016	2020 Best Estimate (GM 2016)
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 correct cavern geometry is implemented in the finite element mesh.

4.5. 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 4-5 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 is 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 4-5. 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
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

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-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
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

5. 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.

5.1. 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 4 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.

5.2. 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.

5.3. 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 theseannual 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 4-5 in Section 4);
2. A library of P2D calculations for each cavern (this is described in Section 6);
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 6);

4. A database to track the cumulative volume change for each cavern. This database (described in Section 6) 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 7.

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 8 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 4 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.

6. 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 6-1 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 6-2 summarizes these data for all the caverns. Table 6-3 lists all the available raw water injection data for BH-109; 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. A library of P2D calculations for each cavern is currently being developed and will be used in the drawdown assessment process for future reports.

Table 6-1. 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 6-2. 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)	Number of OBI Records	Most Recent OBI Date	Most Recent OBI depth (ft)	Number of HS Records	Most Recent HS Date	Most recent Hanging String depth (ft)	Number of TD Records	Most Recent Total Depth Date	Most Recent Total Depth (ft)
BC-15	8/25/2014		2	10/27/2016	3246			N/A	2	10/27/2016	3294
BC-15A			3	8/1/2017	3266	3		3290	3	8/1/2017	3309
BC-17	8/27/2014		1	12/9/2013	3950			N/A	1	11/2/2011	3987
BC-17A			2	7/26/2017	3937	2		3954	2	7/26/2017	3976
BC-18	9/3/2014		3	1/9/2018	3816	1		2153	3	7/17/2018	4220
BC-18A			1	10/6/2017	3820	1		4118	1	10/6/2017	4238
BC-19	10/14/2014		4	5/1/2018	4169	2		4192	4	5/1/2018	4209
BC-19A			1	12/16/2013	4183			N/A	1	5/2/2007	4215
BC-20	1/14/2014	9/25/2018	1	2/3/2014	0	1		4018	1	2/3/2014	4188
BC-20A			1	7/15/2013	2469			N/A	2	5/1/2018	4225
BC-101A	11/10/2014		2	4/26/2017	4753	3	11/25/2016	4786	2	4/26/2017	4806
BC-101B			2	9/19/2016	4737			N/A	2	9/19/2016	4797
BC-102A	2/2/2012	5/2/2017	2	5/2/2017	3505	1		5200	1	6/18/2014	5250
BC-102B			1	4/30/2018	3862			N/A	1	4/30/2018	5070
BH-101A	9/11/2012		4	8/22/2017	4044			N/A	3	8/22/2017	4105
BH-101B			2	9/29/2014	4062	1		4092	2	9/29/2014	4110
BH-102A	8/29/2013		5	8/2/2018	3376			N/A	4	8/2/2018	4040
BH-102B			4	6/27/2018	3385	1		3965	1	6/27/2013	4068
BH-103A	10/4/2011		6	7/25/2018	3718			N/A	4	7/25/2018	3765
BH-103B			4	10/10/2018	3719	5		3773	6	10/10/2018	3789
BH-104A	12/19/2012	4/17/2018	5	4/18/2018	3910			N/A	4	4/18/2018	4178
BH-104B			5	6/5/2018	3819	3		4155	4	6/5/2018	4179

Cavern (Well)	Date of Latest Pre-Sales sonar (Pre-2017)	Date of Latest Post-Sales sonar (2017 forward)	Number of OBI Records	Most Recent OBI Date	Most Recent OBI depth (ft)	Number of HS Records	Most Recent HS Date	Most recent Hanging String depth (ft)	Number of TD Records	Most Recent Total Depth Date	Most Recent Total Depth (ft)
BH-105A	7/16/2013		5	7/30/2018	3242			N/A	4	7/30/2018	4046
BH-105B			3	7/5/2018	3243	1		4008	3	7/5/2018	4025
BH-106A	3/31/2015		4	10/19/2017	4042			N/A	3	10/19/2017	4085
BH-106B			5	2/19/2018	3918	2		4065	5	2/19/2018	4096
BH-107A	8/19/2010		3	5/21/2018	3666			N/A	3	5/21/2018	4098
BH-107B			6	1/29/2018	3669	2		4083	5	1/29/2018	4104
BH-108A	4/24/2015		5	1/30/2018	3574			N/A	4	1/30/2018	4118
BH-108B			3	1/24/2018	3578	4		3986	3	1/24/2018	4104
BH-109A	5/5/2015		5	6/4/2018	3785			N/A	3	6/4/2018	4215
BH-109B			7	2/21/2018	3796	3		4193	8	2/21/2018	4212
BH-110A	4/8/2015		4	9/7/2017	4065			N/A	3	9/7/2017	4189
BH-110B			5	6/6/2018	4045	2		4170	5	6/5/2018	4193
BH-111A	4/9/2015		5	5/22/2018	3896			N/A	3	5/22/2018	4229
BH-111B			5	5/15/2017	3896	2		4222	6	5/15/2017	4244
BH-112A	5/7/2015		4	8/6/2018	4132			N/A	3	2/7/2017	4178
BH-112B			4	2/7/2017	4134	2		4167	4	2/2/2017	4177
BH-113A	9/24/2015		4	7/30/2018	4096			N/A	3	5/30/2017	4149
BH-113B			3	10/7/2015	4092	1		4129	3	9/30/2015	4147
BH-114A	10/24/2013		4	7/24/2017	3809			N/A	4	7/24/2017	4125
BH-114B			3	7/3/2018	3641	2		4060	3	7/3/2018	4109
BM-1	6/17/1996		1	7/14/2009	2725			N/A	1	7/14/2009	2754
BM-1A			5	12/4/2017	2718	3		2736	4	12/4/2017	2753
BM-2	5/11/2015		12	6/7/2016	1456			N/A	7	6/7/2016	1668
BM-2A			10	5/31/2016	1455	2		1656	7	5/31/2016	1676

Cavern (Well)	Date of Latest Pre-Sales sonar (Pre-2017)	Date of Latest Post-Sales sonar (2017 forward)	Number of OBI Records	Most Recent OBI Date	Most Recent OBI depth (ft)	Number of HS Records	Most Recent HS Date	Most recent Hanging String depth (ft)	Number of TD Records	Most Recent Total Depth Date	Most Recent Total Depth (ft)
BM-3	1/1/1979										
BM-4A	9/26/2012		4	2/6/2018	3012			N/A	4	2/6/2018	3080
BM-4B			4	4/15/2015	3022	1		3084	1	5/18/2014	3099
BM-4C			4	2/7/2018	3013	2		3068	5	2/7/2018	3070
BM-5	9/24/1987	6/26/2018	3	4/17/2018	3202	2		3221	4	4/17/2018	3241
BM-5A			4	11/5/2018	2310			N/A	4	6/27/2018	3268
BM-5C			1	10/22/2007	3226	2	4/28/2017	2098	2	2/18/2016	3234
BM-101A	8/23/2016		4	5/8/2018	4074			N/A	3	5/8/2018	4128
BM-101C			4	6/23/2016	4083	3		4108	3	6/23/2016	4128
BM-102B	7/22/2013		3	12/18/2017	4043	2		4232	2	5/17/2017	4248
BM-102C			2	5/16/2017	4124			N/A	2	5/16/2017	4230
BM-103B	6/23/2016		7	5/9/2018	3419			N/A	5	5/9/2018	3995
BM-103C			7	12/14/2017	3412	4		3964	4	2/23/2016	3984
BM-104A	9/7/2011		4	12/13/2017	4101			N/A	3	12/13/2017	4154
BM-104B			4	11/14/2018	4119	1		4146	3	10/22/2018	4166
BM-104C			3	12/12/2017	4101			N/A	3	12/12/2017	4163
BM-105B	8/22/2012		2	3/14/2017	4180			N/A	2	3/14/2017	4200
BM-105C			3	3/13/2017	4179	3		4200	2	11/18/2014	4218
BM-106A	5/5/2016		6	3/7/2017	3742	3		3791	6	3/7/2017	3808
BM-106B			4	5/15/2018	3665			N/A	4	5/15/2018	3820
BM-106C			2	2/22/2017	3746	3		3779	3	2/22/2017	3796
BM-107A	5/10/2016		4	1/10/2017	3980	1		4011	4	1/10/2017	4030
BM-107B			3	5/10/2018	3975			N/A	3	5/10/2018	4011
BM-107C				11/20/2014	3979	3	11/4/2016	3722		11/20/2014	4008

Cavern (Well)	Date of Latest Pre-Sales sonar (Pre-2017)	Date of Latest Post-Sales sonar (2017 forward)	Number of OBI Records	Most Recent OBI Date	Most Recent OBI depth (ft)	Number of HS Records	Most Recent HS Date	Most recent Hanging String depth (ft)	Number of TD Records	Most Recent Total Depth Date	Most Recent Total Depth (ft)
BM-107C			2	11/20/2014	3979	Note	11/11/2016	0	2	11/20/2014	4008
BM-108A	6/20/2016		3	4/18/2018	3661			N/A	3	4/18/2018	4148
BM-108B			5	12/5/2017	3639	1		4118	5	12/5/2017	4142
BM-108C			3	12/14/2015	4068			N/A	3	12/14/2015	4142
BM-109A	5/2/2016		3	11/30/2017	4032	3		4052	5	11/30/2017	4072
BM-109B			2	12/10/2018	3548	1		4073	3	12/10/2018	4176
BM-109C			3	4/18/2018	4049			N/A	3	4/18/2018	4075
BM-110A	5/4/2016		5	8/2/2017	3958	4		4072	5	8/10/2017	4089
BM-110B			2	7/31/2017	3958			N/A	2	7/31/2017	4070
BM-110C			3	8/1/2017	3958			N/A	2	9/4/2014	4116
BM-111A	8/23/2016	4/24/2018	3	4/24/2018	3427			N/A	3	4/24/2018	4137
BM-111B			4	12/5/2017	3420	3		4097	4	12/5/2017	4110
BM-112A	8/29/2006	5/10/2017	3	3/21/2017	3922			N/A	3	3/21/2017	3944
BM-112C			4	8/17/2017	3920	3		3818	5	8/17/2017	3952
BM-113A	8/21/2012		6	2/8/2018	3408	2		3668	4	8/14/2017	4068
BM-113B			1	12/26/2012	2656	3	3/27/2015	2165	1	12/26/2012	4072
BM-114A	1/18/2012		4	9/12/2017	3905			N/A	3	9/12/2017	4103
BM-114B			11	6/20/2018	3910	1		4097	8	6/20/2018	4105
BM-115A	9/13/2011		2	6/27/2017	4008			N/A	2	6/27/2017	4104
BM-115B			6	6/26/2017	4008	3		4084	3	9/2/2015	4103
BM-116A	9/14/2011		3	1/17/2017	3588			N/A	3	1/17/2017	4216
BM-116B			6	6/20/2018	3728	1		4215	4	6/20/2018	4232
WH-6	10/19/2014										
WH-7	5/19/2015										

Cavern (Well)	Date of Latest Pre-Sales sonar (Pre-2017)	Date of Latest Post-Sales sonar (2017 forward)	Number of OBI Records	Most Recent OBI Date	Most Recent OBI depth (ft)	Number of HS Records	Most Recent HS Date	Most recent Hanging String depth (ft)	Number of TD Records	Most Recent Total Depth Date	Most Recent Total Depth (ft)
WH-8	12/17/2014										
WH-9	2/25/2015										
WH-11	10/19/2013	2/28/2018	2	8/16/2017	3502	2	8/16/2017	3721	2	8/16/2017	3736
WH-101	9/23/2016										
WH-102	8/11/2015										
WH-103	10/8/2014		3	5/9/2017	4106	2	5/9/2017	4306	2	9/20/2016	4324
WH-104	10/20/2011										
WH-105	2/7/2015										
WH-106	10/23/2012		3	12/22/2016	4140	3	12/22/2016	4080	3	12/22/2016	4288
WH-107	5/1/2014										
WH-108	2/24/2011	5/7/2018									
WH-109	10/21/2016		5	10/25/2016	4570	5	10/25/2016	4326	5	10/25/2016	4588
WH-109	10/21/2016			?	4469		?	4326		?	4588
WH-110	5/19/2003	10/24/2017									
WH-111	9/8/2015		3	11/16/2017	2980	2	11/16/2017	4517	2	11/16/2017	4531
WH-112	2/15/2013										
WH-113	3/14/2014		2	5/2/2017	4428	1	5/2/2017	4614	1	1/21/2016?	4622
WH-114	5/14/2015		2	8/15/2017	4184	2	8/15/2017	4207	2	8/15/2017	4510
WH-115	12/17/2012		3	3/10/2017	4214	1	1/4/2013	4589	3	3/10/2017	4606
WH-116	12/8/2004	4/4/2018									
WH-117	9/18/2013	5/22/2018									

Table 6-3. Raw water injection events for Cavern BH-109.

Date	Volume (bbls)
12/30/1999	11,970
12/31/1999	5,985
2/26/2000	570
2/29/2000	10,180
5/17/2001	18,970
11/28/2001	9,175
11/29/2001	4,090
11/30/2001	6,190
3/13/2002	6,263
9/3/2005	8,909
9/4/2005	77,529
12/1/2006	5,544
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

7. 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.

Caverns WH-11, BH-104 and BM-111 had post sale sonars taken in 2018 which revealed changes in cavern shapes resulting from the partial leaching due to sales (see Sobolik et al., 2019). One post-sale sonar was taken in 2019 for BH-108 but its analysis is not included in this report as some data quality concerns are under investigation.

8. 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 8-1 and 8-2 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 8-1 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 8-1 show the calculated volume of raw water injected into each cavern since the date of its last sonar, and the resulting estimated current (1/1/2020) cavern volume based on the amount of salt removed. The first four columns of Table 8-2 list the estimated current (1/1/2020) 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 4-1 through Table 4-4 in Section 4), 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. These rows for these five caverns are highlighted in **bold** in Table 8-2.

For the four 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.

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

$$n \in \{1,2,3, \ldots\}$$

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 8-2, 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 8-2 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 8-2 are summarized in Table 9-1 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: BH-101 (the largest increase, 14%, or nearly a full drawdown), BH-102, BH-105, BH-108, BH-109, BM-108, BM-111, BM-115, BM-116, WH-11, WH-103, WH-106, WH-114, and WH-115.

Table 8-1. Estimated cavern volumes on 1/1/2020 for each cavern.

Cavern	Last sonar, date	Last sonar, cav. vol. (MB)	Raw Water since Last Sonar (MB)	Est. cav. vol. 1/1/2020 (MB)
BC-15	8/25/14	16,586	-	16,563
BC-17	8/27/14	11,362	-	11,331
BC-18	9/3/14	18,818	3,511	19,915
BC-19	10/14/14	12,079	-	12,046
BC-20	9/25/18	9,147	-	9,142
BC-101	11/10/14	12,396	-	12,383
BC-102	5/2/17	9,468	917	9,428
BH-101	9/11/12	14,244	255	13,794
BH-102	8/29/13	12,530	2,455	12,848
BH-103	10/4/11	12,583	75	11,988
BH-104	4/17/18	14,352	969	14,531
BH-105	7/16/13	13,103	573	13,029
BH-106	3/31/15	12,652	1,708	12,792
BH-107	**9/17/19**	12,190	4	12,183
BH-108	**12/17/19**	10,994	-	10,994
BH-109	5/5/15	12,141	3,106	12,401
BH-110	4/8/15	12,253	1,109	12,173
BH-111	4/9/15	13,355	898	13,339
BH-112	5/7/15	12,639	(6)	12,512
BH-113	9/14/15	11,921	3	11,868
BH-114	10/24/13	12,574	1,977	12,728

Cavern	Last sonar, date	Last sonar, cav. vol. (MB)	Raw Water since Last Sonar (MB)	Est. cav. vol. 1/1/2020 (MB)
BM-1	6/17/96	6,538	375	6,764
BM-2	5/11/15	6,902	-	6,929
BM-4	9/26/12	19,051	-	18,932
BM-5	6/26/18	33,555	-	33,535
BM-101	8/23/16	13,311	-	13,299
BM-102	**8/14/19**	11,142	295	11,202
BM-103	**8/12/19**	12,782	-	12,776
BM-104	9/7/11	11,896	27	11,903
BM-105	8/22/12	11,345	66	11,349
BM-106	5/5/16	13,148	1,128	13,313
BM-107	5/10/16	12,246	301	12,186
BM-108	**4/9/19**	13,033	-	13,030
BM-109	5/2/16	12,221	560	12,251
BM-110	5/4/16	10,902	295	10,883
BM-111	4/24/18	12,989	944	13,202
BM-112	5/10/17	11,046	-	11,019
BM-113	8/21/12	*8,992	852	8,762
BM-114	1/18/12	9,600	1,807	9,197
BM-115	9/13/11	10,598	671	10,587
BM-116	9/14/11	11,511	2,234	11,447
WH-6	10/19/14	7,357	-	7,299
WH-7	5/19/15	12,961	18	12,848

Cavern	Last sonar, date	Last sonar, cav. vol. (MB)	Raw Water since Last Sonar (MB)	Est. cav. vol. 1/1/2020 (MB)
WH-8	12/17/14	10,228	-	10,189
WH-9	2/25/15	9,003	-	8,932
WH-11	2/28/18	8,503	1,332	8,772
WH-101	9/23/16	10,429	-	10,406
WH-102	8/11/15	10,330	553	10,820
WH-103	**3/6/19**	10,681	-	10,648
WH-104	**4/2/19**	10,314	-	10,353
WH-105	2/7/15	12,336	177	12,142
WH-106	10/23/12	11,945	1,261	12,544
WH-107	**2/8/19**	11,296	-	11,312
WH-108	5/7/18	10,644	659	10,870
WH-109	**5/23/19**	11,149	-	11,148
WH-110	10/24/17	11,698	311	11,580
WH-111	9/8/15	10,186	3,904	11,731
WH-112	2/15/13	10,481	707	10,519
WH-113	**1/9/19**	10,721	335	10,708
WH-114	5/14/15	10,510	4,701	11,744
WH-115	12/17/12	10,901	3,481	11,913
WH-116	4/4/18	10,446	249	10,437
WH-117	**7/16/19**	11,409	1,243	11,733

* 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.

Table 8-2. Calculations of volume increases due to leaching and the resulting spent and available drawdowns for each cavern.

Cavern	Est. cav. vol. 1/1/2020 (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 4)	DD spent due to leaching since 1/1/10	Available DD (Baseline – Spent)
BC-15	16,563	16,576	-		0%	1	-	1
BC-17	11,331	11,423	-		0%	1	-	1
BC-18	19,915	18,439	4,396		4%	1	0.24	1
BC-19	12,046	11,990	-		0%	5	-	5
BC-20	9,142	9,503	-		0%	0	-	0
BC-101	12,383	12,551	22		0%	5	0.00	5
BC-102	9,428	9,895	917		1%	5	0.09	5
BH-101	13,794	12,606	11,751		14%	5	**0.93**	5
BH-102	12,848	12,017	6,312		8%	5	0.53	5
BH-103	11,988	12,482	1,385		2%	5	0.11	5
BH-104	14,531	12,519	15,624	**14,397**	19%	**5**	**1. + 0.21**	**4**
BH-105	13,029	12,137	8,740		11%	5	0.72	5
BH-106	12,792	12,518	1,720		2%	5	0.14	5
BH-107	12,183	12,586	2,763		3%	5	0.22	5
BH-108	10,994	11,024	3,824		5%	5	0.35	5
BH-109	12,401	11,762	3,700		5%	5	0.31	5
BH-110	12,173	12,210	1,512		2%	5	0.12	5
BH-111	13,339	13,753	2,567		3%	5	0.19	5
BH-112	12,512	13,019	(6)		0%	5	0.00	5
BH-113	11,868	12,505	17		0%	5	0.00	5
BH-114	12,728	12,623	1,988		2%	5	0.16	5

Cavern	Est. cav. vol. 1/1/2020 (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 4)	DD spent due to leaching since 1/1/10	Available DD (Baseline – Spent)
BM-1	6,764	6,709	117		0%	2	0.02	2
BM-2	6,929	7,060	96		0%	0	0.01	0
BM-4	18,932	17,372	1,008		1%	2	0.06	2
BM-5	33,535	34,293	358		0%	1	0.01	1
BM-101	13,299	13,474	2,739		3%	5	0.20	5
BM-102	11,202	11,477	1,656		2%	5	0.14	5
BM-103	12,776	14,914	3,761		4%	2	0.25	2
BM-104	11,903	11,495	2,174		3%	3	0.19	3
BM-105	11,349	10,976	67		0%	2	0.01	2
BM-106	13,313	13,285	1,178		1%	5	0.09	5
BM-107	12,186	12,132	308		0%	5	0.03	5
BM-108	13,030	12,068	4,623		6%	2	0.38	2
BM-109	12,251	12,586	701		1%	3	0.06	3
BM-110	10,883	10,683	1,406		2%	5	0.13	5
BM-111	13,202	12,724	4,159		5%	5	0.33	5
BM-112	11,019	12,083	36		0%	5	0.00	5
BM-113	8,762*	6,727	14,876	**8,896**	33%	**5**	**2. + 0.007**	**3**
BM-114	9,197	8,546	8,528	9,828	15%	**5**	**1. + 0.00**	**4**
BM-115	10,587	10,196	4,868		7%	5	0.48	5
BM-116	11,447	10,889	5,974		8%	5	0.55	5
WH-6	7,299	8,376	1		0%	0	0.00	0
WH-7	12,848	14,002	18		0%	5	0.00	5

Cavern	Est. cav. vol. 1/1/2020 (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 4)	DD spent due to leaching since 1/1/10	Available DD (Baseline – Spent)
WH-8	10,189	10,082	-		0%	2	-	2
WH-9	8,932	8,874	-		0%	1	-	1
WH-11	8,772	8,858	3,384		6%	5	0.38	5
WH-101	10,406	11,073	142		0%	5	0.01	5
WH-102	10,820	11,622	2,537		3%	5	0.22	5
WH-103	10,648	11,876	3,992		5%	5	0.34	5
WH-104	10,353	11,216	1,991		3%	5	0.18	5
WH-105	12,142	10,765	13,379	**12,380**	19%	**5**	**1.+0.21**	**4**
WH-106	12,544	11,081	8,046		11%	5	0.73	5
WH-107	11,312	11,868	317		0%	5	0.03	5
WH-108	10,870	12,346	659		1%	5	0.05	5
WH-109	11,148	11,344	2,917		4%	5	0.26	5
WH-110	11,580	12,602	2,359		3%	5	0.19	5
WH-111	11,731	9,240	11,142	**10,626**	18%	**5**	**1.+0.18**	**4**
WH-112	10,519	11,209	707		1%	5	0.06	5
WH-113	10,708	11,767	3,440		4%	5	0.29	5
WH-114	11,744	10,802	4,701		7%	5	0.44	5
WH-115	11,913	10,929	3,481		5%	5	0.32	5
WH-116	10,437	10,988	292		0%	5	0.03	5
WH-117	11,733	11,697	1,972		3%	5	0.17	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.

9. 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 2020:

- Five 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, and BM-114 and WH-105 are added in this 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 9-1.
- 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: BH-101 (the largest increase, 14%), BH-102, BH-105, BH-108, BH-109, BM-108, BM-111, BM-115, BM-116, WH-11, WH-103, WH-106, WH-114, and WH-115.
- The following caverns have had significant changes to their geometry from raw water/leaching operations: BH-104, BM-111, and WH-11. A preliminary analysis indicates no effect on drawdown availability (and in the case of BH-104, no additional effect), but operating conditions on these caverns may need to be modified to prevent additional growth of the base of the cavern.

Table 9-1. Summary of baseline, spent and available drawdowns.

Cavern	Baseline Available DD 2020 (Section 4)	DD spent due to leaching since 1/1/10	Available DD = Baseline - Spent
BC-15	1	-	1
BC-17	1	-	1
BC-18	1	0.24	1
BC-19	5	-	5
BC-20	0	-	0
BC-101	5	0.00	5
BC-102	5	0.09	5
BH-101	5	0.93	5
BH-102	5	0.53	5
BH-103	5	0.11	5
BH-104	**5**	**1.21**	**4**
BH-105	5	0.72	5
BH-106	5	0.14	5
BH-107	5	0.22	5
BH-108	5	0.35	5
BH-109	5	0.31	5
BH-110	5	0.12	5
BH-111	5	0.19	5
BH-112	5	0.00	5
BH-113	5	0.00	5
BH-114	5	0.16	5
BM-1	2	0.02	2
BM-2	0	-	0
BM-4	2	0.06	2
BM-5	1	0.01	1
BM-101	5	0.20	5
BM-102	5	0.14	5
BM-103	2	0.25	2
BM-104	3	0.19	3
BM-105	2	0.01	2
BM-106	5	0098	5

Cavern	Baseline Available DD 2020 (Section 4)	DD spent due to leaching since 1/1/10	Available DD = Baseline - Spent
BM-107	5	0.03	5
BM-108	2	0.38	2
BM-109	3	0.06	3
BM-110	5	0.13	5
BM-111	5	0.33	5
BM-112	5	0.00	5
BM-113	**5**	**2.007**	**3**
BM-114	**5**	**1.00**	**4**
BM-115	5	0.48	5
BM-116	5	0.55	5
WH-6	0	-	0
WH-7	5	0.00	5
WH-8	2	-	2
WH-9	1	-	1
WH-11	5	0.38	5
WH-101	5	0.01	5
WH-102	5	0.22	5
WH-103	5	0.34	5
WH-104	5	0.18	5
WH-105	**5**	**1.21**	**4**
WH-106	5	0.73	5
WH-107	5	0.03	5
WH-108	5	0.05	5
WH-109	5	026	5
WH-110	5	0.19	5
WH-111	**5**	**1.18**	**4**
WH-112	5	0.06	5
WH-113	5	0.29	5
WH-114	5	0.44	5
WH-115	5	0.32	5
WH-116	5	0.03	5
WH-117	5	0.17	5

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