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Identification of SPR Caverns with Multiple Oil Layers

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ABSTRACT

This analysis shows that when lower density crude oil is injected into the top of an underground salt storage cavern containing more dense crude, separate oil phases can form and coexist indefinitely. This has been observed at the U.S. Strategic Petroleum Reserve in spite of geothermal heating and natural convection, which tend to mix the contents of containers with significant vertical extent subjected to wall and bottom heating. Such persistent layering can create operational challenges for meeting delivery specifications if high-value, low-vapor pressure oil becomes trapped below incoming low-density, high-vapor pressure oil, effectively blocking access to the lower layers until the top layer is removed. Previous conceptual models assumed that the oil injection process mixed incoming oil with resident oil in a storage cavern, forming a single oil phase with relatively homogeneous properties. Here, a review of historical data from the Strategic Petroleum Reserve revealed that several caverns contain multiple oil layers. As a result, oil layering needs to be another variable considered when planning oil movements at SPR in order to optimize low-vapor pressure oil availability to assist in oil delivery blending.

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EXECUTIVE SUMMARY

Crude oils can form distinct layers within a Strategic Petroleum Reserve (SPR) cavern when lower density oil is added to the top of higher density oil. Recent temperature logs, sonars, and oil fill histories were collected for SPR's sixty active caverns and investigated for signs of multiple oil layers within the caverns as of late April/early May 2020. The ten caverns found to contain multiple layers were BC102, BH104, BH105, BH111, BM110, BM113, BM114, BM116, WH107, and WH113. Eight of these store sweet crude, while two store sour. Half of the layered caverns developed layers due to low density sweet crude coming from the U.S. midstream. Of note, the other five layered caverns developed layers from cavern-to-cavern or site-to-site transfers. BM113 and BM116 contained three layers due to multiple Domestic Sweet (DSW) exchanges in 2015 and 2018. Upper oil layers in BM113, BM114, and BM116 contain high vapor pressure oils which trap low vapor pressure oil below.

Several suggestions came out of the historical data analysis which would lead to better understanding of the properties of the oil within each cavern:

- It is recommended that when temperature is taken in the slick well for caverns suspected of containing multiple oil layers, downhole pressure is logged as well. These caverns include the ten listed above, as well as caverns that received significant fills since the last temperature logging event. Pressure can be used to calculate in-cavern oil density, which would allow for more direct assessment of oil layering in situations where the temperature log may not be able to adequately detect the presence of layers. Thermally equilibrated oil layers, for example, would have the same temperature, but different densities, so a temperature log would show no difference between the layers, but a pressure log could be used to see the difference in density between the layers.
- It is recommended that both layers in BH104 are sampled downhole for vapor pressure since it is unclear which layer the 2016 TVP-95 downhole sample tested since the sampling depth was within 50' of the oil-oil interface.
- It is recommended that the top layer in WH107 is sampled for vapor pressure since it has not been characterized thus far.
- It is recommended that the bottom layer in BM110 be sampled for vapor pressure since a) it comprises a large volume (4.0 MMBL) and b) the layer is not accurately characterized since it has never been measured using the TVP-95 measurement system.

Due to the decreasing density of crude oils in the U.S. midstream relative to crudes in the SPR caverns, the chance that oil movements block access to high value, low vapor pressure crude oils in the caverns might be increased. Thus, it is recommended that oil movement planning include oil density and potential layering considerations.

ACRONYMS AND DEFINITIONS

Abbreviation	Definition
API	American Petroleum Institute
BC	Bayou Choctaw site
BH	Big Hill site
BM	Bryan Mound site
BPP	bubble-point pressure
CAVEMAN	cavern management software; tracks fluid movements and cavern pressures
DSW	Domestic Sweet (oil)
LLS	Louisiana Light Sweet (oil)
MB	thousand barrels (of oil)
MMBL	million barrels (of oil)
OBI	oil-brine interface
RIK	Royalty in Kind (oil)
SPR	Strategic Petroleum Reserve
VP	vapor pressure
VPC	Vapor Pressure Committee
WH	West Hackberry site
WTI	West Texas Intermediate (oil)

1. INTRODUCTION

1.1. Oil Layering at the SPR

Two crude oils with significantly different properties may not mix when added together, given that lower density oil is allowed to float on top of the higher density oil (Webb 2009). Several oil properties greatly affect the density of a crude oil, which affects the ability for that oil to mix with others. As temperature increases, oil density decreases. At the Strategic Petroleum Reserve (SPR), oils are stored in underground caverns that are heated geothermally through time. Thus, it was previously assumed that since incoming oils are generally cooler than cavern oils, oil added to the top of a cavern would mix with the contents of the cavern. Moreover, as geothermal heating created a layer of warm oil at the walls of the cavern, natural convection induced over these large vertical wall faces was expected mix the entire contents of the caverns. However, oil composition can also affect oil density, and a recent shift in U.S. midstream oil composition towards lower density crude oils has led to the formation of oil layers within the caverns at SPR, despite cooler incoming oil added to the top of warmer cavern oil. Oil layering can have profound effects on vapor pressure (VP) monitoring and mitigation.

SPR's Vapor Pressure Committee (VPC) tracks the vapor pressure of the crudes stored in the caverns through time in order to ensure safe delivery of the crudes. In particular, high vapor pressure crude is strategically blended with low vapor pressure crude to ensure that emissions do not surpass safety limits. When larger scale mitigation is required, the oil can be degassed to remove high vapor pressure constituents. The models employed by the VPC depend on being able to accurately characterize the oil coming out of the top of the caverns. However, when oil layers exist at the top of the caverns, the vapor pressure of the oil coming out of the cavern can greatly differ from VPC models, which generally track middle-of-cavern oil. Thus, it is important to identify oil layers and their properties to improve VPC blending models. In this report, cavern stratification data were obtained for the active caverns at the four SPR sites (Bayou Choctaw – BC, Big Hill – BH, Bryan Mound – BM, and West Hackberry – WH), and oil layer properties were identified for cavern fill histories up until April 2020.

1.2. Report Organization

The organization of this report is given as follows. First, a background on the project history with oil layering is given. Then, the methods used in this oil layering analysis are described, including both an overview of the data used, and the calculations made. Oil layering results are then presented for the sweet and sour oil caverns. Finally, conclusions and recommendations associated with the oil layering analysis are discussed.

2. BACKGROUND

Understanding of cavern-scale oil mixing has evolved since the SPR storage facilities first went into operation in the 1980's. Early concerns about the stability of crude oils in long-term underground storage, with specific application to SPR, were documented in a study by Giles, Koenig et al. (1991). One of their findings was that the combination of typical cavern geometry and geothermal gradient in the salt was sufficient to induce natural convection in SPR caverns, thus mixing the entire cavern contents. They cited data for West Hackberry cavern 7 with a height-to-diameter ratio of about 3:1 that, in spite of being filled with 10 different crudes ranging in density from 0.0813 to 0.8757 (units not given), there was "…relatively little difference in quality throughout a nearly 300-m vertical column of oil." They cited additional unpublished SPR data with more typical height-to-diameter = 10:1 that confirm "…this is the rule and not the exception."

2.1. SPR Layering

Observations across a number of caverns during degasification at the Big Hill and Bryan Mound sites in the 2000's and 2010's challenged this model of well-mixed caverns as the general rule. SPR found that pre-existing oil layering in caverns affected the efficiency of the degasification process, as documented in a series of Sandia reports (Ehgartner, Webb et al. 2005a; Ehgartner, Webb et al. 2005b; Lord and Rudeen 2007; Lord and Rudeen 2013; Hogge, Chojnicki et al. 2019). The oil stratification appeared to correlate strongly with historical fill, where layer heights in the cavern corresponded to fill volumes from specific time periods, and the temperatures of the newer fill layers remained persistently lower than the temperatures of the layers that had been in the cavern longer.

2.2. Laboratory Layering

Related laboratory research directed by Sandia found that persistent layers would readily form in tall cylinders that contained brine with a pre-existing linear density gradient and heated from the bottom and sides (Fernando 2012). An image reproduced from Fernando (2012) is shown in Figure 2-1, showing the formation of multiple layers of brine that formed and persisted as adjacent convection cells throughout the duration of the experiment. This observation indicates that while natural convection can mix the contents of an SPR cavern vertically, the existence of a density gradient due to historical differences in fill in the tall cylindrical cavern may actually support the formation of separate, stacked convection cells, which limits the mixing of the fluid to its own cell and not the entire vertical extent of the cavern.

Figure 2-1. Photograph showing the formation of multiple layers of brine contained in a tall cylindrical tank that was heated from the bottom and sides (reproduced from Fernando (2012)). Note that two images appear in the photograph because of the reflection from a shadowgraph paper in the background.

2.3. Trending in Oil Fill Properties

A graphic representation of crude oil refinery input American Petroleum Institute (API) gravity obtained from the U.S. Energy Information Administration is shown in Figure 2-2 (EIA (2020)). Crude oil on the midstream market in the U.S. and regionally along the Gulf Coast generally grew heavier with time during the first several decades of SPR operation from the 1980's to 2010. Assuming that these oils were representative of those taken by SPR at the time, they would likely sink and mix in the SPR caverns because it was higher in density than inventory already in the caverns. With the start of the domestic shale boom from about 2010 to present day, the refinery inputs trended toward lighter oils with higher API gravity. Relative to oil currently in the SPR inventory, this creates the potential for new fill after about 2010 to float if it is lighter than the oil in the caverns where it is introduced.

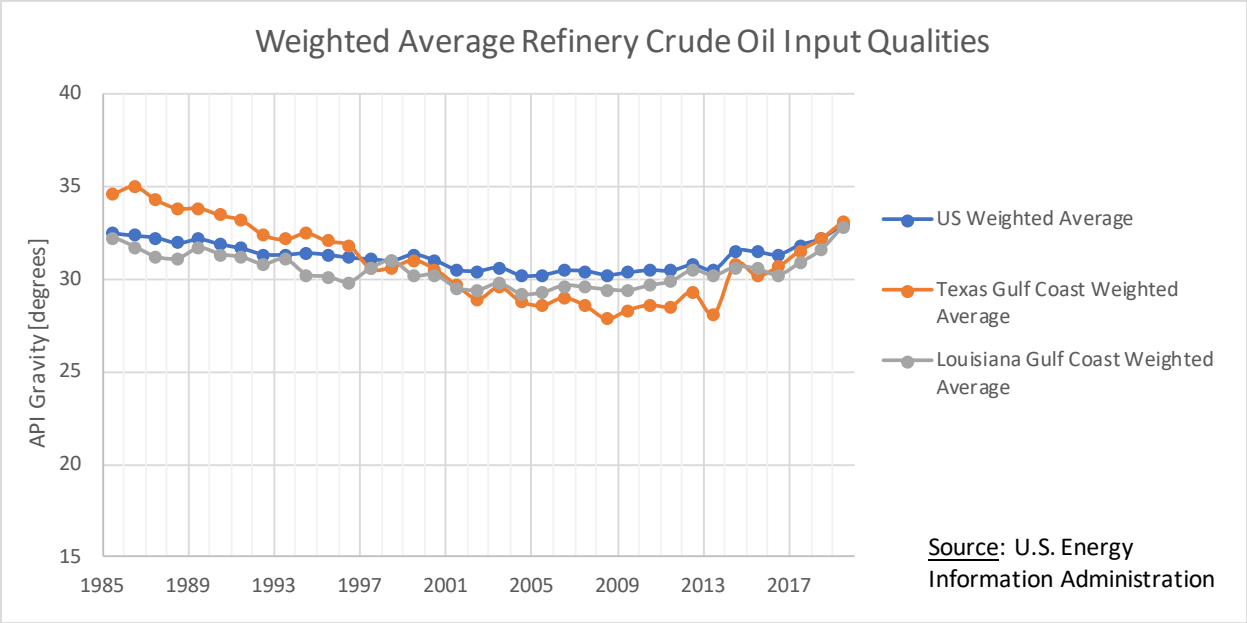


Figure 2-2. Volume-weighted API gravity for refinery inputs from 1985-2019 U.S., Texas Gulf Coast, and Louisiana Gulf Coast (Data source: EIA (2020)).

2.4. Interpretation of Background findings

With these observations it is therefore plausible that generally before 2010, the existence of SPR inventory layering could have been rare, isolated to only a few caverns and/or going generally undetected because new fill was generally higher in density than existing inventory. With the upturn in domestic shale production and generally lighter oils from about 2010 forward, new fill at SPR, especially very light sweet, likely floated. Localized natural convection cells similar to those seen in the laboratory work by Fernando (2012) could have further promoted the persistence of the layers rather than dispersed them.

3. METHODS

Oil layers can be identified when looking at the properties of the oil with depth inside the caverns. Cavern oil data are collected by SPR to support cavern integrity and oil quality programs. Information from existing datasets relevant to oil layering analysis are discussed here.

3.1. Data Overview

3.1.1. Fill History

Cavern oil fill history is tabulated at SPR with the help of the cavern management software CAVEMAN (Ballard and Ehgartner 2000). This report presents graphical fill histories for layered caverns based on the CAVEMAN data. The dates of temperature logs, oil inspections, and degas are also included in these fill histories for context. These charts illustrate how oil measurements, fill history, and degas timing relate to one another, giving clues as to which measurements would best represent the oil just prior and following degas. Figure 3-1 shows the graphical fill history for BC102 as an example. The black dots represent the CAVEMAN fill data, while the triangle symbols indicate the dates for temperature logs. In this example, the two temperature log dates follow significant oil fills, which mean that oil layering could be identified for either of those fills by investigating the temperature logs. In some cases, fill events occurred after the most recent temperature log. In those situations, changes in the total oil volume were passed on to volume changes to the top layer of oil since the oil in the top layer is the first affected by drawdown and injection.

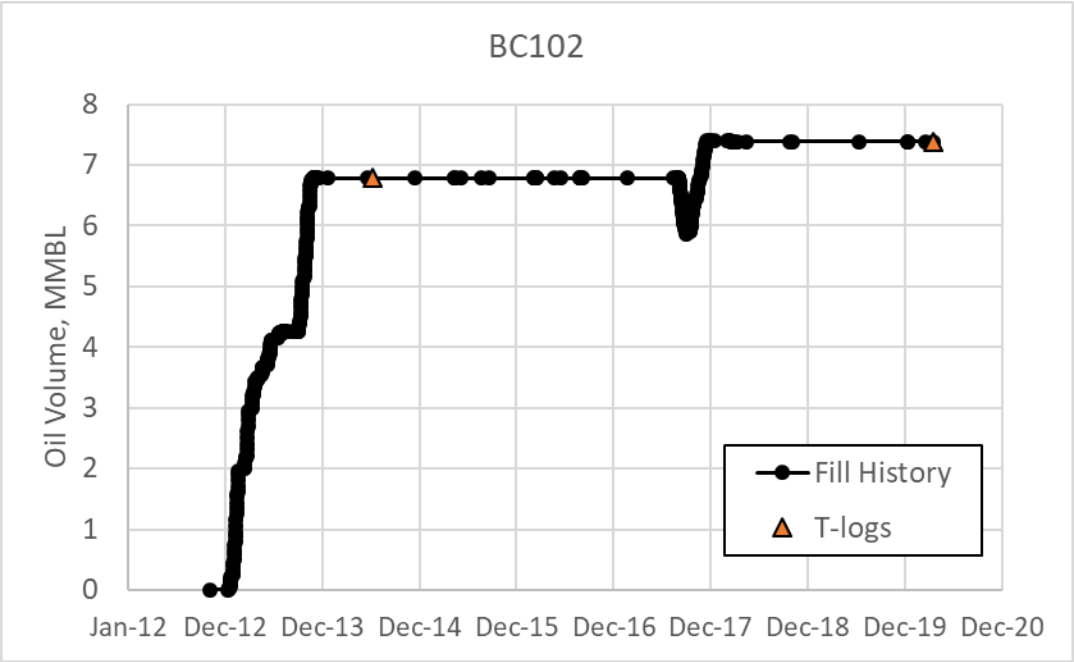


Figure 3-1. Oil Fill and temperature log history for BC102.

3.1.2. Geometry

Cavern geometry is obtained from sonar surveys. Specifically, simplified axisymmetric representations are presented here for layered caverns to provide context for temperature logs, cavern roof depths, oil layer interface depths, and oil-brine interface (OBI) depths. Also, strapping

curves (cumulative oil volume with depth) are included for layered caverns to provide context for oil layer volume calculations.

3.1.3. Temperature Logs

Temperature logs give the temperature with depth as measured on a wireline tool on a given date. A collection of these logs for a given cavern through time can reveal fluid layering and mixing trends. When oil is injected into a cavern, it goes down the well to the top of the cavern. From there, geothermal heating increases the temperature of the oil through time. Therefore, it is quite common to have cooler oil injected to the top of warmer cavern oil. In the case where oil injection leads to layering, the dissimilar temperatures of pre-existing and injection oils appear in the temperature logs as an abrupt change in temperature with depth. For each of the caverns discussed in this report, the most recent temperature log is shown in blue. Temperature logs in BC102 were used to clearly identify layering, so they are presented here as an example. Figure 3-2 gives the temperature logs, axisymmetric cavern geometry, and strapping curve for BC102. There are several step changes in the 2020 temperature log with depth. The temperature change around 2700' appears near the roof of the cavern, so it is most likely a result of roof heating effects. The temperature change around 3800' corresponds to the OBI, which is shown as a dash-dot line. The intermediate temperature change around 2900' corresponds to a change in oil properties, which means that there exist multiple oil layers in the cavern. This information, coupled with fill history, can be used to determine oil layer volumes.

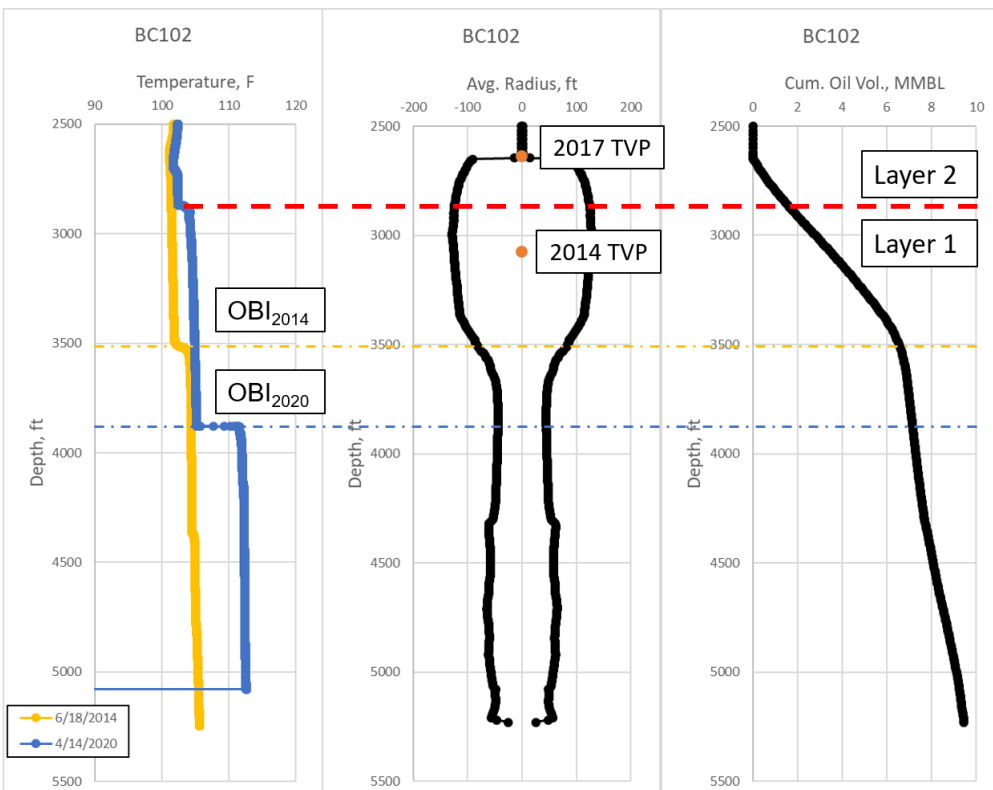


Figure 3-2. Temperature logs, axisymmetric cavern geometry, and strapping curve for BC102.

3.1.4. Crude Oil Inspections

Periodic inspection analyses are run for the crude oil quality program in which a wireline tool is sent into the cavern to retrieve oil samples at selected depths. The oil samples are analyzed for properties such as relative density and viscosity. Since mixing is driven by density differences, relative density and its distribution with depth is an important parameter that can provide evidence for cavern-scale layering. Inspections relevant to oil layering are shown where available but were not generally used in oil layer volume and vapor pressure calculations.

3.1.5. Vapor Pressure

Vapor pressure data are regularly collected at SPR and analyzed with delivery simulation models to assure that oil is delivered within program specifications for vapor pressure and gas-oil ratio. The TVP-95 mobile laboratory is regularly deployed to measure the vapor pressure of the crude oils at SPR. Samples of crude are taken from downhole within the caverns, or from flowing streams at the SPR site. The TVP-95 system measures the bubble point pressure (BPP) at 100°F using a shut-in separator. The Vapor Pressure Committee tracks BPP to determine the deliverability of the crude oils. As such, BPP will be used to represent the vapor pressure of the crude oils in this report.

3.2. Layer Property Calculations

The oil volume and vapor pressure of each layer were calculated in order to identify the amount and volatility of the oils stored within a cavern. These values can be strategically leveraged in oil movement operations to keep blended streams within deliverability specifications. Below, the methods used to determine the oil volume and vapor pressure for each layer are shown, followed by an in-depth example of this process.

3.2.1. Layer Oil Volume Calculation

The volume of oil in each layer was calculated using information from temperature logs, cavern sonars, and the VPC May 2020 quarterly sampling spreadsheets.

- First, the depth of each oil-oil interface was determined by identifying step changes in the temperature logs that did not correspond to roof effects or the oil-brine interface (OBI). If the most recent temperature log found for a cavern did not have any such step changes, then the oil in the cavern was assumed to be well-mixed throughout the cavern.
- Then, the cumulative volumes of oil from the top of the cavern to each oil-oil interface depth were calculated using the volume strapping curves in the most recent sonar for the cavern.
- Next, the volume of oil in each layer at the time of the temperature log was calculated by the difference in cumulative oil volumes for each layer.
- Then, the layer oil volumes were compared to the oil fill histories found in the May 2020 quarterly sampling spreadsheets to determine the dates of the oil transfers into each layer. This step was also used to update the calculated oil layer volumes to coincide with the fill history, which was a lower uncertainty volume determination than the sonar.
- Finally, the volume of the top layer of oil in each cavern was adjusted to meet the cavern oil volume as of the May 2020 quarterly sampling spreadsheets.

With the oil transfer dates and volumes for each layer identified, the next step was to determine the vapor pressure of each layer.

3.2.2. Layer Vapor Pressure Calculation

The vapor pressure for each layer was determined using the best information available, leveraging the oil transfer dates and volumes collected from the layer volume calculation. In all cases, TVP-95 data were used to estimate the vapor pressures, using the following logic:

- If there was a downhole TVP-95 sample taken at a depth and time corresponding to the layer, and there were no major oil transfers into the layer since the TVP-95 sample was taken, the BPP from that TVP-95 measurement was selected as the oil layer vapor pressure.
- If there was a downhole TVP-95 sample taken at a depth and time corresponding to the layer, but there were significant oil movements into the oil layer after the sample was taken, the oil layer vapor pressure was calculated via a volume-weighted average of the pre-existing layer oil BPP and the transfer oil BPP. The transfer oil BPP was selected from other cavern representative BPP's (if the transfer originated from another cavern), flowing incoming oil BPP's (if the transfer originated from offsite), or blended estimates of BPP's (if the transfer contained oils from multiple sources).
- If no downhole TVP-95 sample had been taken from the layer, then the oil layer vapor pressure was calculated from a volume-weighted average of available TVP-95 data, whether they came from cavern representative BPP's (if the transfer originated from another cavern), flowing incoming oil BPP's (if the transfer originated from offsite), or blended estimates of BPP's (if the transfer contained oils from multiple sources).
- If no downhole TVP-95 sample had been taken from the layer, and no other TVP-95 data were available for the oil transfers which composed layer, then the layer vapor pressure was indeterminate.

The resulting vapor pressures can then be assigned to the volumes of oil in each layer. Improved oil layer properties can then be fed into stream property calculations, which would improve the accuracy of the stream deliverability calculations.

3.2.3. Example: BC102

BC102 will be used here to give an example of the layer volume and vapor pressure determination process outlined in the previous sections.

3.2.3.1. BC102 Fill History Analysis

Oil fill history tracked in the May 2020 quarterly spreadsheet was collected to determine if there were oil movements that could result in layering. On 9/29/2017, the oil volume in the cavern reached a local minimum of 5.9 MMBL. Late in 2017, 1.5 MMBL of oil was added, and the cumulative oil volume by 4/15/2020 (when the temperature log was taken) was 7.4 MMBL. Thus, the 2017 fill could potentially have created another oil layer in BC102. The 2017 fill was identified from the May 2020 quarterly spreadsheet, which included the following note related to 2017 blended estimate calculations for BC102:

"Blended estimate with incoming WTI oil total 0.931 MMBL and LLS oil 0.542 MMBL from Hurricane Harvey Exchange."

The oil fill history and fill sources are plotted below in Figure 3-3 with the hypothesized layering scheme for BC102. With this information in hand, temperature logs can be investigated for evidence of layering.

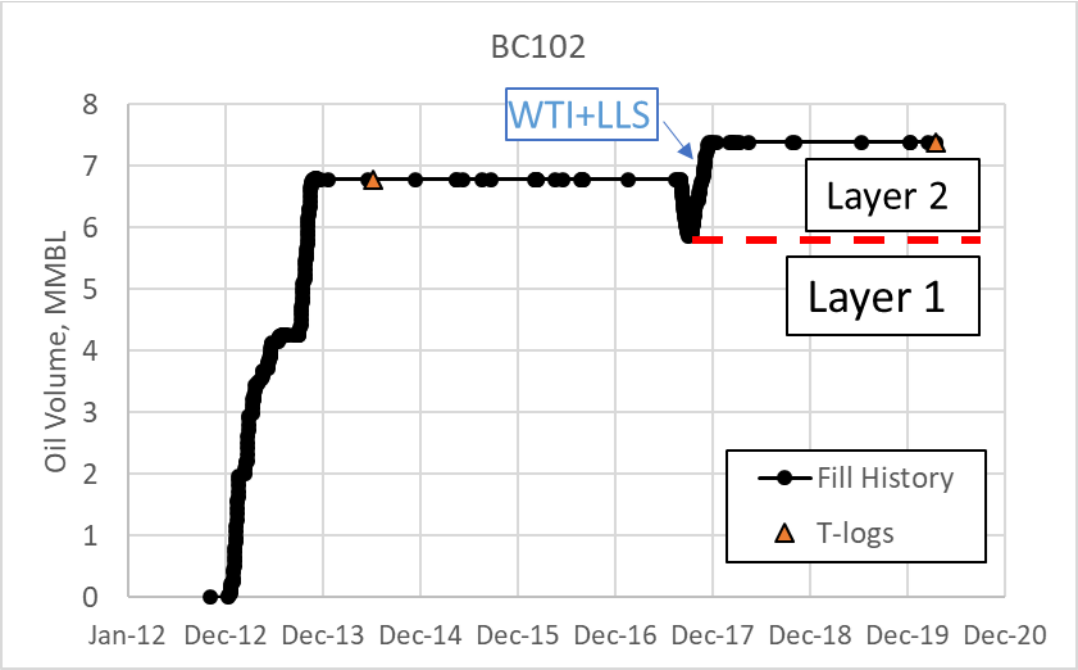
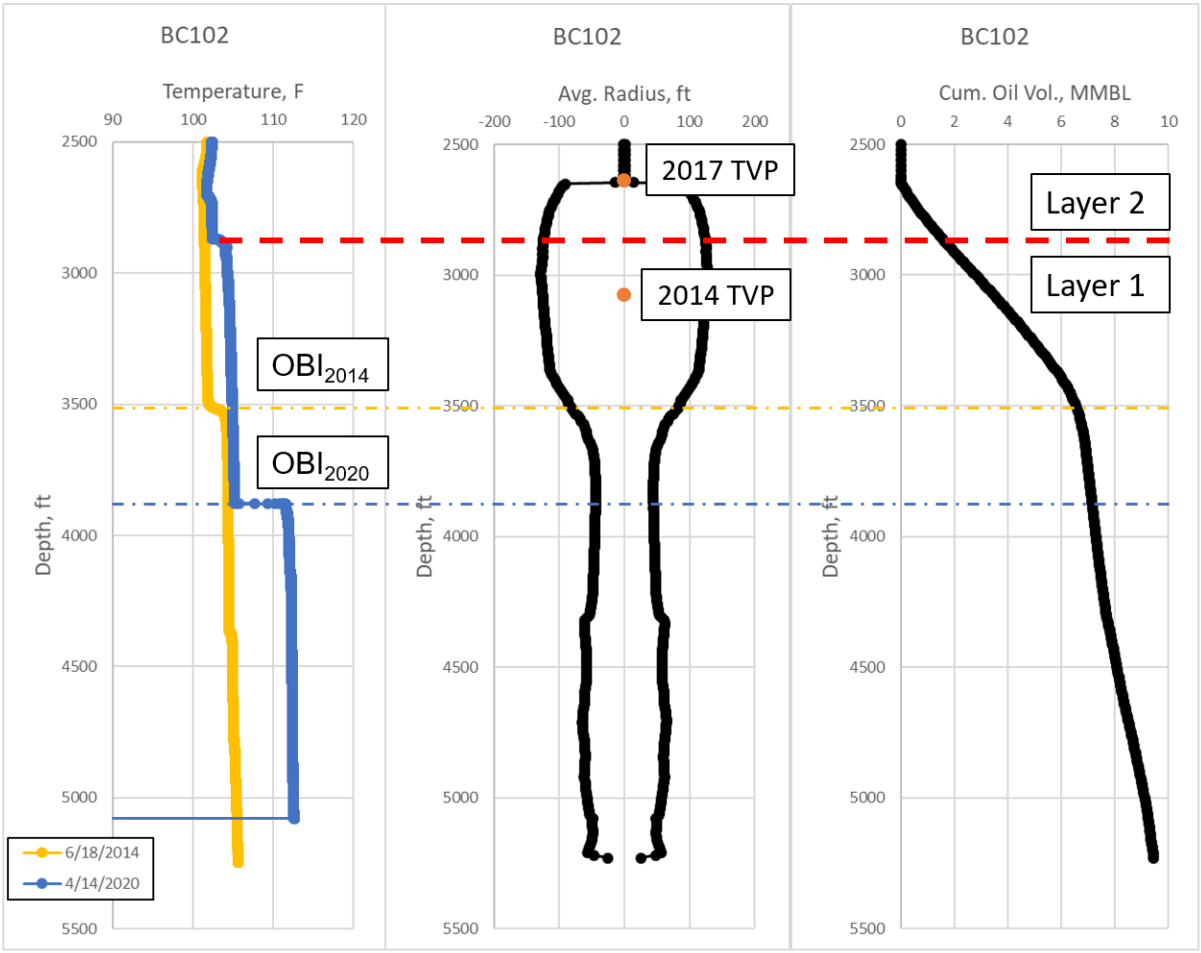


Figure 3-3. Oil fill history for BC102 (circles) with dates for recent temperature logs (triangles) and notation for fill source (blue boxes) and layer volumes (red dashed lines).

3.2.3.2. BC102 Temperature Log and Sonar Analysis

Two temperature logs are shown next to the axisymmetric cavern radius and strapping curve from a 2017 sonar for BC 102 in Figure 3-4. The cavern roof is evident in the avg radius plot at about 2640 ft depth, while the cavern floor sits at about 5200 ft. Temperature logs from 6/8/2014 (yellow) and 4/14/2020 (blue) are plotted. The 2014 log shows an OBI near 3500' and a nearly uniform oil temperature around 102°F between the roof and OBI, with a total oil volume between 6 and 7 MMB according to the strapping curve. In the 2020 temperature log, the OBI was at 3876', and it appears that there are two oil layers separated by a 1.7 °F difference at a depth of about 2880'. The strapping curve indicated that the cumulative oil volume from the chimney to a depth of 2880' was 1.6 MMBL, while the cumulative oil volume from the chimney to the OBI was 7.1 MMBL. Thus, at 4/14/2020, the temperature log and sonar indicated that there was 1.6 MMBL of oil in the top layer, and 5.5 MMBL of oil in the bottom layer. This matched up well with the oil fill history analysis, so with these volume data in hand, the vapor pressures of the layers can be determined.



a) b) c)

Figure 3-4. BC102 data by depth, including a) recent temperature logs, b) axisymmetric radius (with TVP-95 depth), and c) cumulative volume.

3.2.3.3. BC102 Layer Vapor Pressure Analysis

According to the analyses in the previous sections, BC102 contains a bottom layer of 5.9 MMBL of pre-2017 oil and a top layer of 1.5 MMBL of Hurricane Harvey Exchange oil. The top layer consisted of 0.931 MMBL of West Texas Intermediate (WTI), and 0.542 MMBL of Louisiana Light Sweet (LLS). There have been TVP-95 samples taken that represent both oil layers. On 9/27/2017, a flowing TVP-95 sample was taken on oil coming out of BC102, with a BPP of 20.0 psia. On 10/17/2017, a flowing TVP-95 sample was taken on WTI oil coming into BC, with a BPP of 16.4 psia. On 11/21/2017, a flowing TVP-95 sample was taken on LLS oil coming into BC, with a BPP of 18.0 psia. The bottom 5.9 MMBL of oil can be characterized as 20.0 psia oil from the 9/27/2017 flowing sample. The top 1.5 MMBL of oil can be characterized as 17.0 psia oil, which is the volume weighted average of 0.931 MMBL of 16.4 psia WTI and 0.542 MMBL of 18.0 psia LLS. These layer vapor pressures and oil volumes can then be used to update cavern and stream deliverability models.

4. RESULTS

Historical temperature logs, fill histories, and sonars related to the sixty active SPR caverns were gathered and analyzed for oil layering up until late April/early May 2020, the time period associated with the May 2020 VPC quarterly spreadsheet. From said analysis, the vapor pressure for each of the oil layers was estimated by gathering TVP-95 data and calculating volume-weighted blended estimates.

Of the sixty active caverns, ten were found to contain multiple oil layers. Eight of the layered caverns contained sweet oil, while the remaining two layered caverns contained sour oil. Half of the layered caverns developed layers due to low density sweet crude coming from the U.S. midstream. The other five layered caverns developed layers from cavern-to-cavern or site-to-site transfers. The persistent layering observed here was likely the result of a shift in base composition in the crude oils. Thus, the incoming oil was lower density than the native cavern oil, leading to the formation of these layers. In at least three of these caverns, the transfer oils were also higher vapor pressure than the native cavern crudes. For these cases, oil layering increased the vapor pressure of the oil coming out of the cavern, which can impact the deliverability of the crude.

A detailed explanation of this analysis for the sweet and sour oil caverns is given in the following sections.

4.1. Sweet Cavern Analysis

Historical data for the twenty-four active sweet crude caverns at SPR were analyzed. Table 4-1 gives the results of this analysis. The temperature logs were the greatest factor in helping to determine whether there was layering as indicated by step changes in the temperature with depth. Thus, the year of the most recent temperature log for each cavern used for this analysis is also given in the table. Sixteen of the twenty-four caverns do not show evidence of layering. Eight caverns showed distinct evidence of layering (BC102, BH104, BH105, BM113, BM114, BM116, WH107, and WH113). The vapor pressures at 100 °F for each of the caverns were taken from the May 2020 VPC quarterly spreadsheets and listed in the table below for reference. In general, vapor pressures close to or below 14.7 psia are considered "blendstock caverns" that can be used to blend down high vapor pressure oil in order to meet deliverability criteria. Of the nine caverns found to contain oil layers, four caverns (BH104, BH105, BM116, and WH107) contain blendstock oil that is inaccessible due to layering.

Table 4-1. Oil-oil interface historical data analysis summary in the sweet caverns at the four SPR sites.

Cavern	Latest T-Log	Oil-Oil Interface	VP[a], psia
BC18	2018		16.0
BC102	2020	X	19.3
BH101	2014		12.9
BH102	2018		12.9
BH103	2019		12.8
BH104	2018	X	14.8
BH105	2018	X	14.0
BH114	2017		12.8
BM4	2017		14.0
BM106	2018		13.9
BM113	2019	X	15.1
BM114	2017	X	16.6
BM115	2019		16.0
BM116	2020	X	13.6
WH7	2017		13.2
WH101	2019		13.4
WH102	2020		13.7
WH103	2019		15.8
WH104	2019		13.2
WH107	2018	X	15.8
WH108	2018		14.0
WH110	2017		12.7
WH113	2018	X	15.9
WH116	2018		13.2

[a] From May 2020 VPC Quarterly Spreadsheet

The eight sweet caverns found to contain layers will be examined here to better understand the vapor pressures and oil volumes of the layers.

4.1.1. BC102

BC102 started SPR oil storage in 2012. It was filled with 7 MMBL of oil in 2012-2014 comprising a blend of transfer oil from BC20, new fill from the Bakken region, and transfer oil from BC018. A 2014 temperature log indicated a smooth incremental increase in temperature with depth until ~3500', which occurred just above the oil-brine interface (OBI) depth of 3513'. Thus, it appeared that the 2012-2014 fill completely mixed. A downhole TVP-95 measurement on 4/24/2014 taken at 3071' indicated BPP = 19.4 psia, which was representative of the mix. After a 1 MMBL drawdown in mid-2017, about 1.5 MMBL of crude oil was added from the U.S. midstream to the top of the cavern as part of the Hurricane Harvey Exchange (see Figure 4-1). During this time, 0.9 MMBL of West Texas Intermediate (WTI) and 0.5 MMBL of Louisiana Light Sweet (LLS) oils were added to the cavern. An April 2020 temperature log confirmed that an oil-oil interface formed at a depth of about 2880', which occurred above the OBI that was at a depth of 3376'. The oil-oil interface was about 1.5 MMBL into the cavern (see Figure 4-2). Thus, it appears that the 2017 Hurricane Harvey Exchange oil has been floating at the top of the cavern since it was added in 2017. The vapor pressure of the bottom layer (Layer 1) was determined by a 9/27/2017 TVP-95 flowing sample coming out of the cavern to be 20.0 psia. The vapor pressure of the Harvey Exchange layer (Layer 2) was calculated as 17.0 psia by volume-weighting the WTI (0.9 MMBL / 16.4 psia) and LLS (0.5 MMBL / 18.0 psia) TVP-95 flowing sample analyses.

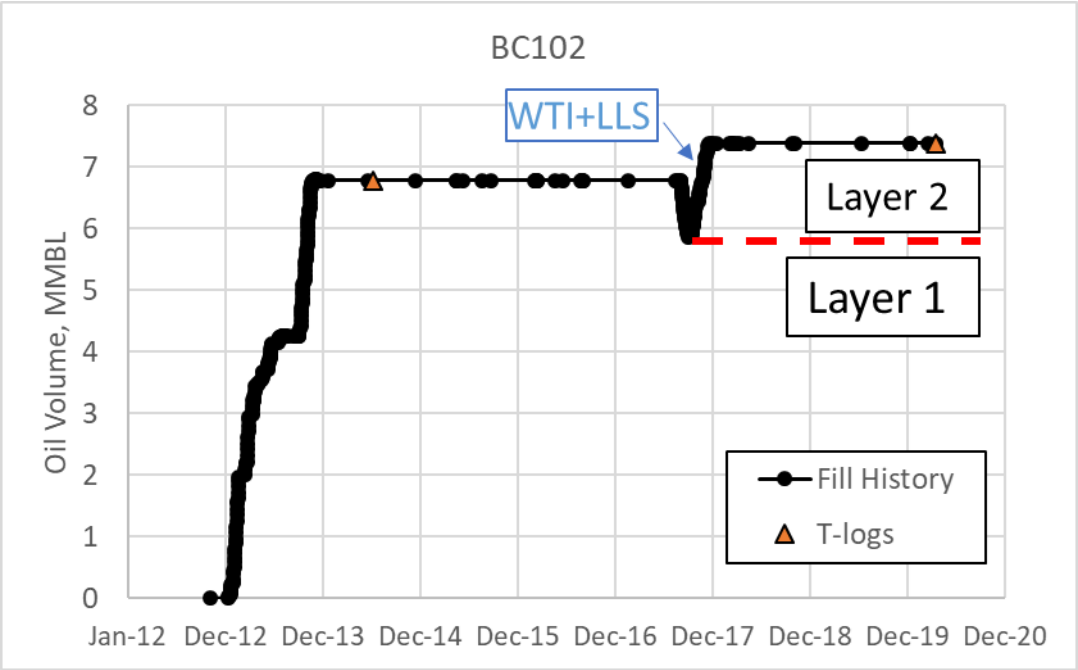
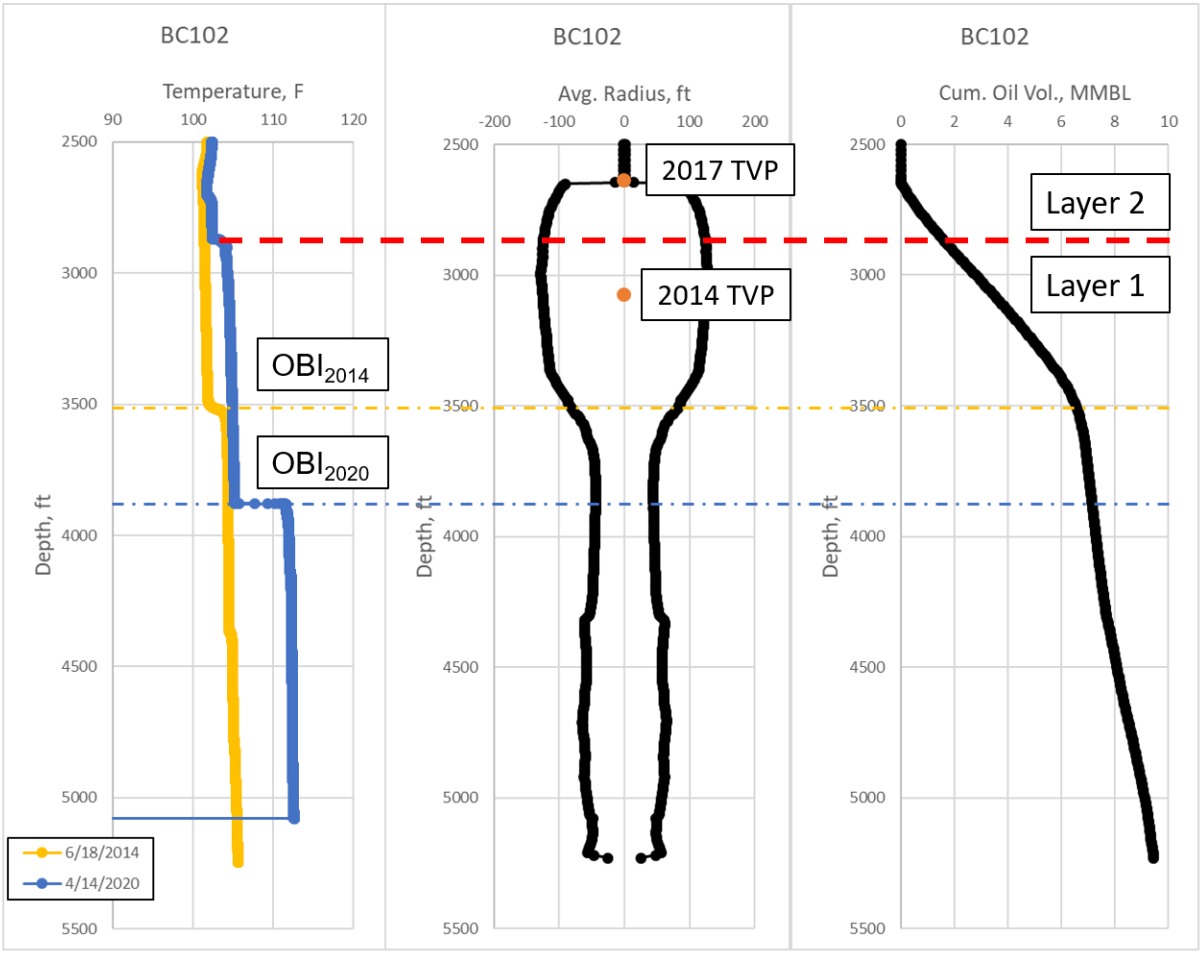


Figure 4-1. Oil fill history for BC102 (circles) with dates for recent temperature logs (triangles) and notation for fill source (blue boxes) and layer volumes (red dashed lines).

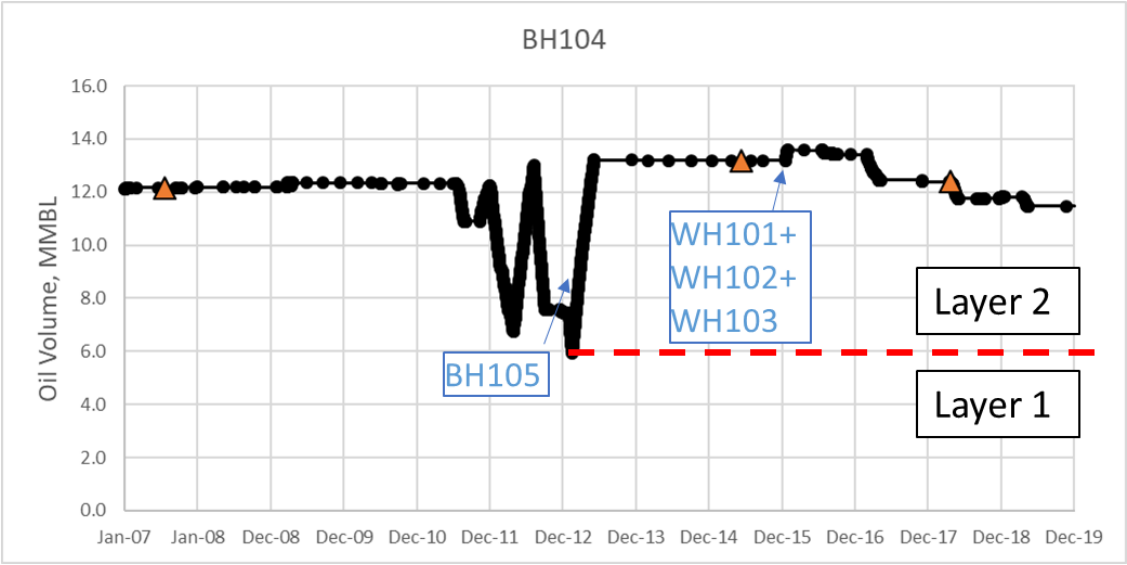


a) b) c)

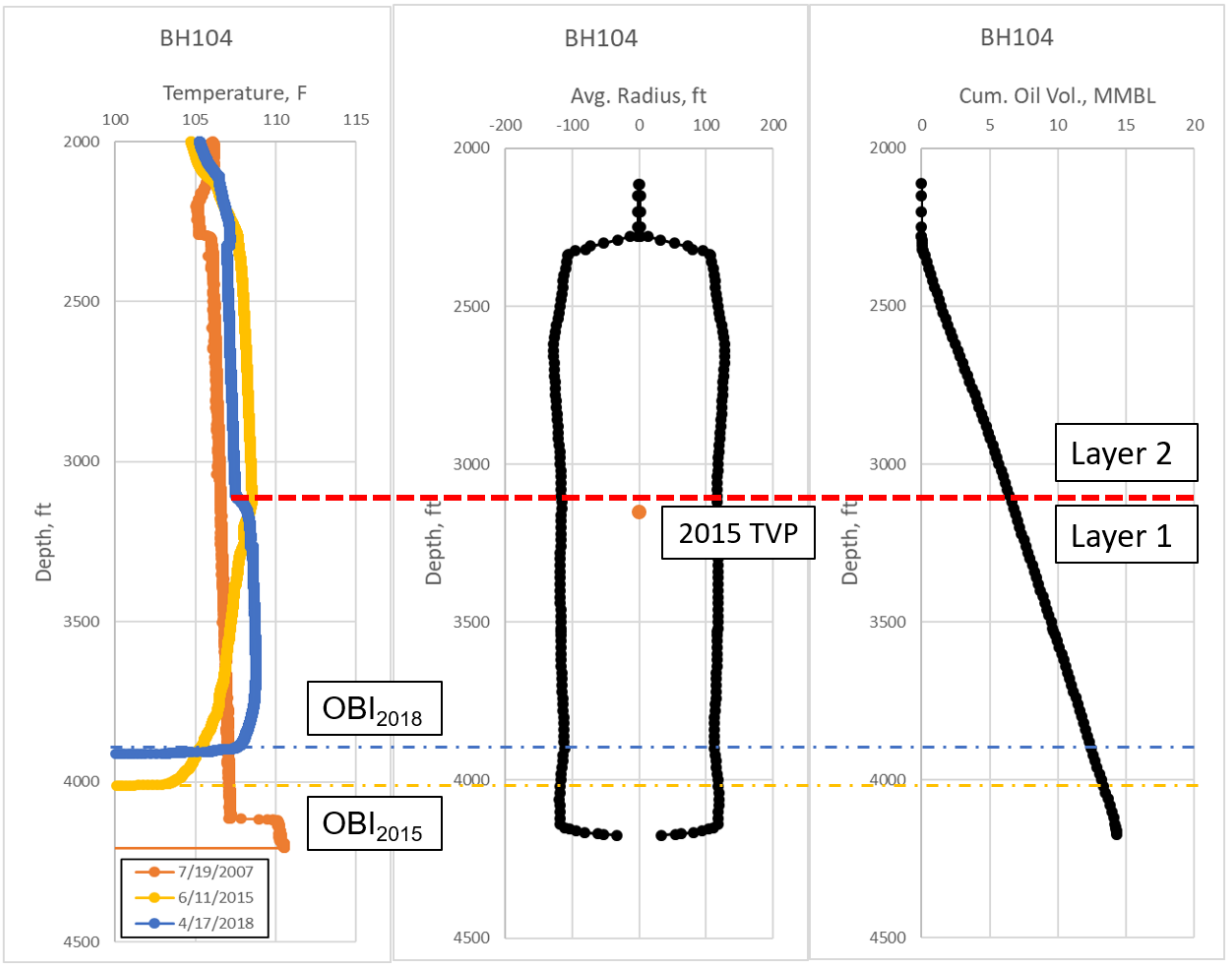
Figure 4-2. BC102 data by depth, including a) recent temperature logs, b) axisymmetric radius (with TVP-95 depth), and c) cumulative volume.

4.1.2. BH104

In the early 2010's, BH104 participated in "daisy chain leaching" with other caverns at BH, evidenced by the series of drawdowns and fills in 2011 and 2012. In 2013, about 7.3 MMBL of crude oil was added to the top of BH104 from BH105 as part of the leaching procedure (see Figure 4-3). Then, in early 2016, about 400 MB of oil from WH101, WH102, and WH103 was added to BH104. Three recent temperature logs are shown in Figure 4-4. While there was no layering evident in the 2007 temperature log, the 2015 temperature log showed a change of slope with depth around 3100', which occurred above the OBI that was at a depth of 4010'. Temperature decreased with depth deep in the cavern, which was different than other temperature logs. Injection of cold water during the leaching events in the early 2010's may have caused prolonged heat transfer from the cavern oil to the brine. Even so, a 2015 oil inspection indicated step changes in both base relative density and viscosity with depth, as shown in Figure 4-5. These changes correspond to different oil layers. The 2018 temperature log showed a step change in oil temperature around the same depth, which again occurred above the OBI that was at a depth of 3910.5'. These support the idea that the 2013 fill floated on top of the pre-2013 oil, forming an oil-oil interface at depths consistent with the volumes reported in the fill history. The TVP-95 was deployed to BH104 on 4/16/2015 and measured 14.9 psia on a downhole sample at 3143'. This depth was within 50' of the calculated oil-oil interface depth at that time, so it is difficult to say whether that sample correlates to the top layer (Layer 2) or bottom layer (Layer 1) in BH104. For this analysis, it was assumed that the TVP-95 measurement corresponded to Layer 1. Thus, Layer 1 vapor pressure was assumed to be 14.9 psia. It was assumed that the WH oil injected in 2016 mixed with the other oil in Layer 2 to give a conservative estimate of the vapor pressure. Thus, Layer 2 vapor pressure was calculated to be 14.5 psia from a volume-weighted average of BH105 oil (7.3 MMBL/14.5 psia) and WH oil (0.4 MMBL/15.3 psia).

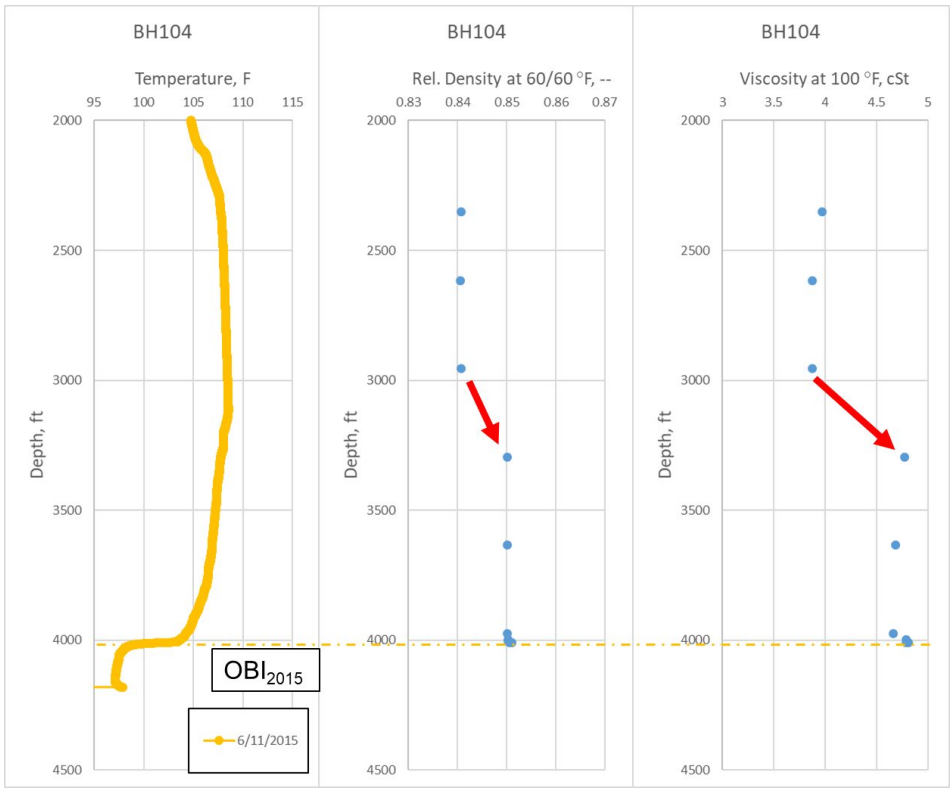


Number 4-3. Oil fill history for BH104 (circles) with dates for recent temperature logs (triangles) and notation for fill source (blue boxes) and layer volumes (red dashed lines).



a) b) c)

Figure 4-4. BH104 data by depth, including a) recent temperature logs, b) axisymmetric radius (with TVP-95 depth), and c) cumulative volume.



a) b) c)

Figure 4-5. BH104 data by depth, including a) the 2015 temperature log, b) the 2015 relative densities, and c) the 2015 viscosities.

4.1.3. BH105

In 2013, BH105 was used in a "daisy chain" leaching operation where oil was transferred from cavern to cavern using raw water drive. This accounted for the 7 MMBL drawdown and subsequent 1.8 MMBL partial refill in 2013 (see Figure 4-6). Both the first 1.5 MMBL fill early in 2013 and the 0.3 MMBL fill late in 2013 were from BH102. However, the first fill most likely contained oil that BH102 had received from BH101 during the daisy chain leaching program in 2011, and the last fill contained oil that had been in BH102 since 2004. About 0.6 MMBL was added to the cavern in early 2016 from WH101, WH102, and WH103. Figure 4-7shows temperature logs from 2005, 2007, and 2018, with cold water injection during the early 2013 drawdown causing a temperature drop from 2007 to 2018. While there was no layering evident in the 2005 and 2007 temperature logs, the 2018 temperature log provided evidence of an oil-oil interface around 2500', which occurred above the OBI that was at a depth of 3242'. This depth corresponded to a cumulative oil volume of 1.25 MMBL, which means that the top layer of oil consists of late 2013 fill from BH102 and early 2016 fill from WH101, WH102, and WH103. A 2016 downhole TVP-95 sample gave a vapor pressure of 14.1 psia. The timing (March) and depth (2773') of the sample placed it firmly in Layer 1. Layer 2 vapor pressure is estimated to be 14.4 psia from a volume-weighted average on oil from BH102 (0.3 MMBL/12.5 psia) and WH101/WH102/WH103 (0.6 MMBL/15.3 psia).

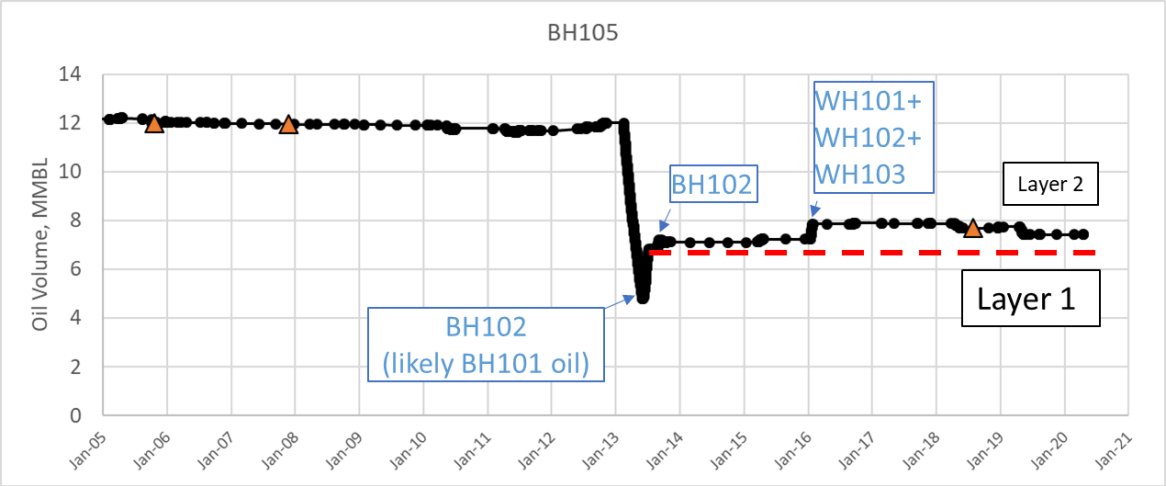
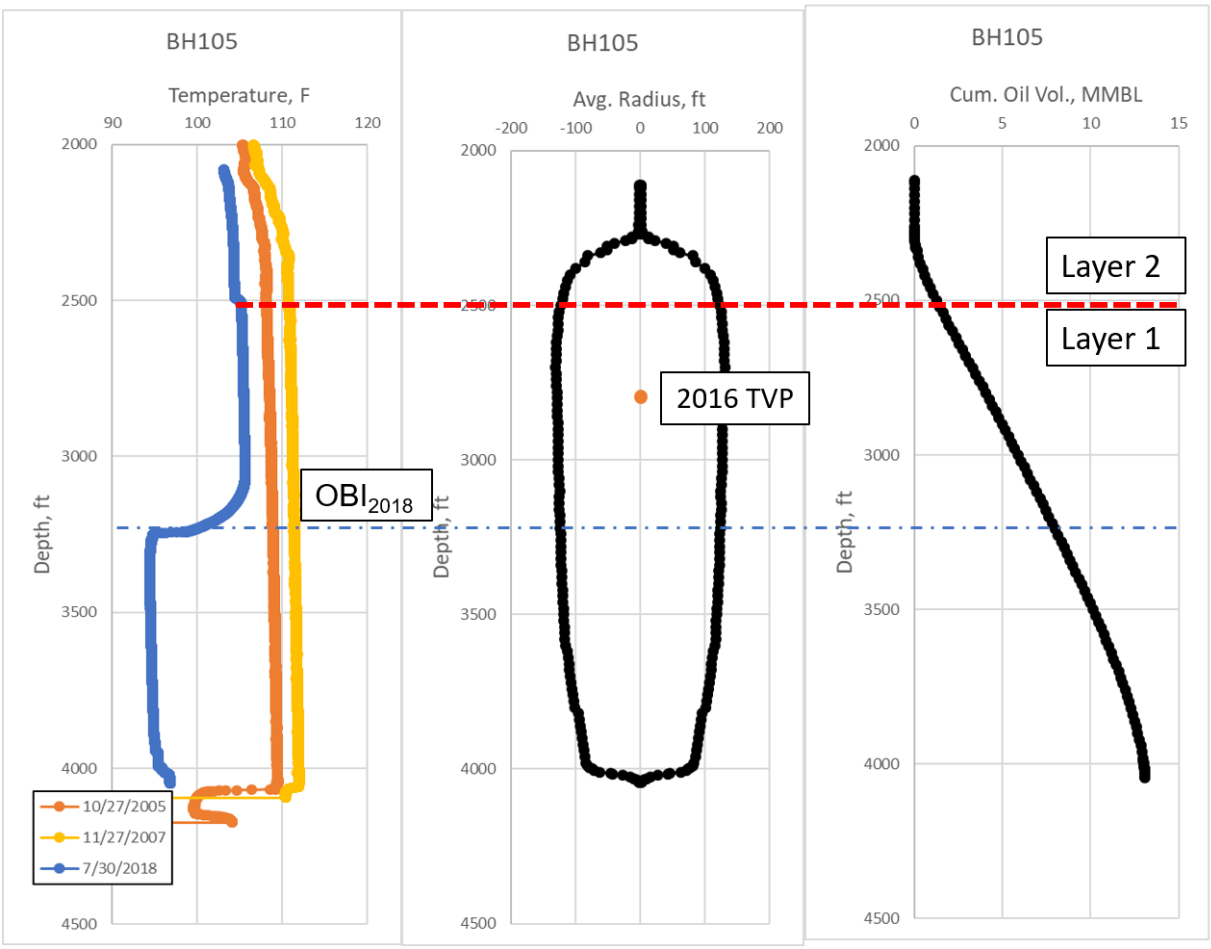


Figure 4-6. Oil fill history for BH105 (circles) with dates for recent temperature logs (triangles) and notation for fill source (blue boxes) and layer volumes (red dashed lines).



a) b) c)

Figure 4-7. BH105 data by depth, including a) recent temperature logs, b) axisymmetric radius (with TVP-95 depth), and c) cumulative volume.

4.1.4. BM113

In the early 2010's, BM113 was targeted for additional leaching to increase cavern space. In late 2011, 4.5 MMBL was drawn down from the cavern, followed by several fill operations through time (Figure 4-8). The first 1.4 MMBL fill in 2012 came from BM115 and BM116. The next 1 MMBL fill in 2012 came from BM116 alone. In 2015, BM113 received about 1.2 MMBL of Domestic Sweet (DSW) oil as part of a hurricane exchange. Then, in 2018, BM113 received another 1.2 MMBL of DSW. Figure 4-9 gives temperature logs from 2010 and 2019. While the 2010 temperature log was smooth (indicating a fully mixed cavern), the 2019 log showed no less than three distinct oil layers in the cavern. The shallowest interface depth (2355') corresponded to a cumulative oil volume of 1.5 MMBL, which means that the 2018 DSW fill created an oil-oil interface and is labeled "Layer 3." The deeper interface depth (2480') corresponded to a layer volume of 1.1 MMBL, which means that the 2015 DSW fill created a new oil layer. Both oil-oil interfaces occurred above the OBI that was at a depth of 3445' in 2018. There have been no TVP-95 measurements on BM113 since 2009 taken at a depth of 3100'. A blended estimate corresponding to Layer 1 created on 1/3/13 gave a vapor pressure of 13.7 psia. Layer 2 vapor pressure was estimated to be 18.5 psia, the vapor pressure of the 2015 DSW oil. Layer 3 vapor pressure was estimated at 17.1 psia from the 2018 DSW TVP-95 flowing sample.

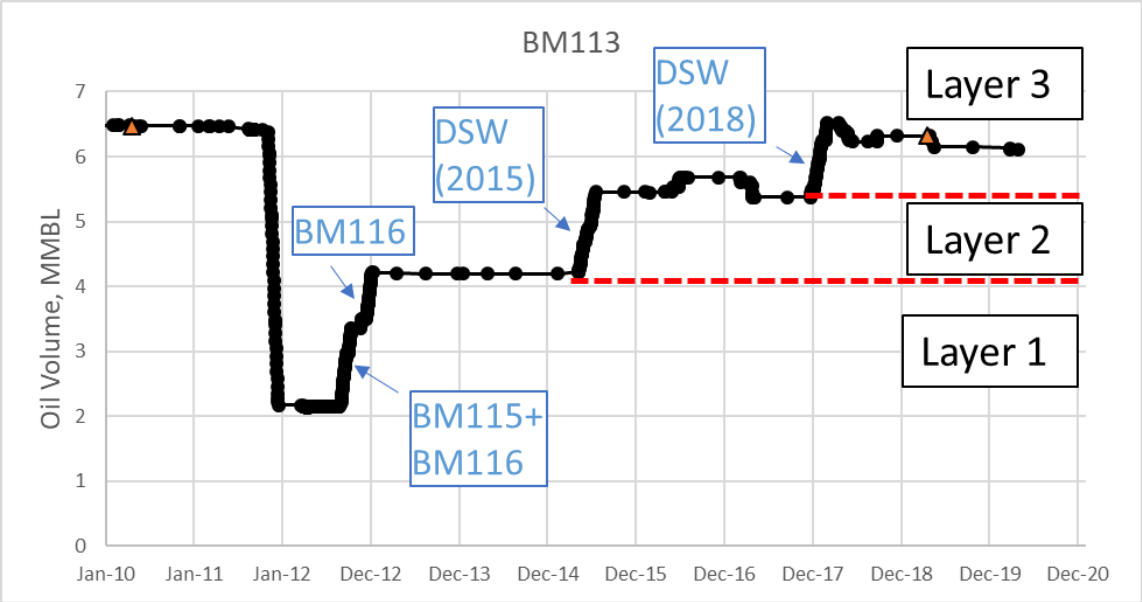
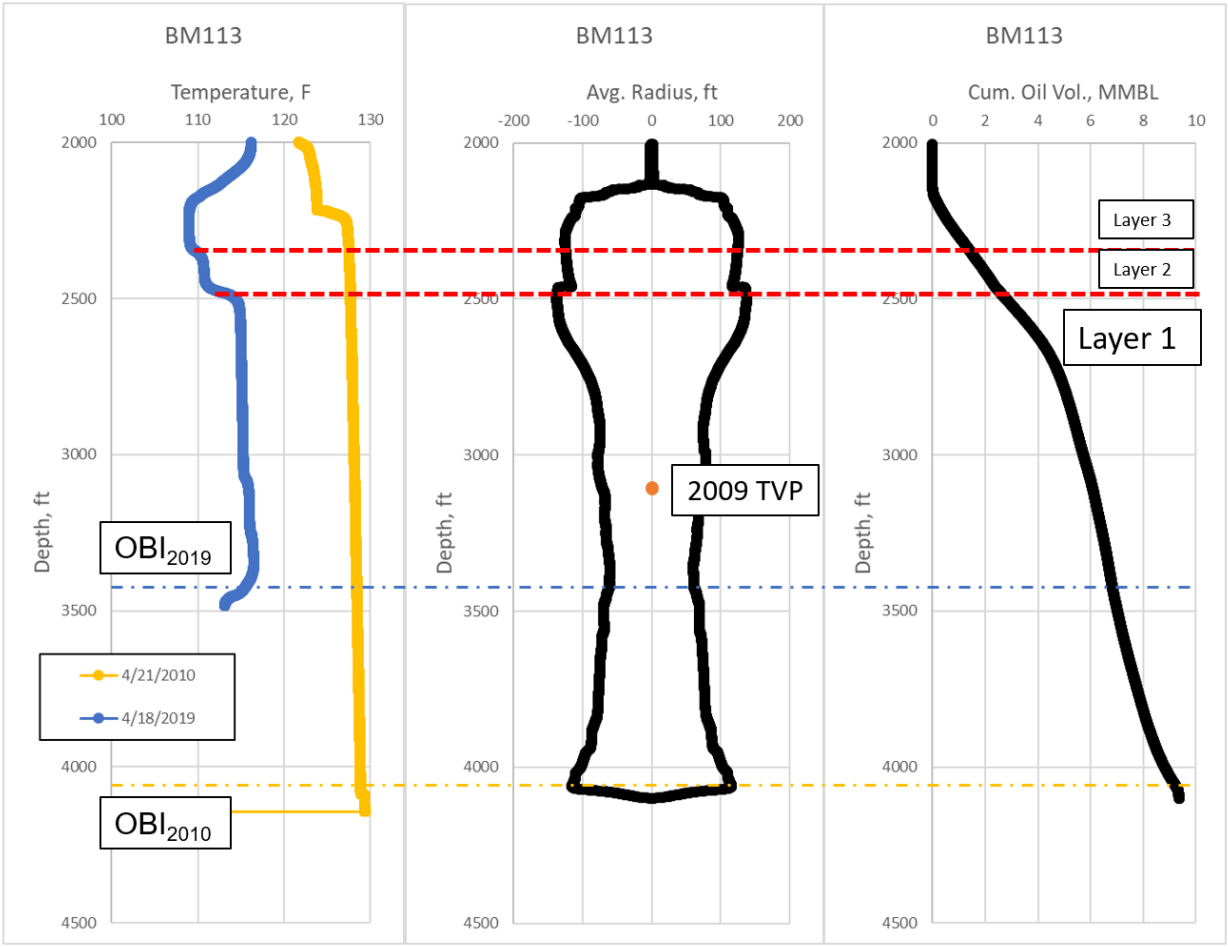


Figure 4-8. Oil fill history for BM113 (circles) with dates for recent temperature logs (triangles) and notation for fill source (blue boxes) and layer volumes (red dashed lines).



a) b) c)

Figure 4-9. BM113 data by depth, including a) recent temperature logs, b) axisymmetric radius (with TVP-95 depth), and c) cumulative volume.

4.1.5. BM114

BM114 saw multiple fill/drawdown operations in the 2010's, as shown in Figure 4-10. The cavern was drawn down to ~4 MMBL in cavern by mid-2011. From there, 2 MMBL was added, which was then drawn down as well. By 2012, 3.1 MMBL of oil remained in BM114. In 2015 to early 2016, 6 MMBL was added to the cavern in three separate fills in 2015-2016. The first 2 MMBL fill was 2015 DSW from a hurricane exchange. The next two 2015-2016 fills came from BM2. Then, in 2017, about 0.5 MMBL was drawn down, and 0.5 MMBL of 2018 DSW was added in 2017-2018, only to be drawn down out of the cavern in 2018. Finally, another 0.5 MMBL of oil was added to the cavern from BM4 in 2020. Figure 4-11 shows temperature logs from 2010 and 2017. While there was no evidence for layering in the 2010 log, an oil-oil interface at 3190' in the 2017 log corresponded to a cumulative oil volume of 5.8 MMBL. The oil-oil interface occurred above the OBI that was at a depth of 3905' in 2017. The layer in 2017 is likely from the 2015-2016 6 MMBL fill forming a new layer on top of the pre-existing oil. The 2/6/14 TVP-95 downhole measurement at 2328' gave a vapor pressure of 13.5 psia in the cavern prior to the ~7 MMBL addition. Thus, the vapor pressure in Layer 1 was estimated to be 13.5 psia. The vapor pressure in Layer 2 was calculated to be 16.4 psia by volume weighting the 2016 TVP-95 downhole sample at 3056' (5.3 MMBL/16.6 psia) with the BM4 2020 fill (0.4 MMBL/14.1 psia). It was assumed that the 2018 DSW fill formed another layer (like it did in the other BM caverns) which was then drawn out of the cavern before the BM4 fill.

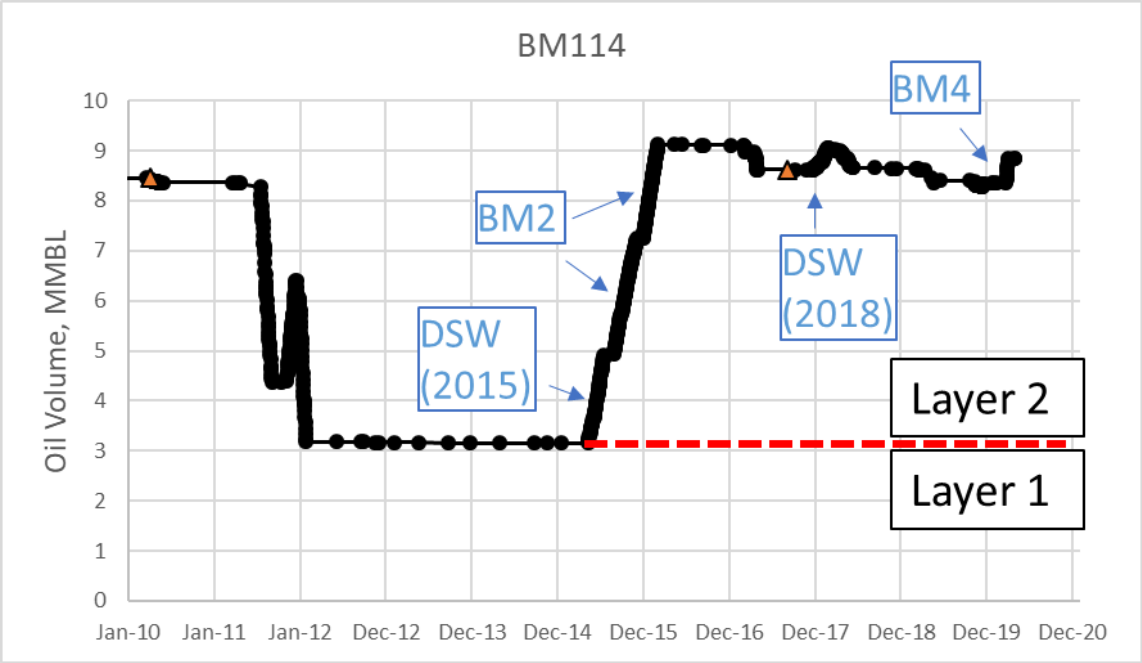
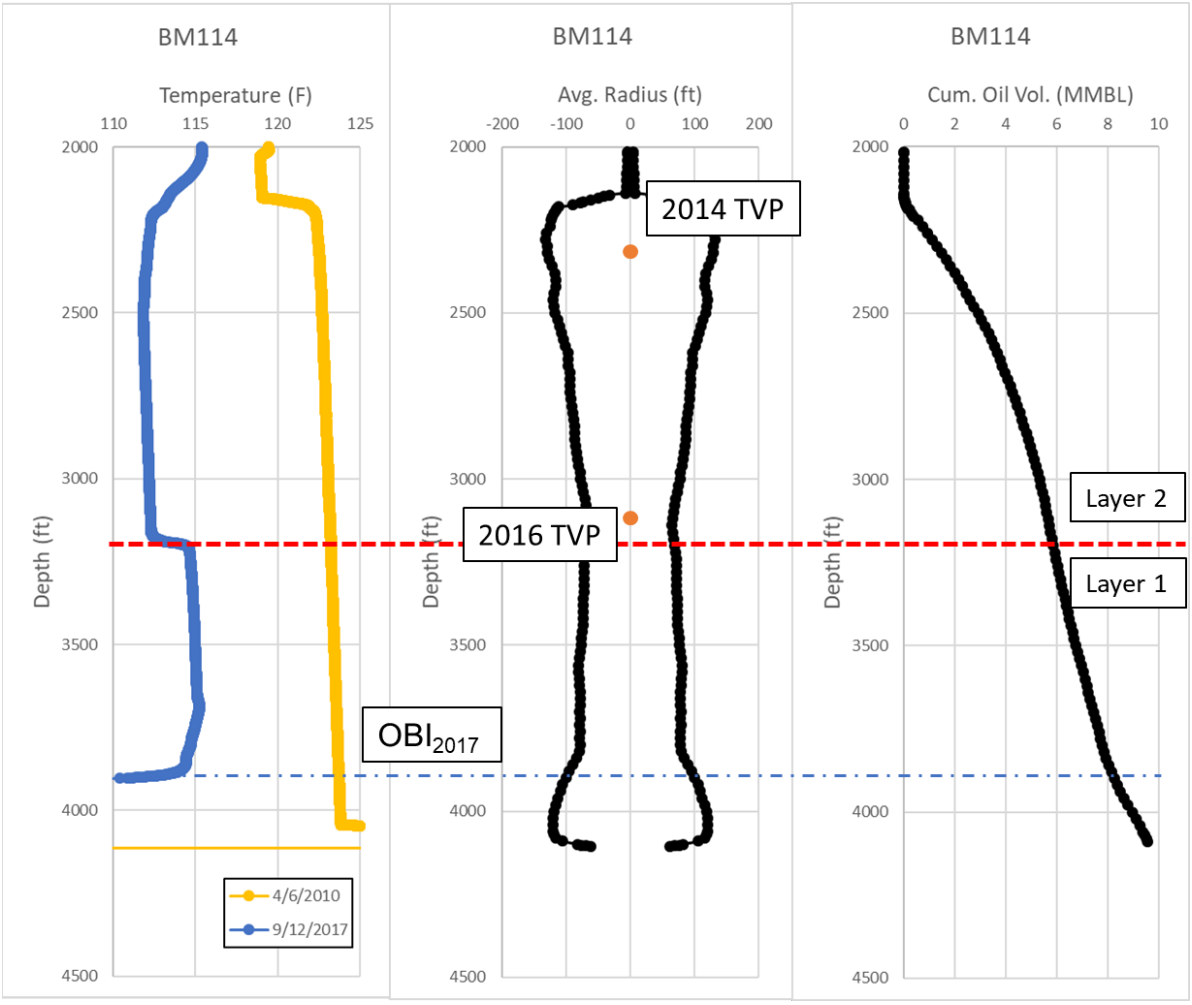


Figure 4-10. Oil fill history for BM114 (circles) with dates for recent temperature logs (triangles) and notation for fill source (blue boxes) and layer volumes (red dashed lines).



a) b) c)

Figure 4-11. BM114 data by depth, including a) recent temperature logs, b) axisymmetric radius (with TVP-95 depths), and c) cumulative volume.

4.1.6. BM116

BM116 saw multiple fill/drawdown operations from 2009-2019, as shown in Figure 4-12. Figure 4-13 gives temperature logs from 2010, 2017, and 2020. While the 2010 temperature log was smooth (indicating a fully mixed cavern), the 2020 log showed no less than three distinct oil layers in the cavern. Both oil-oil interfaces occurred above the OBI that was at a depth of 3680' on 4/23/2020. The shallowest interface depth is labeled "Layer 3" and corresponds to an oil volume of 1.2 MMBL, which was that of the 2018 DSW fill. Layer 3 created an oil-oil interface with a temperature of 113 °F at a vapor pressure of 17.1 psia as determined by a flowing TVP-95 sample. The mid-level interface depth is labeled "Layer 2" and corresponds to an oil volume of 2.2 MMBL, which was that of a mixture fill. The mixture fill sources were from BM114 in 2011, 2015 DSW, and BM2 in 2016. The BM114 fill was assumed to be 0.5 MMBL of 13.5 psia oil, which was the last blended estimate for the cavern. The 2015 DSW comprised 1.2 MMBL of 18.5 psia oil, and the 2016 BM2 fill was 0.2 MMBL of what was assumed to be 15.0 psia oil, as indicated by a 2008 downhole TVP-95 sample taken in BM2. The volume weighted average of these fills produced as layer vapor pressure of 16.8 psia. Layer 2 created an oil-oil interface with a temperature of 116 °F. The deepest interface depth is labeled "Layer 1" and corresponds to a cumulative oil volume of 6.4 MMBL, which was that of degassed oil. Layer 1 created an oil-oil interface with a temperature of 120 °F at a vapor pressure of 13.7 psia, as determined by a 2019 downhole TVP-95 sample at a depth of 2883'.

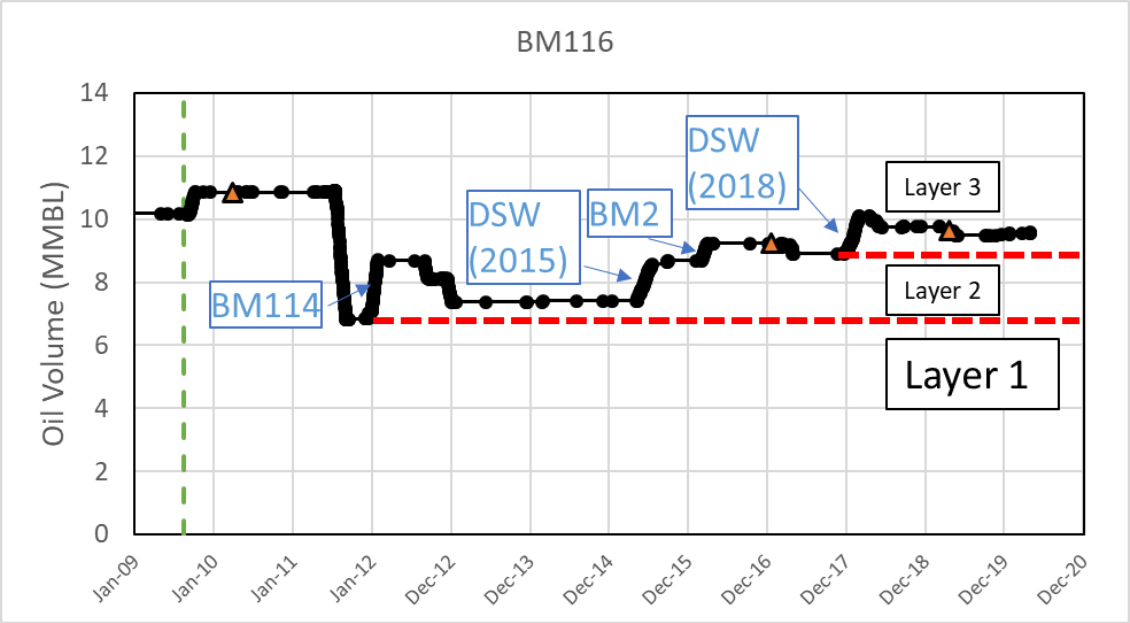
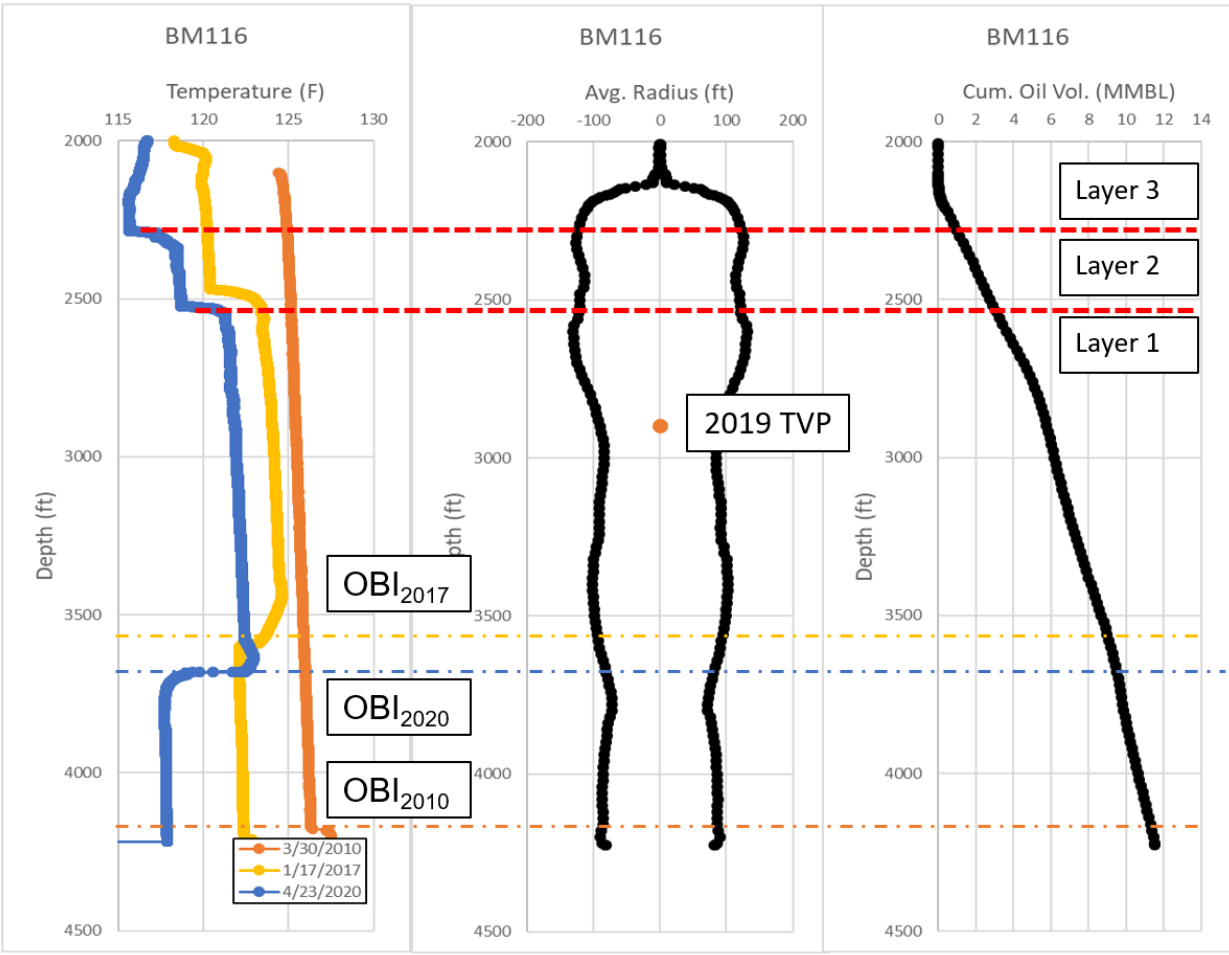


Figure 4-12. Oil fill history for BM116 (circles) with dates for recent temperature logs (triangles) and degas (vertical dashed green line), and notation for fill source (blue boxes) and layer volumes (red dashed lines).



a) b) c)

Figure 4-13. BM116 data by depth, including a) recent temperature logs, b) axisymmetric radius (with TVP-95 depth), and c) cumulative volume.

4.1.7. WH107

WH107 saw a number of fill activities 2000-2009, as shown in Figure 4-14. The relevant fills occurred in 2005, 2008, 2009, and 2016. The 1.7 MMBL fill in 2005 was Royalty in Kind (RIK) oil from various sources, including Nemba, SLS, and Saharan. The 0.8 MMBL fill in 2008, 1.0 MMBL fill in 2009, and 0.3 MMBL fill in 2016 have no clear labeling linking them to oil properties. Temperature logs from 2009, 2018, and 2019 are shown in Figure 4-15. The 2009 temperature log showed evidence of four oil layers which were a result of the chemically dissimilar RIK oils being added to the top of the cavern. The 2018 temperature log showed that there were only two oil layers in the cavern, which means that mixing occurred between 2009 and 2018. The 2019 temperature log confirms that there is an oil-oil interface at depths consistent with the volumes reported in the fill history. Both layers occurred above the OBI that was at a depth of 4467' in 2018 and 4432' in 2019. The 0.3 MMBL draw down and subsequent fill in 2016 may have caused that mixing to occur. Layer 1 vapor pressure was estimated to be 15.8 psia from the TVP-95 downhole sample taken on 5/8/2014 at a depth of 3541'. Layer 2 vapor pressure cannot be easily ascertained from the information available, though the Saharan RIK oil vapor pressure was measured to be 17.1 psia by a TVP-95 flowing sample taken on 7/28/2005.

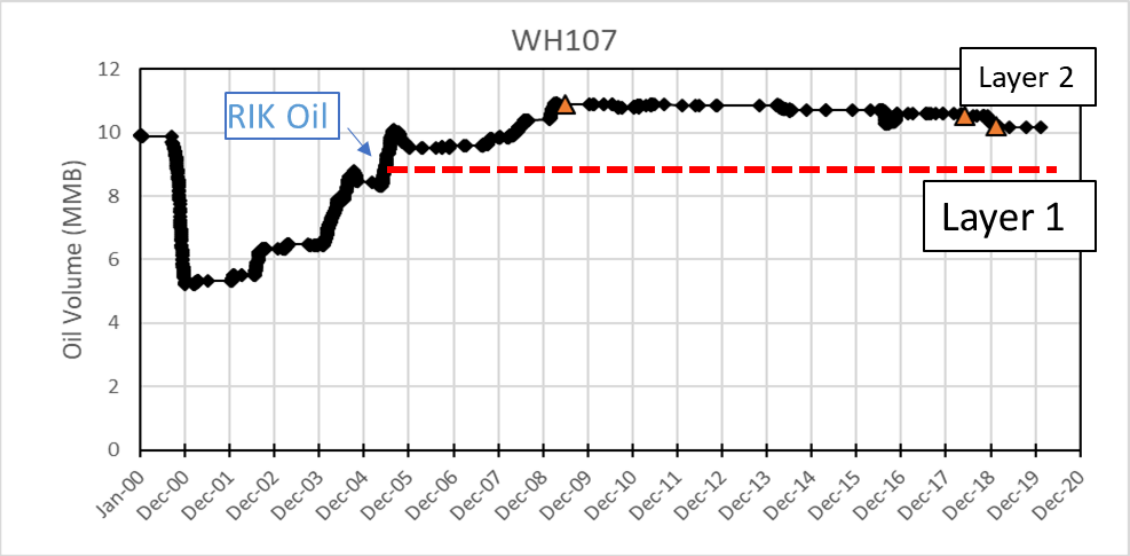
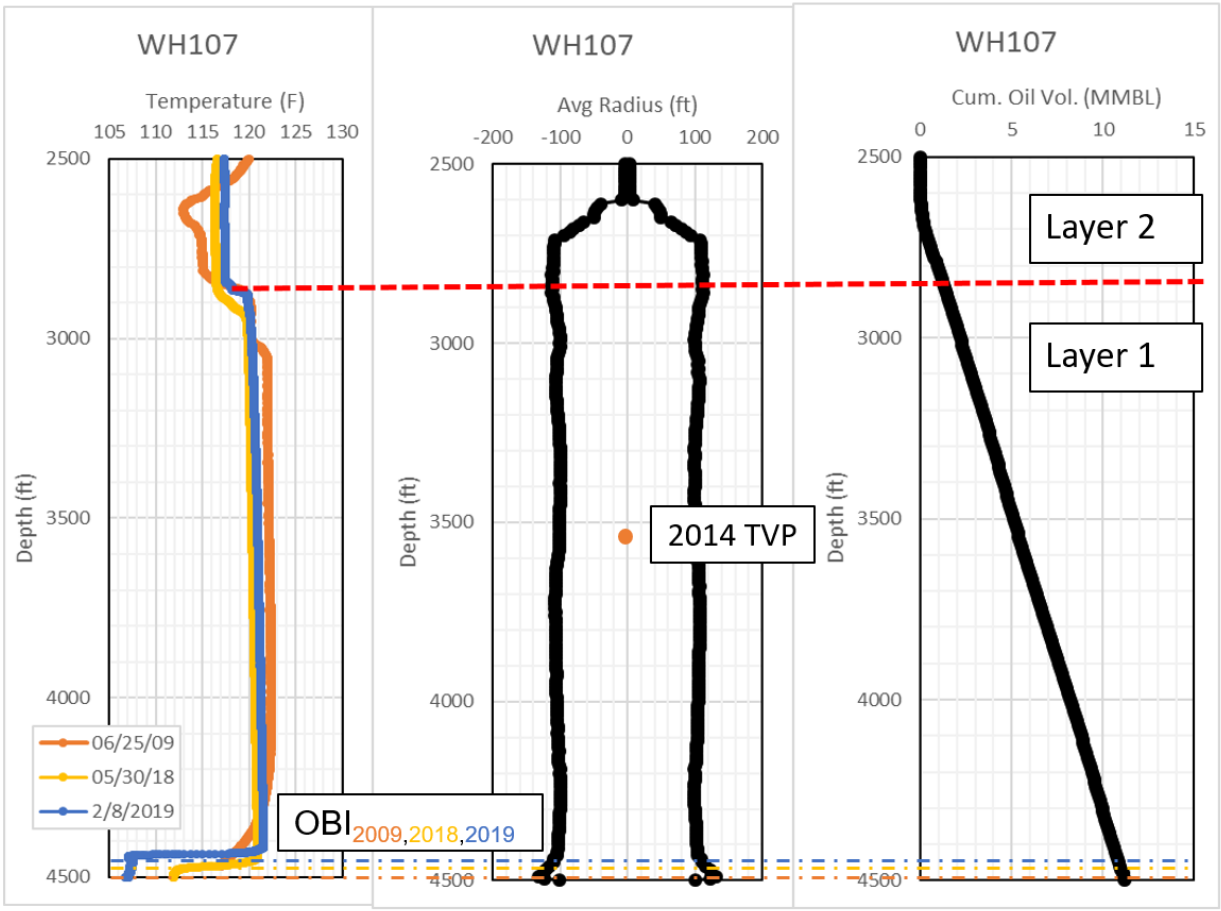


Figure 4-14. Oil fill history for WH107 (circles) with dates for recent temperature logs (triangles) and notation for fill source (blue boxes) and layer volumes (red dashed lines).



a) b) c)

Figure 4-15. WH107 data by depth, including a) recent temperature logs, b) axisymmetric radius (with TVP-95 depth), and c) cumulative volume.

4.1.8. WH113

As shown in Figure 4-16, WH113 saw multiple fill operations in the years 2000-2010. In 2011, about 2 MMBL were drawn down. Later in 2011, WH113 received 2.3 MMBL of oil from WH105 when WH105 was being switched from sweet to sour. Since 2017, about 1.4 MMBL has been drawn down. Figure 4-17 shows temperature logs from 2009, 2018, 2019, and 2020. There were two oil-oil interfaces in the 2009 log, which suggests that three oil layers existed in the cavern in 2009. However, the 2018 temperature log only showed one oil-oil interface at 3090' which corresponded to a cumulative oil volume of 1.0 MMBL. This suggests that the upper layers seen in the 2009 temperature log were drawn down in 2011, and the fill from WH105 in 2011 formed a new layer on top of the pre-existing oil. The oil-oil interface around 3000' occurred above the OBI at a depth of 4349' in 2018, 4326' in 2019, and 4288' in 2020. A downhole TVP-95 measurement in 2014 at 3734' represented Layer 1 with a vapor pressure of 15.9 psia. Since Layer 2 consists of WH105 oil, the vapor pressure of the layer can be estimated as 18.3 psia, which was taken from a flowing TVP-95 measurement taken on WH105 in 2010.

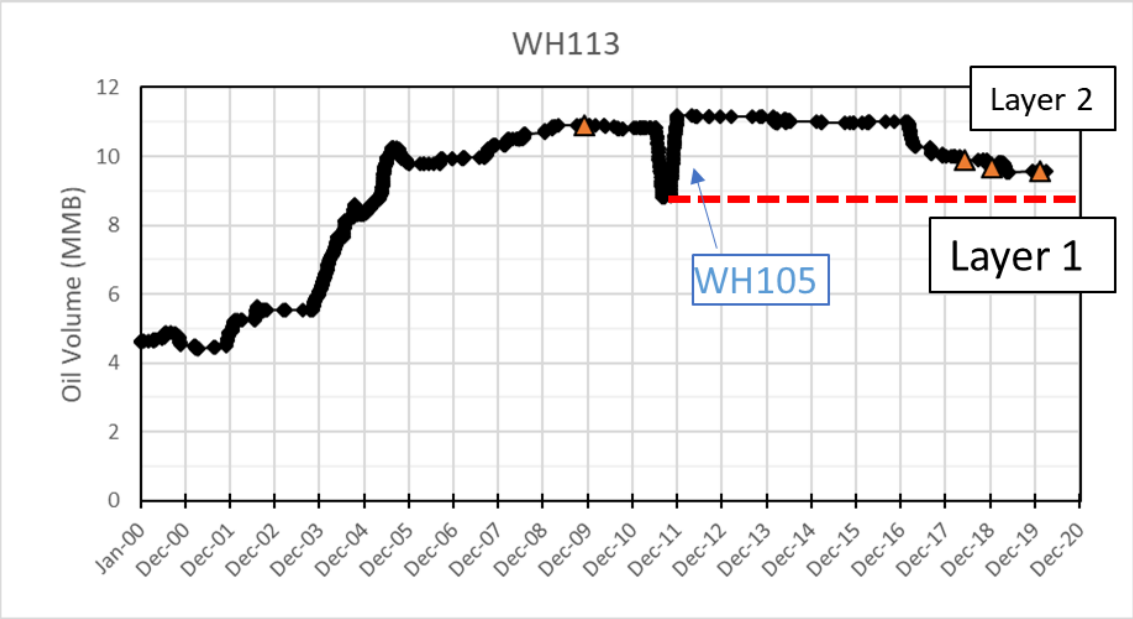
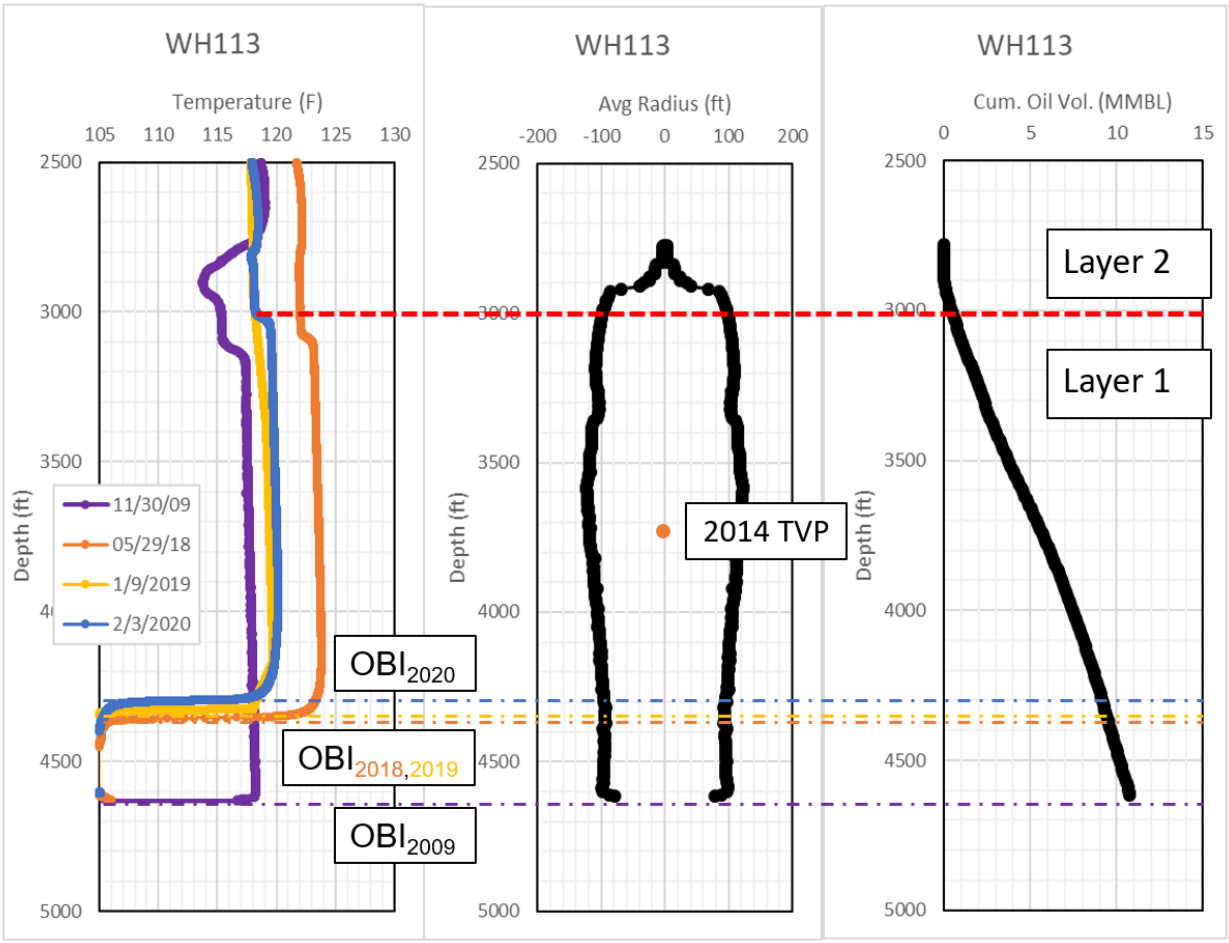


Figure 4-16. Oil fill history for WH113 (circles) with dates for recent temperature logs (triangles) and notation for fill source (blue boxes) and layer volumes (red dashed lines).



a) b) c)

Figure 4-17. WH113 data by depth, including a) recent temperature logs, b) axisymmetric radius (with TVP-95 depth), and c) cumulative volume.

4.2. Sour Cavern Analysis

Historical data for the thirty-six active sour crude caverns at SPR were analyzed. Table 4-2 gives the results of this analysis. The temperature logs were the greatest factor in helping to determine whether there was layering as indicated by step changes in the temperature with depth. Thus, the year of the most recent temperature log for each cavern used for this analysis is also given in Table 4-2. Thirty-four of the thirty-six caverns did not show evidence of layering. One cavern showed distinct evidence of layering (BH111). One other cavern (BM110) displayed irregularities in the temperature logs that could be a result of layering. These two notable caverns will now be discussed.

Table 4-2. Results of historical data analysis for oil-oil interfaces in the sour caverns at the four SPR sites

Cavern	Latest T-Log	Oil-Oil Interface	VP, psia[a]
BC015	2018		16.4
BC017	2019		14.9
BC019	2019		17.4
BC101	2020		18.0
BM001	2019		12.3
BM005	2015		17.5
BM101	2017		14.4
BM102	2019		12.0
BM103	2018		17.9
BM104	2017		12.4
BM105	2019		13.2
BM107	2016		13.5
BM108	2019		12.0
BM109	2018		15.2
BM110	2019	X	13.1
BM111	2016		13.2
BM112	2019		15.6
BH106	2015		14.2
BH107	2018		15.4
BH108	2017		11.7
BH109	2018		15.8
BH110	2019		11.4
BH111	2018	X	17.6
BH112	2015		12.5
BH113	2017		12.8
WH008	2019		16.3
WH009	2009		16.1
WH011	2016		17.9
WH105	2017		10.5
WH106	2008		13.7
WH109	2019		12.6
WH111	2019		11.1
WH112	2019		13.8

Cavern	Latest T-Log	Oil-Oil Interface	VP, psia[a]
WH114	2019		12.6
WH115	2012		13.1
WH117	2018		12.8

[a] From May 2020 VPC Quarterly Spreadsheet

4.2.1. BH111

BH111 saw multiple fill/drawdown operations in the years 2004-2016, as shown in Figure 4-18. Four temperature logs taken 2003, 2005, 2007, and 2018 (see Figure 4-19a) showed a stable interface created during the ~4 MMB fill in 2004-2005 that persisted through 2018. This interface was evident through the ~2 MMB withdrawal in 2013, and ~0.5 MMB fill in 2016. The temperature logs from 2005 to 2018 have confirmed that an oil-oil interface formed at that time, and that two layers of oil have persisted within the cavern (see Figure 4-19). The oil-oil interface around 2600' occurred above the OBI that was at a depth of 3896' in 2018. A 8/3/2017 downhole TVP-95 sample taken at a depth of 3076' gave a bottom layer BPP of 17.5 psia. A 11/14/2019 TVP-95 flowing sample gave a top layer BPP of 17.6 psia.

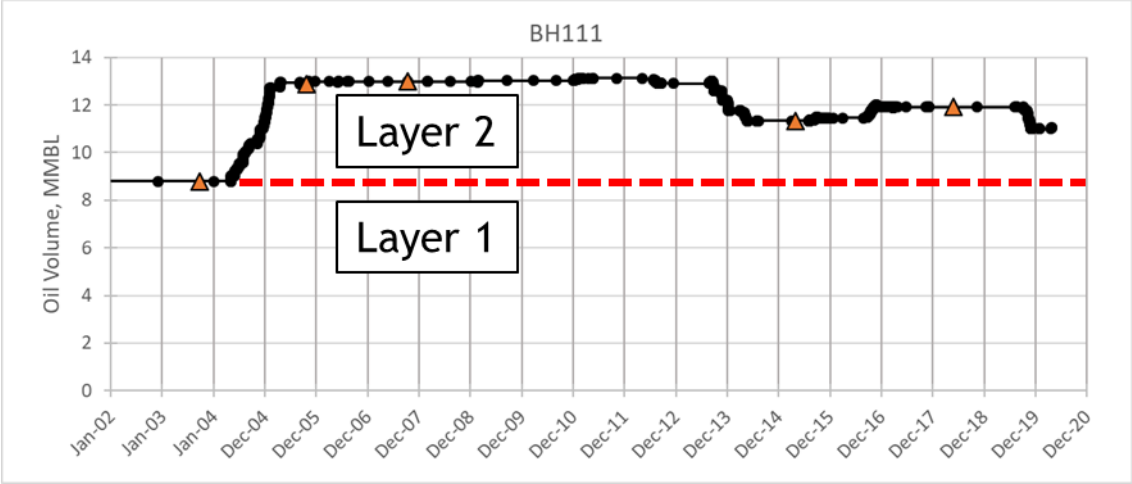
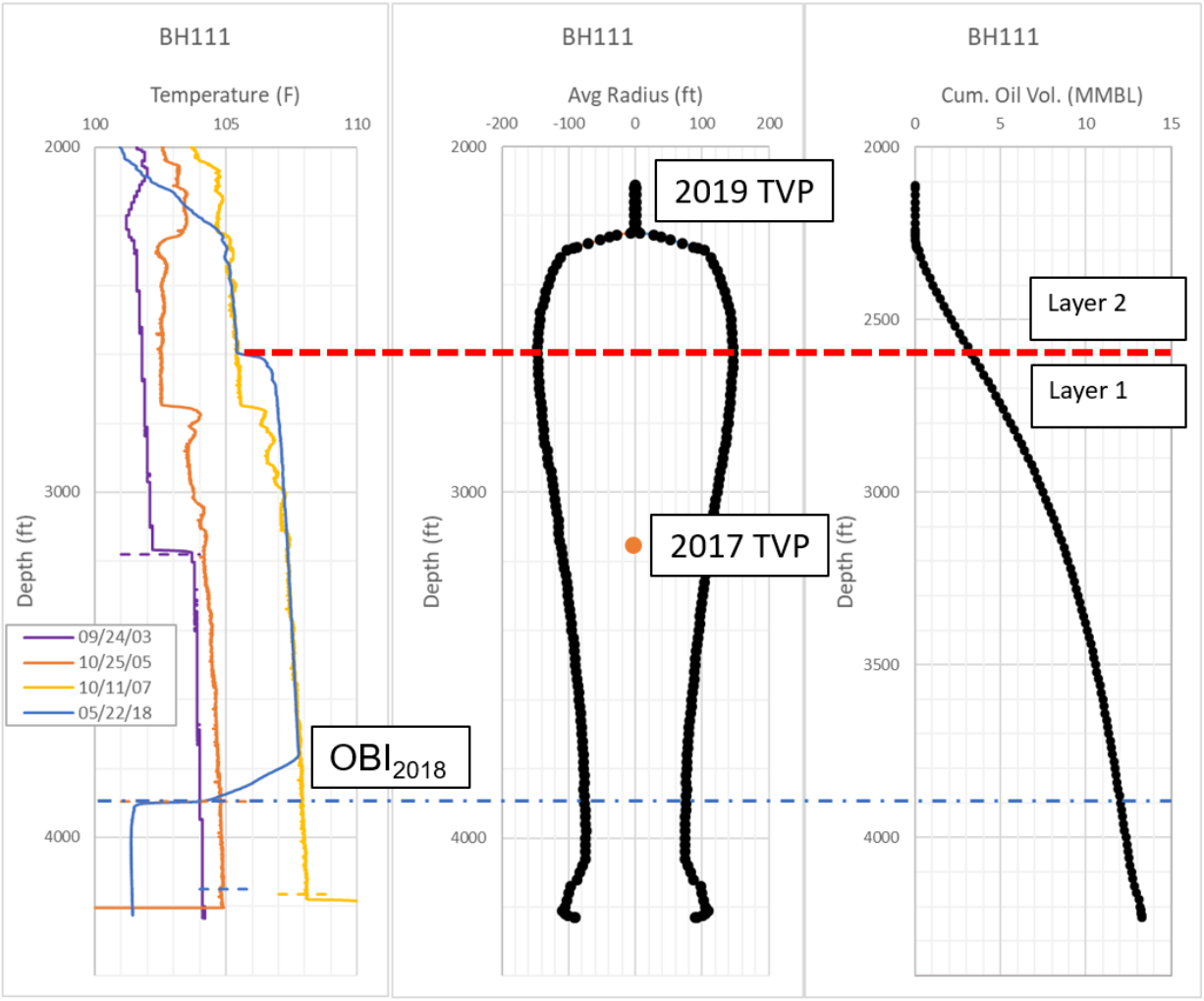


Figure 4-18. Oil fill history for BH111 (circles) with dates for recent temperature logs (colored circles).



a) b) c)

Figure 4-19. BH111 data by depth, including a) recent temperature logs, b) axisymmetric radius (with TVP-95 depths), and c) cumulative volume.

4.2.2. BM110

The historical data for BM110 told a complicated story. Figure 4-20 shows the fill history for this cavern. There was a large 6 MMBL withdrawal in 1995, followed by a 6.5 MMBL transfer of degassed oil from BM101 in 1996. Since then, there have been small additions and withdrawals, including a 1 MMBL withdrawal in 2012. Though BM110 received degassed oil, the bottom 4 MMBL of oil in the cavern likely has not been degassed. It is proposed that there exists an oil-oil interface between the 4 MMBL of original oil leftover from the 1996 withdrawal and the rest of the oil on top. The temperature logs in Figure 4-21a from 2008-2019 show interesting curvature in the bottom half of the cavern providing evidence of oil layering. However, SONAR data in BM110 makes a direct comparison between the apparent oil-oil interface and the cumulative volume curve more interpretive. The apparent oil-oil interface around 3350' occurred above the OBIs for the temperature logs from 2008-2019.

Figure 4-22 shows an overlay of the 2006 SONAR down the B well and the 2016 SONAR down the C well from the four cardinal directions. It is speculated that the notch and ridge seen near the bottom of the SONARs could be the result of insufficient SONAR data due to a lobe around the brine/raw water well (BM110A). Therefore, the cumulative volume vs. depth curves from the SONARs may not accurately represent the whole cavern, which makes consistency-calculations of the oil-oil interface with depth difficult. Another SONAR at BM110 could help resolve some of these questions, as long as the SONAR is down well A.

To further support the proposed two layers, the most recent oil inspection data from 2015 is shown in Figure 4-23. A step change in API gravity, viscosity, water content, and sulfur content near the oil-brine interface could indicate oil stratification. However, the data does not have sufficient vertical depth resolution to determine if the change in properties show a distinct 4 MMBL layer of oil at the bottom of the cavern.

In general, the first ~7 MMBL of oil out of BM110 will contain the top layer, which has been sufficiently characterized using the TVP-95 system. A 3/26/2015 downhole TVP-95 sample taken at a depth of 2987' gave a top layer BPP of 13.2 psia. However, the remaining ~4 MMBL layer at the bottom of the cavern has not been characterized using the TVP-95. If BM110 is to be considered for significant drawdown in the future, it is recommended that a downhole TVP-95 measurement be taken at or below 3500' to characterize the bottom layer.

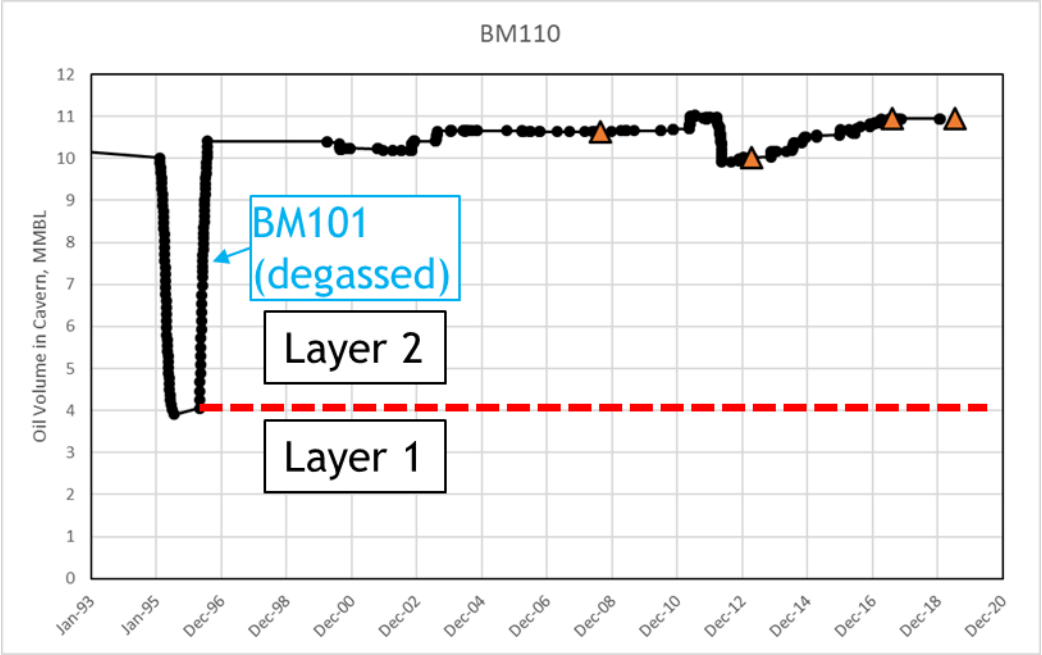
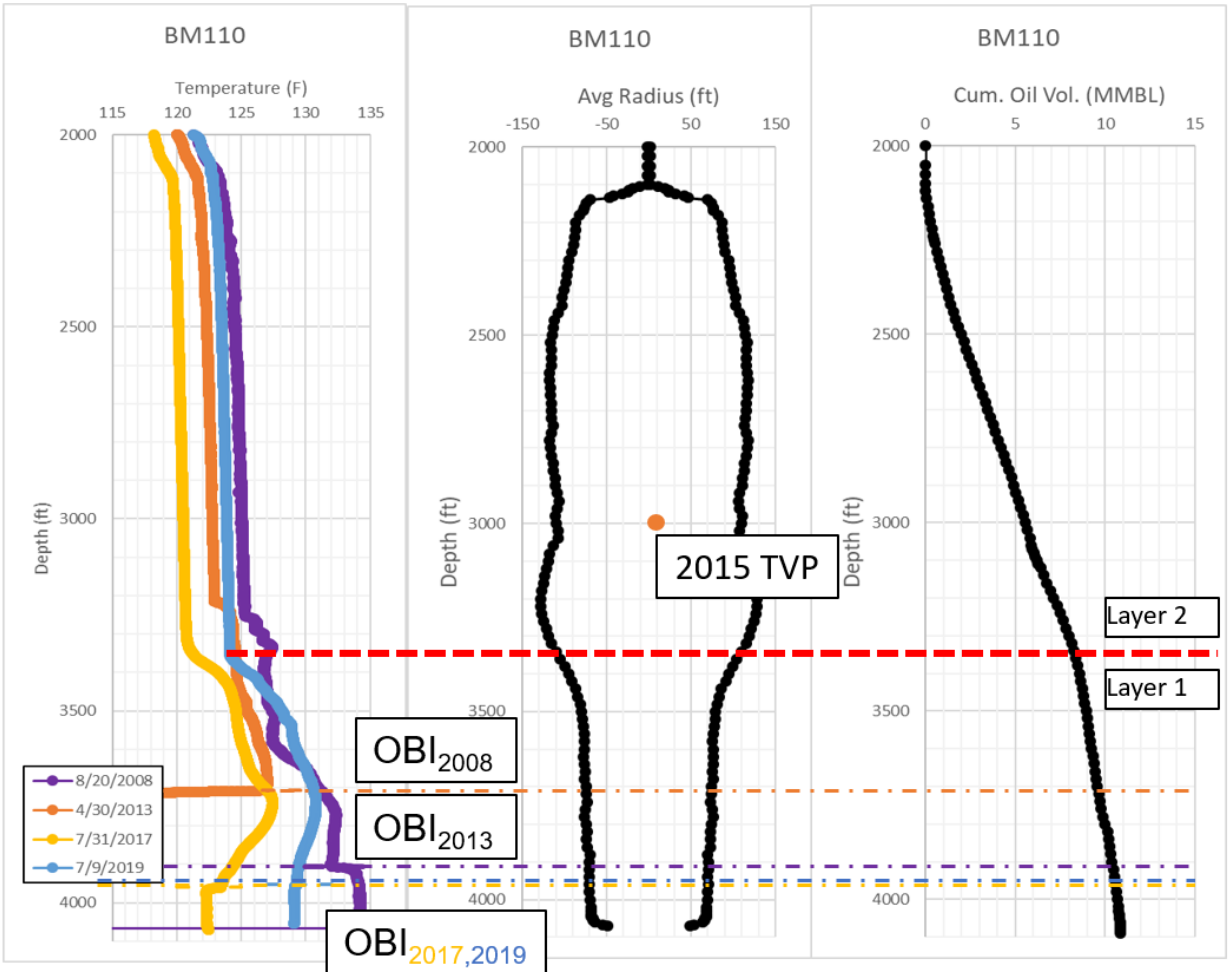


Figure 4-20. Oil fill history for BM110 (circles) with dates for recent temperature logs (triangles).



a) b) c)

Figure 4-21. BM110 data by depth, including a) recent temperature logs, b) axisymmetric radius (with TVP-95 depth), and c) cumulative volume.

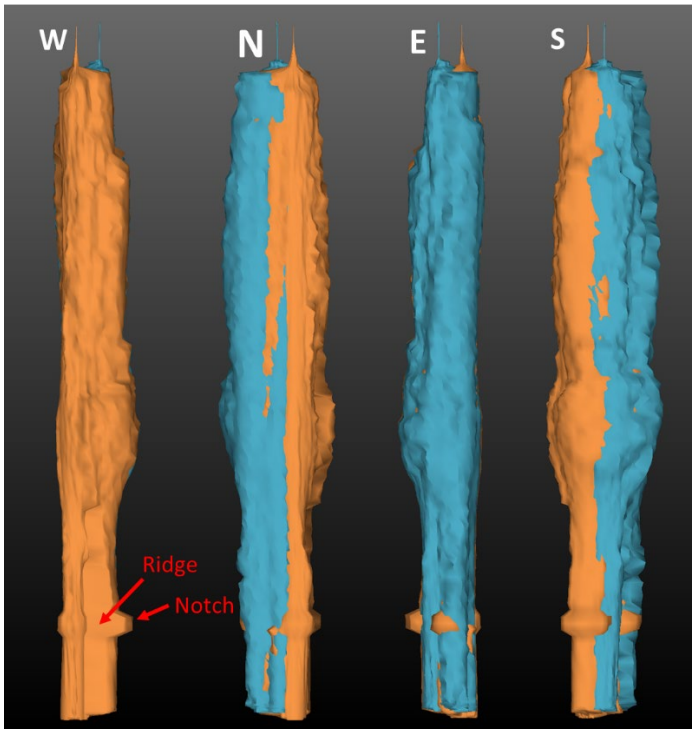


Figure 4-22. Composite SONAR from BM110B in 2006 (aqua) and BM110C in 2016 (orange) viewed facing the four cardinal directions.

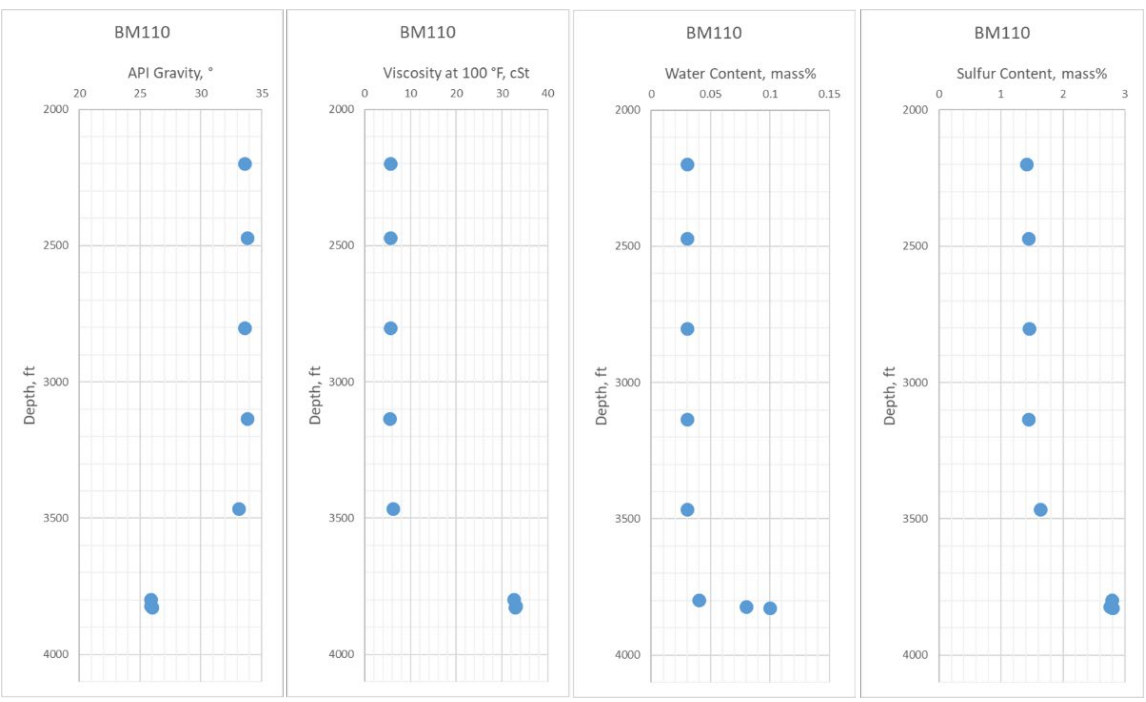


Figure 4-23. BM110 oil inspection data from 6/26/2015.

5. CONCLUSIONS/RECOMMENDATIONS

This report identifies oil stratification SPR caverns, generally resulting from recent fill. Even though such recent fill was typically cooler than oil already in the cavern, the base compositions of the newer oils were sufficiently different from the cavern oils that new/cooler oil was lower in density than the old/warmer oil in the caverns. This led to the newer oil floating on top of the older oil in the caverns. Thus, oil layers can be identified in temperature logs due to step changes in temperature with depth. In the future, as cavern contents thermally equilibrate, other means such as pressure logs can be used to calculate in-situ density, which is a more direct indicator of oil layering.

From an analysis of historical data for sweet caverns, BC102, BH104, BH105, BM113, BM114, BM116, WH107, and WH113 were found to contain evidence of stratification. Small top layers (< 3 MMBL) were found in BC102, BH105, WH107, and WH113. These were the result of dissimilar oils being added to the top of the caverns, whether from new fill received from industry or through transfers from other caverns. Large top layers (> 3 MMBL) were found in BH104 and BM114. These were the result of large drawdowns in the early 2010's, followed by additions of oil from industry and other caverns which all mixed. BM113 and BM116 were found to have three layers of oil. These were the result of large drawdowns in the early 2010's, followed by additions of oil from industry and other caverns, topped off in 2018 with another batch of DSW oil. The three layer cavern state was validated in a previous memo, where in-situ densities for the BM116 oil layers were estimated (Hogge 2020a). In all the caverns studied, the 2018 DSW oil formed another layer due to sufficiently dissimilar oil properties.

A previous analysis of historical data for the sour caverns at BH, BM, and WH found that BH111 and BM110 were stratified (Hogge 2020b). The upper layer in BH111 was formed in 2004 and has persisted since. The upper layer in BM110 was formed in 1996 and has also persisted. All vapor pressure monitoring events for BM110 have sampled the upper layer of oil in the cavern. The bottom 4 MMBL layer of oil in BM110 has never been characterized by the TVP-95 system. The historical data for the sour caverns at BC did not show evidence of oil layering.

Table 5-1 summarizes the volumes and vapor pressures of the layers found in all of the SPR caverns as of April 2020. The table is constructed so that the bottom (least accessible) oil layer is described in the left columns, while the top (first accessible) oil layer is described in the right columns. The volumes given for each layer reflect the state of the cavern before the 2020 oil exchange program and were taken from "Cum Oil Vol" tabs of the May 2020 quarterly spreadsheets. The temperature logs were used with the sonar strapping curves to get initial estimates of the layer volumes. Those estimates were compared to the fill history in the quarterly spreadsheets to give a best estimate of the layer volumes.

Table 5-1. A summary of oil layer properties by cavern as of April 2020. Oil layer volumes were estimated using temperature logs and the May 2020 VPC quarterly spreadsheet "Cum. Oil Vol." tabs.

Cavern	Bottom Layer		Middle Layer		Top Layer	
	Vol, MMBL	VP, psia	Vol, MMBL	VP, psia	Vol, MMBL	VP, psia
BC102	5.9	20.0[b]	--	--	1.5	17.0[c]
BH104	6.0	14.9[a,c]	--	--	6.4	14.5[c,d]
BH105	6.5	14.1[a]	--	--	2.0	14.4[c]
BM110	4.0	?[e]	--	--	7.6	13.2[a]
BM113	4.2	13.7[d]	1.1	18.5[b]	0.85	17.1[b]
BM114	3.2	13.5[a]	--	--	5.6	16.4[c]
BM116	6.4	13.7[a]	2.2	16.8[d]	1.0	17.1[b]
BH111	8.8	17.5[a]	--	--	2.2	17.6[b]
WH107	8.5	15.8[a]	--	--	1.7	?[e]
WH113	8.9	15.9[a]	--	--	0.7	18.3[b]

[a] VP measured in a TVP-95 downhole sample
[b] VP measured in a TVP-95 flowing sample
[c] It is unclear which layer the TVP-95 sampled
[d] VP calculated from a blended estimate
[e] VP cannot be estimated using current information

As evidenced by these analyses, oil movements within and incoming to the SPR can block high-value, low-vapor pressure oil with high-vapor pressure oil. This is especially pertinent when the incoming oil is of lower density than the existing oil. Since new oil recovery technologies created a surge in lower density oil in the U.S. midstream starting in the 2010's (recall Figure 2-2), oil layering considerations should be included in oil movement planning in the future.

Several suggestions came out of the historical data analysis for SPR's caverns which would help SPR more fully understand the properties of the oil within each cavern:

1. It is recommended that when temperature is taken in the slick well for caverns suspected of containing multiple oil layers, downhole pressure is logged as well. These caverns include the ten listed above, as well as caverns that received significant fills since the last temperature logging event. Pressure can be used to calculate in-cavern oil density, which would allow for more direct assessment of oil layering in situations where the temperature log may not be able to adequately detect the presence of layers. Thermally equilibrated oil layers, for example, would have the same temperature, but different densities, so a temperature log would show no difference between the layers, but a pressure log could be used to see the difference in density between the layers.
2. It is recommended that both layers in BH104 are sampled downhole for vapor pressure since it is unclear which layer the 2016 TVP-95 downhole sample tested since the sampling depth was within 50' of the oil-oil interface. In Table 5-1, it was assumed that the TVP-95 sample was taken in the bottom layer. If this was the case, then the top layer needs to be measured since a) it comprises a large volume (5.7 MMBL), b) the current best estimate relies on 8 year old vapor pressure data from BH105, and c) it would be important to verify that BH104 contains blendstock (VP < 14.7 psia).

3. It is recommended that the top layer in WH107 is sampled for vapor pressure since it has not been characterized thus far.
4. It is recommended that the bottom layer in BM110 be sampled for vapor pressure since a) it comprises a large volume (4.0 MMBL) and b) the layer is not accurately characterized since it has never been measured using the TVP-95 measurement system.

As evidenced by these analyses, oil movements within and incoming to the SPR can block high-value, low-vapor pressure oil. This is especially pertinent when the incoming oil is of lower density than the existing oil. Since new oil recovery technologies created a surge in lower density oil in the U.S. midstream starting in the 2010's (see Figure 2-2), oil layering considerations should be included in oil movement planning.

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