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Summary of Degas II Performance at the US Strategic Petroleum Reserve Big Hill Site

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Abstract

Crude oil stored at the US Strategic Petroleum Reserve (SPR) requires mitigation procedures to maintain oil vapor pressure within program delivery standards. Crude oil degasification is one effective method for lowering crude oil vapor pressure, and was implemented at the Big Hill SPR site from 2004-2006. Performance monitoring during and after degasification revealed a range of outcomes for caverns that had similar inventory and geometry. This report analyzed data from SPR degasification and developed a simple degas mixing (SDM) model to assist in the analysis. Cavern-scale oil mixing during degassing and existing oil heterogeneity in the caverns were identified as likely causes for the range of behaviors seen. Apparent cavern mixing patterns ranged from near complete mixing to near plug flow, with more mixing leading to less efficient degassing due to degassed oil re-entering the plant before 100% of the cavern oil volume was processed. The report suggests that the new cavern bubble point and vapor pressure regain rate after degassing be based on direct in-cavern measurements after degassing as opposed to using the plant outlet stream properties as a starting point, which understates starting bubble point and overstates vapor pressure regain. Several means to estimate the cavern bubble point after degas in the absence of direct measurement are presented and discussed.

Acknowledgment

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Nomenclature

$\overline{BP}_{in}$	Average plant inlet BPP prior to breakthrough (psia)
$\overline{BP}_{out}$	Average plant outlet BPP during processing (psia)
BBL	Barrel (42 US gallons)
BH	Big Hill SPR site
BM	Bryan Mound SPR site
BPP	Bubble point pressure (at 100^{o}F), also BP pressure
DM	DynMcDermott Petroleum Operations Company
DOE	U.S. Department of Energy
GOR	Gas oil ratio, scf/bbl
GOV	Gross Observed Volume
GSV	Gross Standard Volume
MB	Thousand barrels (volume)
MMB	Million barrels (volume)
SNL	Sandia National Laboratories
So	Sour crude oil by SPR criteria (total sulfur less than 1.99 mass%)
SPR	Strategic Petroleum Reserve
Sw	Sweet crude oil by SPR criteria (total sulfur less than 0.50 mass%)
TVP	True vapor pressure (psia)
VF	Volume fraction of oil processed through degas plant normalized to cavern oil volume start of degas
VF_B	Volume fraction at breakthrough (when processed oil appears at plant inlet)
VF_T	Volume fraction at completion of degassing
Π	Plug flow similarity index
α	Proportional reduction factor

1 Executive Summary

Crude oil degasification at the US Strategic Petroleum Reserve (SPR) is necessary to maintain oil within program criteria for bubble point pressure and gas-oil-ratio at delivery conditions. This report examines performance features of the 2004-2006 degasification of nine SPR caverns at the Big Hill site. Degasification reduced stream average bubble point pressures from 16.7 to 12.9 psia for sweet oil, and 15.6 to 13.8 psia for sour oil at the oil reference temperature of 100°F. Monitoring of plant inlet stream data revealed considerable changes in plant inlet bubble point as a function of oil volume processed in a given cavern. This observation went against initial process design expectations that oil fluid dynamics in the caverns would support plug flow in which processed oil injected into the top of the cavern would not appear at the plant intake (breakthrough) until nearly 100% of the cavern volume was processed, at which point the plant inlet bubble point would rapidly drop to the plant outlet value. Instead, a variety of inlet profiles were observed with each cavern exhibiting unique characteristics such as the volume fraction at breakthrough and the bubble point pressure drop when breakthrough occurred. Moreover, final inlet values at the completion of processing were several psi above the final plant outlet values, indicating that some volume of oil in each cavern was not processed. The shapes of the inlet profiles and extent of oil not processed are theorized to be determined largely by cavern oil mixing, position of the intake string within the cavern, and existing oil spatial heterogeneity at the start of degas.

In-situ downhole monitoring of bubble points 6 or more months after completion of degas revealed that the bubble points fell between the final plant inlet and outlet values—typically 1-2 psi higher than the average plant outlet value. This is an important observation relative to gas regain calculations because the protocol used after Degas I was to use the plant outlet value as the starting point for regain. The next in-situ point was then always higher, with subsequent values showing no preferred increase or decrease. It is apparent from this work that using the plant outlet value understates the cavern-average bubble point after degas and overstates early post-degas regain estimates. The report presents several means for estimating in-situ bubble point after completion of degas. Most accurate is a downhole measurement 6 or more months after degas. Mathematical options include adding an offset value of 1.4 psia to the plant outlet value based on the average difference seen in similar caverns, using the degas plug flow similarity-breakthrough correlation, or using a simple degas mixing model fit to the observed plant performance curve.

2 Introduction

2.1 Purpose and Scope of Report

The purpose of this report is to investigate the performance of the degasification program at the US Strategic Petroleum Reserve (SPR) based on technical data collected primarily at the Big Hill site from 2004-2006. The report presents an in-depth analysis of the outcome of degassing with a focus on how data collected during the degassing process correlate observed post-degas cavern bubble points. Generally speaking, degassing lowered the average bubble point pressures of all nine caverns processed at Big Hill, but the extent of bubble point pressure lowering and the effort required to get there varied from cavern to cavern. This analysis looks into the reasons behind these variations.

2.2 Degasification at the SPR

Oil stored in underground salt caverns at SPR is subject to several mechanisms that increase its vapor pressure with time. The rate of increase (psi/yr) is referred to as the vapor pressure regain rate, which is quantified for each cavern through the vapor pressure monitoring program at SPR. While not a problem during underground storage, vapor pressure increase poses an environmental safety risk when the oil is transferred to surface storage terminals in large quantities where containment pressure is near atmospheric pressure. Several strategies are implemented to reduce the volatility of the oil including oil cooling, H_2S scavenging, and oil degasification, depending on specific conditions. Both oil cooling and H_2S scavenging are applied at the time of oil delivery just before the oil leaves the SPR site boundary. Oil degasification is done on a cavern basis well in advance of delivery.

Two oil degasification programs have been implemented so far at SPR. Degas I, implemented over a 4-year period during the mid-1990's, processed about 171 MMB of crude oil with a mobile plant that was moved from site to site (DOE, 2003). A combination of new oil deliveries, geothermal heating, and gas regain created need for another round of degassing. Degas II, proposed in 2001, called for another mobile degassing unit that would be moved across the four existing sites. The design basis for the new plant was to assure that the blended site gas-oil ratio[1] (GOR) remained below 0.6 scf/bbl for all streams at all sites at delivery conditions. Oil processing rates and site/stream/cavern order in Degas II were chosen based on best estimates of gas regain in the 2000-2001 time frame. Long-term plant location and scheduling remain flexible in order to adjust to an evolving understanding of the properties of the storage system and dynamic inventory. Details of the Big Hill degassing plan are given in DeLuca (2005a,b).

Degasification at SPR is achieved by flashing the crude in a processing plant to separate volatile gases where the excess gas is incinerated on-site and processed oil is re-injected into the cavern. A simple schematic of this concept is shown in Figure 2-1. The hanging string in the cavern to be degassed is positioned so that it terminates in the oil several feet above the oil-brine interface.

[1] Gas-oil ratio is the equilibrium volumetric ratio of gas evolved (units standard cubic feet) from a barrel of oil once it is depressurized to a standard state, typically to atmospheric pressure and an oil temperature of 100°F (311K) for SPR oils. The standard cubic foot of gas is given at a temperature of 60°F (289K) and 14.7 psia (101kPa) pressure.

A sufficient pressure difference is maintained between the cavern and the plant such that oil flows up the hanging string and into the plant where the oil passes through a flash drum that separates the oil into a liquid and a gas stream. The process is effectively isothermal with no heat actively added or removed to effect a noticeable change in oil temperature. The gas stream is processed to reabsorb some of the propane and H_2S and then the remaining gas, primarily nitrogen, methane, and ethane is vented to a flare stack. The degassed oil passes through a pump to boost the pressure for re-injection into the top of the cavern. Oil passing into and out of the plant is sampled for a variety of properties, most importantly bubble point pressure, using an instrument system called the TVP-2000.

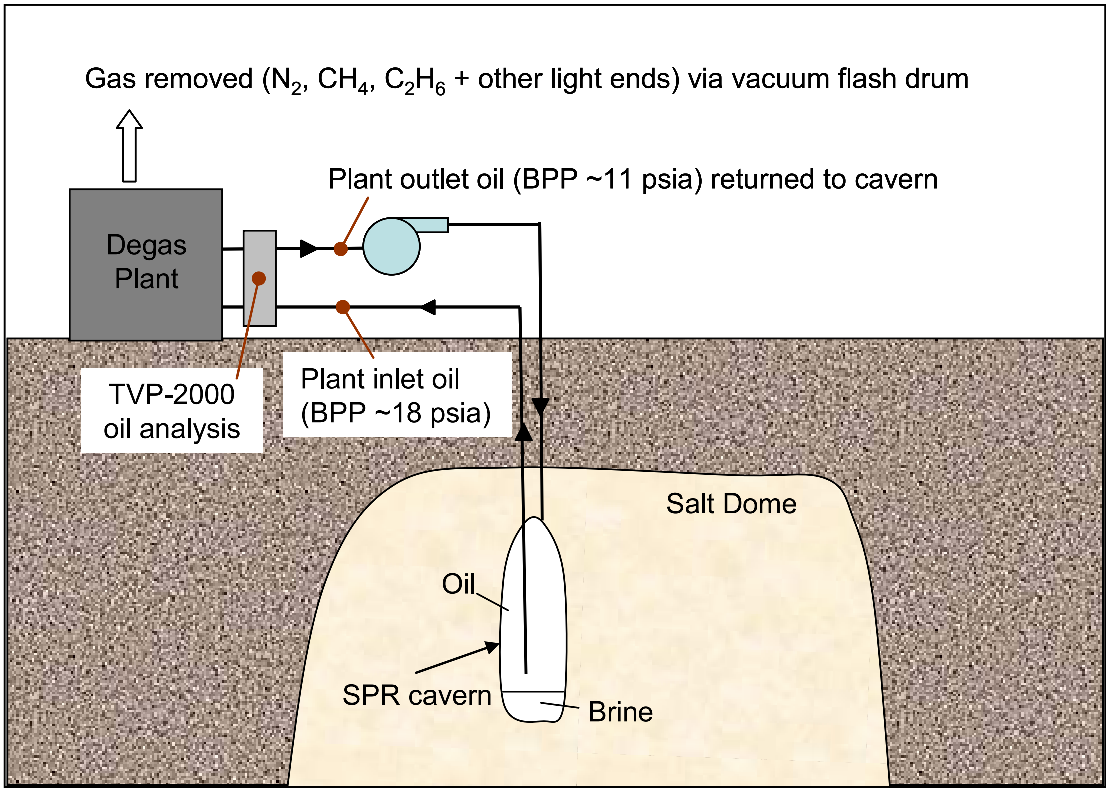


Figure 2-1. Schematic of Degasification Plant and SPR Cavern as It Is Operated for Degas II.

3 Current Degas Performance Summary

Degas II entered the operational stage in April 2004 at the Big Hill SPR facility. All nine caverns scheduled for degas at Big Hill were completed by October 2006. Table 3-1 summarizes parameters of interest including pre-degas BPP and GOR, in-situ measured post degas BPP, and fraction of cavern oil volume processed, VF, which is the volume of oil processed divided by a representative cavern volume. The in-situ post-degas bubble point (BP_{cav}) defined by the first downhole TVP sample taken after degas was completed, gives an indication of the true effectiveness of degasification in reducing the cavern BPP. Coupled analysis of plant performance data gives insight into mixing behavior that causes in-situ BPP to be larger than the plant outlet BPP. Mixing behavior is discussed in more detail in Section 4.

Big Hill degas caverns required processing times that ranged from 77 to 111 days, averaging about 3 months to process around 11 MMB of oil. Average plant outlet bubble point was reasonably stable and remained within the range 10.4-11.7 psia for all caverns degassed. End-of-processing was generally reached around 110% of the normalized cavern volume ($VF_T = 1.1$), though exceptions were encountered in both directions. The one significant deviation above $VF_T = 1.1$ was cavern BH101 which exhibited a plant inlet bubble point that drifted downward during the entirety of processing implying a large-scale mixing mechanism[2] within the cavern during degas. Two significant deviations below $VF_T = 1.1$ were caverns 104 and 114, which appeared to exhibit nearly ideal plug flow and return of degassed oil to the plant inlet right near $VF_T = 1.0$, so that no further processing was needed.

An important observation from the oil properties summary in Table 3-1b is that the first in-cavern measured bubble point pressure (BP_{cav}) is always higher than the average bubble point pressure measured in the plant outlet stream $\overline{BP}_{out}$ for a given cavern. The column labeled "$BP_{cav} - \overline{BP}_{out}$" quantifies this difference. The differences range in magnitude from 0.4 psia, to 3.8 psia, with a mean value of 1.5 psia shown at the bottom of the table. Similar observations after Degas I were interpreted as gas regain, though in the current analysis of Degas II, the authors propose that this difference is due to in-cavern mixing of processed and unprocessed oil. Section 4 of this report elaborates on the mixing theory. Note that at the time of this report cavern BH110 had not been tested post degas for in-situ BPP.

[2] The mixing hypothesis for BH101 was further supported by downhole TVP measurements several months after completion of degas that found a uniform 13.1 psia bubble point pressure at four selected depths.

Table 3-1. Summary of Degas II Performance.

a. Volumetric Parameters.

Cavern	Stream (Sweet[a] = 1 Sour[b] = 2)	Start Date	Days of Processing	Pre-Degas GSV[c] (MMB)	Volume Fraction Processed VF_T (GSV)
BH108	2	4/20/04	84	9.77	1.10
BH113	2	7/13/04	76.9	9.98	1.08
BH103	1	9/28/04	95.8	11.8	1.07
BH101	1	1/3/05	111	11.61	1.24
BH104	1	4/26/05	88.7	12.25	0.94
BH112	2	7/24/05	76.9	10.38[d] (12.4)	1.10 (0.92)
BH102	1	12/22/05	99	11.7	1.10
BH114	1	4/1/06	90.0	12.1	0.97
BH110	2	6/29/06	102.0	12	1.13

[a] Sweet crude oil by SPR criteria (total sulfur less than 0.50 mass%).

[b] Sour crude oil by SPR criteria (total sulfur less than 1.99 mass%).

[c] GSV - Gross Standard Volume. The total volume of all petroleum liquids and sediment and water, excluding free water, corrected by the appropriate volume correction factor (Ctl) for the observed temperature and API gravity, relative density, or density to a standard temperature such as 60°F or 15°C and also corrected by the applicable pressure correction factor (Cpl) and meter factor.

[d] Accessible volume (10.38 MMB) is based on 296 ft reduction in string length. Actual cavern oil volume is 12.4 MMB (Aug 06 Quarterly VP Report). Fraction processed for degas operations is based on the accessible cavern volume whereas, analyses discussed below are based on the actual volume.

b. Oil Properties (at Reference Oil T = 100°F).

Cavern	Stream (Sweet = 1 Sour = 2	Pre-Degas BPP[a] (psia)	Ave Outlet BPP (psia)	Post-Degas BPP (psia)	$BP_{cav} - BP_{out}$, (psi)
BH108	2	17.8	10.7	11.1	0.4
BH113	2	16.9	10.2	12.0	1.8
BH103	1	18.6	11.4	12.3	0.9
BH101	1	17.2	11.6	13.1	1.5
BH104	1	16.9	11.1	12.2	1.1
BH112	2	16.5	10.4	14.2(13.5)[b]	3.8(3.1)
BH102	1	16.4	11.2	12.9	1.7
BH114	1	17.6	11.5	12.6	1.1
BH110	2	16.0	10.3	-	-
Ave					1.5(1.4)[c]

[a] Pre Degas BPP are from 5/15/04 Quarterly VP Spreadsheet Report and represent project understanding at time of degas.

[b] Parenthetical value uses accessible volume

[c] Mean in-situ – outlet, when corrected for accessible volume in cavern BH112, is reduced to 1.4 psia. See discussion immediately below for explanation.

Cavern BH112 presents a special case for volumetric and oil property analysis in Degas II because it was the only cavern among the nine processed that had the intake string shortened 296 due to a salt fall. This left 10.4 MMB inventory accessible for processing as stated in the BH112 degas completion report (Mihalik, 2006). Discussions within the vapor pressure project team led to an agreement that the 3.8 psi difference between measured post-degas (14.2 psi) and average outlet (10.4) (see Table 3-1b above) is an outlier in part because the accessible volume of 10.4 MMB is notably smaller than the total oil volume of 12.4 MMB. Using a simple mixing model that assumes that the 10.4 MMB accessible volume were mixed after degas with 2 MMB of 18 psi of inaccessible volume, the vapor pressure team proposed the following formula to estimate BP_{cav} of the 10.4 MMB accessible volume:

$$10.4\,MMB \times BPP + 2\,MMB \times 18\,psia = 12.4\,MMB \times 14.2\,psia \qquad (3.1)$$

Rearranging the equation above to solve for BPP yields 13.5 psia. If a post-degas value of 13.5 psia is used for the BH112 accessible volume instead of the 14.2 measured for the entire volume, the difference between plant outlet and accessible volume is then 3.1 psi. Moreover, the mean in-situ – plant outlet value for Degas II based on accessible volume for degas is then 1.4 psia. For the purpose of predicting in-situ bubble point from degas parameters, the simplest approach is therefore to add 1.4 psi to the plant outlet stream average.

3.1 Big Hill Stream Averaged BPP

High BPP/GOR caverns at Big Hill were degassed to assure that future oil deliveries meet Level II criteria. A simple measure of the effectiveness of degasification in improving the deliverability of Big Hill oil is a comparison of pre and post degas stream average BP pressures. Stream averaged properties are determined by oil volume weighting, which is a first order estimate for full scale draw downs by stream (sweet or sour). Table 3-2 presents stream averaged BPP based on Quarterly Report[3] data published on 5/15/2004 (pre degas) and 5/15/2007 (post degas). The estimated in-situ BPP value for BH110 (shown in italics) is calculated by adding 1.4 psi to the average plant outlet value from Table 3-1, which represents the average difference between plant outlet and in-situ BPP seen in the eight Degas II caverns measured post-degas (see Table 3-1b). Also provided in the Table 3-2 "Comments" column are interpretations of significant changes in BP pressure between 2004 and 2007 for caverns not degassed during this period.

[3] Quarterly vapor pressure reports are produced by DynMcDermott Petroleum Operations and maintained in SPR Project records on the file management system Konfig CM PDM.

Table 3-2. Stream Averaged BP Pressures – Pre and Post Degas.
Degas II caverns are shown in bold. Data taken from Quarterly Vapor Pressure Reports from dates shown. Oil is at reference temperature T = 100°F.

	5/15/04		5/15/07		
Sweet	**Volume (MMB)**	**BPP (psia)**	**Volume (MMB)**	**BPP (psia)**	**Comments**
101	11.48	17.2	11.70	13.2	
102	11.81	16.4	11.62	12.9	
103	10.86	18.6	11.66	12.3	
104	8.77	16.9	12.26	12.1	
105	10.79	13.7	12.06	14.4	20% new oil since late 2004.
114	9	17.6	12.0	12.5	
Stream	**62.71**	**16.7**	**71.26**	**12.9**	
Sour					
106	10.34	13.6	12.6	14.0	New oil.
107	9.30	14.0	11.8	14.9[b]	New oil. .
108	9.77	17.8	10.9	11.1	
109	9.10	14.5	12.5	14.5	
110	8.86	16.0	11.9	*11.7*[a]	Post degas estimated.
111	8.64	15.5	12.9	17.6	New oil.
112	10.90	16.5	12.7	14.2	
113	10.00	16.9	12.1	12.0	
Stream	**76.91**	**15.6**	**97.40**	**13.8**	

[a] The BH110 BPP listed for 5/15/07 represents an estimate based on the degas plant outlet average (10.3 psia) plus the mean "in-situ – outlet" (1.4 psia).
[b] The BH107 value listed for 5/15/07 represents the last measured BPP for that cavern on 5/26/2004. The 5/15/07 Quarterly Vapor Pressure spreadsheet shows a value of 17.4 psia for this cavern, which is an error.

Table 3-2 indicates that Big Hill sweet stream BPP was lowered from 16.7 psia to 12.9 psia as a result of degasification, while the Big Hill sour stream BPP was lowered from 15.6 psia to 13.8 psia over the same period. The larger drop in BPP for the sweet stream (3.8 psi) relative to sour (1.8 psi) is observed because a larger percentage of the sweet caverns were degassed – 5 of 6 sweet caverns versus 4 of 8 sour caverns. Both the sweet and sour stream average BP pressures fall below atmospheric which assures stream averaged GOR = 0 at the reference condition T = 100°F. Note that the increase in BPP for caverns BH107 (14 to 14.9 psia), and BH111 (15.5 to 17.6 psia) from 5/15/2004 to 5/15/2007 is not likely driven by gas regain alone, but by a combination of oil transfers, measurement uncertainty, and regain.

3.1.1 Discussion of Degassing Target BPP

Degas planning requires a target BPP for degassed oil that satisfies long-term site and stream delivery requirements. Given that the cavern value for BPP after degassing is slightly higher than the plant outlet value due to cavern oil mixing, a sufficiently low plant target should be chosen to accommodate this offset. Plant inlet and outlet BPP are monitored continuously by the TVP2000 system, so real-time feedback is available to assist with process optimization to reach a target outlet value. DeLuca (2005b) proposed target values of 10.5 psia for sour and 12.0 psia for sweet, which were achieved at the plant outlet as listed in Table 3-1b. Cavern oil mixing adds an average of 1.4 psi to plant outlet to yield the post-degas BPP values listed in Table 3-1b. While outside the scope of this report, the cavern BPP values in Table 3-1b should then be incorporated in a vapor pressure regain forecasting model to evaluate how far out into the future the stream value will meet delivery requirements. If improvements are needed, a strategy to lower the target bubble point or degas more oil from a given stream must be considered. Plant operational limits factor into the achievable target outlet values, and sometimes processing more oil (i.e., an additional cavern) is more feasible than processing the same oil to lower outlet BPP.

3.2 Plant Performance Curves

Performance curves are defined in this report as degas plant inlet and outlet BP pressure histories overlaid on a single figure where time is represented as the processed oil volume fraction. The volume fraction (*VF*) is defined as the cumulative volume of oil processed divided by a representative cavern volume, in this case the oil volume at the start of degas. The actual baseline oil volume in the cavern is not static during degasification. For example, cavern to cavern oil transfers to maintain cavern pressure can occur during degasification, and oil shrinkage occurs when gas is removed. Also, the depth of the hanging string where oil is collected for processing will affect the proportion of cavern oil volume available for processing. Generally, the shorter the string, the smaller the cavern volume available. In spite of these effects, the magnitudes of these differences affecting the baseline oil volume are generally small and do not affect the overall interpretation of the performance curve. The primary information of interest are the general shape and slope of the curve, difference between inlet and outlet BPP, particularly at completion, and the processed volume fraction at the time of breakthrough (VF_B). Here, breakthrough is an abrupt change in inlet BPP interpreted as the arrival of degassed oil (or more likely a mixture of degassed and in-cavern oil) at the inlet to the degas plant. Changes in inlet BPP can also be due to stratification of the oil in the cavern, adding some difficulty to interpretation of the driving mechanism for an apparent breakthrough. Supposing that cavern stratification is a contributing mechanism, one would expect both increases and/or decreases in BPP in the plant inlet performance curves. Abrupt increases in plant inlet bubble point were not seen in the BH caverns. It is also possible that natural stratification could provide boundaries to the mixing. Performance curves, particularly the plant inlet, have proven valuable in monitoring how the cavern responds to processing in real-time.

Performance curves for all caverns are shown in Table 3-1. There are four general shape categories for plant *inlet* performance curves:

- A stable value until approximately 100% of the cavern has been processed followed by an abrupt drop in BPP to a value close to outlet BPP. This ideal situation corresponds to plug flow and is best represented by cavern BH114.
- An initially stable value with an abrupt change in BPP that occurs at variable processed volume fractions and with variable sizes of the drop - best represented by caverns BH113, BH104, BH112, BH102 and BH110.
- An initially stable value for much of the cavern volume followed by a steady decrease in BPP - best represented by caverns BH108 and BH103.

- A slow decrease in BPP from very early time. This occurred for cavern BH101 and was the subject of considerable debate and analysis (Ehgartner at al, 2005a,b) that concluded that significant mixing had occurred almost from the start of degas.

Plant *outlet* performance curves are generally flat with a value between 10 and 12 psia and show a slight decrease in BPP as processed volume fraction increases, reflecting the generally decreasing inlet BPP.

The hanging string used in degassing operations for Cavern BH112 was 296 ft shorter than normal because an event, likely a salt block fall, sheared the string. This resulted in a decrease in the volume of oil accessible for degassing from 12.4 MMB to 10.4 MMB. The degas plant operational criteria of processing 110% of cavern volume was met based on the 10.4 MMB accessible volume. However, in Table 3-1 the performance curve for cavern BH112 is based on the full cavern oil volume of 12.4 MMB. The full volume was used because in situ post degas BPP is determined by cavern scale mixing that is independent of string length. The overall effect of degas on stream averaged properties and in-situ degas effectiveness, discussed below, should reflect the behavior of the entire cavern.

Another important feature of the performance curves, aside from shape, is the difference between inlet and outlet BPP at the completion of degas. The fact that they are different implies that in-situ post degas BPP is not going to be as low as the plant outlet BPP, nor is the last inlet BPP necessarily representative of the entire cavern. The difference between last measured inlet and outlet seems to correlate with the post degas in-situ BPP - the larger the difference, the higher the expected in-situ BPP. This relationship is developed further in section 4.3.

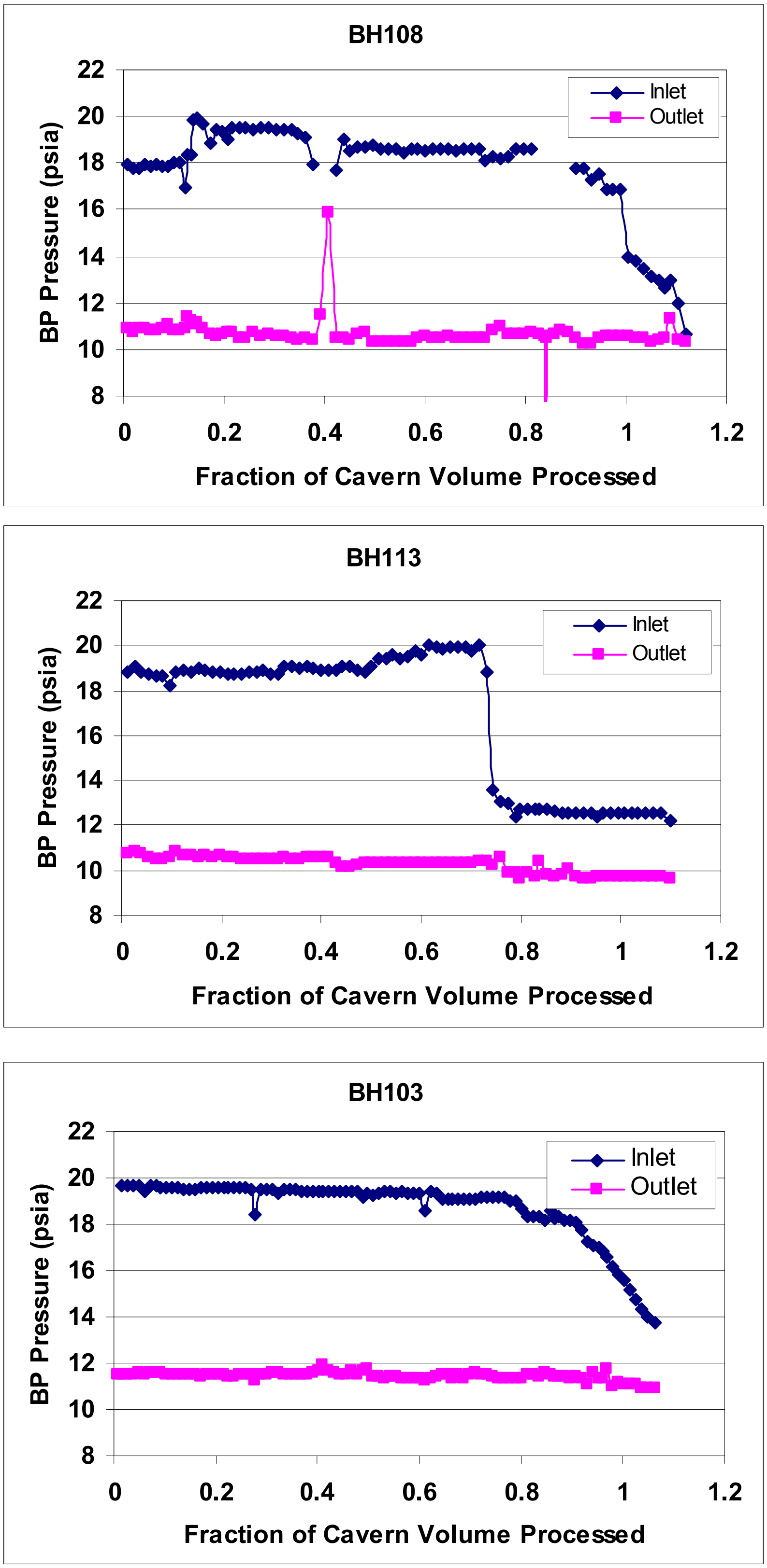


Figure 3-1. Big Hill Degas II Performance Curves.

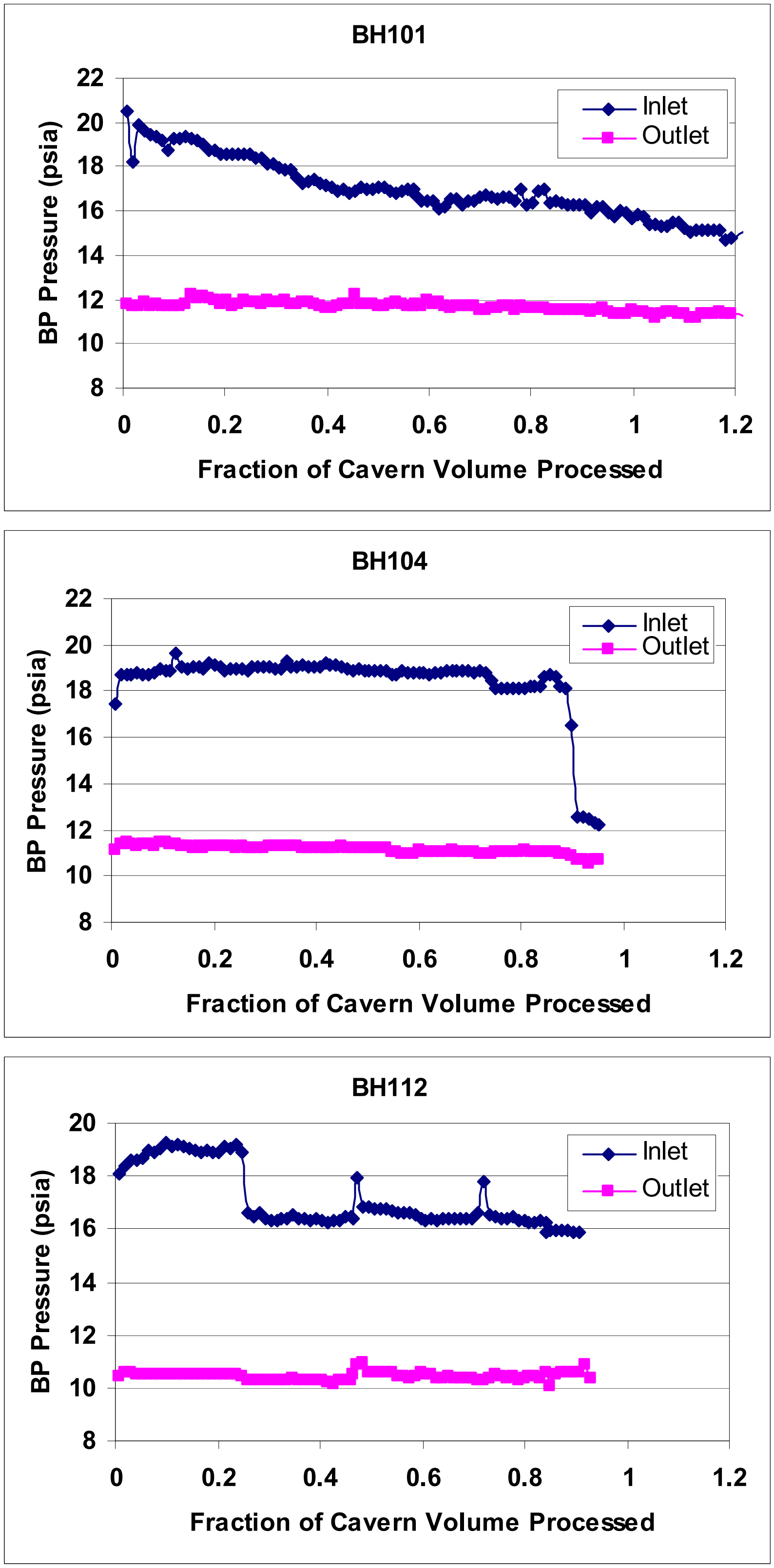
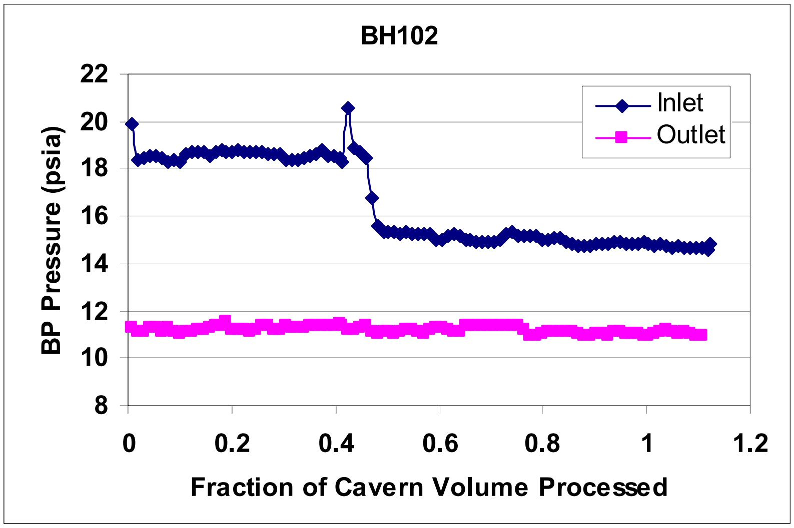
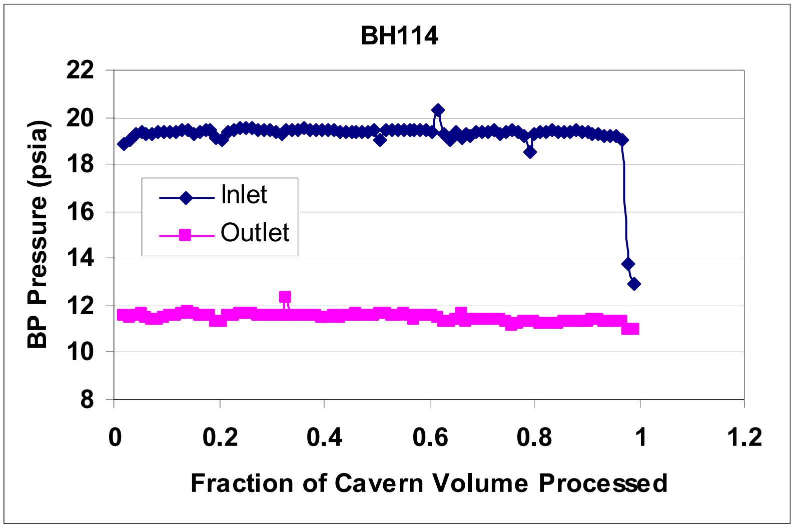


Figure 3-1. Big Hill Degas II Performance Curves (Continued).





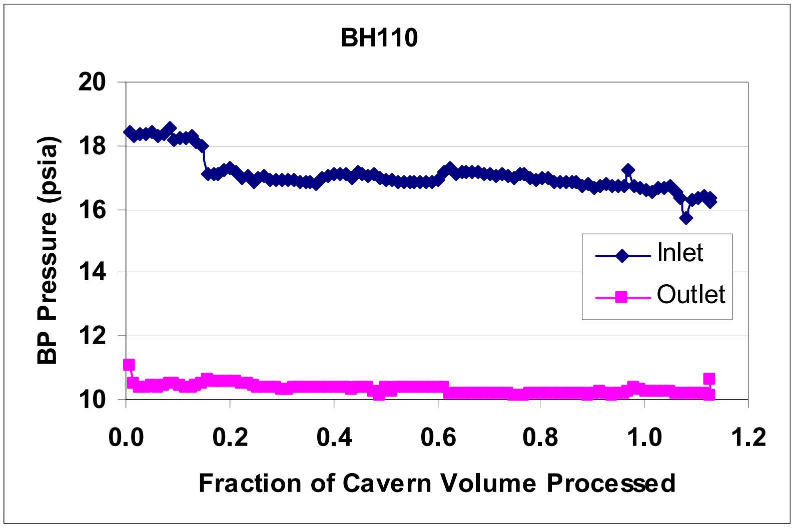


Figure 3-1. Big Hill Degas II Performance Curves (Continued).

4 Cavern Scale Mixing

4.1 Mixing Defined

Evaluation of the performance curves discussed in Section 3, particularly the extensive analysis of cavern BH101 (Ehgartner at al, 2005a,b), has led to the conclusion that there is some degree of cavern scale mixing of oil during degasification. Performance data imply that a mixing zone moves processed oil into the plant inlet ahead of the theoretical arrival of a plug flow interface. Months to years after degas, full cavern-scale mixing will result in an observed cavern BPP that falls between the plant inlet and outlet values at the end of degas. Variable degrees of mixing leads to a range of values for the post degas in-situ BPP. The primary evidence includes plant inlet and outlet BPP values that never overlay, even after as much as 124% cavern volume processed, and measured post degas in situ BP pressures that differ from plant outlet.

The spectrum of possible in-cavern mixing scenarios is depicted conceptually in Figure 4-1 - ranging from ideal plug flow to partial mixing (fingering or localized interface mixing) to complete mixing. Corresponding examples of actual performance curves from Degas II are also shown in the figure. Ideal plug flow is depicted on the left extreme, while complete mixing is depicted on the right extreme. For plug flow, the fluid flow velocities in the cavern are assumed uniform through any horizontal cross-section, much like a solid plug flowing through the cavern. The interface between gassy oil and processed oil remains distinct and intact during the entire processing time, and it moves downward as the volume of oil processed increases. This is the most efficient mixing scenario for the current degas configuration, as no processed oil is drawn into the plant. Cavern BH114 exhibited a plant performance curve that suggests nearly ideal plug flow. On the opposite end of the mixing spectrum, a completely mixed scenario supports no such barrier between gassy oil and processed oil, rapidly distributing processed oil throughout the cavern so that it appears in the plant inlet in gradually increasing amounts as the cavern volume is degassed. This is the least efficient scenario for degassing purposes, requiring a relatively large volume of oil processed for effective removal of gas to project specifications. Cavern BH101 exhibited a performance curve that suggests nearly complete mixing. The wide range of possibilities between these extremes is depicted as intermediate mixing. In this scenario, some degree of effective plug flow is experienced early in processing as oil taken into the plant inlet is uniformly gassy with a bubble point of ~18 psia. At some volume fraction typically greater than 20% but less than 90%, a significant decrease in plant inlet bubble point is observed, and this implies the arrival of a mixture of gassy and processed oil. The processing efficiency of an intermediate mixing case falls between the plug flow and completely mixed. BH102 and BH103 performance curves suggest intermediate mixing.

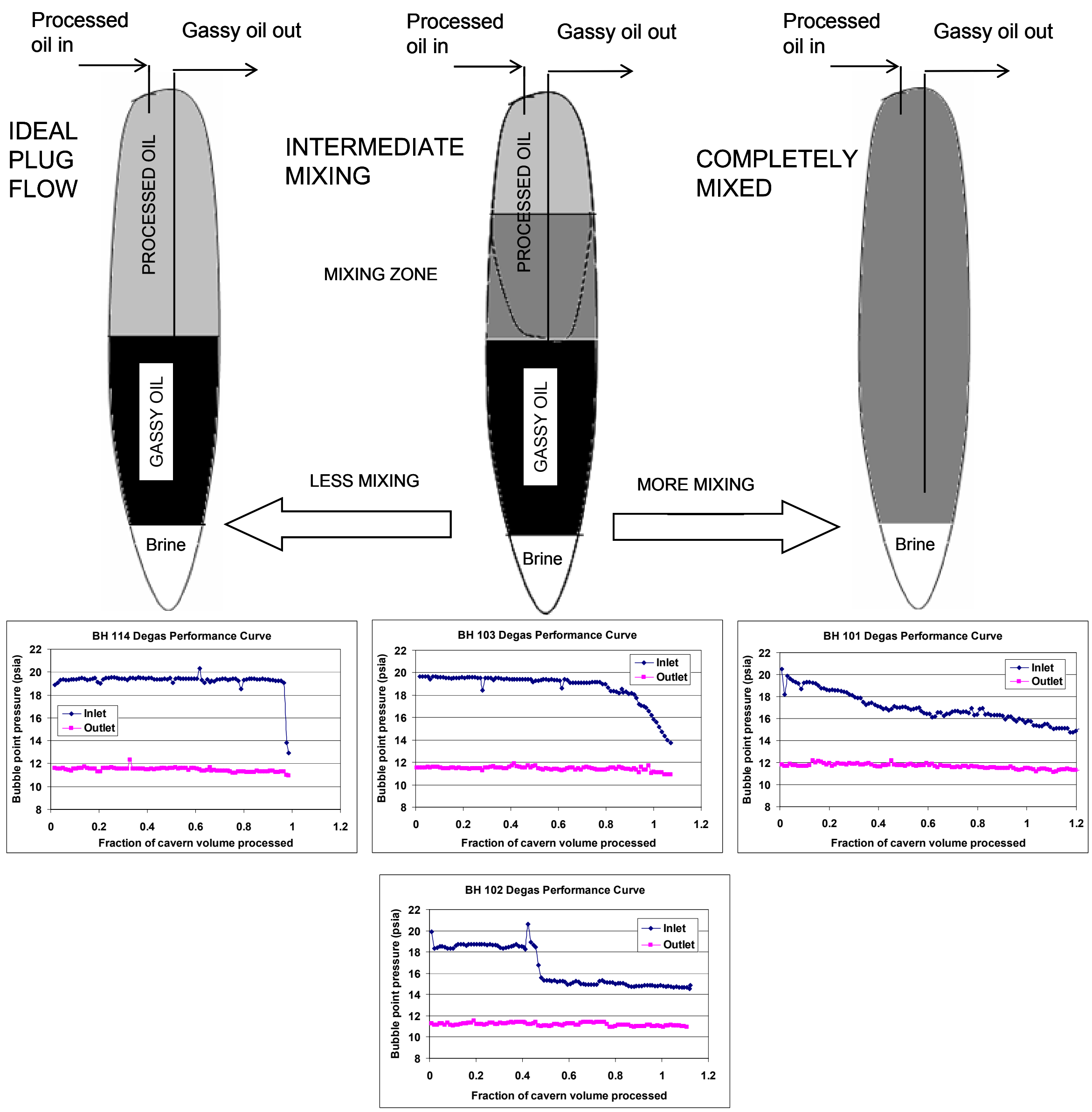


Figure 4-1. Conceptual Representations of Possible Mixing Scenarios.

4.2 Overlay of Degas II Performance Curves

Overlaying the available plant inlet performance curves and analyzing them in the context of the above discussion of mixing is also instructive. Figure 4-2 displays an overlay of all available plant inlet performance curves, effectively condensing the data presented in Table 3-1 onto one set of axes. The breakthrough volume fractions for most caverns are clearly discernable except for caverns 101, 103, and 110. Formally, the breakthrough was defined as the *VF* corresponding to the average of a representative initial inlet pressure and the final inlet pressure – the halfway point in bubble point reduction seen in the inlet stream. The breakthrough point on each curve is annotated on the figure with a bold "+", where breakthrough VF_B is defined as the volume fraction corresponding to the average of the initial and final inlet pressures. The labels above each curve give the cavern name and measured post degas in situ BPP. BP_{cav} for cavern BH110 labeled in red text has not yet been measured as of this report. There appears to be a trend of decreasing post-degas in situ BPP as the processed volume fraction associated with the breakthrough point increases. Late arrival of breakthrough also appears to correlate with low bubble point in the plant inlet by the end of degas. The mechanism behind the formation of the breakthrough curves is not clearly known, nor is it known whether the mechanism is the same for all curves. Several potential causes for the breakthrough curves occurring at values other than *VF* = 1 are (1) existing heterogeneity in cavern inventory, (2) string configuration that accesses less than the full oil volume in cavern, (3) varying degrees of cavern mixing during degas, and (4) uncertainty in cavern oil volume. Cavern BH110 presents a unique situation for defining breakthrough because the plant inlet BPP ended above 16 psia, leaving no conspicuous breakthrough event. An early mini-breakthrough occurred around *VF* = 0.15, but the persistence of BPP = 16-17 psia for the duration of the degassing suggests that maybe another breakthrough is imminent.

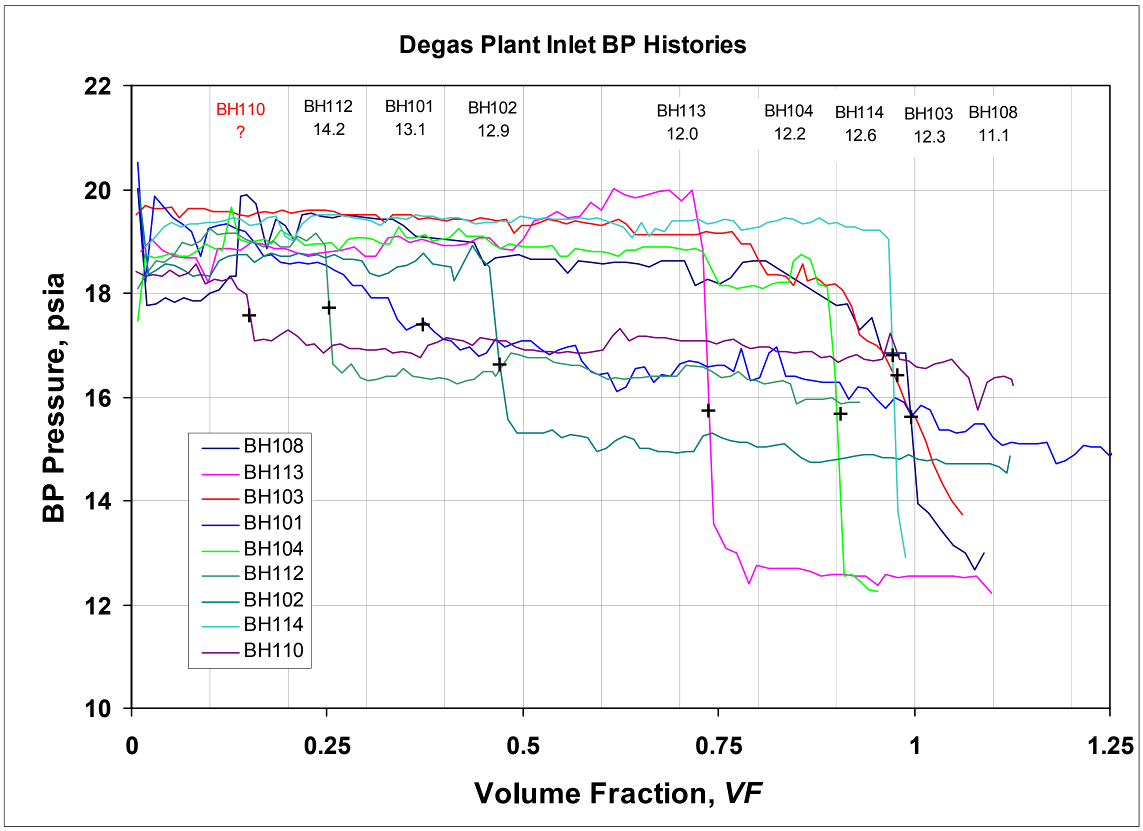


Figure 4-2. Overlay of Degas II Inlet Performance Curves.
Cavern ID and post degas in-situ BP pressure shown at top of figure are in order of breakthrough designated with plus signs (+).

4.3 Mixing Effects on Degassing

The end-result of degassing a cavern is a volume of oil with a lower bubble point than at the start of degas. How much lower and what effort was required to get there appears to vary from cavern to cavern, presumably linked to oil mixing within the cavern during the degasification process. A cursory review of the Degas II cavern geometry, inventory and long-term vapor pressure regain at Big Hill shows more similarities than differences, and do not appear as factors driving the cavern-specific differences in response to degassing. An interesting observation from Figure 4-2 above is that the arrival of breakthrough VF_B appears to correlate with the degree of bubble point drop in the plant inlet at breakthrough as well as the bubble point observed at the plant inlet when degassing was completed. The current analysis explores available degassing data to determine what, if any data may be correlated to build an understanding of what properties are associated with cavern degassing performance characteristics.

4.3.1 Data Considered

Selected parameters are presented in Table 4-1 for comparison with system performance. Caverns are listed in descending order of $BP_{cav} - \overline{BP}_{out}$, a key dependent variable. Notation for column headings is defined below the table. BP_{cav} for BH110 has not been measured as of the publication date of this report.

Table 4-1. Selected Degassing Parameters Used to Explore Mixing Effects on Degas.

Cavern	Stream (Sw = 1 So = 2)	$\overline{BP}_{in}$ (psia)	VF_B (-)	ΔP at VF_B (psia)	VF_T (-)	$BP_{cav} - BP_{out}$ (psia)	α (-)	Π (-)
BH112	2	18.9	0.26	5.4	0.92	3.8	0.56	0.60
BH113	2	19.1	0.73	6.3	1.08	1.8	0.80	0.74
BH102	1	18.6	0.48	5.6	1.10	1.7	0.77	0.70
BH101	1	19.3	0.39	-	1.24	1.5	0.81	0.65
BH104	1	18.8	0.91	6.4	0.94	1.1	0.86	0.92
BH114	1	19.4	0.97	2.5	0.97	1.1	0.86	0.88
BH103	1	19.3	0.96	3.3	1.07	0.9	0.89	0.83
BH108	2	18.7	1.00	6.5	1.10	0.4	0.95	0.86
BH110	2	18.3	0.15	1.2	1.13	–	–	–

Notation for Table 4-1:

Sw(1)/So(2)	SPR sweet (1) or sour (2) oil designated by mass% sulfur
$\overline{BP}_{in}$	Average plant inlet BPP prior to breakthrough
VF_B	Volume fraction processed at breakthrough (defined in section 4.2)
ΔP at VF_B	Drop in plant inlet bubble point pressure at breakthrough
VF_T	Volume fraction processed at end of degassing
α	Proportional reduction in bubble point pressure (defined below in section 4.3.4)
Π	Plug flow similarity index (defined below in section 4.3.5)

4.3.2 Bubble Point Drop at Breakthrough

The observation from Figure 4-2 that the magnitude of bubble point drop ΔP in the plant inlet appears to correlate with the arrival of breakthrough VF_B was examined with a scatterplot in Figure 4-3. A best-fit line is drawn with correlation coefficient $R^2 = 0.87$ indicating a reasonable degree of correlation. Earlier breakthroughs tend to result in lower bubble point pressure drops, while breakthroughs approaching $VF = 1.0$ are high and clustered around 6 psia. The mechanism behind each breakthrough is not currently known, but it is likely a combination of mixing and oil layering. An oil inventory layering scenario could form sharp breakthroughs prior to $VF = 1$, but layering does not, by itself, explain the correlation with the magnitude of coupled bubble point reduction ΔP. Layering could lead to a rise or fall in bubble point, and the magnitude of ΔP would not necessarily be linked to the value of VF_B. Moreover, a plug flow scenario with layered oil would also necessarily see a second breakthrough at $VF = 1.0$, which was not observed for any cavern with an early breakthrough (see Figure 3-1). The observations here are more consistent with a mixing mechanism that may be coupled with oil layering that forms mixing boundaries. This issue is explored further with the Simple Degas Mixing Model presented in section 5.

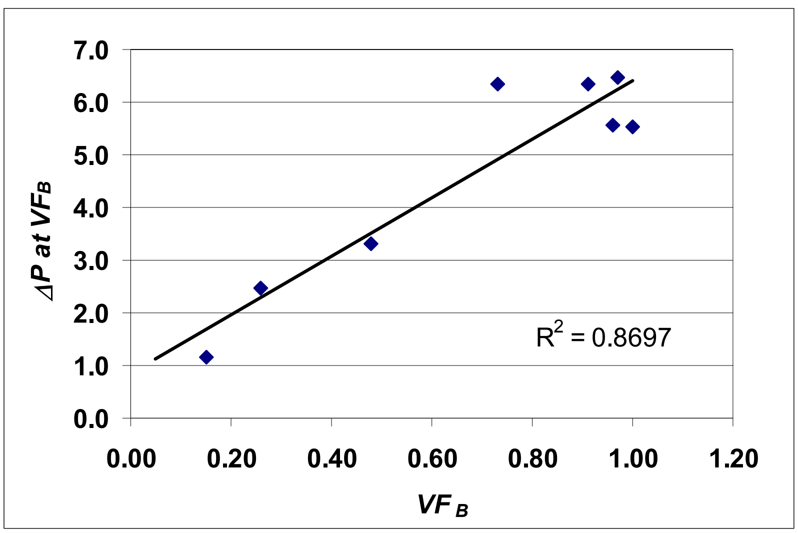


Figure 4-3. Scatter Plot of Bubble Point Drop at Breakthrough vs. Volume Fraction at Breakthrough.
Correlation Coefficient R^2 Is Shown for the Best-Fit Line.

4.3.3 Bubble Point Difference Between Plant Outlet and In-Situ

The difference between BP_{cav} and $\overline{BP}_{out}$ is an important parameter to examine since it quantifies the difference between the post-degas cavern BPP and the plant output set point. This difference reflects the effects of mixing, partial degas, and gas intrusion between degassing and the first in-situ measurement. $BP_{cav} - \overline{BP}_{out}$ was compared to the parameters volume fraction at breakthrough (VF_B) and volume fraction at completion of degas (VF_T), with the results shown graphically in the scatter plots in Figure 4-4. A best-fit line is drawn on each with correlation coefficient R^2 shown. The moderate value of $R^2 = 0.67$ for the VF_B plot indicates that there is a weak correlation between variables, where $BP_{cav} - \overline{BP}_{out}$ tends to decrease with later arrival of breakthrough. Note also that the four smallest $BP_{cav} - \overline{BP}_{out}$ values all occur where VF_B is close to 1.0 – near plug-flow conditions. Alternatively, a very low value of $R^2 = 0.12$ is observed for the VF_T plot, indicating no direct correlation of $BP_{cav} - \overline{BP}_{out}$ with the amount of oil processed. This suggests that increasing processing volume alone is not sufficient to drive the $BP_{cav} - \overline{BP}_{out}$ value down.

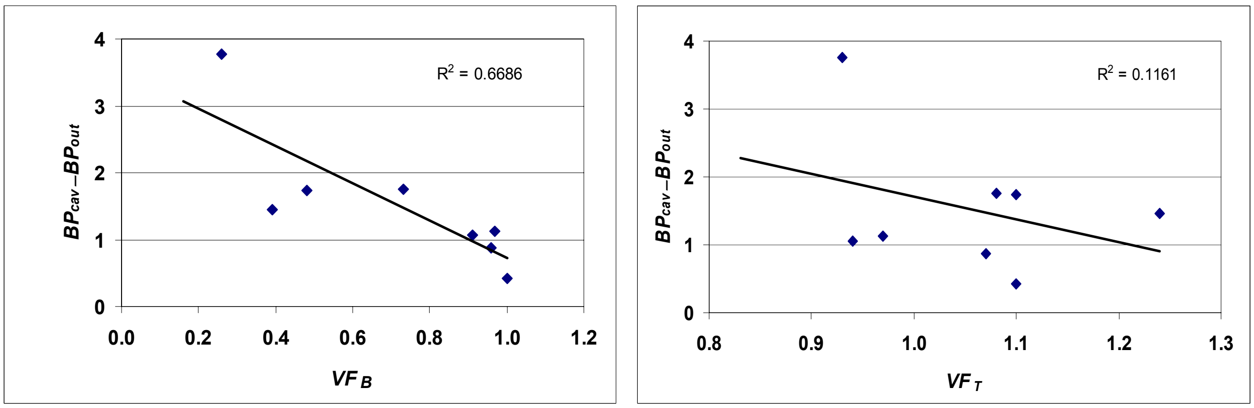


Figure 4-4. Scatter Plots Showing the Relationship $BP_{cav} - \overline{BP}_{out}$ vs. VF_B and $BP_{cav} - \overline{BP}_{out}$ vs. VF_T. Correlation Coefficient R^2 Is Shown for Each Best-Fit Line.

4.3.4 Proportional Reduction in Bubble Point Pressure

An alternate means to quantify the effectiveness of the degassing against the ideal case is to look at the proportional reduction in bubble point α as defined in Eq. 4.1:

$$\alpha = \frac{\overline{BP}_{in} - BP_{cav}}{\overline{BP}_{in} - \overline{BP}_{out}} \tag{4.1}$$

The numerator in Eq. 4.1 quantifies the difference in BPP between the plant inlet and in-situ, the effective lowering of cavern-average bubble point by degasification. This value is affected by system variables including cavern oil mixing, proportion of cavern volume degassed, and gas intrusion from the storage environment. The denominator quantifies the difference in BPP between plant inlet and outlet, a value controlled directly by degas plant operations. The concept of the proportional reduction is illustrated graphically for BH103 in Figure 4-5. With a pre degas $\overline{BP}_{in}$ = 19.3 psia, a degas plant outlet $\overline{BP}_{out}$ = 11.4 psia, an in-situ BP_{cav} = 12.3, $\alpha = \left[\frac{19.3 - 12.3}{19.3 - 11.4}\right] = 0.89$. A value of $\alpha = 1.0$ would indicate that upon completion of degassing, the entire cavern inventory exhibits the same bubble point as the plant outlet stream average, an example of perfect plug flow for an entire cavern inventory with no gas regain. All real caverns should exhibit a proportional reduction factor less than 1.0.

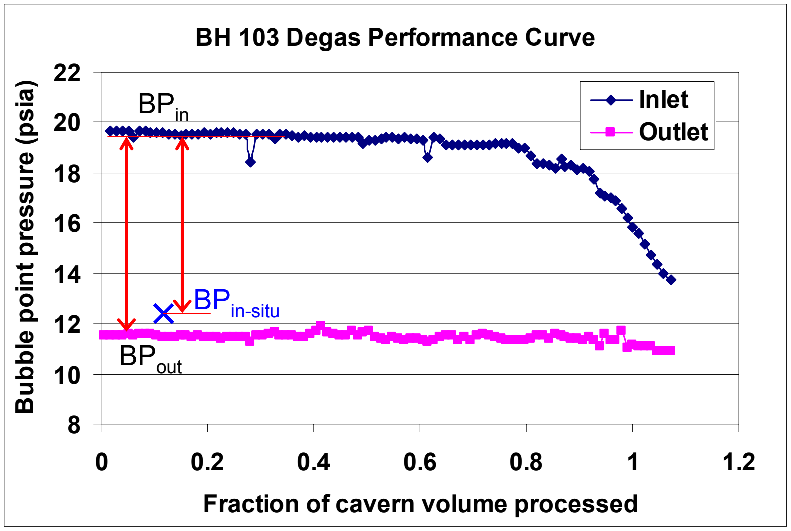


Figure 4-5. Annotated Performance Curve from BH103 Showing Graphical Interpretation of Proportional Reduction Factor α.

In Degas II, actual proportional reduction factors range from 0.55 to 0.95 as shown in Table 4-1, with cavern BH112 exhibiting the lowest reduction factor and cavern BH108 exhibiting the highest. The causes behind this range of α-values are complex, and some insight may be gained from looking at scatter plots of α with VF_B and VF_T shown in Figure 4-6. The reduction factor does correlate to some degree with VF_B, with R^2 = 0.72. Here, later breakthroughs occurring near VF_B = 1.0 lead to more proportional bubble point reduction resembling plug flow. Alternatively, α appears to have no correlation with the total volume fraction processed VF_T, as the R^2 for this plot is only 0.10. Presumably at some level, the total volume fraction processed must affect the reduction factor, especially for a partially degassed cavern. With the range shown here from VF_T = 0.93 to 1.24 for Degas II, no direct relationship is apparent. This implies that other factors such as cavern mixing or gas regain are impacting the in-situ BPP.

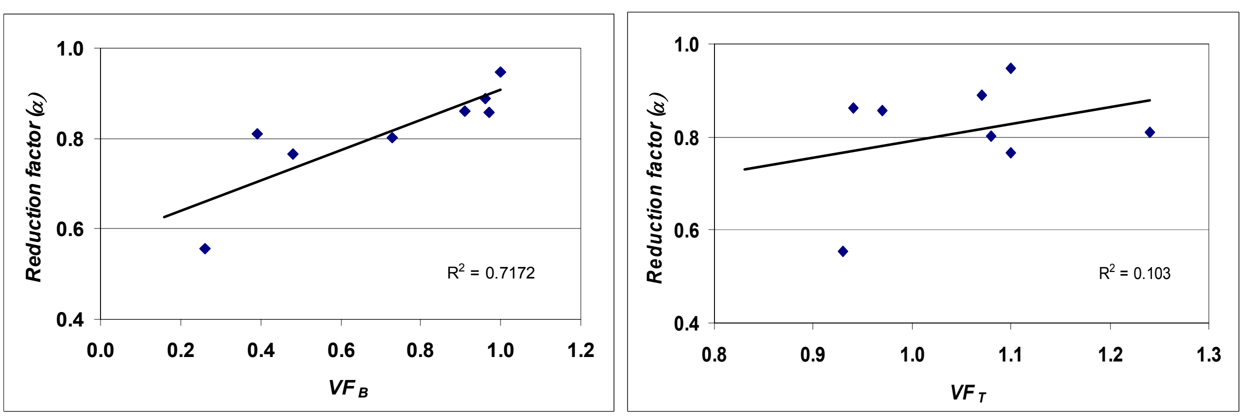


Figure 4-6. Scatter Plots Showing the Relationship α vs. VF_B and α Vs. VF_T. Correlation Coefficient R^2 Is Shown for Each Best-Fit Line.

4.3.5 Degassing Plug Flow Similarity Index (Π)

Dividing the proportional reduction in bubble point α by the total volume fraction processed VF_T yields a parameter that combines both the net effectiveness of degassing and the effort invested in what the authors define as a plug flow similarity index:

$$\Pi = \frac{\alpha}{VF_T} \tag{4.1}$$

For the ideal plug flow degassing process, $\Pi = 1.0$, indicating that after the entire cavern volume is processed ($VF_T = 1.0$) the in situ BPP is the same as the plant outlet (α=1). With cavern scale mixing, the degas process is less efficient than plug flow, and $\Pi < 1.0$. Using cavern BH103 as an example, the proportional reduction factor $\alpha = 0.89$ and the total processed volume fraction $VF_{T,} = 1.07$, so the plug flow similarity index was = 0.83. The BPP reduction due to the degas process was therefore 83% of what an ideal plug flow system could achieve. This parameter Π is a means to condense the complex degas performance data into a simple index for evaluating degas operations against ideal in-situ results.

Plug flow similarity is calculated for Degas II caverns and shown in the last column of Table 4-1. Π rages from 0.60 for cavern BH112 to 0.92 for cavern BH104. The high in-situ bubble point for cavern BH112 was the leading factor in decreasing its plug flow index. Cavern BH101 was also low at $\Pi = 0.65$, with a moderate α and a large VF_T driving Π down. The most favorable results were seen in caverns BH104 ($\Pi = 0.92$), BH114 ($\Pi = 0.88$), and BH108 ($\Pi = 0.86$) where the systems behaved most closely to plug flow.

Plotting the plug flow similarity index against the volume fraction of breakthrough reveals a reasonably strong correlation at $R^2 = 0.91$ (Figure 4-7), implying that breakthrough VF has an impact on Π and the final in-situ BP. Utilizing the best-fit line to the data in Figure 4-7, Π may be estimated from observation of breakthrough. Moreover, this relationship may be used to estimate BP_{cav} for caverns that have not been tested in-situ yet, like BH110. Using this methodology for BH110, which exhibits an early $VF_B = 0.15$, yields a prediction of $\Pi = 0.56$ and $BP_{cav} = 13.3$ psia. Alternatively, simply adding 1.4 psia (see discussion associated with Table 3-1) to $\overline{BP_{out}}$ yields a prediction of $BP_{cav} = 11.7$ psia. A third estimate using the SDM model is shown in section 5.5.

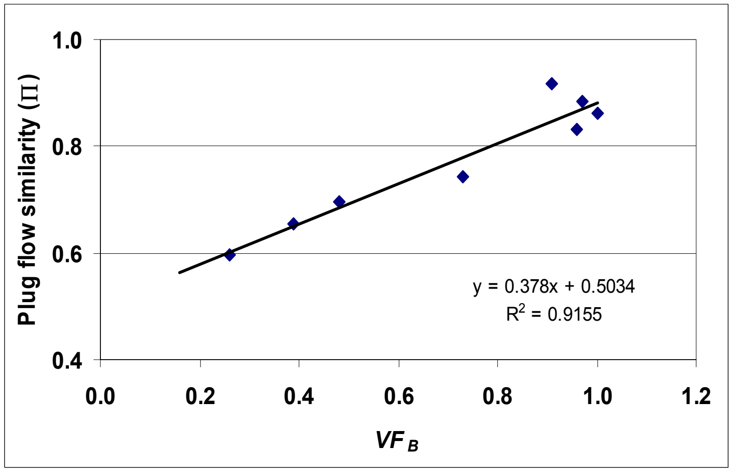


Figure 4-7. Scatter Plot of Plug Flow Similarity Index (Π) vs. Breakthrough Volume Fraction (VF_B).

4.3.6 Considering Regain Effects on $BP_{cav} - \overline{BP}_{out}$

It has been established that some caverns at SPR experience vapor pressure rise with time due to a gas regain mechanism. The rates of vapor pressure rise in some caverns appear to be unsteady, but sampling frequency has not been high enough to resolve much detail in the unsteady parts. Instead, "long-term" regain rates are calculated based on data collected since 1994. Current long-term regain rates are shown below in Table 4-2 for the Big Hill Degas II caverns. Also shown are estimates of what the "short-term" regain rate would have to be if regain was the only mechanism causing the bubble point rise from the end of degas to the first in-situ measurement, a period of 0.5 to 1.5 years. Note that the mean long-term regain for the degassed caverns is about 0.03 psi/yr, while the mean short-term regain is over 4 psi/yr, differing by a factor of about 100. Even if BH112 is removed as an outlier, the mean short-term regain is 2 psi/yr. Regain occurring between the end of degas and the first in-situ cavern measurement was hypothesized to be the cause of systematic vapor pressure increases observed after Degas I, which led to concern that regain rates were very high. A short-term regain effect could, for example, result from lowering the cavern operating pressure for activities surrounding a degas event. In this scenario, creep closure rate, which is strongly dependent upon fluid pressures in the cavern, will increase over baseline during degassing, and may promote a temporary increase in gas regain rate. Annual cavern testing after Degas I showed that vapor pressures did not continue to increase, and in many cases, remained steady, with effective regain rate of zero. Rather than a short-term regain mechanism followed by a long-term mechanism with near zero regain, the authors hypothesize that the $BP_{cav} - \overline{BP}_{out}$ phenomenon is more reasonably explained by cavern mixing.

A scatterplot comparing long-term regain rates with $BP_{cav} - \overline{BP}_{out}$ is shown in Figure 4-8, testing the premise that perhaps long-term regain may have some relationship to the bubble point rise after degas. No correlation is evident, with $R^2 = 0.18$.

Table 4-2. Comparison of Hypothetical Short-Term Rate and Long-Term Regain Rates.

Cavern	Time from Degas to BP_{cav}	Short-Term Regain Rate Estimate	Long-Term Regain Rate[a] (psi/yr)
	Yrs	*psi/yr*	*psi/yr*
BH108	0.92	0.46	0.2
BH113	1.35	1.30	0
BH103	1.42	0.61	0
BH101	0.21	6.91	0
BH104	0.87	1.22	0
BH112	0.19	19.92	0
BH102	0.93	1.86	0.05
BH114	0.72	1.57	0
BH110			0.03
AVG	*0.83*	*4.23*	*0.03*

[a] Source: Lord and Rudeen, 2007.

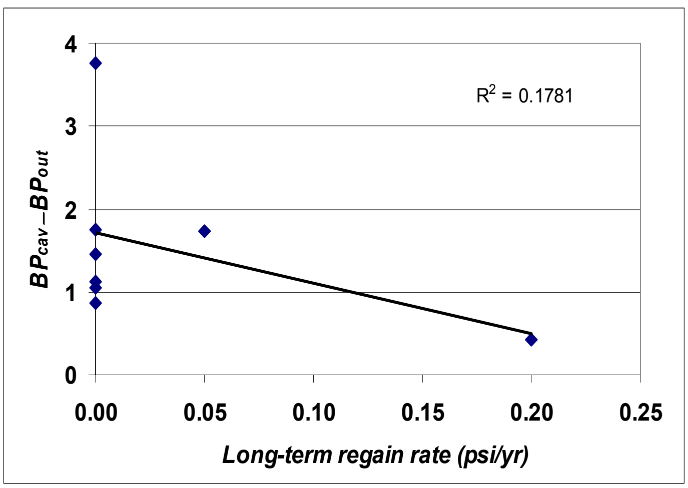


Figure 4-8. Scatter Plot of Long-Term Regain Rate vs. $BP_{cav} - \overline{BP}_{out}$ **.**

4.3.7 Sweet and Sour Caverns

The designation of sweet or sour according to sulfur content is important for maintaining quality control over SPR inventory for sales. The impacts of sulfur content on cavern degassing performance are unclear. The bar charts shown below divide the BH Degas II caverns into sweet and sour, comparing VF_B (Figure 4-9) and $BP_{cav} - \overline{BP}_{out}$ (Figure 4-10) for each. These parameters do not appear to correlate by oil with sweet or sour designation.

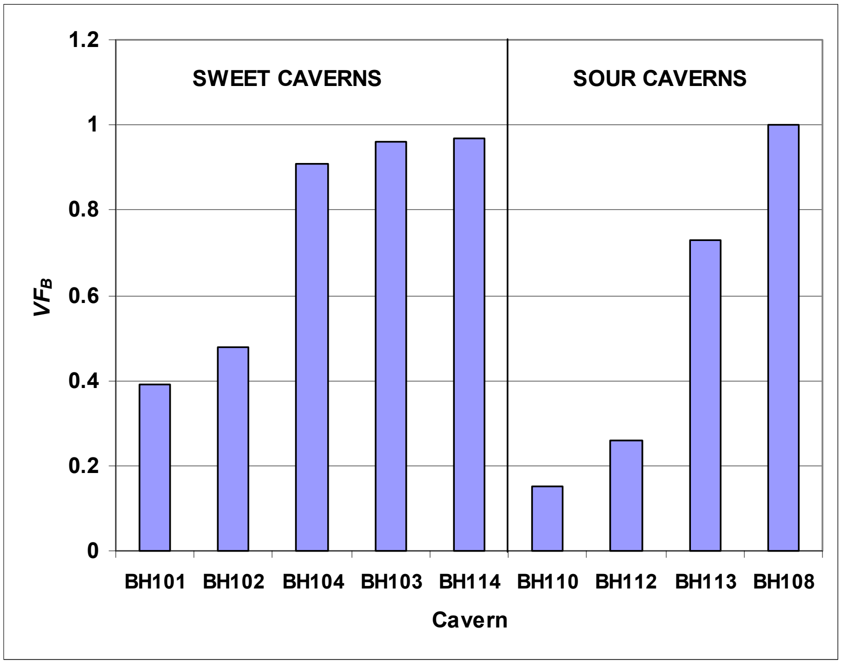


Figure 4-9. Bar Chart Comparing the Breakthrough Volume Fraction for Sweet and Sour Caverns.

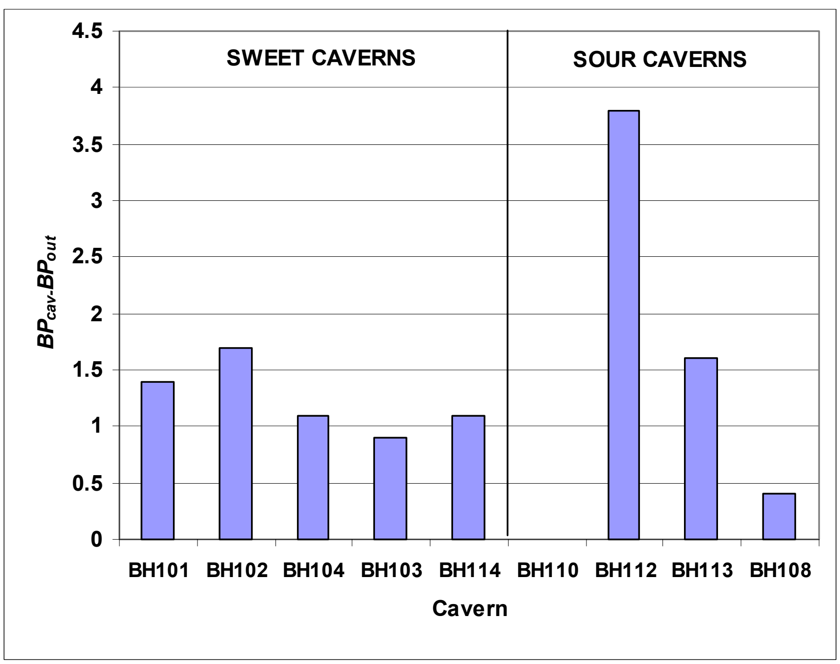
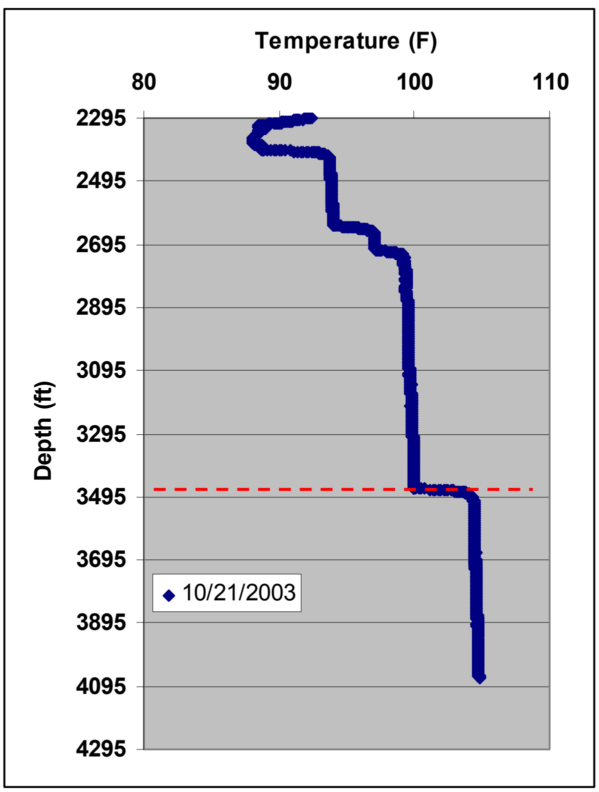


Figure 4-10. Bar Chart Comparing $BP_{cav} - \overline{BP}_{out}$ **for Sweet and Sour Caverns.**

4.4 Contribution of In-Situ Spatial Heterogeneity

Oil heterogeneity within a cavern prior to the start of degas likely plays a role in determining the shape of the plant performance curve. Pre-degas spatial data from BH102 are presented below as an example. There has been no monitoring of vapor pressure as a function of depth to date, so other parameters must be examined. Several data sources indicate heterogeneity in-situ, including the crude oil inspection analysis done when cavern fill is completed and periodic temperature logs. A temperature log for BH102 is shown in Figure 4-11 that clearly indicates thermal layering. The cavern roof is at 2295 feet, and the oil-brine interface is at 3490 feet. Cavern oil therefore comprises the fluid for all depths above the red dotted line on Figure 4-11. Conspicuous layering is present, with a dividing line around 2695 feet. Oil above this line is cooler than 95°F, and represents fill since 2001. Oil below this line is hotter at 99-100°F, representing a much earlier fill from 1992-1993. The existence of these thermal layers for several years suggests that the oil picked up in the degas plant inlet may also exhibit heterogeneities during processing. A review of the oil temperature at the plant inlet during processing did not exhibit any notable changes with *VF* processed, but since the oil is withdrawn through a ~4000 foot steel hanging string that is exposed to the cavern oil on the outside, it is likely that heat transfer through the string wall would normalize the temperature of the oil and mask any temperature layering.



Note: Oil volume on 10/21/2003 was about 9.4 MMB, which is 80% the volume at the start of degas in April 2006. Red dotted line is brine-oil interface.

Figure 4-11. Temperature Log for BH102 Indicating Thermal Layering in Cavern in 2003.

The crude oil inspection analysis for BH102 also reveals in-situ spatial heterogeneity in oil properties. The inspection is created by collecting downhole oil samples at selected depth intervals and analyzing in the lab for oil density, viscosity, and several other properties, though vapor pressure is not one of those measured properties. An inspection for BH102 was collected on 8/5/2004, analyzed on 8/13/2004, and is shown below in Table 4-3. The information in the inspection indicated that oil density and viscosity varied with depth, particularly across a line between 2817 and 3081 feet deep. Operational data from the degas plant processing BH102 oil show a marked change in inlet bubble point and plant operating pressure on February 2, 2006, which corresponded to about 5.5 MMB processed ($VF = 0.47$) and is evident in Figure 3-1. It is possible that this change in inlet conditions is a result of the arrival of the oil property break observed in the oil inspection. The volume of oil between the plant intake line at 3922 feet and the oil property break is between 4.1 and 5.8 MMB according to sonar surveys. This volume range is consistent with the 5.5 MMB processed as of February 2, 2006. The stability of the plant inlet bubble point through the end of processing (see Figure 3-1) suggests that there may have been considerable mixing behind the front, because with plug flow alone, another drop in bubble point would have been expected around $VF = 1.0$.

Table 4-3. Crude Oil Inspection Analysis for BH102 Collected on 8/5/2004.
Note abrupt changes in properties between 2817 and 3081 foot depths marked by the dotted line. This reflects a persistent layering between oil fills.

SPR CRUDE OIL INSPECTION ANALYSIS

Date Started 8/5/2004 Sample ID Big Hill, Cavern 102A Date Reported 8/13/2004

Sample No. Date Collected	Bottle Label	Depth (ft.)	Relative Density D 5002 at 60/60° F	Gravity °API	Pour Pt. D 5853 °F	Nitrogen D 5762 (wt. %)	Sulfur D 4294/XRF (wt. %)	Viscosity centistokes, D 445 at 77° F	Viscosity centistokes, D 445 at 100° F	Water D 4928 (wt. %)	Acid No. D 664 mg KOH/g
2004SPR119 7/21/04	BH040721-007	2289	0.8473	35.5	15	0.153	0.434	5.608	4.067	0.02	0.27
2004SPR120 7/21/04	BH040721-006	2553	0.8468	35.6	20	0.155	0.433	5.536	4.010	0.02	0.28
2004SPR121 7/21/04	BH040721-005	2817	0.8468	35.6	20	0.150	0.429	5.770	4.043	0.02	0.27
2004SPR122 7/21/04	BH040721-004	3081	0.8556	33.9	0	0.274	0.661	6.590	4.732	0.06	0.44
2004SPR123 7/21/04	BH040721-003	3344	0.8559	33.8	0	0.255	0.665	6.707	4.791	0.02	0.43
2004SPR124 7/21/04	BH040721-002	3608	0.8558	33.8	5	0.225	0.669	6.588	4.694	0.02	0.44
2004SPR125 7/21/04	BH040721-001	3872	0.8555	33.9	5	0.247	0.657	6.620	4.769	0.02	0.46
2004SPR126 7/20/04	BH040720-004	3922	0.8559	33.8	5	0.224	0.664	6.710	4.780	0.16	0.46
2004SPR127 7/20/04	BH040720-003	3927	--	--	--	--	Sludge	--	--	16.7	--
2004SPR128 7/20/04	BH040720-002	3932	1.2052	--	--	--	Brine	--	--	--	--
2004SPR129 7/20/04	BH040720-001	3936	1.2051	--	--	--	Brine	--	--	--	--

4.5 Degas I Evaluation – Hindsight

Early vapor pressure trending analyses, including the planning calculations for Degas II, interpreted the increase in BPP after Degas I as a result of regain or influx of gas, particularly methane, from the surrounding host salt. The gas intrusion theory was reinforced by numerous observations during cavern development and leaching in which gas was produced at the wellheads. Moreover, very high bubble point pressures were encountered early in the fill process in some caverns with small oil volumes limited mainly to roof oil. This is currently the case with BM112 which has an oil volume of 240,000 BBL and a bubble point pressure of 30 psia with a GOR of 5.4 scf/bbl (last measured on 11/14/2001). These observations led to a belief that gas regain was relatively high and widespread around the SPR complex.

A 2005 review (Lord and Rudeen, 2005) of the vapor pressure dataset contained in the DM quarterly vapor pressure reports resulted in a new interpretation of the in-cavern BPP behavior after Degas I. The new review benefited from having more data with ever improving quality over an extended time frame. The primary finding was that post Degas I vapor pressure history consists of two stages – an early rapid but small increase or jump from the plant outlet value to the first in-situ BPP measurement, and a later much slower regain for subsequent measurements. This implies that either (1) the regain must be transient because BPP rises quickly and the levels off or (2) there are two distinct phenomena that occur in series– early mixing between degassed and gassy oil, followed by slow to negligible regain. The extensive data obtained during Degas II (Section 3) helped to strengthen the cavern scale mixing interpretation made in 2005.

Table 4-4 provides a summary of selected parameters from Degas I, with caverns represented by individual rows, grouped by site and stream. All caverns degassed during Degas I are included in the table. Column headings are defined as follows:

- "Sw 1, So 2": 1 denotes sweet cavern, 2 denotes sour cavern.
- "Start Date" and "End Date": start and end dates of degassing.
- "Outlet BPP (psia)": This is the BPP reported in the Quarterly VP spreadsheet for the degassed oil BPP. For caverns that were completely degassed, it represents the daily weighted average of the degas plant outlet as measured by the TVP1000. For caverns that were partially degassed, this represents a weighted average of the degassed and non-degassed oil volumes .
- "1st Measured BPP (psia)" and "Date of 1st measured": first BPP measured on in-situ cavern sample after Degas I.
- "Best Guess Post-Degas BPP (psia)": The best guess in-situ BPP was either the first measured BPP, a later measurement, or a value extrapolated back to the time of degas using a linear regression. The comments column specifies the method used when the best guess BPP is different than the first measured.

- "Difference Measured (psia)": Difference between first measured in-situ and outlet value.

- "Difference Best Guess (psia)": Difference between best guess and Degas outlet value.

The data in Table 4-4 provide some basis for evaluating cavern scale mixing during Degas I. The table is organized so that the plant outlet BPP value and the first measured in-situ BPP value are in adjacent columns for direct comparison. The best guess data was used in the analysis when the first measured value was an outlier, significantly delayed or there were significant oil transfers that could have affected the in-situ BPP. Most degassed caverns showed a jump in BPP followed by a flattening of the rate of BPP increase thus justifying extrapolation. Author judgment was used as to when and what value to use as a best guess estimate. Also, if the resulting difference between the first post degas measured BPP and the degas BPP was negative or large (>3 psi), or the degas BP pressure was large (> 13 psia) the difference was excluded from the average calculation. The average difference between reported degas outlet BPP and the 'best guess' in-situ BPP for all included Degas I caverns, independent of site or stream, is 1.5 psi which is effectively the same as was observed for Degas II. Some of the reported outlet and post degas in-situ values are high because several caverns were only partially degassed and other caverns showed substantial fill immediately after degas. These caverns were not used in the current Degas I analysis. These observations and the fact that some caverns were degassed from one cavern to another as opposed to in-place makes additional analyses, such as estimating degas effectiveness, problematic.

The primary message from this quick review of Degas I is that the jump in BPP from plant outlet to first in-situ was observed, and on average, it was the same magnitude as seen in Degas II. The authors believe that the reason for the jump in both cases is that the plant outlet BPP is simply not representative of the in-cavern value, and on average, is about 1.5 psi lower than the in-situ cavern value after degas.

Table 4-4. Degas I BP Pressure Summary.

Cavern	Stream Sw = 1 So = 2	Start Date	End Date	Outlet BPP (psia)	1st Measured BPP (psia)	Date of 1st Measured BPP (psia)	Best Guess Post Degas BPP (psia)	Difference Measured (psi)	Difference Best Guess (psi)	Comments
BC17	2	6/22/96	8/30/96	12.1	13.8	5/10/01	13.8	1.70	1.70	20% new oil since degas and prior to first post degas measurement
BC18	1	4/5/96	6/22/96	11.9	16.4	5/5/01	14.4	4.50		later measured shows 14.4, but Equilbrium. ?
BH105	1	11/6/96	2/1/97	11.3	13.0	8/5/98	12.4	1.71	1.10	extrapolation back gives 12.4
BH106	2	2/1/97	4/12/97	11.1	13.9	2/23/99	13.9	2.80	2.80	
BH107	2	4/12/97	5/29/97	11.1	13.4	6/25/98	13.2	2.30	2.10	extrapolation back gives 13.2
BH108	2	5/29/97	11/11/97	11.3	19.2	7/1/98	15.2	7.90		17.4 in 1/29/02, could be as low as 15.2
BH109	2	5/29/97	11/11/97	11.3	14.1	7/29/98	14.1	2.80	2.80	
BM2	1	12/17/95	2/27/96	12.3	13.9	12/3/98	13.6	1.60	1.30	13.6 extrapolated back
BM106	1	10/1/97	12/1/97	13.9	17.7	9/17/98	17.7	3.80		Notes on crude mixing test at end of degas
BM113	1	10/1/95	12/1/95	12.3	12.7	12/1/98	12.7	0.38	0.38	12.4 extrapolated back
BM114	1	2/1/96	5/1/96	12.0	12.5	1/29/97	12.3	0.53	0.33	12.3 extrapolated back
BM115	1	8/1/95	10/1/95	15.8	20.7	8/7/98	20.7	4.86		Partial degas. BP estimated
BM116	1	8/1/95	10/1/95	15.7	17.4	1/12/99	17.4	1.73		Partial degas. BP estimated
BM1	2	8/1/97	10/1/97	12.0	12.7	9/10/99	12.7	0.75	0.75	? Degas dates
BM101	2	8/1/96	11/1/96	12.2	13.6	10/15/98	13.2	1.45	1.05	13.2 extrapolated back
BM103	2	8/1/96	11/1/96	12.4	13.3	10/14/98	13.1	0.94	0.74	13.1 extrapolate back
BM107	2	6/1/97	9/1/97	11.1	12.9	9/30/98	12.9	1.80	1.80	
BM109	2	1/1/97	3/1/97	12.2	13.8	10/7/98	13.5	1.56	1.26	13.5 extrapolated
BM110	2	6/1/96	8/1/96	13.5	11.6	10/2/98	13.5	-1.90		Odd. shows only 60% degassed, but extrapolation back shows 10.9. New interpretation indicates regain
BM111	2	9/1/97	10/1/97	12.0	15.9	6/23/98	15.9	3.90		15.7 extrapolated. Regain? Maybe affected by oil shipments after degas
WH103	1	11/18/95	1/4/96	11.9	14.2	11/7/00	13.5	2.30	1.60	13.5 extrapolated back
WH107	1	9/23/95	11/18/95	11.5	14.98	1/4/00	14.98	3.48	3.48	
WH113	1	7/29/95	9/23/95	11.4	13.2	11/3/00	13.2	1.80	1.80	
									1.47	

4.6 Implications

The cavern scale mixing of degassed and unprocessed oil has significant implications for vapor pressure program. Among the more important are:

- More mixing leads to less efficient degassing and longer processing times. Recall that cavern BH101, which appears to approach complete mixing in Degas II, has an in situ BPP = 13.1 psia even after 120% of cavern volume was processed over 111 days with a plant outlet average BPP = 11.7 psia.
- In-situ BP pressures are higher than the plant outlet average and are unknown until measured. Measured in-situ BPP values for Degas II at Big Hill were in the range 11.1 to 14.2 psia.
- Estimation of gas regain rates is significantly affected by selection of the first effective BPP after degassing. Using plant outlet BPP as a starting point for post-degas BPP has historically overstated regain. Using the first measured in-situ BPP is a more appropriate choice.
- Currently there is no known simple remedy for preventing mixing of processed and unprocessed oil when degassing removes oil from and re-injects oil to the same cavern
- Cavern-scale oil fluid dynamics model development currently in process (i.e. Webb, 2007) may give some insight to mixing mechanisms.

5 Simple Degas Mixing Model

A simple degas cavern mixing model, referred to here as the SDM model, is presented as a means to test the viability of several ideal model configurations to simulate observed behavior in Degas II. Note that the internal features of the degas plant are not considered in the SDM model. The degas plant simply changes the properties of the oil stream passing through it according to user input.

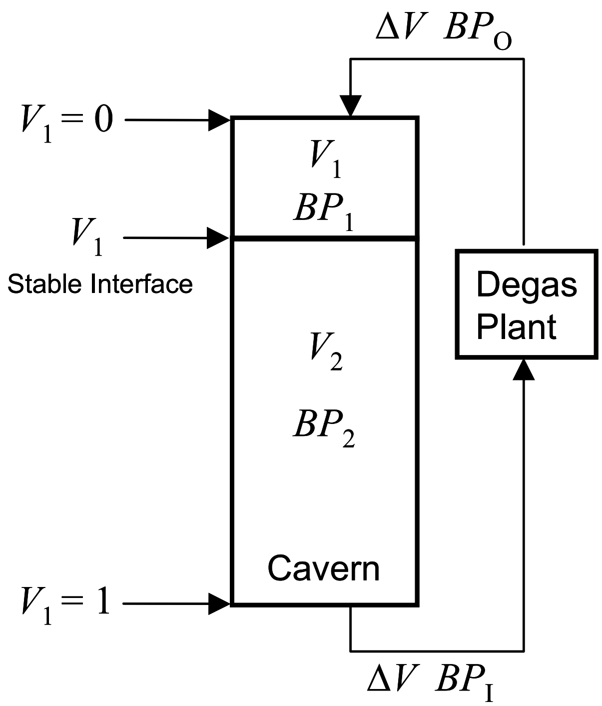
5.1 Model Description

A conceptual flow diagram for the model is shown in Figure 5-1. The idealized model comprises a cavern completely filled with oil and a degas plant, with oil flowing out of the bottom of the cavern, passing through the degas plant, and returning into the top of the cavern, forming a closed loop. Cavern oil volume (V) is fixed at 1 implying volume processed and volume fraction processed are the same. Oil processing is simulated by removing an incremental volume (ΔV) out of the bottom of the cavern exhibiting plant inlet bubble point = BP_I, passing it through the degas plant so that it exhibits a plant outlet bubble point = BP_O, and reinjecting that incremental volume into the top of the cavern. The cavern is subdivided into two zones, V_1 and V_2, with a stable boundary between the two. As the cavern volume is processed, the location of the mixing boundary moves down according to the cumulative volume processed. In an ideal plug flow scenario, this mixing boundary starts at the top at the beginning of processing, and ends at the bottom exactly as volume fraction processed VF =1.0. In an ideal completely mixed scenario, this mixing boundary starts at the bottom and stays there. In a system with layered inventory, the mixing boundary could start in-between.

5.2 SDM Model Bounding Cases

A conceptual depiction of the progress of degasification in the SDM model bounding cases is shown in Figure 5-2. The complete mixing and plug flow models are shown, with VF increasing from left to right. At VF = 0, all oil is gassy, color coded black. As VF increases, degassed oil, color coded white, is introduced at the top where it either mixes thoroughly (completely mixed case) or remains above the mixing interface (plug flow). At exactly VF = 1.0, the plug flow model shows all degassed oil. The complete mixing model still has some gassy oil mixed with processed oil at VF = 1.0, and only asymptotically approaches a completely degassed state.

The SDM model is implemented in an Excel spreadsheet using ΔV as a master variable that is incremented forward (denoted in Figure 5-1 with subscript n) so that volume fraction (VF) processed increases from 0 to 1 or greater in increments of 0.01. Relevant system equations are shown next to the process flow diagram in Figure 5-1. For the simulations done in this report, all oil in the cavern starts at $BP_1 = BP_2$ = 19 psia unless otherwise specified. Degas plant outlet is fixed at BP_O = 11.0 psia.



$$V_1^n = \min\left(1.0,\ V_1^{n-1} + \Delta V\right)$$

$$V_2^n = \max\left(0,\ V_2^{n-1} - \Delta V\right)$$

$$V^n = V_1^n + V_2^n = 1.0$$

$$BP_1^n = \left(\frac{V_1^{n-1} BP_1^{n-1} + \Delta V\, BP_O}{V_1^n}\right)$$

$$\overline{BP}^n = \left(\frac{V_1^n BP_1^n + V_2^n BP_2}{V^n}\right)$$

$$BP_I^n = \begin{cases} BP_2 & \text{if } V_1^n < 1.0 \\ BP_1^n & \text{if } V_1^n = 1.0 \end{cases}$$

Initial conditions:

$$V_1^0 = \begin{cases} 0 & \text{; for plug flow} \\ 1 & \text{; for complete mixing} \\ 0 < v < 1 & \text{; for mixing to an interface} \end{cases}$$

$$BP_1^0,\ BP_2,\ BP_O$$

$$\Delta V$$

Figure 5-1. Conceptual Flow Diagram for the Simple Degas Cavern Mixing Model. BP_I as a Function Of Time Is The Degas Plant Inlet Performance History. BP_O is the plant outlet performance curve. $\overline{BP}^n$ is the cavern average BP pressure. Initial placement of interface V_1^0 determines plug flow (V_1^0 = 0) or complete mixing (V_1^0 = 1) as bounding cases.

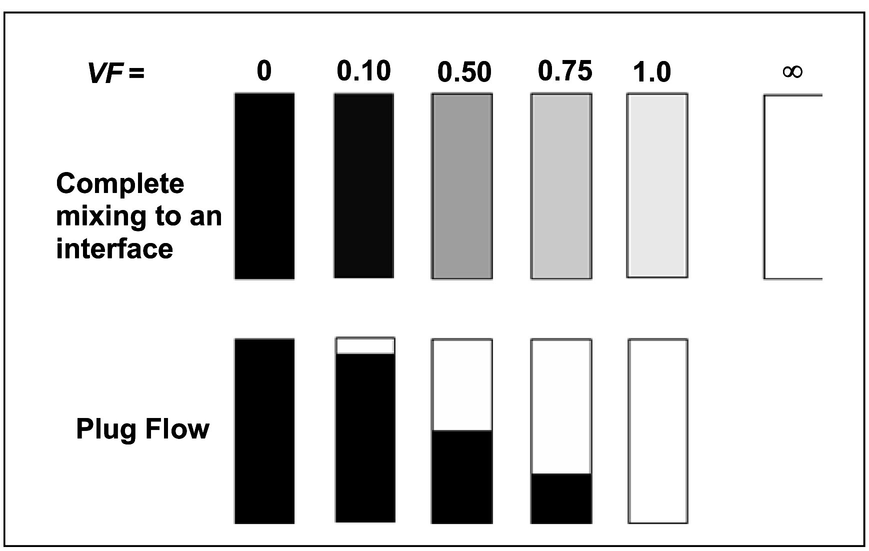


Figure 5-2. Bounding Conceptual Models for Complete Mixing and Plug Flow. *VF* denotes volume fraction processed, and increases from left to right. Gassy oil is color coded black, while processed oil is white.

Sample SDM model output performance curves for the bounding cases of complete mixing and plug flow are overlaid in Figure 5-3. Both models were run to VF = 1.24. Note that the completely mixed model shows a continuous decrease in plant inlet bubble point pressure (BP_I) throughout processing, while the plug flow model breaks at VF = 1.0 and then remains at BP_I = BP_O = 11 psia. By comparison, the completely mixed plant inlet (and consequently cavern average) is 13.4 psia at VF = 1.2. These two performance curves define the boundaries of expected behavior for the real systems, with the area marked in Figure 5-3 as "region of possible non-ideal mixing performance curves." Also, the post-degas in-situ bubble point should be generally bounded by the complete mixing performance curve from above and the diagonal dotted line representing the best-case plug flow from below, marked in Figure 5-3 as "region of non-ideal mixing cavern average BP."

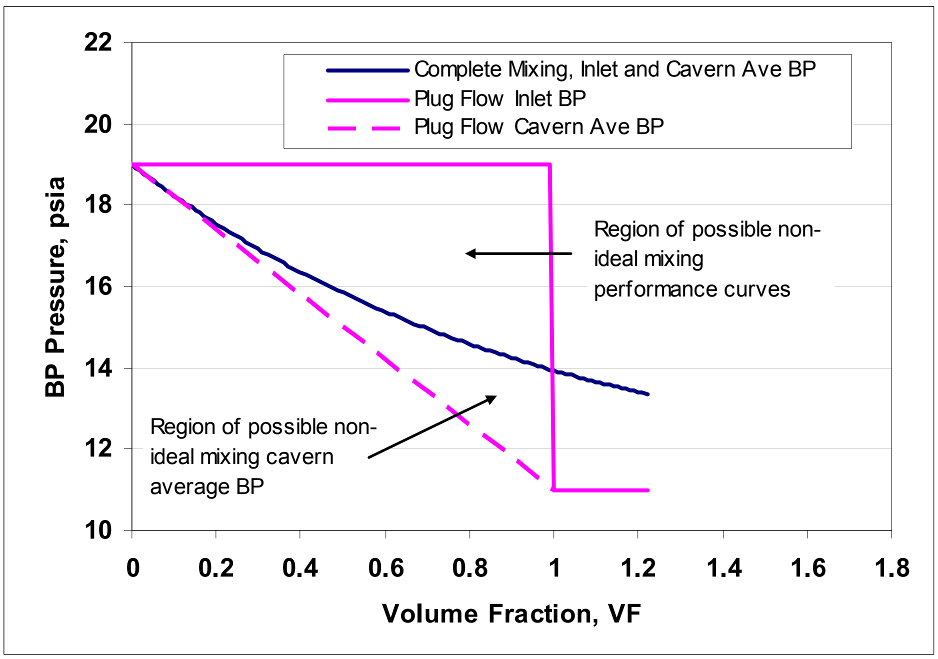


Figure 5-3. SDM Model Results Showing BP_I Histories (Performance Curves) for Complete Mixing and Plug Flow Bounding Cases.
For the plug flow case, the average BPP in the cavern computed by volume weighting is given by the diagonal dotted line.

5.3 SDM Model Intermediate Cases

Inspection of the real performance curves shown in Figure 3-1 reveals that perhaps three of the nine Degas II caverns at Big Hill resemble either of the bounding cases. Many exhibit some sort of intermediate behavior with a break in inlet bubble point occurring sometime in the middle of processing, behaving almost as a plug flow cavern until the break, and then proceeding with something between plug flow and mixed for the remainder of processing. The SDM model was configured so that it can simulate a mixing barrier that moves downward with volume fraction processed, starting from an arbitrary point and reaching a completely mixed state before VF = 1.0. A conceptual depiction of this model is given in Figure 5-4. In both cases shown, the cavern is divided into two zones separated by a mixing boundary in early processing. Plug flow occurs in the bottom zone, while either mixing or plug flow occur in the top zone (this model does not distinguish between the two mixing modes in the top of the cavern). At some point during processing, the mixing boundary is eliminated either because it is drawn into the intake at the bottom of the cavern or it simply breaks apart. After this point, the cavern is completely mixed and proceeds as such for the remainder of processing. For this example, *VF* = 0.25 was arbitrarily chosen for the breakdown of the mixing barrier.

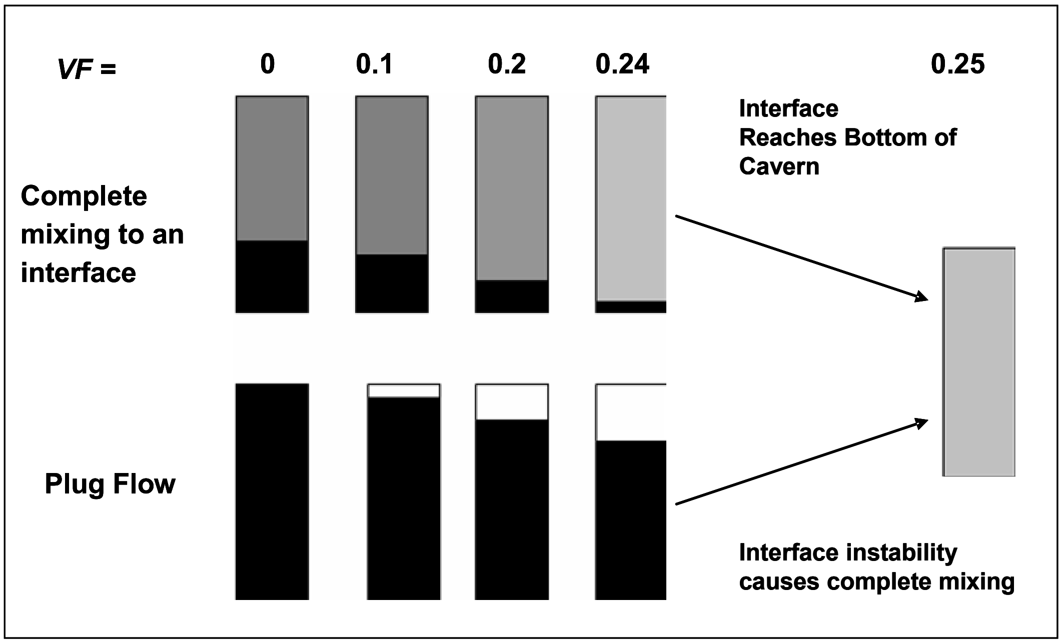


Figure 5-4. Two Possible Conceptual Models That Exhibit Plug Flow in the Bottom of the Cavern at Early *VF* and Then Transition to a Completely Mixed State Later in Processing (at *VF* = 0.25 In This Example).

Running a case with the SDM model in which the mixing barrier breaks down at an arbitrary point (*VF* = 0.5) during processing yields the performance curves shown in Figure 5-5. Plant inlet BP is 19 psi until *VF* = 0.5 at which point the entire cavern mixes to a uniform state. The new starting point either goes to plug flow again, shown as the horizontal line, or complete mixing, which is the gradually decreasing BP. The dotted lines represent the cavern-average BPP for the ideal plug flow model—the lower bound for cavern BPP if the processing was stopped at the corresponding *VF*.

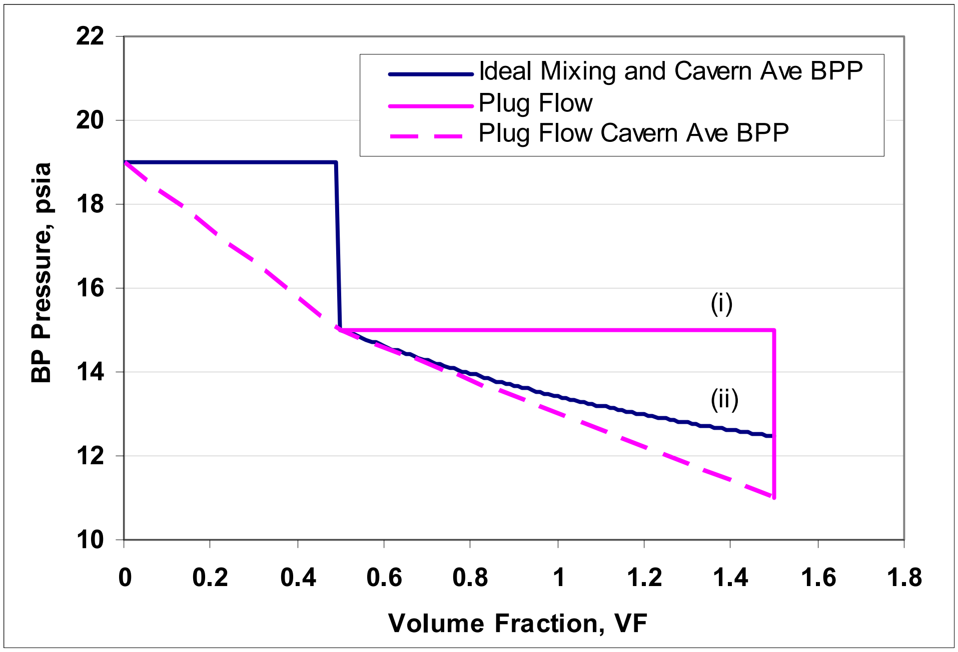


Figure 5-5. SDM Model Performance Curves Depicting Plug Flow Until *VF* = 0.5, at Which Point the Entire Cavern Mixes and Proceeds with Either (i) Plug Flow or (ii) Complete Mixing until *VF* = 1.5.

5.4 Data-Model Comparisons

Several specific cases of measured data versus SDM model results are explored. Note that the model is not used in a predictive manner here, but rather in a post-process analysis to see if real system behavior is at least quantitatively consistent with the features of the simple conceptual cavern mixing models.

Plug flow vs. BH104. The first data-model comparison is for cavern BH104, which exhibited near plug flow with a plug flow similarity index $\Pi = 0.92$ (see section 4.3.5). The SDM model initial inlet bubble point pressure was set to 18.9 psia, the outlet was set to 11.1 psia, and the model was run as a plug flow cavern until the breakthrough point set to $VF_B = 0.92$ to simulate observed conditions. The measured data and SDM model results shown in Figure 5-6 overlay quite closely, with the magnitude of bubble point pressure drop at breakthrough comparing to within 1 psi. The SDM model simulation after breakthrough was run in two modes: (1) continue plug flow, or (2) complete mixing. Since degas operations were completed at $VF_T = 0.94$ for this cavern, there was no chance to compare the model versus measured performance curves post-breakthrough. A final post-degas value of $BP_{cav} = 12.2$ psia was measured, which compares well with the 11.8 psia simulated for both plug and complete mixing SDM model at $VF_T = 0.94$ when processing was completed.

Complete mixing vs. BH101. Ehgartner et al (2005a,b) first recognized BH101 as a mixing cavern, hence the plug flow similarity index for this cavern is low at $\Pi = 0.65$. To facilitate the comparison here, the SDM initial inlet bubble point pressure BP_I was set to 20 psia, and the outlet was set to 11.7 psia to match BH101 observed conditions. The overlay of BH101 actual and SDM model results for plant inlet BPP is shown below in Figure 5-7. Agreement between model and observed is quite close, with the observed BH101 inlet bubble points a little higher than in the complete mixing model late in processing. Since the complete mixing model provides a lower boundary for expected behavior, the BH101 observed performance is within expectations and is probably well-mixed, yet short of complete mixing. Post-degas testing of the in-situ bubble point pressure of BH101 returned a value of 13.1 psia for four different cavern oil depths. The SDM model calculates a plant inlet bubble point at the end of degas (*VF* = 1.25) of 14 psia, which for a completely mixed system, is equivalent to the average in-situ bubble point. The fact that the actual performance curve deviated slightly upward from the model curve and had a slightly lower in-situ BPP after degas than the model supports the theory that this cavern was well mixed but not completely mixed.

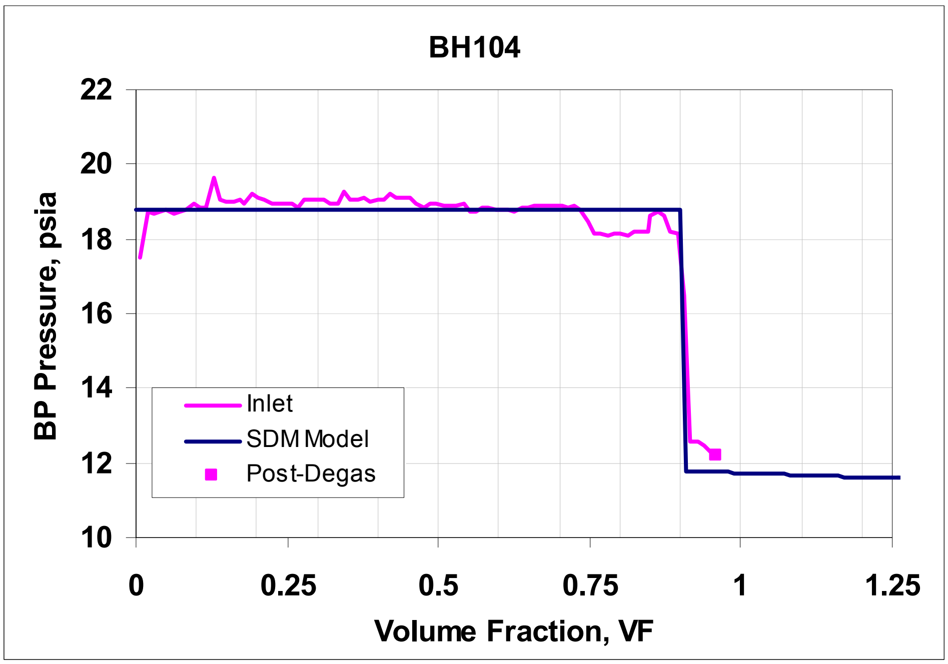


Figure 5-6. Comparison of BH104 Inlet BPP with SDM Complete Mixing Model where BP_i = 18.9 psia and BP_O = 11.1 psia.

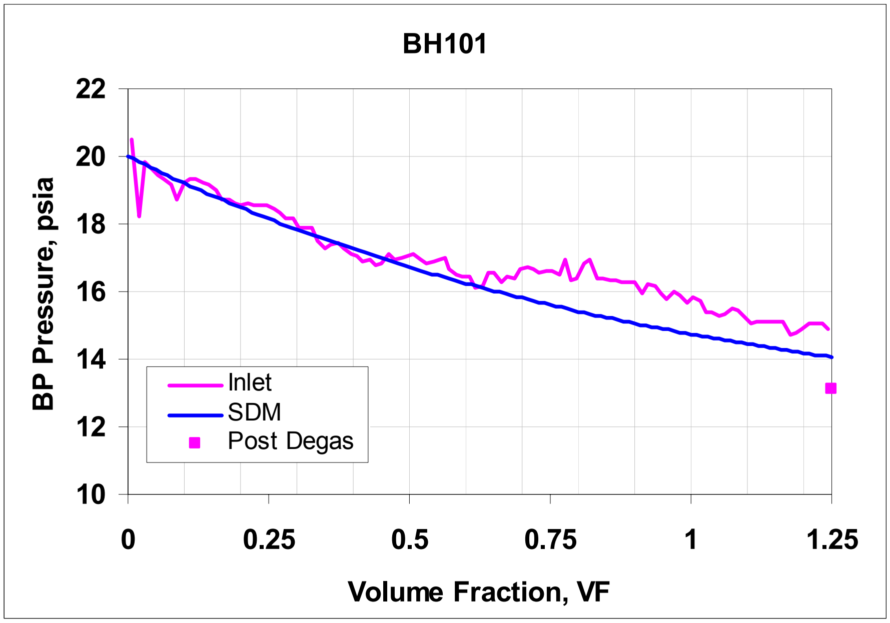


Figure 5-7. Comparison of BH101 Inlet BPP with SDM Complete Mixing Model where BP_I = 20 psia and BP_O = 11.7 psia.

Intermediate model vs. BH102. BH102 exhibited a 2.5 psi break in inlet BPP at VF = 0.47, and continued with a slightly downward-sloping performance curve from Figure 3-1). This cavern was therefore neither a plug flow nor strong mixer, but something in between. Note that BH102 had a stratified inventory according to a top-to-bottom analysis from August 2004 (see Table 4-3) upon completion of fill which was 16 months prior to the start of degas. In particular, there was a break in viscosity and density between 2817 and 3081 feet depth. This appeared to be a good candidate for the intermediate model. The SDM model was run so that plug flow controlled the plant inlet BPP until a mixing barrier was broken at VF = 0.47 and the cavern mixed completely at that point. After this, both plug and complete mixing models were run and plotted with the BH102 data, shown in Figure 5-8. Interestingly, the magnitude of the BPP drop at VF = 0.47 matches quite well between the model and real systems, suggesting that a cavern-scale mixing event may have occurred after a mixing barrier was broken. From the break forward, the real system had a slow downward trend that looked like mainly plug flow with a little mixing or a BP pressure gradient. A post-degas downhole measured sampled on 3/19/2007 returned BP_{cav} = 12. 9 psia. For comparison, the complete mixing model run to VF = 1.15 predicts a post-degas BP = 13.5 psia, while the plug flow model predicts a value around 12.5 psia. The ideal cases therefore bound the observed behavior.

Intermediate model vs. BH113. BH113 experienced a breakthrough around VF = 75%, making it a candidate for an intermediate SDM model comparison. The model run was set up with BP_I = 18.9 psia, outlet BP = 11.7 psia, and VF_B = 0.73. The data-model comparison is shown graphically in Figure 5-9. Similar to what was seen for BH102 discussed above, the magnitude of the BP pressure drop once breakthrough occurred was quite similar between model and measured. Both plug flow and completely mixed SDM models were run from the breakthrough forward and the actual measured performance curve fell between the two cases. The measured BP_{cav} = 12.0 psia, which is at the top end of the range of 11.7 to 11.9 psia predicted by the SDM model.

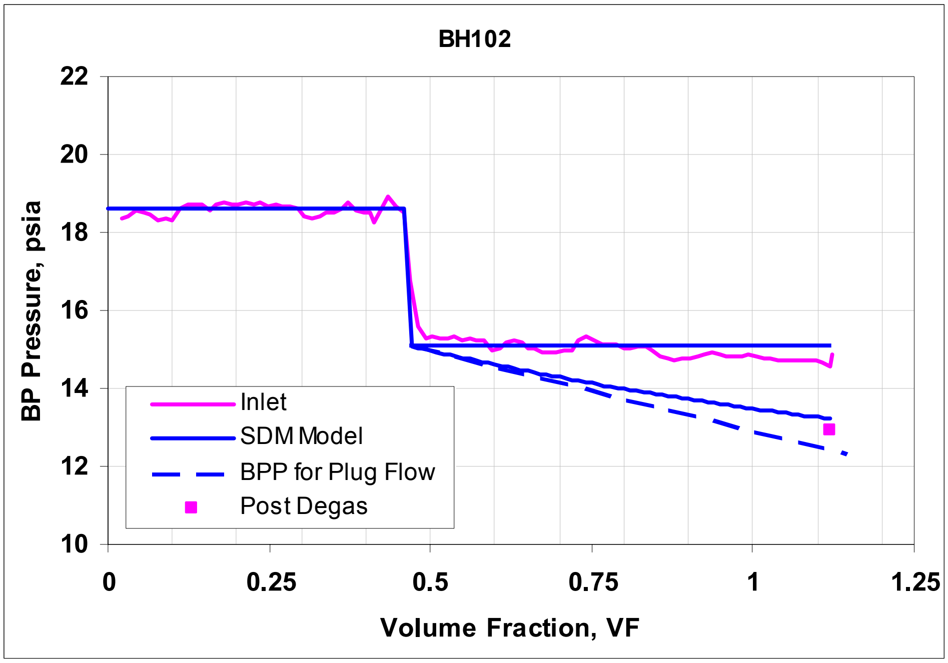


Figure 5-8. Comparison of SDM Model with BH102.
SDM Model was Operated as Plug Flow until VF = 0.47, When the Mixing Boundary was breached and the entire cavern mixed. From that point forward, completely mixed and plug flow simulations were modeled.

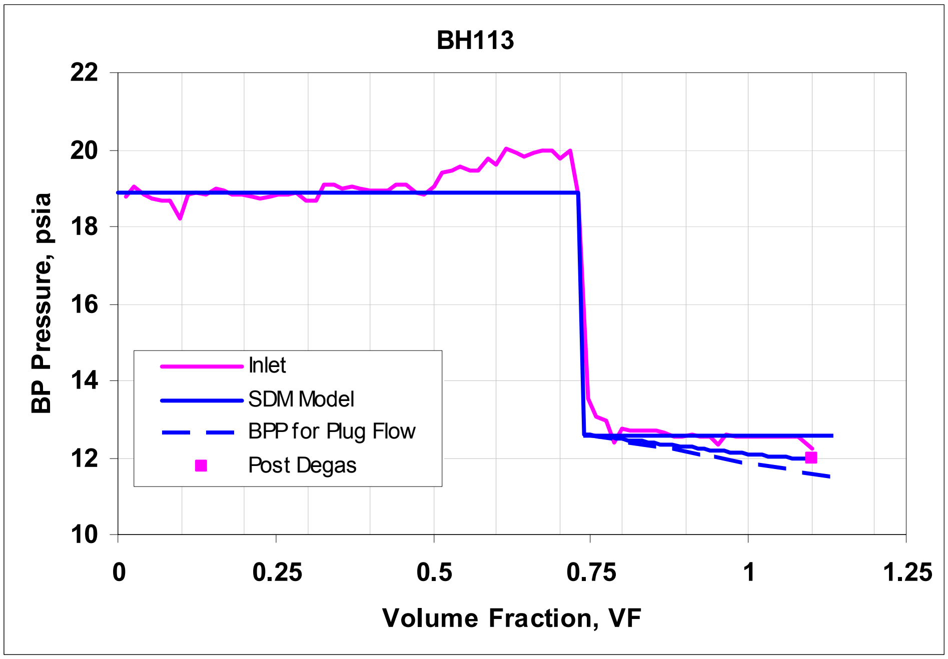


Figure 5-9. Comparison of SDM model with BH113.
SDM model was operated as plug flow until VF = 0.73, when the mixing boundary was breached and the entire cavern mixed. From that point forward, completely mixed and plug flow simulations were modeled.

Break point and intermediate model—all caverns. One feature of the intermediate mixing model that correlated notably well with observed data was the magnitude of the drop in bubble point pressure that occurred when the performance curve broke. This is illustrated in Figure 5-10 where the performance curves for all nine caverns degassed at BH are overlaid. In sequence, the caverns that exhibit a sharp break are BH110, BH112, BH102, BH113, BH104, and BH114. Note that the magnitude of the break, the lower "knee" of each curve, align near the dotted line on the figure. This dotted line corresponds to the cavern-average bubble point predicted by running a plug flow model (19 psia inlet, 11 psia outlet) until the break point, and then completely mixing the cavern so that the inlet bubble point represents the cavern average. The SDM model analog to this plot is shown in Figure 5-11. Arbitrary break points were selected at *VF* = 0.25, 0.5, and 0.75 for this figure. For figure clarity, only the ideal plug flow after the breakthrough is shown. Note the similarities in the shapes between real and model system performance curves, as well as the magnitudes of inlet BPP drops when they break.

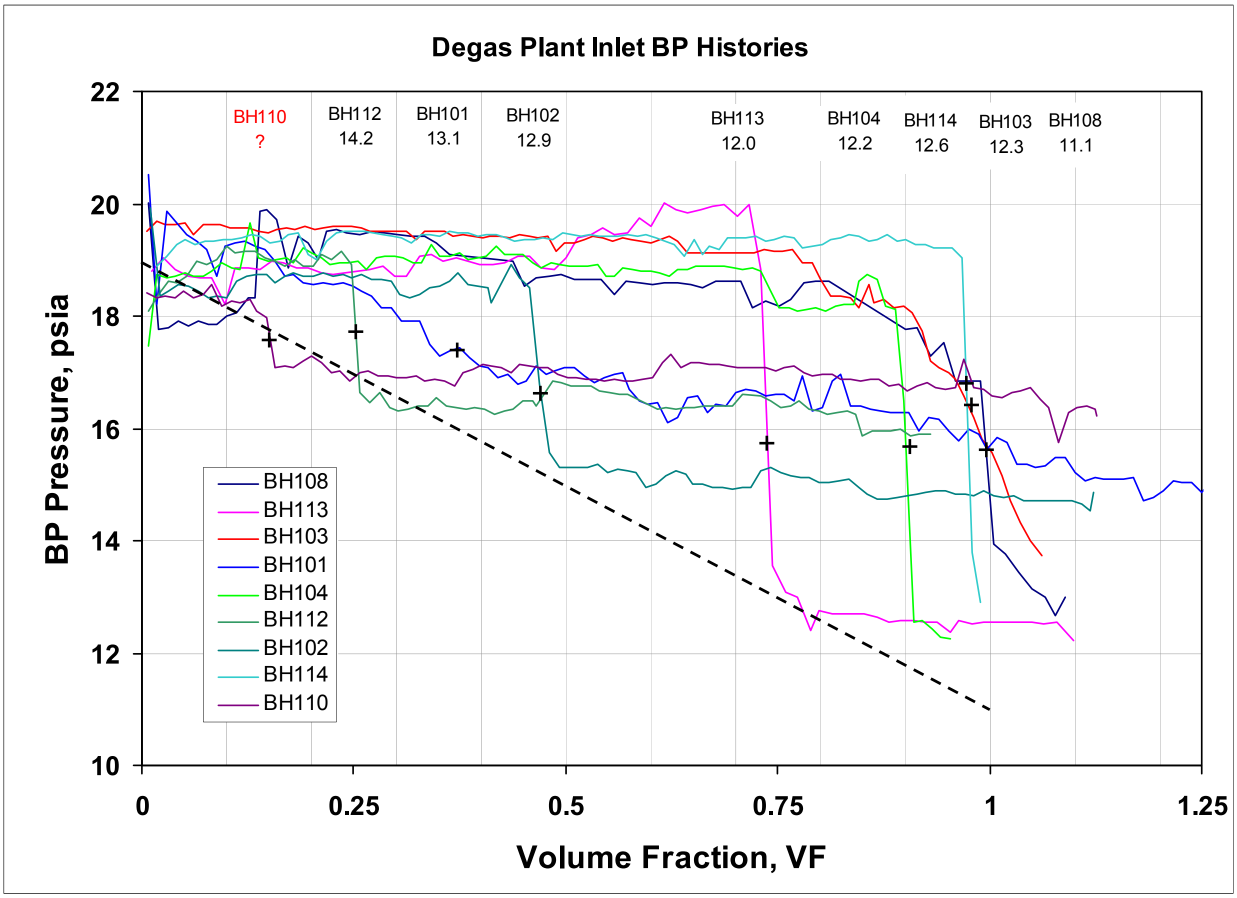


Figure 5-10. Measured Performance Curves for All Degas II Big Hill Caverns Overlaid with Plug Flow Model Cavern-Average Bubble Point Prediction (Dotted Line).

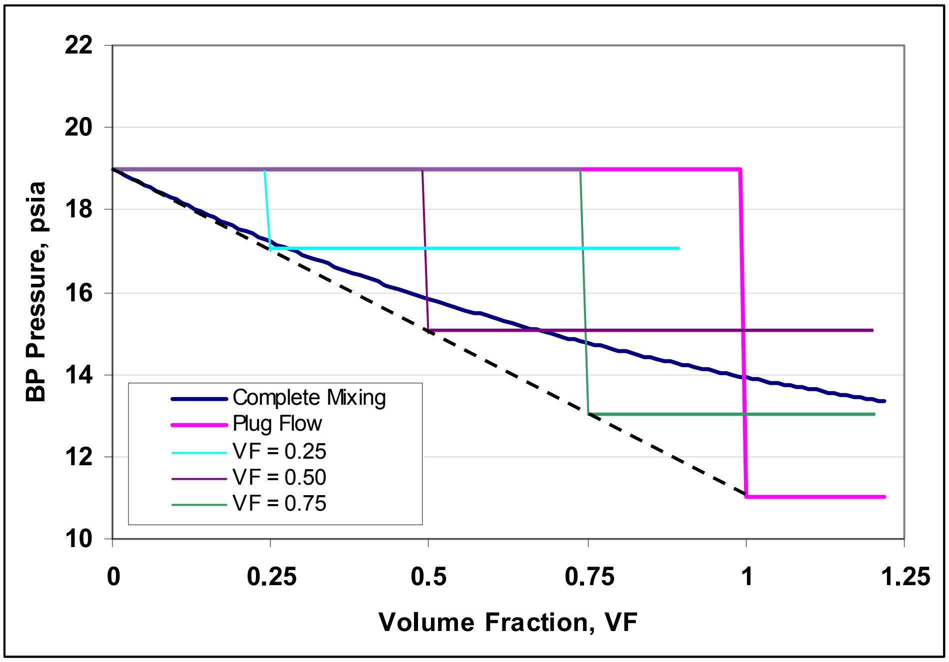


Figure 5-11. Idealized Performance Curves Overlaid with Plug Flow Model Cavern-Average BP Pressure Prediction (Dotted Line).

5.5 SDM Predictions for BH110 Post Degas In-Situ Bubble Point Pressure

BH110 has not yet been measured for BP_{cav}. Several methods are available to predict this value. The simplest is to add 1.4 psi to the average plant outlet value (10.3 psia) for a prediction of 11.7 psia, as was done in Table 3-2. Alternatively, the $V_B - \Pi$ relationship discussed in section 4.3.5 predicts a value of 13.3 psia. The SDM model can also be used to predict BP_{cav} based on matching the performance curve as shown in Figure 5-12. The SDM model was run as plug flow with plant inlet at 18.2 psia, outlet at 10.3 psia, and breakthrough at 15%. After breakthrough, SDM was run for ideal plug flow and ideal mixing until $VF_T = 1.13$. The range of possible BP_{cav} is then defined by space between the "Ideal Mixing" curve and the "In-situ BPP for plug flow" curve, as shown in the figure. For this cavern, the high end of the range is about 13.7 psia, while the low end of the range is about 10.5 psia at $VF_T = 1.13$. A measured performance curve that follows the plug flow line will tend to yield a BP_{cav} closer to the bottom of this range, while a performance curve that matches the ideal mixing curve will tend to yield a BP_{cav} closer to the top of this range. In the case of BH110, the measured performance curve follows plug flow for most of the processing time after the 15% early breakthrough, and deviates downward slightly after VF = 80%. The system therefore behaves much like plug flow for the majority of processing time after the 15% breakthrough, and would be expected to yield a BP_{cav} closer to the bottom of the range. An educated guess based on all prior information would put BP_{cav} in the range 11-12 psia. This is quite a bit lower than the 13.3 psia that the $V_B - \Pi$ relationship predicts. The authors plan to evaluate which model prediction was closer and why as the BH110 post-degas measurement becomes available.

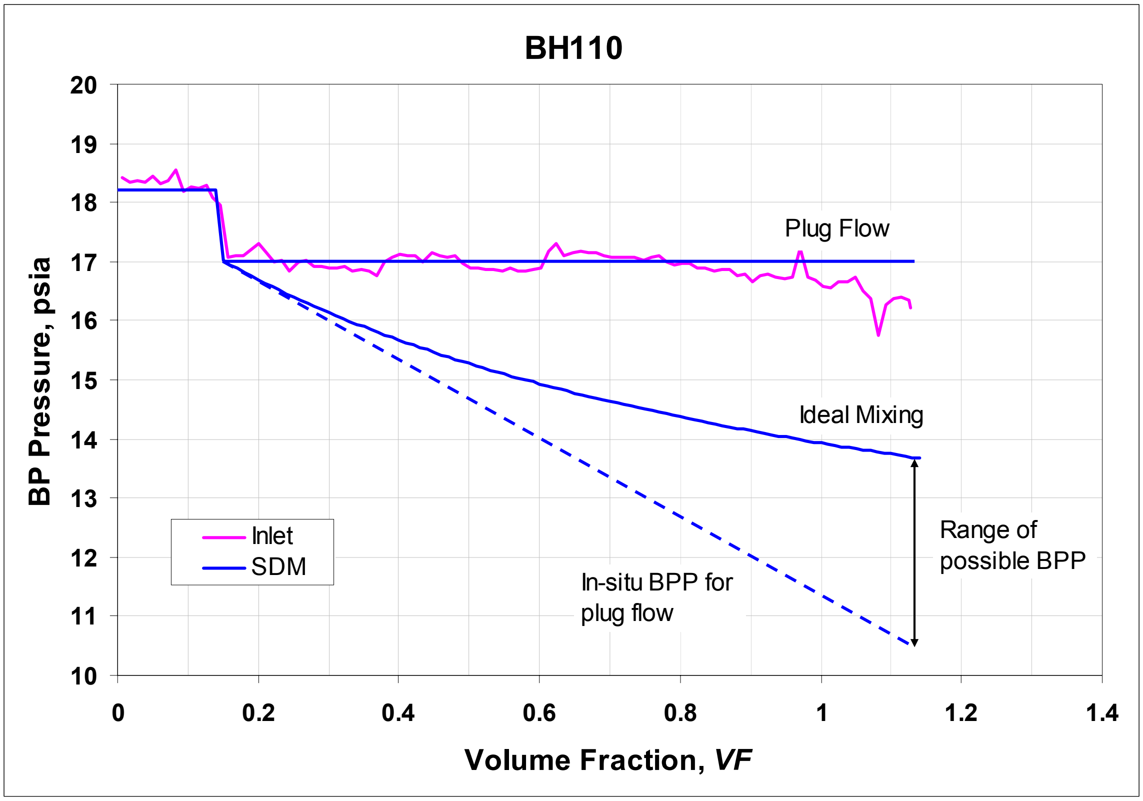


Figure 5-12. SDM Predictions of BH110 Post Degas In-Situ BP Pressure. BPP is likely to be in lower half of range (<12 psia) because inlet performance curve is closer to plug flow.

5.6 Summary Comments on SDM Ideal Plug Flow and Mixing Modeling

The ideal plug flow and mixing models discussed above and implemented in the SDM model appear to capture some of the features of the cavern mixing evident from Degas II. Perhaps the most useful feature of the ideal models is that they can set bounds for the expected performance of the real degas systems, with plug flow rendering the highest efficiency, and complete mixing rendering the lowest efficiency[4]. Also interesting is the finding that the magnitude of drop in inlet bubble point pressure that occurs when the performance curve breaks in the real systems corresponds reasonably well with simple mixing theory. The SDM model may be useful in this sense for putting bounds on (i) the expected magnitude of BPP drop according to the value of *VF* when the break occurs, and (ii) the bounds on expected in-situ BPP as a function of processing from the break point forward. As post-degas in-situ BP values are collected for cavern BH110, the predictive capability of the model from the break point forward can be tested further. The SDM model cannot predict when a break will occur, or how a system will respond to changes in operational parameters like string configuration or pumping rates.

[4] This assumes that there are no major flow short-circuiting mechanisms like would occur if the plant intake string had a hole near the top that drew in processed oil just injected into the top of the cavern.

6 Report Summary

This report examines the effectiveness of the Degas II program against vapor pressure program goals based on observations from the degassing of nine caverns at Big Hill during the period April 2004 to September, 2006. During Degas II at Big Hill, approximately 108 MMB of oil were processed, reducing stream average bubble points from 16.7 to 12.9 psia for sweet oil, and 15.6 to 13.8 psia for sour oil. Uncertainties in actual vapor pressure regain rates and future events require that the vapor pressure be monitored and program needs reviewed on a periodic basis in order to assure that the Big Hill streams remain within deliverable limits.

Primary observations from this study include:

- Post-degas in-situ bubble point is systematically higher than plant outlet stream bubble point in both Degas I and Degas II A first-order approach to determine in-situ BPP is to add 1.4 psi to the plant outlet value.
- Plant performance curves (inlet bubble point versus volume processed) vary considerably across caverns as characterized by breakthrough volume fractions and plant inlet bubble points after breakthrough.
- The wide variations in plant performance curves suggest that a similarly wide variety of oil mixing regimes exist within the caverns during degasification.
- Degas plug flow similarity (Π) defined earlier in this report appears to correlate well with the timing of the first breakthrough in the plant performance curve. This allows for an empirical estimate of the in-situ bubble point pressure after degas that is more representative of the cavern average than the plant outlet stream.

6.1 Implications for Future Degas

The information gained from experience during Degas II and collected in this report lead the authors to make several suggestions for a path forward in degassing SPR oils:

- Assure that long-term goals for stream BPP and GOR are met by including oil mixing effects in the Bryan Mound degassing plan (caverns, target BPP, total degas volume)

- During degassing operations at BM, conduct weekly reviews of performance data using analysis tools developed in this report to evaluate likely extent of mixing and outcome from degassing, particularly after $VF = 0.5$ or arrival of breakthrough in the plant inlet performance curve.

- Monitor West Hackberry and Bayou Choctaw vapor pressures and regain rates closely to determine best strategy for moving plant once Bryan Mound degassing is complete.

- Continue investigating the causes of cavern-scale oil mixing to see if we can correlate any existing data with mixing/non-mixing caverns.

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Appendix A Methodology for Determining BPP and GOR from Crude Oil TVP Analysis

Crude oil bubble point pressure and gas-oil ratio are determined by several means on the SPR project. This section explains how various values were obtained for use in this report.

A.1. Degas Plant Values

The degasification plant is instrumented with an in-line Grabner True Vapor Pressure Analyzer that obtains pressure-expansion data that are, in turn, used to calculate plant inlet and outlet stream bubble point pressures. The operating principle of the Grabner TVP analyzer is to collect a liquid oil sample at a confining pressure higher than its bubble point pressure and perform three very precise, sequential, fixed mass, isothermal volumetric expansions to create a two-phase system that is measured for equilibrium pressure at each expansion point. From the three expansion points, a curve is built and a bubble point is calculated where the curve intersects the zero expansion axis as illustrated below in Figure A-1.

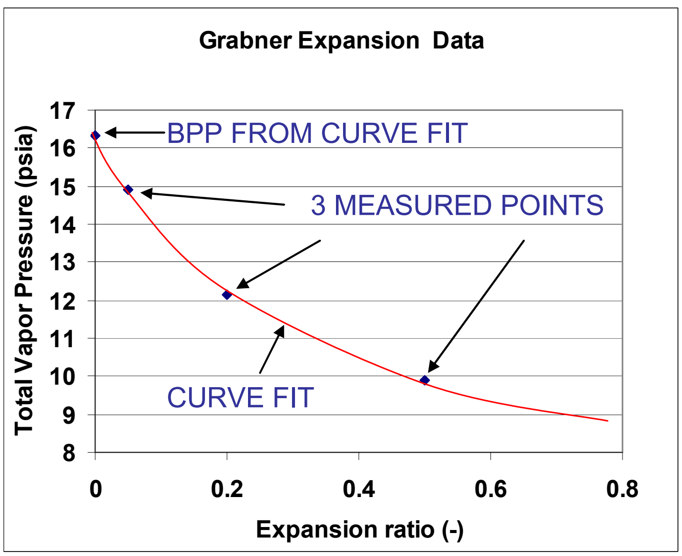

Figure A-1. Illustration of Curve Fit to Obtain Bubble Point Pressure from Grabner Expansion Data.
Expansion ratio is defined as volume of gas to volume of liquid (Vg/Vl) in a two-phase system. The bubble point pressure occurs at the first formation of bubbles during expansion, effectively where expansion ratio = 0.

The bubble point pressures are measured on the degas plant inlet stream and outlet stream continuously during cavern oil processing (see Figure 2-1), with a cycle time of about 45 to 60 minutes for a three-point expansion. The plant performance curves shown in section 3.2 for example, represent sequential daily average values from each the plant inlet an outlet. A single performance curve is therefore a series of daily averages reported against volume fraction of cavern oil processed.

Average plant inlet bubble point pressure, $\overline{BP}_{in}$, reported in Table 4-1b and section 4.3, is the mean daily plant inlet bubble point from the start of degassing a cavern up until breakthrough is detected. Average plant outlet bubble point pressure, $\overline{BP}_{out}$, is the mean daily plant outlet bubble point throughout the entire degassing of a single cavern.

A.2. Pre and Post Degas Values for BPP and GOR

Values reported in Table 3-1b labeled pre- and post-degas were derived from individual cavern sampling with the TVP-95 instrument. It must be recognized that the liter-scale sample collected and analyzed for the purpose of characterizing bubble point pressure for an entire 10-12 MMB cavern is going to represent an estimate with an uncertainty of perhaps ± 1.5 psi due largely to oil heterogeneity within the cavern. Currently, there is no provision within the vapor pressure monitoring program to obtain multi-depth samples, so the single-depth samples are the only source of vapor pressure data.

The Post-degas BPP values were obtained by direct measurement of downhole samples, and since there was only one sampling event per cavern as of the time of this report, the value cited corresponds to this single sampling event.

The Pre-degas BPP and GOR for each cavern was the last successfully TVP95 measured value prior to and reported in the May 15, 2004 Quarterly VP Report (Spreadsheet) produced by DynMcDermott Petroleum Operations and maintained in SPR Project records on the file management system Konfig CM PDM.

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