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Technical Conference Paper

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PRESSURE TRENDING ANALYSIS TO SUPPORT CAVERN INTEGRITY MONITORING AT THE U.S. STRATEGIC PETROLEUM RESERVE

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Abstract

Sixty three oil storage caverns at the United States Strategic Petroleum Reserve (SPR) are monitored daily in order to verify cavern integrity. Daily cavern pressure by itself, however is not entirely sufficient to determine the health of a cavern. A new approach of comparing static cavern pressurization cycles to historic static cavern pressurization cycles has proven to be an effective way to assess the integrity of the cavern system. The components of the closed boundary storage cavern system include the cavern, wellbore, and wellhead. Since the system is closed and the cavern is continuously losing storage volume due to creep while the internal fluid volume is increasing due to geothermal heating, pressure in the cavern gradually increases over time. Digital pressure transmitters measure wellhead pressures and these data are stored in a database for further analysis. Since the SPR facilities are non-commercial oil filled caverns intended for long-term storage, months to years pass between drawdown cycles and significant fluid movements. Hence, static cavern conditions provide unique datasets for analysis to fully understand site salt dome creep and cavern behavior. When adjacent caverns are de-pressured during workovers, neighboring caverns demonstrate increased pressurization rates. For caverns that were affected by water injection (either leaching or oil movements), there are negative cavern pressurization rates, followed by a return to "normal" increasing pressurization rates. The technical analysis group at the SPR analyzes daily cavern pressure data to identify and understand changes to normal cavern pressure behaviors. The caverns behave in predictable ways, so when incoming data veer from the expected normal trend, the cause is investigated. Corrective action may then be taken to maintain cavern integrity. This paper summarizes the utility of the cavern monitoring technology being used to analyze cavern pressurization data at the SPR.

Key words: Static cavern pressurization cycles, salt dome creep, oil storage caverns.

Introduction

The Strategic Petroleum Reserve (SPR) is the United States Government's underground crude oil storage facilities and infrastructure located in Texas and Louisiana. The four sites contain approximately 695 million bbls (MMbbl) of crude oil. The SPR was established by the Energy Conservation Act of 1975. Drawdown at the SPR is performed in order to reduce the adverse economic impact of a major petroleum supply interruption to the United States. The SPR is the largest emergency crude oil reserve in the world. There are 63 caverns and over 100 wellbores that provide access from the surface wellhead to the cavern.

Limited frequency of fluid transfers in and out of the caverns at the SPR allows the technical analysis group to study static oil storage cavern conditions to better understand their behavior. Caverns generally show gradual increase in wellhead pressure due to long-term creep closure in the salt coupled with thermal expansion of the contained fluids. There are also identifiable relationships between neighboring caverns at each site. When an adjacent cavern is bled down and kept at atmospheric pressure, the adjacent cavern pressurization rate increases. When a cavern is being leached, low salinity brine or water is injected and dissolves the salt formation, resulting in increased cavern sizes. The pressurization rate of this leached cavern decreases due to the expanding cavern volume. After leaching stops, the cavern returns to normal static behavior, and the cavern pressures increase over time. Since creep occurs continuously, a lower-than-normal cavern pressurization rate may indicate a cavern or wellbore integrity issue, even though the cavern pressure increases.

Therefore, while current pressure trending may indicate whether or not there are issues with cavern integrity, these data are even more useful when it is plotted versus time and compared to the historic pressure trends. A cavern that is behaving "normal" should closely match the historic pressurization rates. A pressurization cycle that "flattens" out over time may indicate a compromise to cavern or wellbore integrity.

Analysis and Interpretation

Three main topics of analysis and interpretation involving cavern behavior will be discussed. The first topic is the analysis of normal cavern behavior. By comparing historic static cavern pressurization cycles to the current pressurization cycle, anomalous pressure trends are identified. Three case studies are provided in detail, describing the analysis that was conducted in order to identify compromises in wellbore integrity. Remedial work was then performed (cemented liner) in order to restore service. The second topic is the identification of relationships between adjacent caverns, and a discussion of the inter-relationship of different cavern behaviors within the same salt dome. The oil storage caverns at the Big Hill site demonstrate how reducing cavern pressure for a work-over in one cavern increases the pressurization rates of an adjacent cavern. The third topic is a discussion of changes in cavern pressurization rates and specific gravity after water has been injected into the cavern for leaching.

Topic 1 – Static Cavern Pressurization Analysis

When analyzing static cavern pressurization rates, it is important to understand existing cavern conditions and the factors that contribute to differences in behavior. For each of the 63 caverns at the SPR, pressure transmitters measure cavern pressures every two seconds. The cavern pressures are monitored in the control room, and the data compressed for storage in the data historian. The site cavern engineers submit a daily report of cavern pressures that are further analyzed by the technical analysis group when assessing the “health” of the cavern system.

There are usually three cavern pressure monitoring points that are used to obtain cavern pressure data. As seen in Figure 1, there are digital pressure transmitters monitoring cavern wellhead pressures at the slick hole, static annulus, and hanging brine string measured nominally at ground surface elevation. Since the static annulus is the least frequently used for fluid movements of all three, the cavern pressure data from this source is often used for analysis.

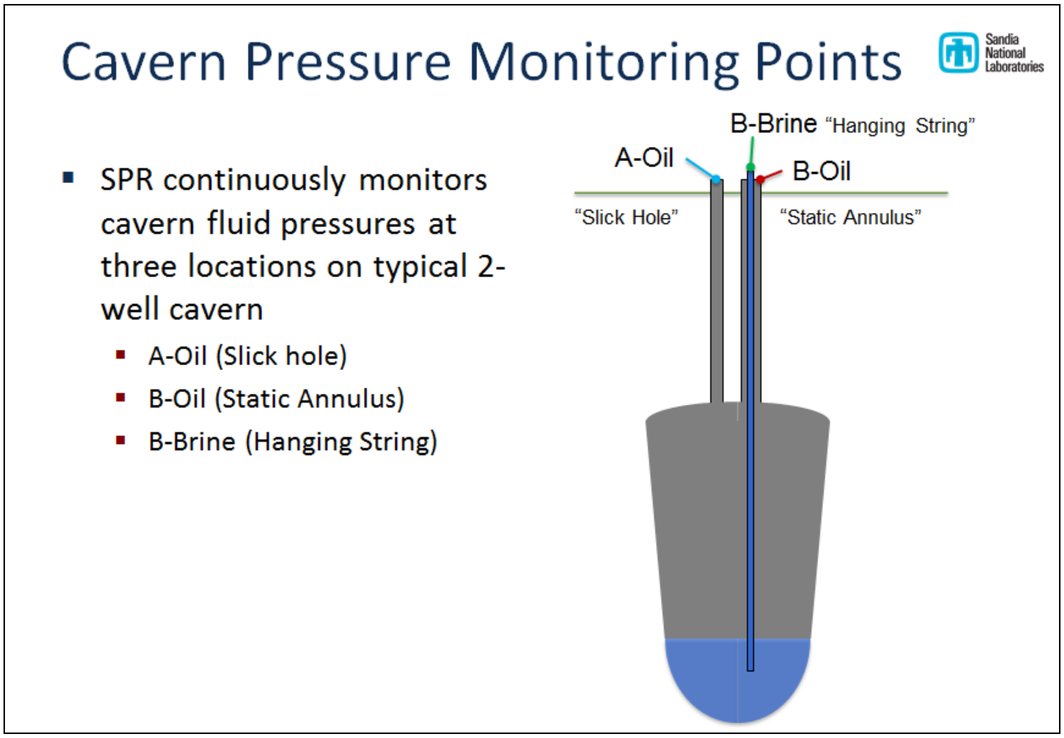

Figure 1 – *Example of two well cavern configuration with pressure instrumentation*

When analyzing cavern pressure data, the first step is identifying “normal” cavern pressurization rates. Figure 2 shows the data from a typical cavern with no unusual influences on the cavern pressure trending. The cavern pressure is maintained within a normal operating range. The cavern pressures up from the bottom of the operating range to the top of the operating range, before brine is bled off to return the cavern to the bottom of the operating range. Typical cavern pressure trends overlap for all pressure cycles. Therefore, by stacking these pressure trends as cycles, the normal expected cavern behavior is referenced. By comparing the current trend (dotted line) with the historical trends, one can see if the cavern is pressuring up within the expected normal behavior. The current pressurization rate should be similar to the historic pressurization rates. If there are deviations from “normal” cavern behavior, they are first analyzed to see if there is a known reason for the anomalous behavior.

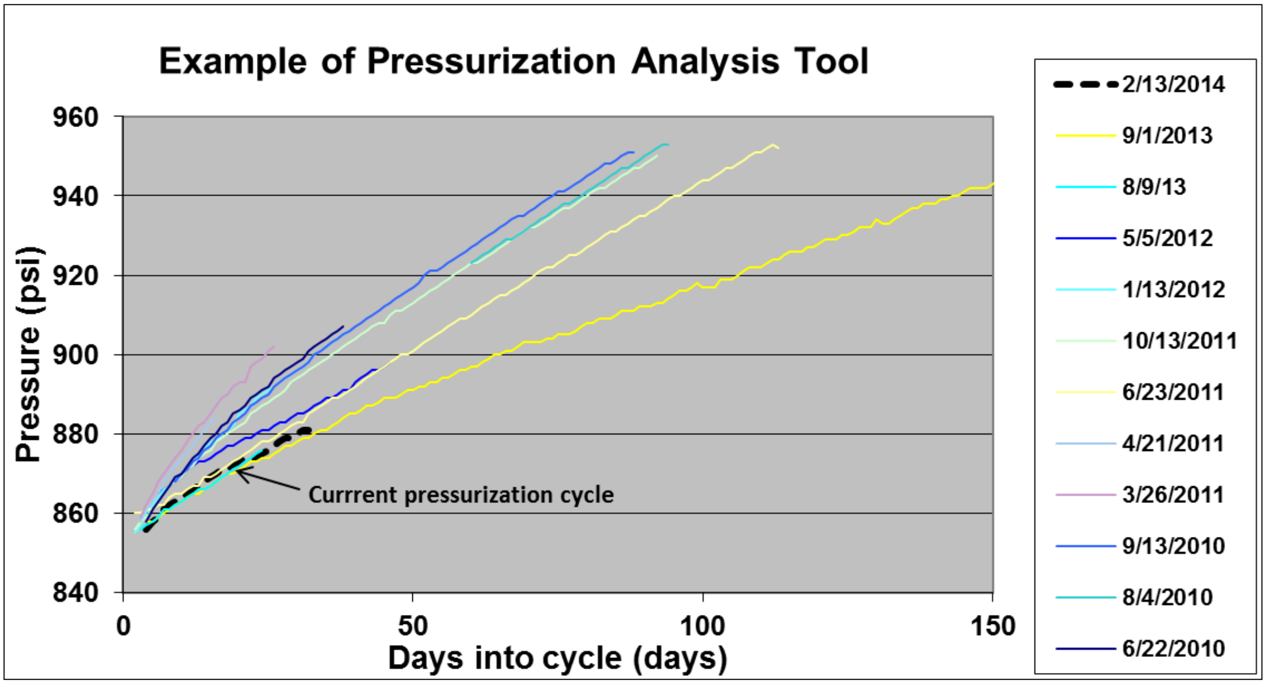

Figure 2 – *Example of pressurization analysis tool. Current cavern pressure (dotted line) is potted vs time. Comparison of historic static cavern pressurization cycles to a current pressurization cycle*

The pressurization cycle starts when the cavern is no longer affected by fluid movements into or out of the cavern and no salt dissolution is taking place. The cavern pressures should be normally increasing due to salt creep and thermal expansion of the cavern fluids. The pressurization cycle ends when a scheduled fluid movement occurs and the cavern classification changes from being considered "static" to "dynamic".

During "static" cavern pressurization cycles, the pressurization rate changes over time. The pressure buildup as a function of time can be best described as a second order or third order polynomial. At lower operating pressures, creep rate is higher. Therefore, pressurization rates are greatest at the beginning of a pressurization cycle. As the cavern pressures increase over the cycle, creep rate decreases. The pressurization rates therefore decrease as the pressures approach the upper limit of the operating range. The pressurization rate is calculated over different pressure intervals (10 psi) of the pressurization cycle. The rate is calculated by subtracting the ending pressure by the starting pressure and dividing by the time interval.

Comparing the current cavern pressurization cycles to the historic cavern pressurization cycles is the initial step when identifying compromised SPR cavern systems. However, this procedure cannot be applied to a single cavern by itself. A proper comparison must consider the effects of neighbor caverns and their operating conditions, as discussed in detail in the following section, Topic 2. In addition to this, injecting fresh water into a cavern also has a strong effect on changing the cavern pressurization rate. This is further discussed the last section, Topic 3.

There are three examples of known compromised wellbores at the Big Hill site (BH105, BH109, BH114) that required a remedial 10 ¾'' casing liner to be cemented in order to restore wellbore integrity. For each of these three examples, a change to wellbore integrity was indicated by "flat" or "decreasing" cavern pressures, under static cavern conditions. This pressure behavior indicates that the cavern system is no longer "closed".

Since creep continues decreasing cavern volumes over time, cavern pressures should increase over time in a closed system. If the pressurization rate becomes negative, the leakage rate of fluid migrating from the cavern system is greater than the cavern creep that is naturally occurring. Nitrogen was injected into the wellbore to verify a compromised depth zone. If identified, then the cavern was depressured in order to cement a plug in the wellbore beneath this zone of interest. Later, a remedial cemented liner work-over is performed.

Case Study 1

BH105 is a 13.2 MMbbl cavern in a Gulf Coast salt dome containing 7.3 MMbbl of sweet oil. The top of the cavern depth is 2283 ft and the bottom of the cavern depth is 4206 ft. The cavern has two wellbores, BH105A (slick oil well) and BH105B (brine string well). The "slick oil well" is not equipped with a suspended brine string. The "brine string well" normally has a 10 ¾'' hanging casing filled with brine. The innermost last cemented casing size for both wells is 13 3/8'', set to a depth of 2112 ft.

This was the first cavern identified with a wellbore integrity issue. The data for this cavern is presented in hindsight and was the basis for developing our current cavern pressure monitoring program. The historic cavern pressure cycles (solid lines, Fig.3) demonstrated a baseline for what was expected for a static, closed cavern system. The pressurization cycles nearly overlap, only ending with a fluid movement, changing the cavern status from "static" to "dynamic". During the leak pressurization cycle (dotted line), the cavern pressures built up slower-than-normal, then started to flat-line, and were followed by decreasing pressures.

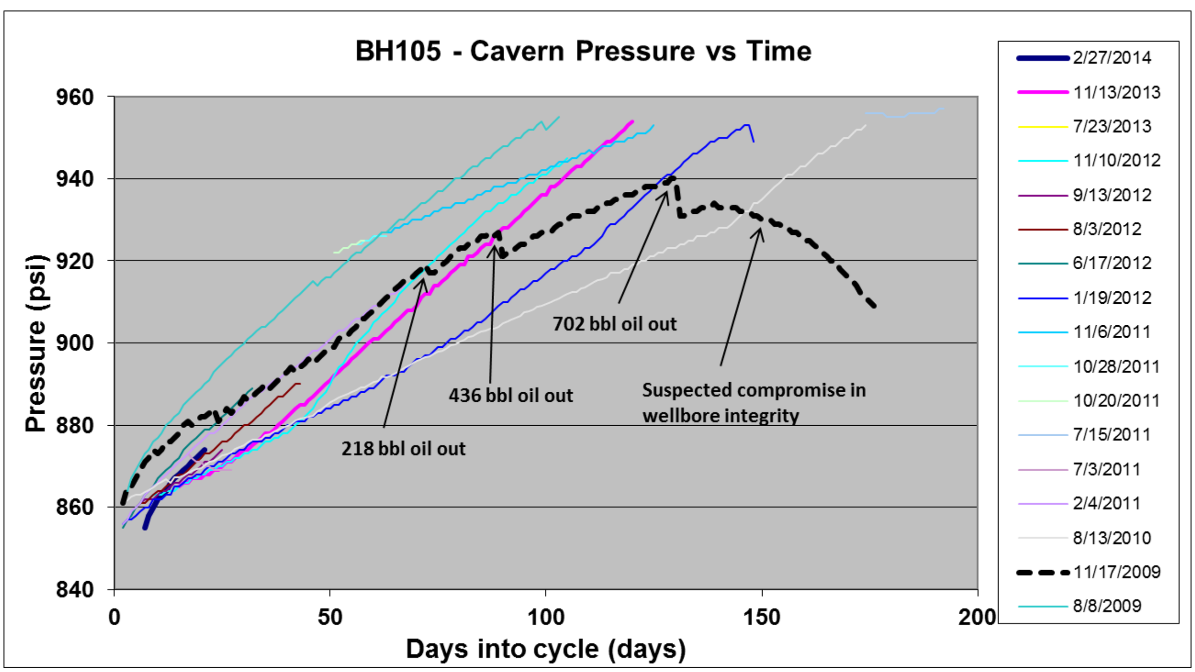

Figure 3 – *BH105. Cavern pressure vs. time. Comparison of historic static cavern pressurization cycles to a leak pressurization cycle (dotted line)*

There were several fluid movements out of the cavern at different days (218 bbl, 436 bbl, 702 bbl oil) in order to pressure up a nearby pipeline, highlighted by sudden pressure decreases (annotated in Fig3). At 125 days into the cycle, the cavern pressures started to decrease, labeled in Figure 4 as "suspected compromise in wellbore integrity". Nitrogen was injected into both A and B wellbores at day 175, placing the N2-oil interface depth below the suspected sensitive zone. The B-wellbore was unable to hold pressure under nitrogen the same as the A-wellbore, and the N_2-Oil interface moved upward rapidly from its initial placement in the B-wellbore. In addition, multi-sensor caliper surveys of the cemented casings in both wells indicated significant deformation at the level consistent with where the B-wellbore nitrogen pressure slowed its descent. These data, taken in aggregate indicated that the leaking wellbore was the brine string well, BH105B.

To remediate the wellbore, the 10 ¾'' brine string was pulled from the well and a 10 ¾'' liner was cemented from a depth of 2067 ft to the surface. The existing brine string was replaced with a smaller sized 8 5/8'' brine string. After the workover was completed, the cavern was pressured up and held at normal operating pressures without incident.

Case Study 2

BH109 is a 12.4 MMbbl cavern containing 12.2 MMbbl of sour oil. The top of the cavern depth is 2266 ft and the bottom of the cavern depth is 4251 ft. The cavern has two wellbores, BH109A (slick oil well) and BH109B (brine string well). The innermost last cemented casing size for both wells is 13 3/8'', set to a depth of 2113 ft. As the pressurization analysis tool was being developed, BH109 started to demonstrate similar behavior to what was observed for case study 1, BH105. The pressurization cycle "flattened" over time under static cavern conditions.

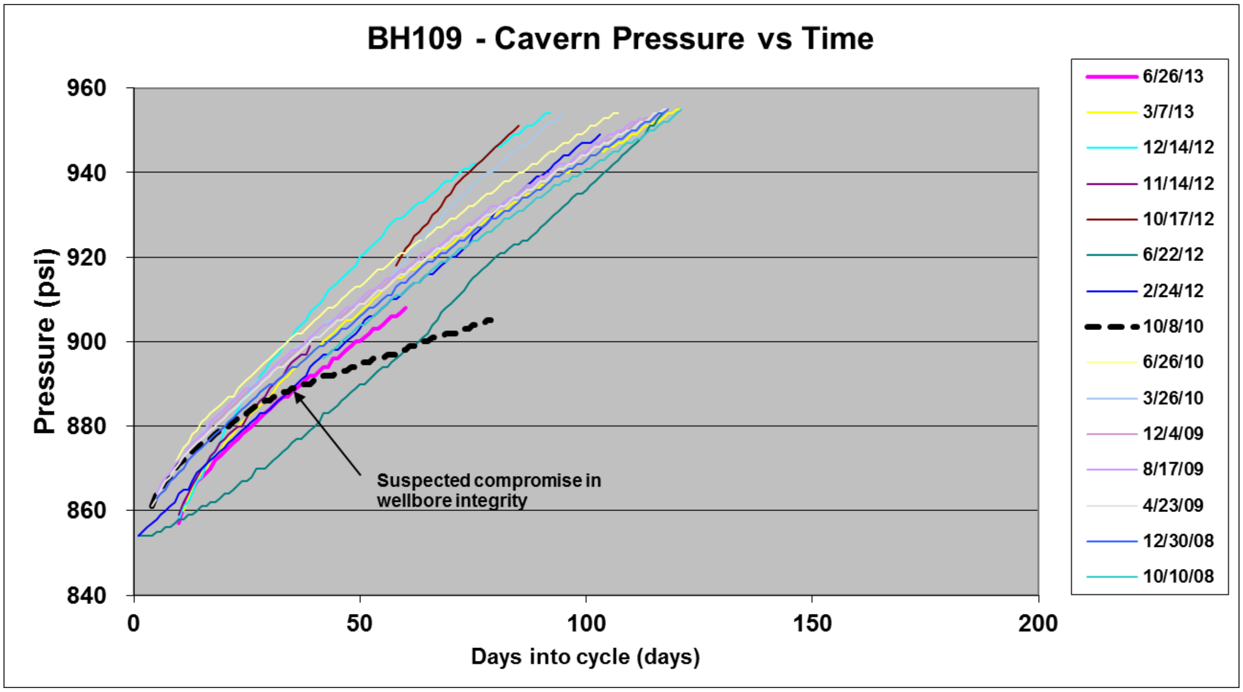

Figure 4 – *BH109. Cavern pressure vs. time. Comparison of historic cavern pressurization cycles (solid) to a leak pressurization cycle (dotted black)*

Much internal discussion ensued over the validity of tracking cavern pressure cycles. In an abundance of caution, nitrogen was injected in the BH109 wellbore and a leak in the BH109B was confirmed. A 10 ¾'' liner was cemented inside the 13 3/8'' casing to restore wellbore integrity. This validated the concept of comparing cavern pressurization trends as a method of monitoring cavern/wellbore integrity.

Case Study 3

BH114 is a 12.0 MMbbl cavern containing 11.8 MMbbl of sour oil. The top of the cavern depth is 2327 ft and the bottom of the cavern depth is 4137 ft. The cavern has two wellbores, BH114A (slick oil well) and BH114B (brine string well). The innermost last cemented casing size for both wells is 13 3/8'', set to a depth of 2136 ft. In fall 2012, the pressurization cycle "flattened" over time under static conditions. At the time this cavern pressure anomaly was observed, the pressurization analysis tool had been fully developed and used on a daily basis.

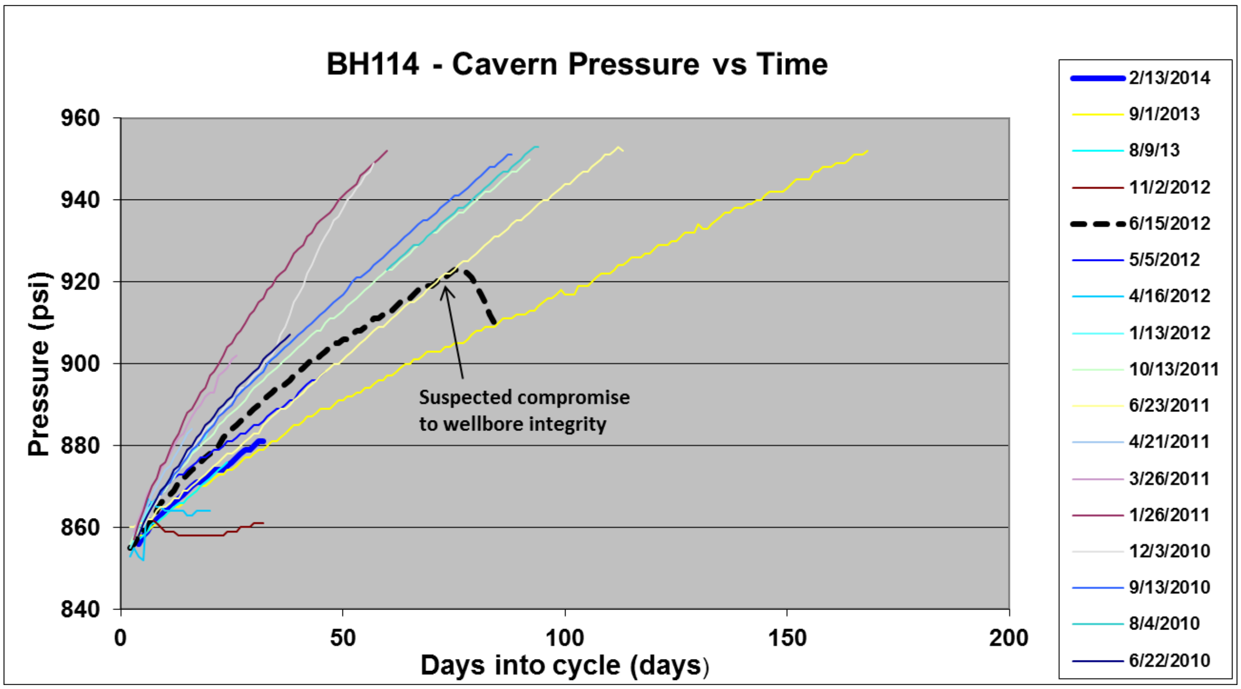

Figure 5 – *BH114. Cavern pressure vs. time. Comparison of historic cavern pressurization cycles (solid) to a leak pressurization cycle (dotted black)*

BH114 had recently undergone a workover to pull the string in the B well and run a multi-arm caliper log. Following a workover, the cavern pressurization trends showed less-than-normal pressurization cycles for one to two cycles. So the reduced pressure trend on BH114 was not in and of itself so alarming. It was only when the pressure trend went flat and then decreased that concern was voiced and nitrogen was injected into the wells. This confirmed the leak on BH114A. The well was temporarily plugged, isolating the leak zone from the cavern. A remediation workover (liner in the well) was then completed.

Topic 2 – Adjacent Cavern Behavior and Their Effects on Pressurization Rates

As has been documented in published literature, salt behaves as a visco-plastic material that creeps over time due to deviatoric stress. The cavern creep rate (volume reduction) is a function of many different factors. These include salt characteristics, cavern ullage, operating pressures, and type of stored fluids.

Cavern creep has been an observed characteristic for domal salt caverns for many years. Salt continuously tries to "heal itself" or return to original conditions. The geological movement of the salt matrix reduces the volume of the solution mined cavern at different rates. Since the forces acting on the outside of the cavern due to lithostatic stresses are greater than the internal forces on the cavern, the cavern "shrinks" or "creeps". Cavern creep is diminished when the wellhead pressure or hydrostatic column is increases. Higher cavern pressures decrease the deviatoric stress in a cavern.

Creep is a concern for cavern operators because it reduces the available volume that can be used for product storage. Previously published authors have described creep and its effect on the caverns. In order to keep the cavern pressures within a specified operating range, operations must periodically transfer fluid out of the cavern. Daily cavern pressures have previously been used as an indicator of current cavern conditions, especially for operators that frequently cycle the cavern for temporary product storage.

At the SPR, changes in the adjacent cavern affects the pressurization rates of neighboring caverns. Therefore, when analyzing individual cavern pressures, the behavior of the adjacent caverns must be taken into account. There are interdependencies between caverns within a single salt dome.

For example, at the Big Hill facility, 14 storage caverns are located at depths between approximately 2000 ft and 4000 ft in the salt dome. The distance between the maximum diameters of the cavern range in hundreds of feet. Figure 7 is a planar view of the caverns at the Big Hill site. Adjacent caverns are those that are located directly next to the cavern under observation. For example, the adjacent caverns to BH112 (highlighted) are BH113, BH108, BH107, and BH111.

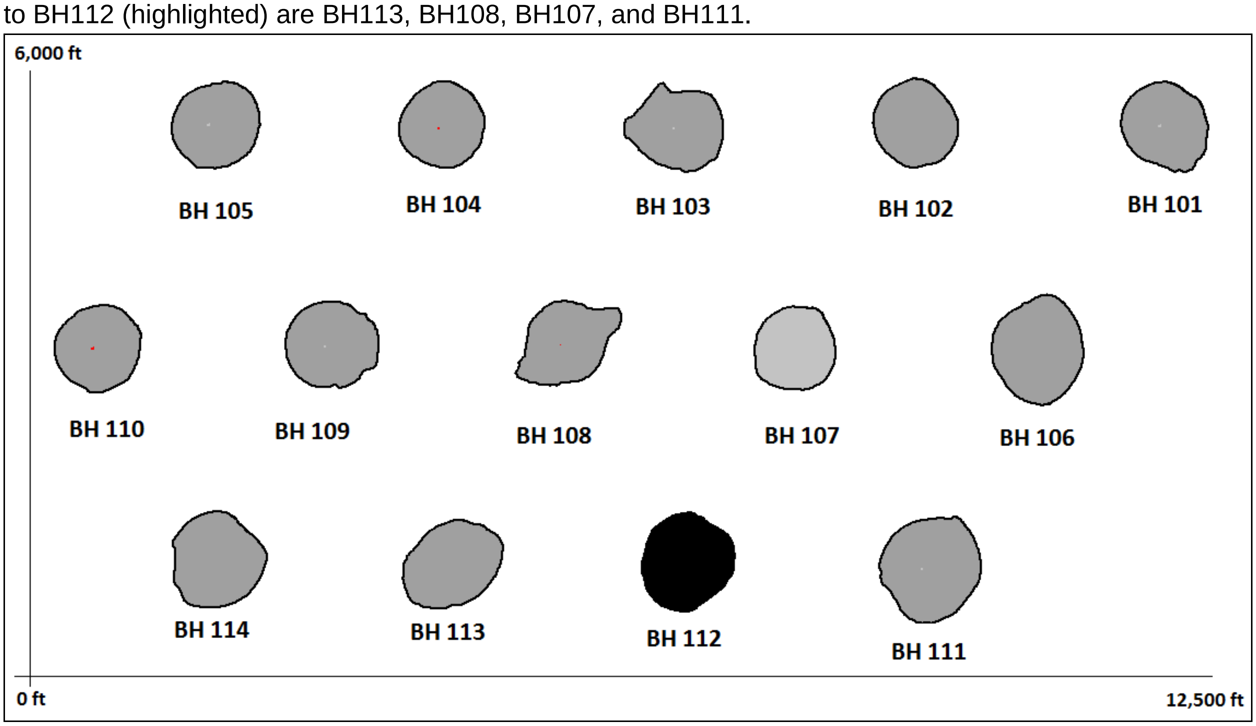

Figure 6 – *Planar view of the Big Hill Facility (highlighted BH112 cavern as an example)*

There are several examples of an adjacent cavern pressurization rate increasing significantly after an adjacent cavern was depressured. Four case studies are provided. The pressurization rate was calculated by dividing the change in pressure by the change in time.

Case Study 1

For case study 1, cavern BH102 was pressuring up at a rate of 0.82 psi/day for the first part of the pressurization cycle starting on 01/06/12 (Fig.7). At 80 days into the pressurization cycle an adjacent cavern, BH103 was depressured to 0 psi. For the next 10 days in the pressurization cycle, the pressurization rate of BH102 increased to 3.0 psi/day.

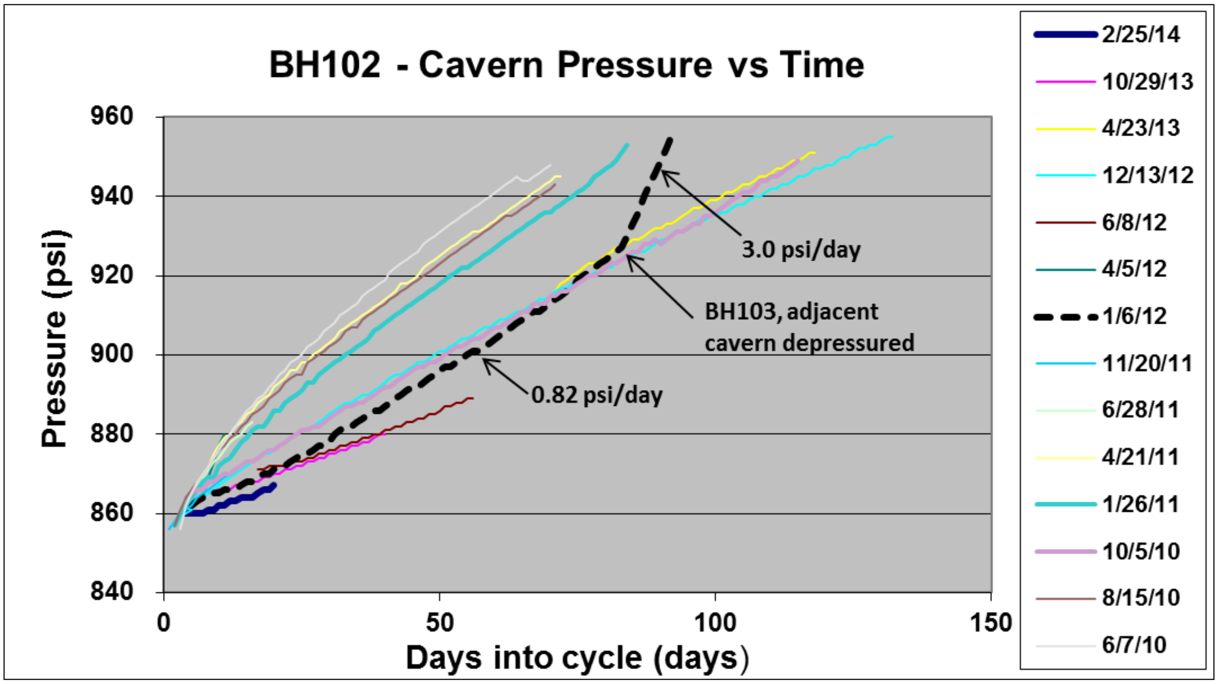

Figure 7 – *Cavern BH102 pressurization rate increased from 0.82 psi/day to 3.0 psi/day when the adjacent cavern, BH103 was depressured*

Case Study 2

For case study 2, cavern BH110 was pressuring up at a rate of 0.97 psi/day for the first part of the pressurization cycle starting on 12/28/11 (Fig.8). At 63 days into the pressurization cycle an adjacent cavern, BH114 was depressured to atmospheric conditions. For the next 15 days in the pressurization cycle, BH110 pressured up at a rate of 2.2 psi/day.

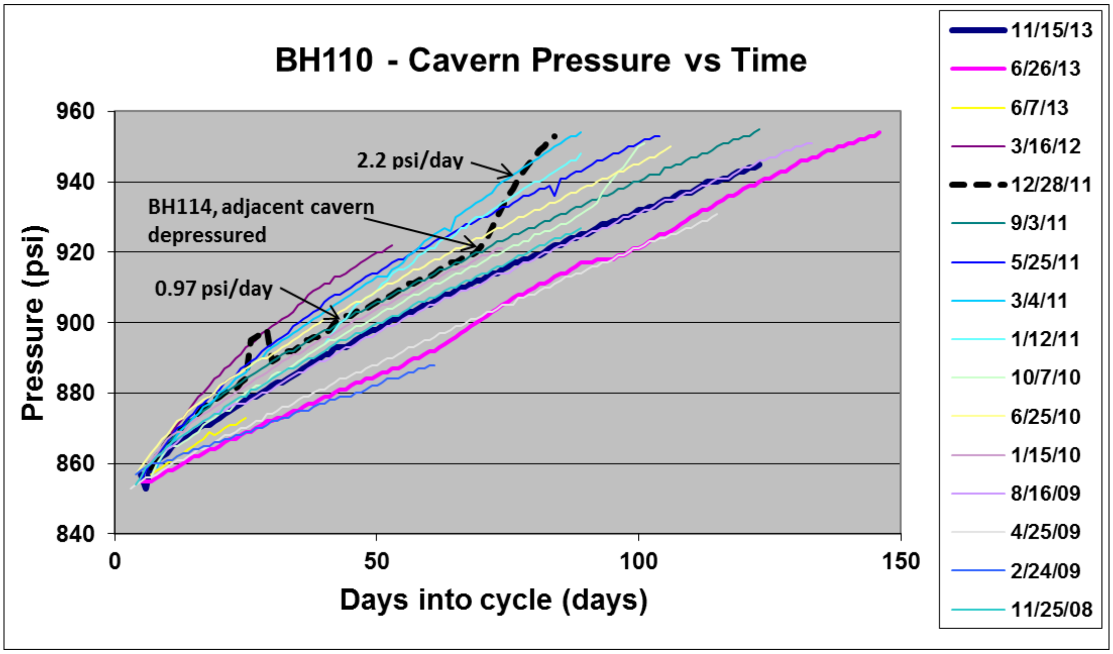

Figure 8 – *Cavern BH110 pressurization rate increased from 0.97 psi/day to 2.2 psi/day when the adjacent cavern, BH114 was depressured.*

Case Study 3

For case study 3, cavern BH106 was pressuring up at a rate of 0.63 psi/day for the first part of the pressurization cycle starting on 05/16/12 (Fig.9). At 81 days into the pressurization cycle an adjacent cavern, BH111 was depressured to atmospheric conditions. For the next 35 days in the pressurization cycle, the cavern pressured up at a rate of 1.2 psi/day

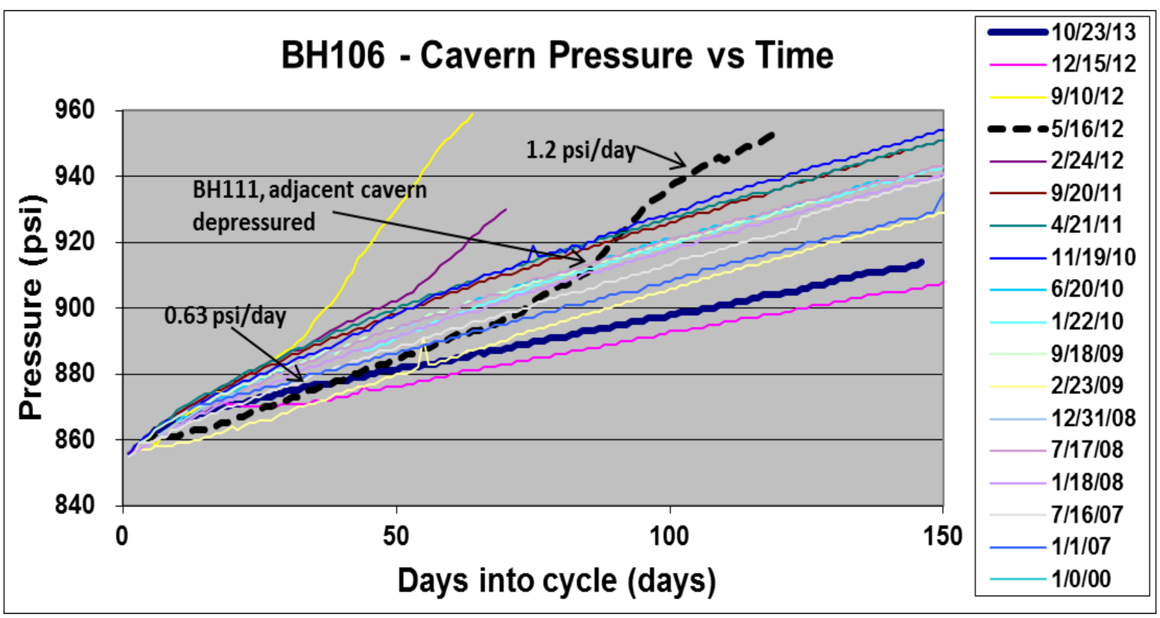

Figure 9 – *Cavern BH106 pressurization rate increased from 0.63 psi/day to 1.2 psi/day when the adjacent cavern, BH111 was depressured*

Case Study 4

For case study 4, cavern BH113 was pressuring up at a rate of 1.06 psi/day for the first part of the pressurization cycle starting on 01/28/12 (Fig.10). At 32 days into the pressurization cycle an adjacent cavern, BH114 was depressured to atmospheric conditions. For the next 36 days in the pressurization cycle, the cavern pressured up at a rate of 1.6 psi/day.

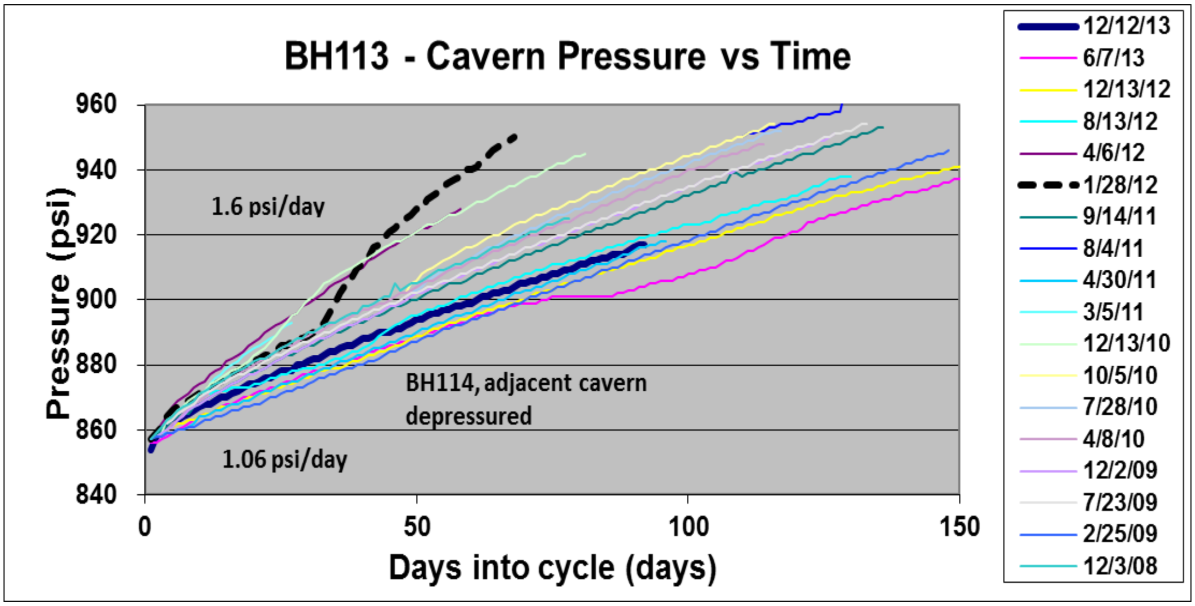

Figure 10 – *Cavern BH113 pressurization rate increased from 1.06 psi/day to 1.6 psi/day when the adjacent cavern, BH114 was depressured.*

In summary, the reason for this increase in pressurization rates is a result of the geo-mechanics of the salt dome and caverns. For each case study, the de-pressured adjacent cavern no longer supports the entire salt overburden between the network of caverns. Therefore, the additional fraction of the salt load is supported, in part by the adjacent caverns. The additional salt load on adjacent caverns results pressuring up faster-than-normal and remains at this heightened pressurization rate for the remainder of the workover period. Following the workover, the cavern pressures returned to within the normal operating pressure range. The new pressurization cycle is reset in the tool and is represented by a different cycle start date.

Topic 3 – Water Injection and Its Effect on Cavern Behavior

Injecting unsaturated brine into a cavern will temporarily change the observed pressurization rate, as the salt going into solution takes up less volume than the rock salt. As the leaching potential is exhausted and the brine becomes saturated, the cavern pressurization rate will return to its normal pattern. There is a direct relationship between the specific gravity of the fluid and the cavern pressures over time. An example is presented for SPR cavern BH102.

The average specific gravity of the cavern brine over time was modeled by Sandia National Labs leaching software (SANSMIC) based on cavern geometry and fluid injection rates, and compared with observed wellhead pressure in Figure 10. The mechanisms that affect cavern pressure changes during quiescent cavern conditions are demonstrated by Lampe, 2013.

Raw water was injected over the first 25 days, followed by a quiescent period from days 25-75, injected again for several days, and again left quiescent from days 85-100. Specific gravity dipped quickly over the first few days of injection and then began to recover. Cavern pressure during the same period is erratic under dynamic pumping conditions. During the first quiescent period from day 25-75, the average specific gravity in the cavern monotonically increased with time. Alternatively, the cavern pressure decreased rapidly until ~40-50 days at which point it reached a minimum and then started increasing as creep closure overtook leach-related volume expansion. A similar pattern is seen in the second injection period around 75-90 days. This should not be mistaken for a compromised cavern system, rather it is a cavern responding to salt dissolution.

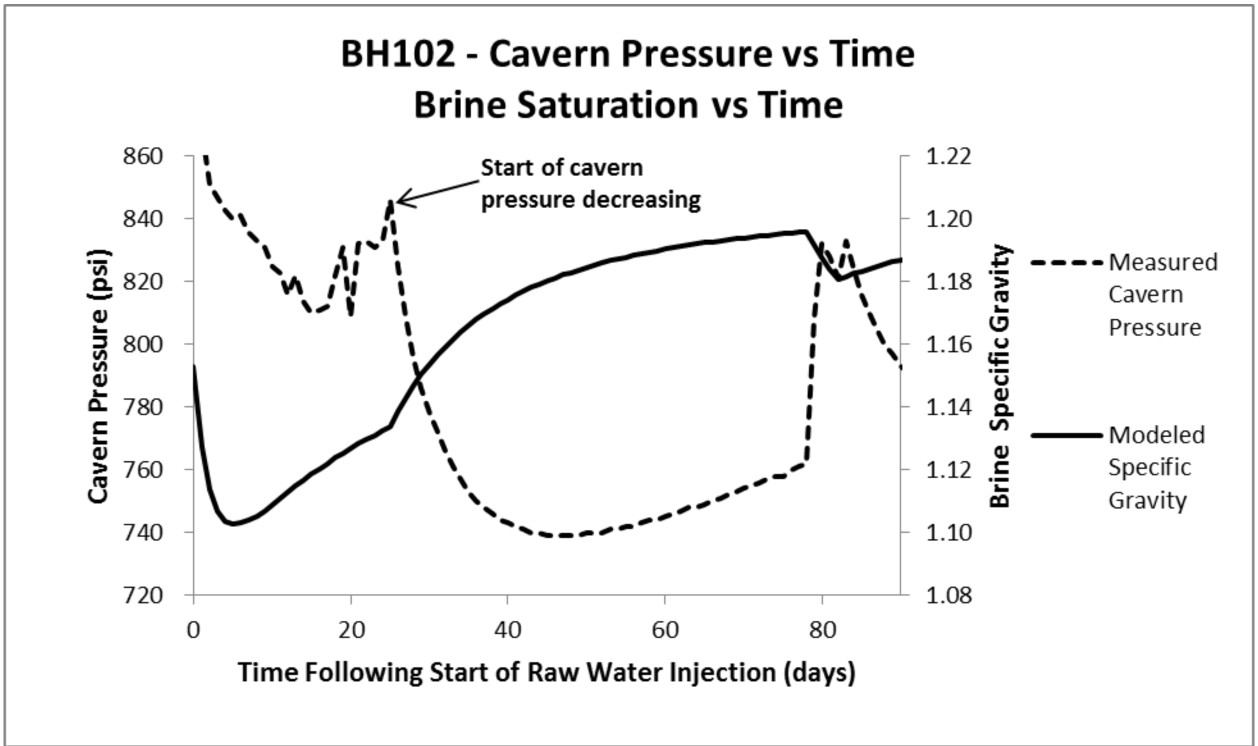

Figure 11 – *Comparison of measured cavern wellhead pressure with modeled brine specific gravity for SPR cavern BH102 during a two-stage raw water injection*

Several authors have documented how cavern pressures decrease after injecting water into the cavern. Saberian calculated cavern pressures during leaching in order to predict the required pump loads and flow rates, but not during the quiescent period (Saberian, 1974). The author developed a numerical model to simulate the salt dissolution process of a single cavity in homogenous salt. The model's predictions were then compared with field data. At the SPR, the dissolution ratio between volumes of raw water injected to cavern space created is estimated to be a water-salt volume ratio of "7 to 1". There are other factors that contribute to this ratio such as the raw water temperature used during injection (Lord and Rudeen, 2011) (Ehgartner, 2011).

For cavern BH102, the pressurization rates were negative during leaching, but "flattened out" as the brine reached higher saturation levels, and dissolution rates decreased. Finally, as the pressurization rates returned to positive, the brine reached higher levels of specific gravity. As a comparison to the historic pressurization cycles, the cavern pressures during leaching are displayed on the pressure vs. time chart in Figure 12. This chart demonstrates the magnitude of the different pressurization rates during normal static cavern conditions and during leaching periods.

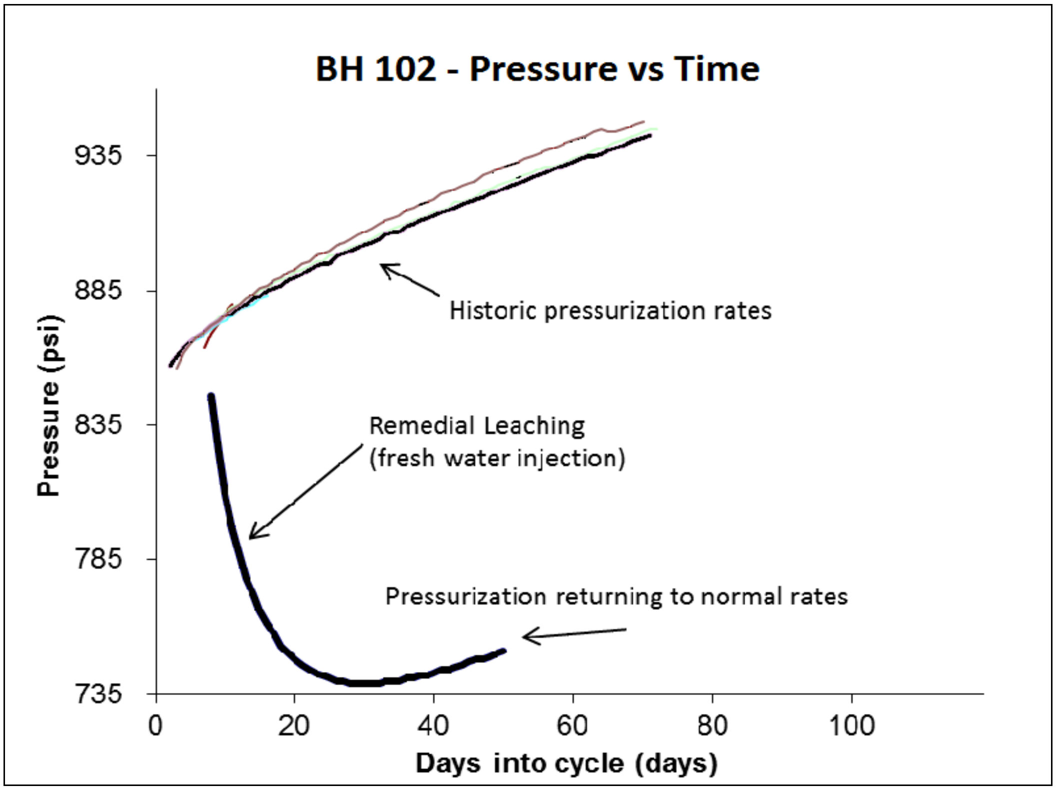

Figure 12 - *Example cavern, BH102 had fresh water injected into the cavern. This dissolution is identified by negative pressurization rates, followed by a return to normal pressurization rates*

Whenever water injection occurs, the cavern pressures will change accordingly and the cavern is no longer considered a "static" cavern. Rather, these "dynamic" caverns are changing and the pressurization rates are no longer used for wellbore integrity evaluation purposes. Before a MIT is performed on the well, the pressures must return to "static" cavern conditions and reach normal operating pressure levels.

Conclusion

The SPR cavern pressure analysis tools provide the ability to better understand past cavern operational behavior and to anticipate future static cavern pressures. Data analysis and interpretation helps to better understand and predict the behavior of SPR caverns. Operators that infrequently cycle their caverns (fluid transfers) can use these findings. Pressure transmitters constantly measure cavern pressure and the data are stored in a data historian for analysis. A majority of the literature has focused on "dynamic" caverns, where cyclization of fluids is more common than found at a government owned storage facility. Since the SPR caverns are primarily "static" for oil storage, this presented a unique opportunity to study and understand caverns that are used for different purposes than temporary fluid storage. Individual cavern behavior is adjusted to account for the conditions of surrounding caverns. At each site, when adjacent caverns are de-pressured, neighboring cavern pressurization rates increase higher than normal.

When fluids (oil, brine) are moved into or out of the cavern, cavern pressures fluctuate to reflect changes in this dynamic system. Over time, the proper cavern analysis and interpretation of static cavern data improves the ability to quantitatively assess cavern integrity and to identify compromises to the cavern system. By doing so, the technical analysis team anticipates problems identified by deviations from normal cavern behavior. Actions are then taken to assess cavern/wellbore integrity. This includes nitrogen injection-monitoring, casing inspection with a multi-arm caliper, and installation of cemented liners where needed. These actions promote proactive environmental stewardship, and return caverns to drawdown ready status.

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