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SAND2010-3016
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U.S. Strategic Petroleum Reserve Vapor Pressure Committee 2009 Annual Report

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Abstract

This report comprises an annual summary of activities under the U.S. Strategic Petroleum Reserve (SPR) Vapor Pressure Committee in FY2009. The committee provides guidance to senior project management on the issues of crude oil vapor pressure monitoring and mitigation. The principal objectives of the vapor pressure program are, in the event of an SPR drawdown, to minimize the impact on the environment and assure worker safety and public health from crude oil vapor emissions. The annual report reviews key program areas including monitoring program status, mitigation program status, new developments in measurements and modeling, and path forward including specific recommendations on cavern sampling for the next year. The contents of this report were first presented to SPR senior management in December 2009, in a deliverable from the vapor pressure committee. The current SAND report is an adaptation for the Sandia technical audience.

Acknowledgements

This work was supported by the Strategic Petroleum Reserve Project Office under the U.S. Department of Energy..

Table of Contents

1 Executive Summary 9
2 Introduction 11
2.1 Background 11
2.2 Vapor Pressure Program Objectives 11
2.3 Vapor Pressure Committee Roles and Responsibilities 12
2.4 Scope of Annual Report 12
3 Monitoring Program Status 13
3.1 Data Review Meeting in June 2009 13
3.2 FY09 Cavern Sampling 13
3.3 TVP Analysis of Receipt Oil 14
3.3.1 Distribution Functions 14
3.3.2 Seasonal Effects on Receipt Oil BPP 15
4 Mitigation Program Status 17
4.1 Degas Program 17
4.1.1 Bryan Mound Degas Program 17
4.1.2 Planning for Degas Move to West Hackberry 17
4.2 Heat Exchangers 17
4.3 H_2S Scavenger 18
4.3.1 New Approved Chemicals 19
4.3.2 New Exchange Criteria 19
5 Method Development 20
5.1 Measurements 20
5.1.1 Grabner TVP Expansions at Nonstandard Temperature 20
5.2 Modeling 22
5.2.1 New 2009 VP-EOS Solver 22
5.3 Current EOS Model Performance Against Measured Data 22
5.3.1 Bubblepoint Pressure 23
5.3.2 Gas-Oil Ratio 23
5.3.3 Expansion Curves 24
5.3.4 Closing Comments on Current EOS Model Performance 25
5.4 Program Collaboration with Industry and Peer Groups 25
6 Other Work During FY08 26
6.1 Degas Mixing Studies 26
6.1.1 Historical Review of Degas Operations 26
6.1.2 Observations from Degas II Operations Data 27
6.1.3 CFD Simulations of Mixing 28
6.1.4 Summary Comments on Degas Mixing 31
7 Path Forward 32
7.1 Summary of Site/Stream Deliverability 32
7.1.1 Current Performance Criteria 32
7.1.2 Seasonal Vapor Pressure Impacts 32
7.2 Sampling Recommendations for FY11 35
7.3 Regain Monitoring 35
7.4 EOS Model Calibration Sampling 35
7.5 BC102, BC103 and BC104 Impacts 36

7.6 Impacts of Remedial Leach on Vapor Pressure 36
8 Cited References 37
Glossary 39
Appendix A1 43
Appendix A2 44

Figures

Figure 3-1. Comparison of Distribution Functions of BP Pressures upon Receipt, Prior to Degas and Current 15
Figure 3-2. BPP (at T = 100°F) of Oil Receipts by Month. 16
Figure 5-1. Comparison of Grabner Measured and EOS Model for BM004 Degas Plant Inlet Oil Pressure-Expansion Relationship at Three Selected Temperatures with Default BICs = 0 (no tuning). 21
Figure 5-2. Comparison of Grabner Measured and EOS Model for BM108 Degas Plant Inlet Oil Pressure-Expansion Relationship at Three Selected Temperatures with Default BICs = 0 (no tuning). 21
Figure 5-3. Grabner Measured BPP versus TVP-95 Measure BPP. 23
Figure 5-4. EOS Calculated GOR from BP Test Data Normalized to Measured GOR as a Function of Time 24
Figure 5-5. Grabner Measured and EOS Calculated Expansion Curves Before and After April 2006 QC Implementation at BH114. 25
Figure 6-1. Graphic Showing Patterns Observed for Degas Caverns and Mixing Behavior. 27
Figure 6-2. Comparison of Representative Degas Plant Performance (Left Side) with Crude Oil Temperature Change Across Plant (Right). 28
Figure 6-3. Schematic of Simple CFD Model Domain Representing Idealized SPR Degas Cavern (Reproduced from Webb, 2009). 29
Figure 6-4. CFD Model Normalized Inlet BP vs. Cavern Volumes Achieved by Re-Injecting Lighter Oil at Top of Cavern (Reproduced from Webb, 2009). 29
Figure 6-5. CFD Model Normalized Inlet BP vs. Cavern Volumes Achieved by Re-Injecting Heavier Oil at Top of Cavern (Reproduced from Webb, 2009). 30
Figure 6-6. CFD Model Normalized Inlet BP vs. Cavern Volumes Achieved by Re-Injecting Heavier Oil at Bottom of Cavern (Reproduced from Webb, 2009). 31
Figure 7-1. Seasonal Vapor Pressure Projections as Reported by the Vapor Pressure Committee in November 2009 34

Tables

Table 3-1. Summary of FY09 Cavern Sampling for Vapor Pressure. 13
Table 7-1. Regain Sampling Summary. 35
Table 7-2. Regain Sampling Estimated Costs 35
Table 7-3. Parallel Flowing and C30+ Sampling Summary. 36
Table 7-4. Parallel Flowing and C30+ Estimated Costs. 36

Acronyms and Abbreviations

BBL	Barrel (42 US gallons)
BC	Bayou Choctaw SPR Site
BH	Big Hill SPR site
BIC	Binary interaction coefficients (EOS parameters)
BM	Bryan Mound SPR site
BOA	Basic ordering agreement
BPP	Bubble point pressure (at 100°F), also BP pressure
DM	DynMcDermott Petroleum Operations Company
DOE	U.S. Department of Energy
EOS	Equation of state
GOR	Gas oil ratio, scf/bbl
GOV	Gross Observed Volume
GSV	Gross Standard Volume
MB	Thousand barrels (volume)
MBD	Thousand barrels per day (volume rate)
MMB	Million barrels (volume)
RYG	Red yellow green
scf	Standard cubic feet (gas volume)
SNL	Sandia National Laboratories
So	Sour crude oil by SPR criteria (total sulfur less than 2.0 mass%)
SPR	Strategic Petroleum Reserve
Sw	Sweet crude oil by SPR criteria (total sulfur less than 0.5 mass%)
WH	West Hackberry SPR site

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1 Executive Summary

This report comprises an annual summary of activities under the U.S. Strategic Petroleum Reserve Vapor Pressure Committee in FY2009. Sitting members on the committee include a chair from DOE systems and projects, a member from DOE maintenance and operations, a member from DynMcDermott (M&O contractor), and a member from Sandia National Laboratories. The committee meets on an as-needed basis to address real-time issues, and at least once a quarter for regular business.

Crude oil vapor pressure is an important issue at SPR because transport from underground to surface storage facilities has the potential to expose the oil to containment pressure lower than its bubble point, which will cause phase separation and evolution of a mixture of gases, including components regulated by federal and state agencies. A combination of gas regain and geothermal heating cause the bubble points of SPR crudes to increase with time in storage, and the vapor pressure committee was developed in order to advise management on recommended means to monitor and mitigate the vapor pressure issues.

Vapor pressure monitoring across the storage complex reveals a reasonably stable environment, with most caverns exhibiting no measurable regain. There are several exceptions distributed across the four sites, and these are being monitored closely. Among the regain caverns, there are some showing steady increases in bubblepoint over a decade of regular sampling (BM111-BM114), while others show recent step increases of several psi (WH6, WH7). The reasons for the step increases have not been determined. There is some uncertainty at Big Hill due to a dynamic inventory and degasification during the test period, but monitoring is continuing with no visible problems to date.

Vapor pressure mitigation activities continue at Bryan Mound as six caverns have been degassed, a seventh is in process, and four remain on the schedule, due to complete in 2011. The degas plant will then be moved to West Hackberry to start processing oil there in 2012. The Degas II program has led to measurable improvements in stream deliverability for both Big Hill and Bryan Mound sites, with no anticipated requirements for selective blending or H_2S scavenger to achieve maximum drawdown rates in the next 3 years. Degasification will be required at West Hackberry and Bayou Choctaw in order to bring those streams to an OK status for maximum rate drawdown with no H_2S scavenger for all months.

Cavern-scale mixing during degas has been observed for all six Bryan Mound caverns degassed through December, 2009, and poses negative effects on cost, schedule, and effectiveness of degasification relative to a baseline characterized by plug flow. Sandia conducted a detailed investigation of cavern-scale oil mixing during degasification in FY2009 that has led to a better understanding of the likely causes. The primary hypothesis is that cavern oil cools as it is exposed to surface conditions during degasification and becomes more dense. When this cooler, denser oil is re-injected at the top of the cavern at current processing rates, the jet penetrates to the bottom of the cavern and leads to rapid mixing of the entire cavern contents. Neutral or less dense oil will not penetrate to the same extent, and therefore will mix the cavern to a much lesser extent, if at all. This knowledge could be used to design a mitigation strategy such as reversing

the injection and withdrawal points in the cavern so the cooler oil is injected at the bottom rather than at the top.

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2 Introduction

This report provides an FY09 summary on the status of the U.S. Strategic Petroleum Reserve vapor pressure program. A similar version of this report was presented to SPR senior management at the Project Management office in New Orleans in written form in December 2009, as required in the vapor pressure committee management plan (US DOE, 2007). The SAND version written here is an adaptation for a more general audience and is intended to preserve key historical information on the vapor pressure project within Sandia permanent records. For readers new to the SPR project an extensive glossary is provided. Glossary entries are *italicized* the first time they are referenced.

2.1 Background

The SPR, managed by the U.S. Department of Energy (DOE), currently stores about 700 million barrels of crude oil in 62 sub-surface, solution-mined salt-caverns along the U.S. Gulf Coast. While these salt domes exhibit many attractive characteristics for large-volume, long-term storage of oil such as low cost for construction, low permeability for effective fluids containment, and secure location deep underground, they also present unique technical challenges for maintaining oil quality within delivery standards. One of these standards is maintaining an oil *bubble point pressure (BPP)* of 14.7 psia or less at delivery conditions. Failure to meet this criterion may lead to excessive atmospheric emissions of gases from the oil that pose explosion hazards (i.e., light hydrocarbons), health hazards (i.e., hydrogen sulfide, benzene), or handling problems (i.e., foaming) in floating roof storage tanks at atmospheric pressure. Both geothermal heating and intrusion of gases such as methane, carbon dioxide, and nitrogen from the host geology contribute to a problematic rise in bubble point pressure. Recognizing these potential occupational health and safety issues and environmental risks, the DOE implemented a crude oil vapor pressure monitoring program in 1993 that collects vapor pressure data for all the storage caverns. *Pencor* Laboratory is currently contracted to collect cavern oil samples, perform vapor pressure tests and provide test reports to the project, the new vapor pressure data is entered into the *vapor pressure database* consisting of Excel spreadsheets and *EOS* utilities. From these data, DOE evaluates the rate-of-change in vapor pressures (*regain rates*) of its oils in the SPR and provides the project with quarterly vapor pressure snapshots. Moreover, DOE implemented a vapor pressure mitigation program in which the oils are degassed periodically and will be cooled immediately prior to delivery in order to reduce the vapor pressure to safe handling levels.

2.2 Vapor Pressure Program Objectives

The principal objectives of the vapor pressure program are, in the event of an SPR drawdown, to minimize the impact on the environment and assure worker safety and public health from crude oil vapor emissions. Vapor pressure is managed effectively at SPR by implementing both a monitoring program and a mitigation program. The monitoring program establishes the current condition of vapor pressure at SPR using periodic cavern sampling. These monitoring data provide input to forecasting models that are compared against project performance criteria, and are used by the vapor pressure committee and project management to guide mitigation strategy. Vapor pressure mitigation at SPR comprises three main elements: (1) heat exchangers to reduce

oil temperature at the time of drawdown, (2) *degasification plant* to remove volatile gases from selected caverns during standby, and (3) *H_2S scavenging* at the time of drawdown if conditions require.

2.3 Vapor Pressure Committee Roles and Responsibilities

The SPR Vapor Pressure Committee was formed in 2007 with the primary purpose to identify the methodologies, procedures, participants, resources, and schedules that ensure compliance with the environmental and safety requirements related to vapor pressure while meeting the SPR drawdown mission (US DOE, 2007). Sitting members on the committee include a chair from DOE Systems and Projects, a member from DOE Maintenance and Operations, a member from *DynMcDermott*, and a member from Sandia National Laboratories. The committee meets on an as-needed basis to address real-time issues, and at least once a quarter for regular business. Given the technical needs within the program, periodic working group sessions are organized in order to satisfy priorities and action items raised by the committee. Working group members comprise subject-matter experts from the technical community who are invited to participate by committee members.

2.4 Scope of Annual Report

The annual report summarizes the important developments in the vapor pressure program. The report covers sampling strategy and results, model development and results, and mitigation activities such as degasification. Forecasts of oil deliverability against program criteria are also given, along with sampling recommendations for the coming year. Supporting information and data are given in the list of cited references at the end of the report.

3 Monitoring Program Status

The SPR vapor pressure monitoring program uses a combination of direct measurements and process simulation models to establish the current and future vapor pressure conditions at SPR. These are compared against program criteria for oil deliverability and process safety. The following section provides an overview of recent activity within the monitoring program.

3.1 Data Review Meeting in June 2009

The annual vapor pressure data review session brought 12 technical experts and one DOE observer together at Pencor headquarters in Broussard, LA, to study data collected between May 2008 and June 2009 for relevance and technical validity toward calculating vapor pressure regain rates. Sandia coordinated the review process, provided all handouts, kept meeting notes, and summarized the meeting outcome in a 16-page letter report to the vapor pressure committee chairman transmitted on July 17, 2009 (Lord and Rudeen, 2009a). The data review focused on new measurements and those flagged as having indeterminate regain or special issues to consider. Among the 24 new measurements, 23 were accepted as adequate representation of current cavern bubble point pressure, with 16 of those utilized for calculating current cavern regain, 5 not used because they were the first measurement after degas and require a second point to calculate slope, and 2 were *stream* values.

3.2 FY09 Cavern Sampling

Cavern sampling for *bubblepoint pressure (BPP)*, *gas-oil ratio (GOR*), and flash gas compositions in FY09 are summarized in Table 3-1. All reported samples were collected and analyzed with the *TVP-95* instrument operated by *Pencor Laboratorie*s. Note that flash gas compositions were also collected (but not shown here) for each of the samples in Table 3-1. The compositions are used in building the oil compositional models.

Table 3-1. Summary of FY09 Cavern Sampling for Vapor Pressure.

Date	Cavern	Depth (ft)	*Tool(T) or Flowing(F)*	BPP (psia)	Measured GOR (scf/bbl)
10/8/2008	BC20	0	F	19.9	2.77
11/7/2008	BM105	3067	T	12.5	-
12/12/2008	WH8	2927	T	16.1	0.30
1/29/2009	WH117	3557	T	18.1	1.68
2/3/2009	BH112	3227	T	12.9	-
2/5/2009	BH113	3189	T	12.6	-
2/11/2009	WH103	3387	T	15.2	0.16
2/12/2009	WH111	0	F	20.7	1.86
4/20/2009	BM115	3060	T	15.4	0.32
5/4/2009	BC101	3618	T	18.1	0.67
5/19/2009	BC15	2928	T	16.4	0.37
5/21/2009	BC17	3273	T	15.5	0.20
5/27/2009	BC19	3568	T	17.6	0.63
6/9/2009	BH105	3167	T	14.6	-
6/11/2009	BH107	3148	T	15.5	0.22

Date	Cavern	Depth (ft)	*Tool(T) or Flowing(F)*	BPP (psia)	Measured GOR (scf/bbl)
7/29/2009	WH112	0	F	25.2	3.50
7/28/2009	WH114	0	F	17.1	0.99
7/27/2009	WH115	0	F	17.3	1.23
8/4/2009	BH103	3041	T	12.3	-
8/6/2009	BH104	3224	T	12.1	-
8/19/2009	BM110	3026	T	13.1	-
9/3/2009	BH109	3215	T	15.3	0.14
9/1/2009	BH106	3146	T	14.3	-
9/18/2009	BM104	3112	T	12.3	-

Source example: WH114-04-07-20-F-30040-5004078435.xls

BPP and GOR measurements generally fall in line for all caverns except WH112 and BH112. WH112 showed a BPP = 25.2 psia which was attributed to N_2 contamination. The BH112 sampling was the second after degassing and showed a drop in BPP from 14.1 to 12.9 psia which is likely due to continued mixing of degassed oil. The BPP measurements for BM105, BM115 and BM104 were the first post degas samples for those caverns and are consistent with predicted ideal mixing values.

3.3 TVP Analysis of Receipt Oil

One of the accepted facts recognized by the SPR project is that BP pressure (at 100°F) increases over time for some SPR caverns. This increase is attributed to the influx of light hydrocarbons (primarily methane, some ethane, propane, etc.) from the surrounding salt. This theory is supported by the observation that significant amounts methane were generated and released or incinerated during leaching of the caverns at BH and BM, demonstrating that light hydrocarbon gases are common in the salt dome environment and will be absorbed into cavern fluids and subsequently released when the fluids are depressurized.

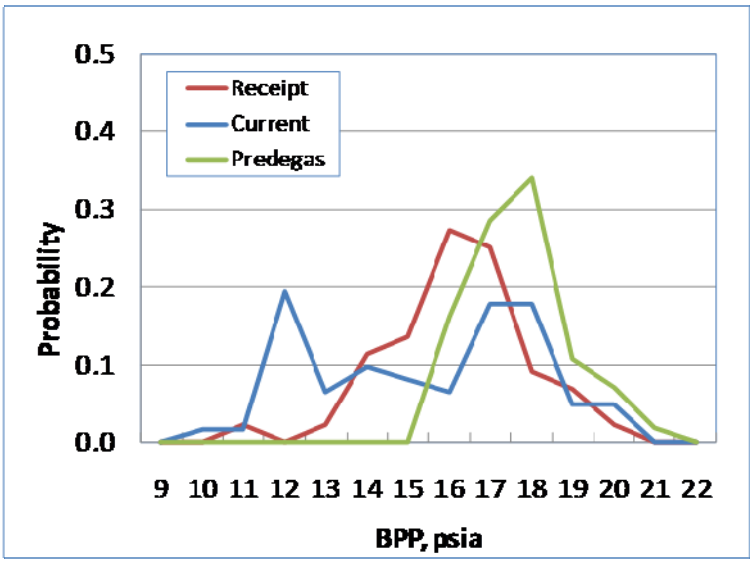
To the extent that data are available, it would be useful to examine the vapor pressure of SPR oils before they are placed in the cavern so that this baseline may be compared to oils in storage at a later date. SPR does not have a systematic vapor pressure monitoring program for incoming oil. It does have some data on incoming oil, though the related volumes and destination caverns are not readily available.

3.3.1 Distribution Functions

Figure 3-1 provides a comparison of three distribution functions:

- BPP of oil receipts (sampled between July 1999 and September 2008)
- BPP of cavern oils just prior to degassing (possibly includes regain)
- BPP of current cavern oils (includes degas effects)

Care must be exercised in interpreting results in Figure 3-1, since the distribution functions represent frequency of occurrence and do not account for oil volume.



Data Source: Lanier, C. *Bubble Point Status Report 09-09-23.xls*

Figure 3-1. Comparison of Distribution Functions of BP Pressures upon Receipt, Prior to Degas and Current.

Starting with the receipt oil (red curve in Figure 3-1), notice that BPP ranged from 11 to 20 psia, with a peak frequency at 16 psia. For comparison, oil sampled from caverns prior to degas (pre-degas green curve) ranged from 16-21 psia, with a peak at 18 psia. These data indicate an upward shift in BPP from receipt to cavern, with gas regain a possible cause. Another plausible explanation is that there were large deliveries of high BPP oil and small deliveries of low BPP oil (<15), or that a lot of high BPP oil was already at SPR before the time frame when receipts were monitored. At the current time, it is impossible to distinguish which explanation, if any, is most accurate because the volume and destination of receipt oil is not coupled with the BPP values. If one assumes that receipt volumes are roughly the same and that receipt oil has had the same properties throughout SPR history, then the shift in the "Predegas" curve to higher BPP could represent regain. A more meaningful analysis can be performed if volumes can be associated with each receipt, and cavern volumes are factored in to the "Current" and "Predegas" distributions. The analysis will be repeated once receipt volumes are obtained.

Since both "Predegas" and "Current" distribution functions are for the same set of caverns, direct comparisons are justified since caverns are generally of similar volume. Comparison shows the dramatic effect of degassing. Caverns with 17-19 psia oil (peak in green curve) have been shifted to 11 – 13 psia oil (first peak in blue curve).

3.3.2 Seasonal Effects on Receipt Oil BPP

A second part of the incoming oil analysis looked for trends in BPP with the time of year of the receipt. These data help to test the hypothesis that receipts in hot summer months will yield lower BPP oil because they off-gas their light ends more readily in handling and transit than oil received in the cooler months. Figure 3-3 shows a plot of BPP as a function of month of receipt, with no obvious trends evident. Month of receipt therefore does not appear to influence the BPP of oil (at T = 100°F).

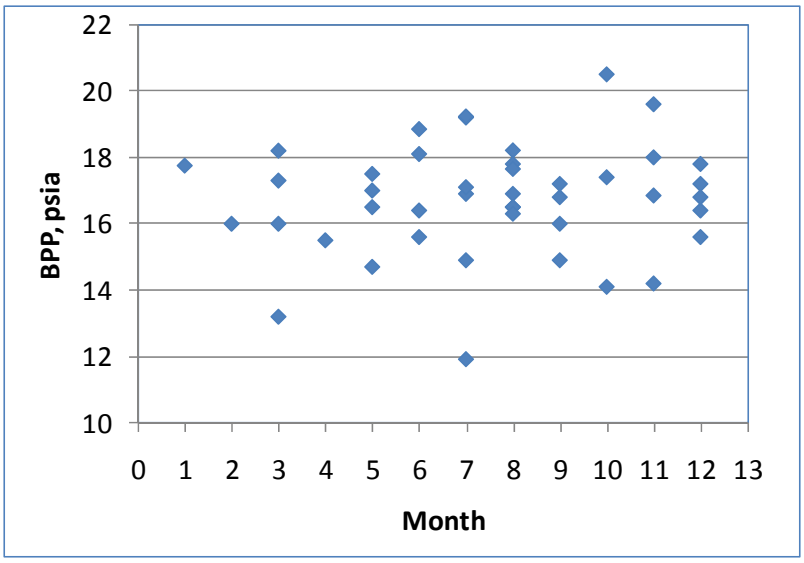


Figure 3-2. BPP (at T = 100°F) of Oil Receipts by Month.

4 Mitigation Program Status

Vapor pressure mitigation at SPR comprises three main elements: (1) degasification plant to remove volatile gases from selected caverns during standby, (2) heat exchangers to reduce oil temperature at the time of drawdown, and (3) H_2S scavenging at the time of drawdown if conditions require. Recent activities in each area are discussed below.

4.1 Degas Program

The Degas II Performance Plan was revised twice during FY2009 in versions A5 (DeLuca, 2009a) published March 17, 2009 and A6 (DeLuca, 2009b) published July 20, 2009. The A5 revision to the Degas Plan incorporated current Bryan Mound (BM) and West Hackberry (WH) vapor pressure data GOR projections as well as BM and WH fill projections. These fill projections now consider the use of cavern BM-112 for storage under the SPR 727 million barrel configuration as well as increases to other individual BM and WH cavern volumes previously incorporated under Plan Version A4. The A5 plan also includes WH cavern 6 due to increased bubble point pressure measurements recorded during recent cavern sampling. The A5 plan increases the total degassed volume for BM to 149.08 million barrels (GSV) and WH to 191.91 million barrels (GSV). The additional volumes to be degassed also extended the estimated Degas Completion dates for both Bryan Mound and West Hackberry to May 2, 2011 and December 9, 2016, respectively.

Plan revision A6 incorporated a change in the sequence of caverns to be degassed, moving cavern BM-108 (*sour)* before BM-114 (*sweet)* to accommodate fill. This revision also reflects the actual degas rate performance and revised the estimated Bryan Mound Degas Completion date to April 17, 2011 versus the previous estimate of May 2, 2011.

4.1.1 Bryan Mound Degas Program

The Degas plant through FY 2009 has successfully processed 87.04 million barrels from caverns BM105, BM115, BM102, BM104, BM4, BM116, and BM108 (in process). Appendix A1 contains the current processing quantities and key processing parameters for these caverns and the degassing plan for BM caverns scheduled to be processed. Bryan Mound Cavern 4 and 116 completion reports were published on May 28 and September 10, respectively.

4.1.2 Planning for Degas Move to West Hackberry

Planning is underway by the relocation team including representatives from DOE, DM, AGSC, S&B and Allen Energy Services for the degas move from the BM site to WH. The revised Degas II Performance Plan (Revision A6) maintains the target date for start of Degas at WH of January 28, 2012. Appendix A2 contains the current degassing plan for WH caverns to be degassed.

4.2 Heat Exchangers

Shell and tube type heat exchangers were installed at all four sites to help mitigate the impact of geothermal heating on the crude oil stored over long periods of time. The heat exchangers are utilized at drawdown and use raw water to cool the crude oil being withdrawn from the cavern prior to delivery offsite. The heat exchangers are designed to handle the projected cavern

temperatures to the year 2025. The heat exchanger installation was completed in March, 1995 for Bryan Mound, West Hackberry and Bayou Choctaw and April, 1998 for Big Hill.

After several service cycles, it was determined that the heat exchanger tube material should be upgraded from standard carbon steel to SeaCure (superferritic stainless steel) to provide improved exchanger life. The upgrade to SeaCure tubes was completed in 2006. Only the West Hackberry exchangers had been placed into service prior to this year since the upgrade in tube material. A study was completed (Jones and Brothers, 2007) after the WH exchangers last use in 2006, to determine the best means of exchanger decommissioning, cleaning and prepping for long-term lay-up. This study included the boroscoping of the exchangers prior to cleaning; cleaning the exchangers utilizing multiple methods; and post-cleaning boroscope inspections to determine the optimum cleaning method. The results of the study were reviewed and recommendations implemented into the site layup procedures. The water side of the exchangers will be isolated and flushed with a water/hydrogen peroxide biocide mixture to kill organics. The water side will then be drained and laid up with a nitrogen blanket. The crude oil side will be isolated and drained and left with a nitrogen blanket. This methodology is significantly more cost effective than the previous methodology requiring the removal of the vessel head. DynMcDermott Operational Systems Engineering will monitor pressure drops in the exchangers during operation and flag the need for more extensive cleaning in the future. Procurement for a heat exchanger hydrogen peroxide cleaning vendor to apply the biocide mixture to the water side of the exchangers has been completed and a Basic Ordering Agreement (BOA) is in place for their services when needed.

Due to the impacts of hurricanes Gustav and Ike in 2008, the blinds were removed from the heat exchangers at Bryan Mound, Bayou Choctaw and West Hackberry in preparation for crude oil exchanges. Big Hill did not require heat exchangers to be exchange ready due to completion of the degassing program at BH and because of the relatively cool crude oil temperatures (approximately 109 degrees F). Crude oil deliveries successfully flowed through the WH exchangers (approximately 1,000,000 barrels) and the BC heat exchangers (approximately 4,400,000 barrels). The BM heat exchangers were prepared but not utilized. However, since the BM heat exchanger blinds are open they were in the Fill oil flowpath for all the oil put into the caverns. The exchangers are currently awaiting the decision to reinstall blinds and removal from service.

4.3 H_2S Scavenger

The Vapor Pressure Management Plan assumes H_2S scavenger may be required to reduce potential H_2S emissions at various crude oil delivery points during a presidentially ordered drawdown. This assumption was modified this year per section 4.3.2 New Exchange Criteria below. H_2S requirements are dependent upon the raw water temperature, which is utilized as the cooling medium in the heat exchangers discussed above. If the heat exchangers are unable to maintain the delivery GOR at or below 0 scf/bbl, H_2S scavenger injection is required. Note that no deliveries are allowed if the GOR exceeds 0.6 scf/bbl at the first point of delivery or first exposure to the atmosphere, with or without scavenger. The delivery GOR for all sites are simulated on a seasonal basis in the *RYG charts* (See "Seasonal Vapor Pressure Projections as Reported by Vapor Pressure Committee in November 2009", Figure 7-1) to provide guidance

on the potential need for H_2S scavenger. These RYG charts provide a 2 year look ahead as to crude oil inventory availability and H_2S scavenging requirements.

Detailed plans have been developed to accomplish H_2S scavenging. Basic Ordering Agreements (BOAS) have been put in place to purchase H_2S scavenger from two different companies. Manifolds have been fabricated to interface between the chemical injection equipment for the scavenging chemicals and the site's crude oil system. The pumping equipment and personnel to inject and test the scavenger have been added to the BOAs. Quantities of scavenger by crude oil *stream* type and ppm content have been developed through laboratory analysis for the carryover BOA. One new BOA was approved this calendar year. The quantities as recommended by the chemical manufacturer will be used as an injection starting point until further laboratory analyses can be conducted on the new approved H_2S scavenger chemical. To ensure the readiness of the new contractor, New Orleans Engineering and Operations met with the new contractor at the West Hackberry site on November 19, 2009 to review procedures and setup for injection of their H2S scavenger.

H_2S scavenger has been used to date only once on the SPR. This was on 9/19 and 9/20, 2008 for a transfer to the Lake Charles Meter Station as reported in the 2008 Vapor Pressure Annual Report.

4.3.1 New Approved Chemicals

One new H_2S scavenger chemical, Multi-Chem MC MX 8-1519 Hydrogen Sulfide Scavenger, was approved this year for the new BOA contractor. This was done through risk assessment based on the MSDS sheet provided. There are now a total of four approved chemicals.

4.3.2 New Exchange Criteria

Change Proposal VA-M/O-8524 "Revise Technical Performance Criteria Level 1 to Include Emergency Exchange" was approved on 9/30/09. This change essentially allows for the use of H_2S scavenger in emergency exchanges. These changes could increase the frequency of H_2S usage on the SPR since most crude oil movements offsite have historically been small exchanges.

5 Method Development

This section discusses changes and improvements in methodology for activities that support the vapor pressure program objectives. This discussion focuses mainly on changes to data collection (conditions, instrumentation) and data analysis (models).

5.1 Measurements

5.1.1 Grabner TVP Expansions at Nonstandard Temperature

The *Grabner TVP analyzer* at the degas plant at Bryan Mound was configured to obtain crude oil multiphase pressure-volume data for plant inlet crude oil at selected nonstandard temperatures and expansion ratios in order to provide calibration data for the equation of state models used in the SPR vapor pressure program. At SPR, standard PVT test conditions are limited to the bubblepoint pressure and P = 14.7 psia, and T = 100°F. The nonstandard data collected on the Grabner tool are important because many of the numerical simulations that underlie program planning tools such as the red-yellow-green charts and degas rate plan documents are run at process environment temperatures ranging approximately ~90°F in blending and delivery scenarios to ~120°F in the degasification plant.

In FY09, Grabner temperature test data were collected for caverns BM004 and BM108. EOS models for the respective cavern oils were run in parallel for comparison. Summary results are shown in Figure 5-1 and Figure 5-2, where pressure-expansion curves for T = 90, 100, and 120°F are constructed from Grabner measurements (dotted lines) and EOS model runs with no tuning (solid lines). Similar to what was seen for other Bryan Mound degas plant inlet oils tested by this procedure in 2008, the EOS model predicts higher expansion ratio (more volume gas per volume liquid) than was observed in the Grabner data for pressures below the bubblepoint. The general implications from this are that the model will predict bubblepoint fairly well, but will tend to overstate flash gas volumes (GOR). Hence, planning tools like the red-yellow-green charts and degas plant *HYSYS* model will similarly overstate GOR.

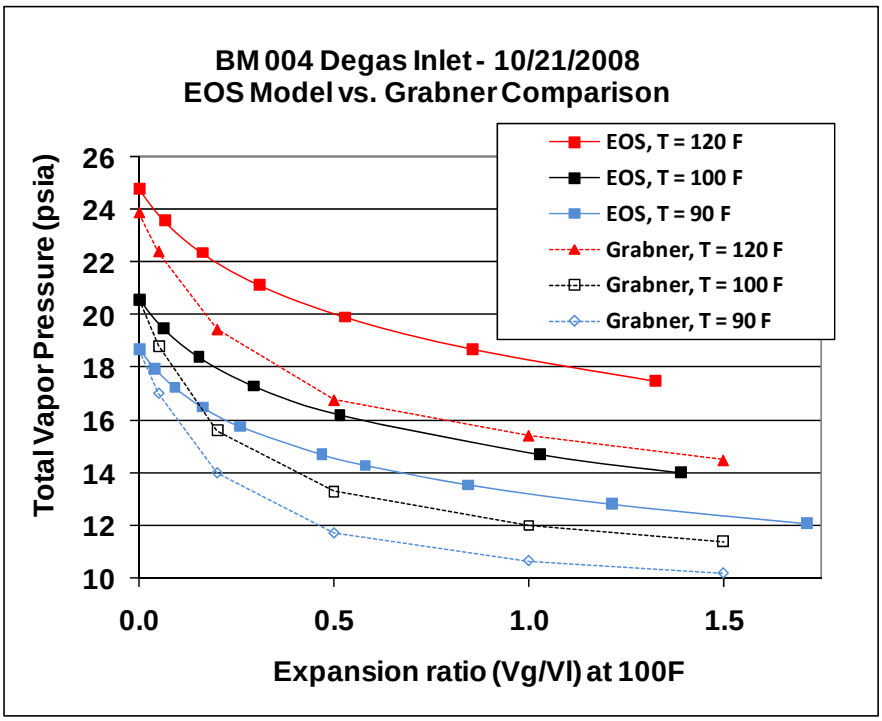


Figure 5-1. Comparison of Grabner Measured and EOS Model for BM004 Degas Plant Inlet Oil Pressure-Expansion Relationship at Three Selected Temperatures with Default BICs = 0 (no tuning).

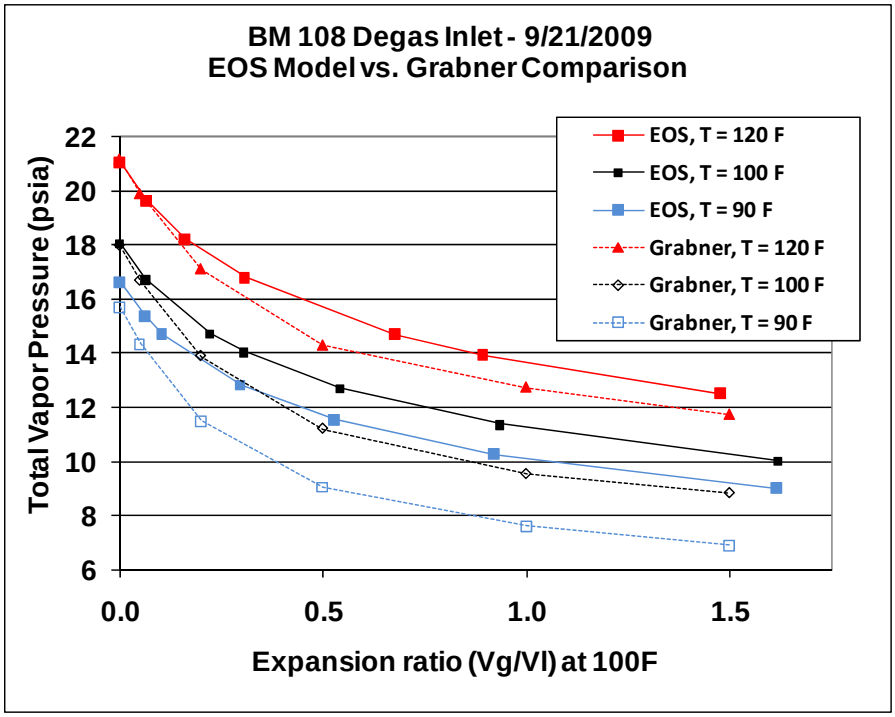


Figure 5-2. Comparison of Grabner Measured and EOS Model for BM108 Degas Plant Inlet Oil Pressure-Expansion Relationship at Three Selected Temperatures with Default BICs = 0 (no tuning).

5.2 Modeling

5.2.1 New 2009 VP-EOS Solver

The 2009 version of the *Vapor Pressure Database* & EOS Solver provides a number of improvements over the prior version of the Sandia Solver which has been in place in the Vapor Pressure Program since before the start of Degas II. Improvements include better capability to store and utilize results from the annual data review sessions, as well as automated compilation and reporting of vapor pressure data that once were done manually.

The Software Development Document (Rudeen and Lord, 2009), delivered in April 2009, covers basic software quality assurance principles, including: (i) software requirements (what the tool is supposed to do), (ii) program design/engineering (what the tool looks like and how it works), (iii) software verification (confirm that the calculations and automated features work correctly), and (iv) user instructions.

Sandia worked with DM on the installation of the 2009 software package on the SPR system. The package comprises a set of Excel workbooks with Visual Basic Macros. Initial testing on the SPR system indicates full desired functionality. Note that SPR has upgraded from Office 2003 to Office 2007, and this version change has been incorporated into the 2009 Vapor Pressure & EOS Solver Design. Both the 2003 and 2007 versions are available. User training and testing against the prior Sandia Solver for use in production calculations is ongoing, and will be completed under the direction of the vapor pressure committee. The new VP database and EOS Solver have been used for quarterly reporting.

5.3 Current EOS Model Performance Against Measured Data

Improvements in quality control on phase behavior measurements in 2006 coupled with a growing body of degasification plant operations data have created a solid measurement baseline that has served to inform and significantly improve project understanding on phase behavior of SPR oils. With this baseline in place, the features and limitations of the current equation of state model have been explored by utilizing the baseline data for model inputs and model output comparisons. Generally favorable performance was seen for model predictions of crude oil bubblepoint pressure, where uncertainty in measurements and uncertainty in model predictions are comparable. Less accuracy was observed in the gas-oil ratio predictions from the equation of state models, where there appears to be a bias of overstating gas production. Some bias is actually expected because the model must be calibrated or tuned for the specific application. Systematic tuning of the model based on proven practices from the technical literature have shown to reduce model bias and match observed data very well, though this model tuning effort is currently in process at SPR and based on preliminary data. A draft SAND report, delivered as a project milestone (Lord and Rudeen, 2009b), addresses many of the steps that have helped to build a strong baseline of data coupled with sufficient understanding of model features so that calibration is possible. In current SPR applications, the default un-tuned model is used for all production calculations. The end goal of this work is to develop a tuned equation of state model that will be used in production calculations that are used to inform management decisions on safe operations and program direction.

5.3.1 Bubblepoint Pressure

Two methods regularly used to measure crude oil BP pressure at SPR are the *TVP-95* BPP test and the Grabner TVP analyzer located in the *TVP-2000* at the degas plant. *Parallel testing* at BH during degassing in 2004-2006 allows for direct comparison of the two methods. Parallel testing refers to a test configuration in which the TVP-95 and TVP-2000 instrument systems are run side-by-side using a flowing source crude oil from the same *stream* at the degas plant. Measured BP pressures from the degas plant inlet and outlet streams for the two measurement systems are compared in Figure 5-3. Also, plotted in Figure 5-3 are equivalent data for the BM inlet stream, except pre-degas TVP-95data is used in place of parallel data. From Figure 5-3 it is evident that the Grabner measurements are always higher with difference increasing with increasing BP pressure.

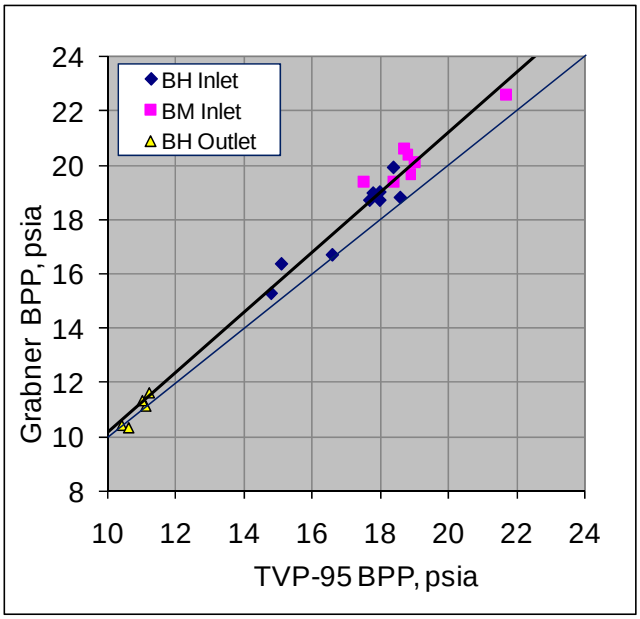


Figure 5-3. Grabner Measured BPP versus TVP-95 Measure BPP.

There are several possibilities for why the Grabner and TVP-95 BPP measurements lead to apparent systematic differences in bubblepoint pressure. One is that there could be a systematic measurement error in one or both of the instruments. Another is that the systems are measuring vapor pressure accurately, but since neither can directly measure the exact point at which the first bubbles appear (the true incipient bubblepoint), the interpretations of the specific data collected by each instrument lead to a bias. Note that bubblepoint pressure is a special case of vapor pressure where gas volume is zero, but the slightest decrease in system pressure or increase in temperature from that position will create a positive, nonzero volume of gas.

5.3.2 Gas-Oil Ratio

The effects of the 2006 QC improvements on GOR estimates are illustrated in Figure 5-4 which shows a history of GOR calculated from the TVP-95 BPP test, labeled GOR(BPP), normalized by the measured GOR. If both the measured and EOS calculated GOR are equal the ratio would be 1.0. The figure shows a dramatic improvement after April 2006 (marked in the figure with a

blue vertical line). Normalized GOR ranges from 0 to 10 prior to April 2006 with many values exceeding 3. After April 2006 the data is relatively tightly grouped around 1. However, the ratio still varies by a factor of 2, meaning the BPP test data is significantly improved but there is still significant uncertainty in the measured GOR and/or in the EOS modeled GOR.

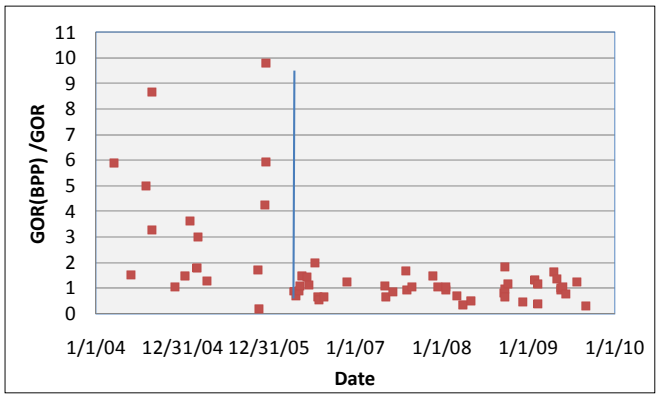
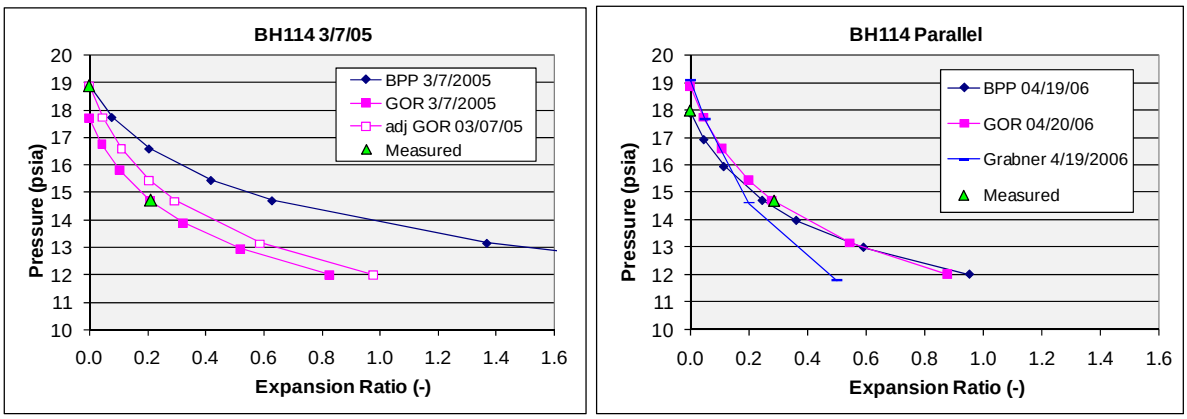


Figure 5-4. EOS Calculated GOR from BP Test Data Normalized to Measured GOR as a Function of Time.

5.3.3 Expansion Curves

The evolution of the PVT modeling at SPR can also be illustrated by the pre and post April 2006 QC expansion-curve comparisons shown in Figure 5-5 for cavern BH114, which is representative of the much broader available set of EOS calculated expansion data. Figure 5-5 presents EOS expansions based on TVP-95 data (a) prior to degassing BH114 and (b) during parallel testing at BH114 in April. EOS calculated expansion curves using TVP-95 BPP test data are shown with blue diamonds, GOR test data are shown with pink squares and adjGOR are shown with hollow pink squares. The two green triangles mark the measured BP pressure at zero expansion and the measured GOR at 14.7 psia. The separation of the three curves in Figure 5-5(a) implies that the EOS calculated significantly different whole oil compositions for the three sets of test data in spite of simulating a single oil sample. Thus, the data from the two TVP-95 tests (BPP and GOR) are inconsistent. The disagreement was found during the QC analyses to be the poor conditioning of the BPP gas and the resulting GC compositions, which contributed to the very flat BPP expansion curve. Conversely, the close overlay of the three expansion curves in Figure 5-5(b) implies good consistency between BPP and GOR test data.

The convergence of curves in Figure 5-5(b) indicates considerable improvement in consistency among BPP and GOR measurements and the EOS model, though model accuracy is not confirmed by these data alone. Parallel testing with the Grabner allows for validation of the EOS model results. Figure 5-5(b) also provides a comparison of the EOS-calculated expansion-curves with the Grabner measured expansion curve (blue dash). The comparison shows that the EOS calculated expansion curves predict significantly larger gas volumes at a given pressure than the Grabner measured expansion curve and the difference between measured and calculated increases with decreasing vapor pressure.



(a) Prior to April 2006 (b) After April 2006

Figure 5-5. Grabner Measured and EOS Calculated Expansion Curves Before and After April 2006 QC Implementation at BH114.

5.3.4 Closing Comments on Current EOS Model Performance

The EOS model used at SPR underlies all vapor pressure forecasting and performance tools, including the 3-year planning red-yellow-green charts (see section 7.1.2), longer-term ~10-year planning *1-Plant Model*, and the HYSYS degas plant simulator model. In all cases, the accuracy of the system modeling hinges on the accuracy of both the underlying data and EOS model. Improvements in QA/QC on phase behavior measurements stemming from parallel testing in 2006 led to considerably improved measurement accuracy, which was then realized in improved EOS model accuracy. Further improvements in EOS model accuracy are possible, though some specialized calibration measurements are required to make progress. Given the tight margins between modeled delivery conditions and program criteria at West Hackberry and Bayou Choctaw, EOS model advances could pay off by reducing model uncertainty and increasing cavern availability in critical streams over the next decade before Degas II is complete.

5.4 Program Collaboration with Industry and Peer Groups

The Sandia member of the vapor pressure committee sits on the American Petroleum Institute working group for establishing standards for Phase Behavior Applications, API Manual of Petroleum Measurement Standards, Chapter 20.4. The new API standard is currently in draft form. The objective is to present a detailed explanation of how to use currently available measurement and modeling techniques to determine crude oil phase behavior in production streams. The primary application of this standard is intended to address revenue allocation in commingled production streams, but other applications include flow assurance, phase stability, and vapor emissions in oil and gas gathering, storage, and distribution systems. The API working group chair has asked Sandia to provide a detailed example problem for the standard to illustrate the workflow for monitoring and modeling phase behavior in the SPR crude oil storage system. A draft version is due to API in the first quarter CY2010. Sandia has obtained approval from the SPR vapor pressure committee and Sandia management to develop this test problem. All written material will undergo official review and approval through DOE and SNL prior to release to API.

6 Other Work During FY08

6.1 Degas Mixing Studies

Cavern-scale oil mixing during degas has several negative effects relative to a baseline condition of no mixing. First, the cavern inventory will only be ~63% degassed when one full cavern volume has passed through the plant if the degassed oil mixes completely with the gassy oil. Second, the diminishing returns from a completely mixed cavern mean that the entire inventory of the cavern will never be degassed to plant outlet values, independent of how many plant volumes are processed. The general implications are that mixing results in higher degassed oil bubblepoints and longer schedule relative to a non-mixing baseline.

The vapor pressure committee theorizes that the cause for cavern-scale mixing is that returning cooler, denser, degassed oil to the top of the cavern at current processing rates causes it to sink and mix throughout the cavern. This theory was developed behind work done at Sandia that looked closely at degas operations data coupled with computational fluid dynamics modeling. The following sections elaborate on the Sandia findings.

6.1.1 Historical Review of Degas Operations

A review of past degas operations was initiated in FY09 in order to gain a historical perspective of influences and impacts of degas mixing. Impacts were first documented in a SAND Report by Lord and Rudeen (2005) and correlated with mixing behavior in Lord and Rudeen (2007). At that time, degas mixing was only a conjectured cause of the observed discrepancy in the Degas Plant outlet BPP and first post-degas measured BPP. With current knowledge of cavern-scale mixing, a further review of historical degas operations, particularly Degas 1, could possibly provide additional background knowledge of the impacts of returning degassed oil to a cavern containing un-degas oil. As part of that review, several degas oil flow configurations were identified as follows:

- Big Hill and West Hackberry were degassed removing the oil from the top of the cavern and returning the degassed oil to the bottom of the cavern through the brine string.
- Bayou Choctaw was degassed the same way as Degas 2, oil was removed from the bottom of the cavern and degassed oil returned to the top of the same cavern it came from.
- Bryan Mound caverns (with the exception of the BM106) were degassed into another cavern, thus, the documented degas volumes reflect the oil degassed out of that cavern, not into that cavern.
- For BM1 and BM113, brine produced from the receiving cavern was used to displace the oil from the source cavern.
- The remaining BM caverns used raw water as the driver to displace oil to the degas plant. The brine displaced from the receiving cavern was disposed through the brine disposal line.

- During Degas 1 planning, it was expected that treatment of up to 110% of the cavern volume would be necessary in anticipation that there could be some amount of mixing at the degassed/undegassed oil interface. It was not until degassing of BH101 during Degas 2 that cavern scale-mixing was seriously considered.

The historical review has compiled considerable amount of data that combined with current investigations, discussed below, could assist in developing new degas configurations for mitigating cavern-scale mixing and also provide information on VOC uptake by brine and oil and remedial leaching. These analyses are left as future work.

6.1.2 Observations from Degas II Operations Data

Degas II plant performance data from 9 Big Hill and 6 Bryan Mound caverns completed to date indicate a wide range of mixing behaviors. Upon reviewing operations data, some patterns were evident, illustrated in Figure 6-1. Generally, Big Hill caverns showed varied mixing, exhibited oil temperatures near 100°F at the time of degasification, and saw oil temperature gains across the plant. In contrast, Bryan Mound caverns all showed complete mixing, exhibited oil temperatures from 115-125°F at the time of degas, and showed oil temperature losses across the plant.

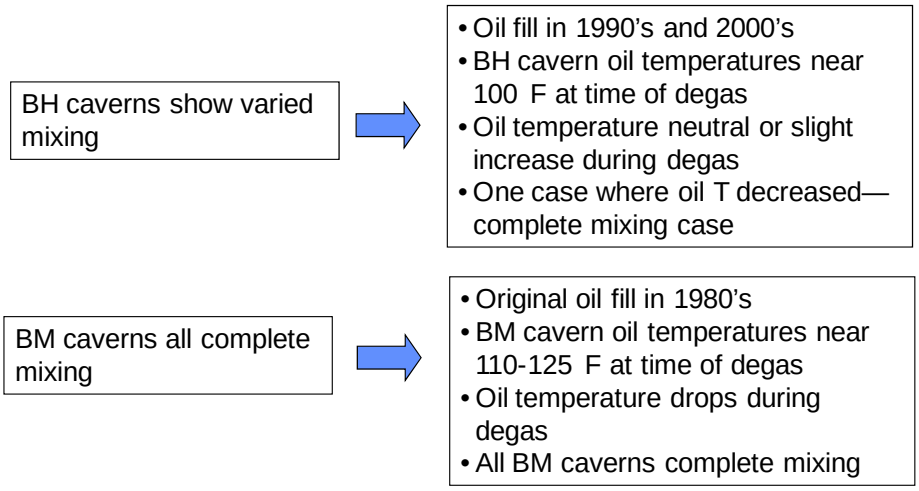


Figure 6-1. Graphic Showing Patterns Observed for Degas Caverns and Mixing Behavior.

A closer review of operations data coupled with oil temperature revealed a strong correlation between crude oil temperature change across the plant and oil mixing behavior. Key features of this correlation are illustrated in Figure 6-2. Three primary mixing regimes are illustrated on the left in the form of actual plant performance curves, representing plug flow, intermediate, and complete mixing. These are compared with crude oil temperature change across the plant, shown on the right side of Figure 6-2. The temperature plot shows daily average temperature change across the plant for 14 caverns listed on the right margin. Caverns that gained temperature greater that 1°F are shown in red. Caverns that gained temperature between 0 and 1°F are shown in yellow. Caverns that lost temperature across the plant are shown in blue. While all the cavern performance curves are not shown explicitly, they fall consistently into the

three categories shown on the left. For example, oils that gained more than 1°F across the plant did not mix during degas. Oils that lost temperature mixed completely. Hence, the temperature gain or loss appears to directly correlate with performance and mixing.

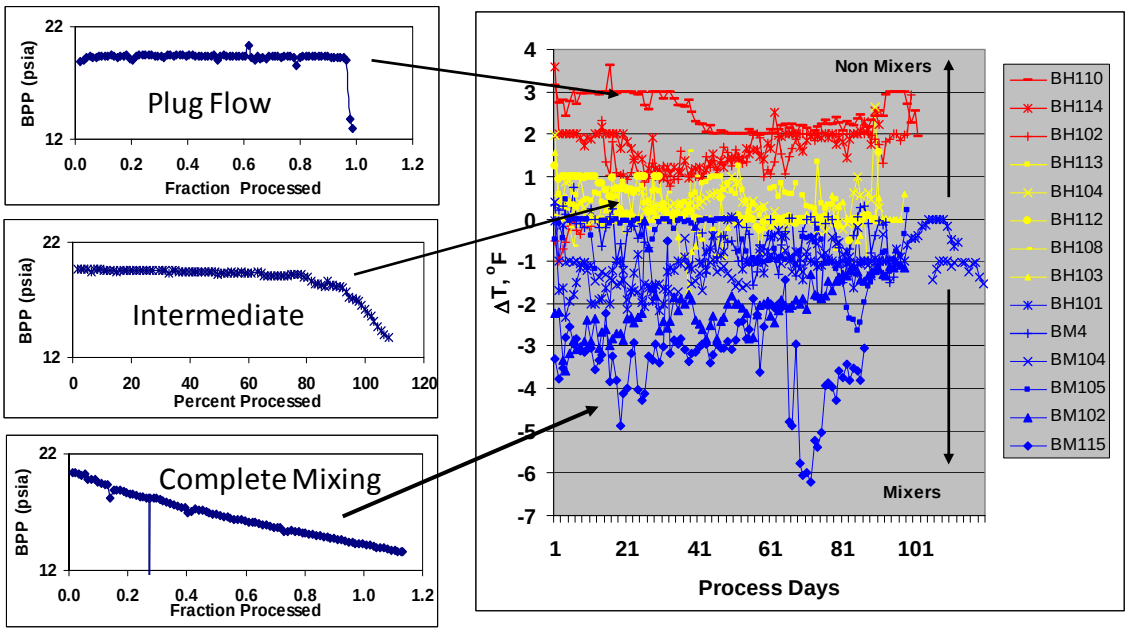


Figure 6-2. Comparison of Representative Degas Plant Performance (Left Side) with Crude Oil Temperature Change Across Plant (Right).

6.1.3 CFD Simulations of Mixing

Computational fluid dynamics (CFD) modeling by Sandia (Webb, 2009) provided an opportunity to explore if and why temperature gain or loss across the plant could drive cavern-scale mixing at the levels observed at SPR. Webb set up a simple model domain as a right circular cylinder measuring 2000 ft tall and 200 ft in diameter with oil inlet/outlet strings along the cylinder axis 100 feet from the top and 200 feet from the bottom (see Figure 6-3). Properties of diesel were used for the oil, and a 130,000 bbl/day processing rate was implemented.

Figure 6-3. Schematic of Simple CFD Model Domain Representing Idealized SPR Degas Cavern (Reproduced from Webb, 2009).

Several degas scenarios were run in which oil was removed from the bottom string, the density of the oil was changed (lighter, same, heavier), and the oil was re-injected into the top, which represents the current degas configuration at SPR. The same sequence was repeated for oil removed from the top and injected into the bottom, which represents a reversal of the current degas configuration at SPR. Results were plotted as performance curves against the ideal plug flow and complete mixing cases. Bubblepoint was normalized to inlet conditions, so gassy oil exhibits normalized BP of 1.0, and degassed oil exhibits normalized BP of 0.0. Processed oil volume was normalized to the cavern volume, so an entire cavern volume would evaluate to 1.0.

The normal flow configuration results with lighter oil injected at the top are summarized in Figure 6-4, overlaid with ideal plug flow and complete mixing bounding cases. Three simulations were run with oil at 0.01 %, 0.1%, and 1.0% lighter oil injected. Note that all three cases approached plug flow, as the lighter oil remained near the top of the cavern and did not readily mix with the oil in the bottom. Injecting heavier oil (0.01 %, 0.1%, and 1.0%) into the same configuration led to significantly different results, showing direct overlay with the complete mixing case. In this case the heavier injected fluid flowed rapidly to the bottom and induced complete mixing in the cavern.

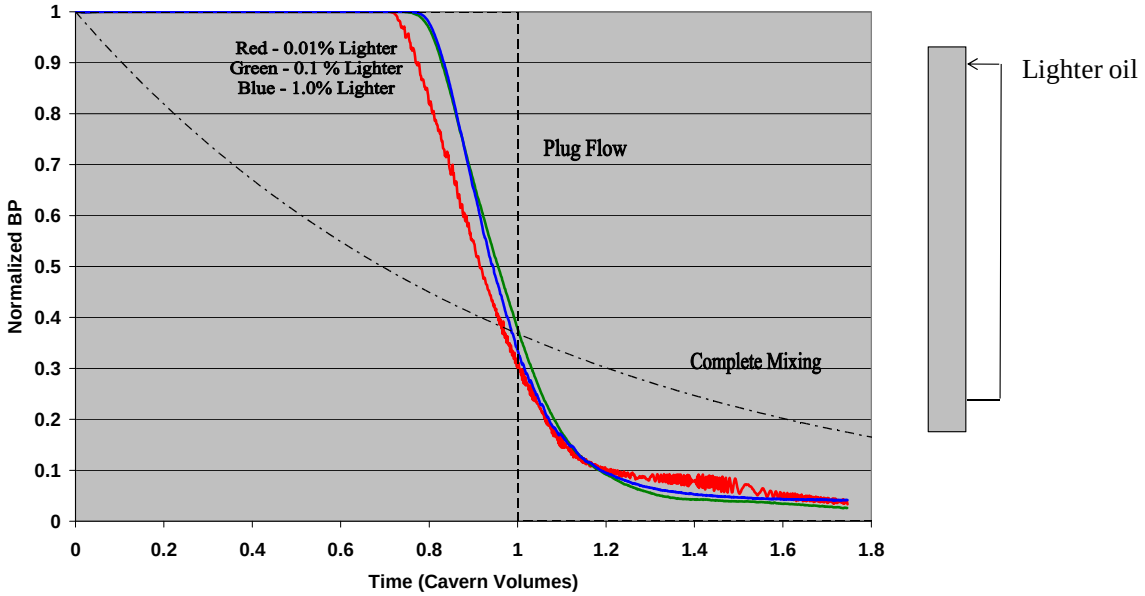


Figure 6-4. CFD Model Normalized Inlet BP vs. Cavern Volumes Achieved by Re-Injecting Lighter Oil at Top of Cavern (Reproduced from Webb, 2009).

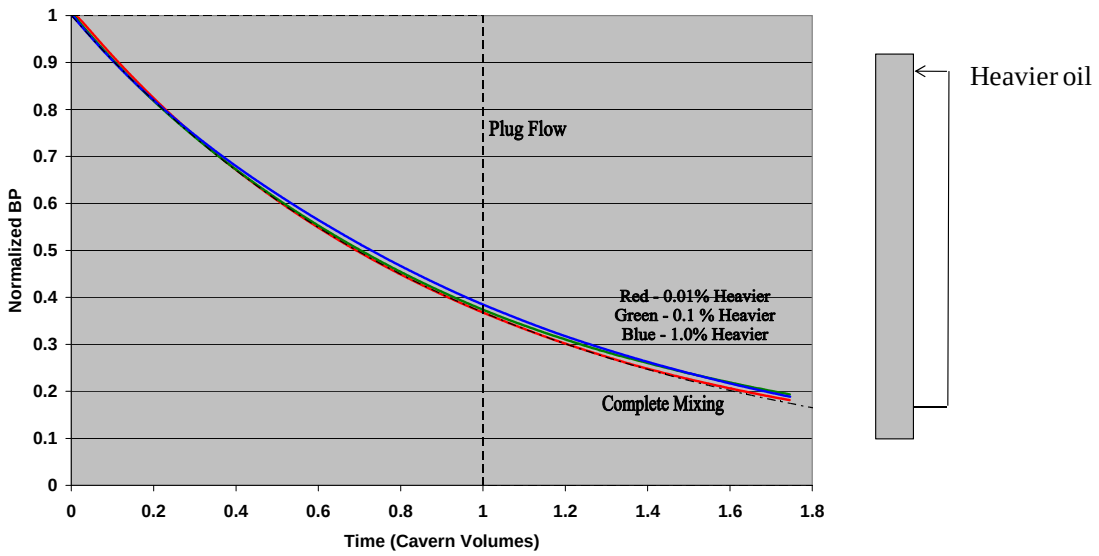


Figure 6-5. CFD Model Normalized Inlet BP vs. Cavern Volumes Achieved by Re-Injecting Heavier Oil at Top of Cavern (Reproduced from Webb, 2009).

The reverse flow configuration was also simulated in which oil was re-injected into the bottom of the cavern, with results shown in Figure 6-6. Heavier oil injected into the bottom of the cavern behaved largely like plug flow. In this case, the heavier oil stayed in the bottom of the cavern and gradually displaced the lighter oil above.

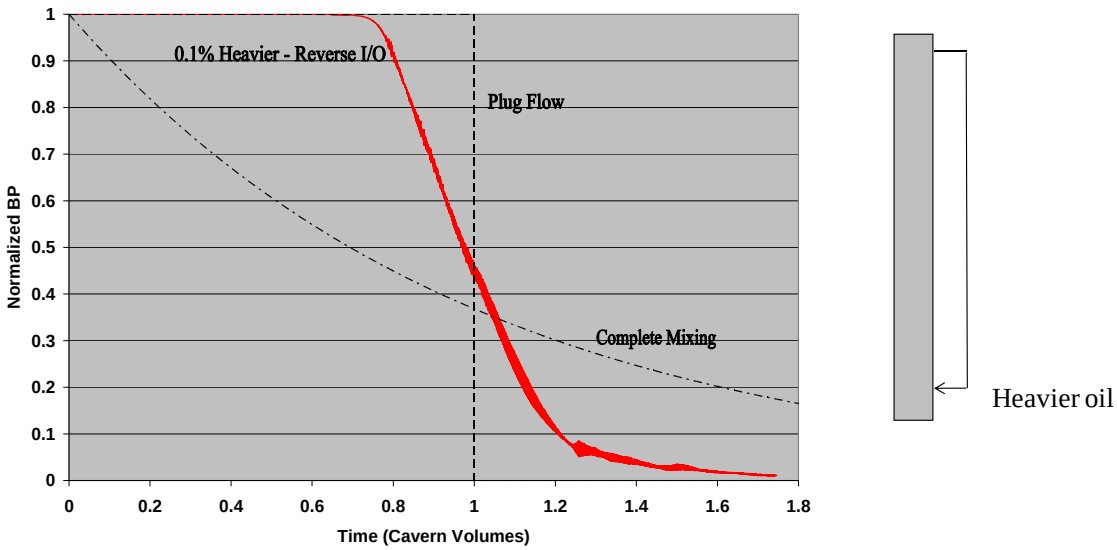


Figure 6-6. CFD Model Normalized Inlet BP vs. Cavern Volumes Achieved by Re-Injecting Heavier Oil at Bottom of Cavern (Reproduced from Webb, 2009).

6.1.4 Summary Comments on Degas Mixing

The current position of the vapor pressure committee is that the cavern-scale oil mixing during degasification likely results from injecting cooler, denser oil at the top of the cavern at current processing rates. The oil cooling is not intentional; rather, it occurs as hot (> 100°F) oil from the SPR caverns is exposed to ambient surface conditions through surface piping and degas plant unit operations. Given that all current Bryan Mound oils are hot, and West Hackberry oils are similarly hot, there is a high likelihood that all of the remaining degas caverns outlined in the Degas rate plan A6 will mix.

A test plan is currently in place (Lord and Sattler, 2009) to collect temperature and high-resolution quartz gauge pressure logs in order to directly characterize the in-situ fluid temperature and density environment just prior to and just after degasification. These data should prove useful for testing the current hypothesis that the mixing is driven by a temperature-density phenomenon. The data will be used in future CFD modeling to establish initial and final conditions in real cavern scenarios, allowing Sandia to first calibrate, and then potentially validate the mixing models for real SPR caverns.

The utility in having a validated mixing model is that remediation scenarios may be explored, such as reversing inlet and outlet positions to injecting cooler oil at the bottom, which looks

promising in the simple model above. Other options include retaining current top-of-cavern injection while lowering inlet velocity (re-inject into two caverns) or heating the oil.

7 Path Forward

7.1 Summary of Site/Stream Deliverability

7.1.1 Current Performance Criteria

SPR Level II criteria (US DOE, 2005, as amended) requires "for a Presidentially ordered drawdown at SPR Level I, Appendix A sustained drawdown rates:

- the maximum allowable volume of gasses evolving from the crude oil at atmospheric pressure shall not be greater than 0.6 standard cubic feet per barrel (GOR) at the SPR property line or any on-site crude oil storage tanks open to the atmosphere, at temperature.
- "scavenging shall be used to limit the evolution of H_2S to within state and federal regulatory limits for all streams with a GOR > 0 at the SPR property line or any on-site crude oil storage tanks open to the atmosphere.

"For all other oil movements:

- the calculated maximum true vapor pressure (TVP) of the crude oil as defined by API 2517 shall be 11.0 pounds per square inch absolute (psia) or less, at temperature, at the point of custody transfer or any crude oil storage tanks open to the atmosphere
- the calculated maximum bubble point of the crude oil shall be 14.7 psia or less at temperature, at the point of custody transfer or any crude oil storage tanks open to the atmosphere."

7.1.2 Seasonal Vapor Pressure Impacts

Several natural factors combine to affect the delivery properties of oil with time, including:

- Seasonal temperature changes in cooling water
- Long-term geothermal heating of oil in caverns
- Gas regain into oil in caverns

These natural effects are mitigated by selective oil cooling, degassing, and H_2S scavenging. The net impacts on oil deliverability are computed in a HYSYS oil delivery model maintained by DM Engineering. The results of this model are presented quarterly in a figure called "Projected Seasonal Vapor Pressure Impacts," known informally as the red-yellow-green charts. The November, 2009 version is presented below in Figure 7-1. The model forecasts oil deliverability against Level II criteria each month for three years into the future on a site/stream basis. The default stream is built from all *sweet or sour caverns* at a site blended in direct proportion to their current oil inventory.

Oil streams that are forecast to exhibit BPP less than 14.7 psia at delivery temperature and meet all drawdown criteria with proportional drawdown are labeled with OK in Figure 7-1.

Both streams at Big Hill and Bryan Mound meet this condition in all months for the next three years, largely as a result of degasification. Moreover, all streams at all sites meet this condition during the cooler months of November through March for all years shown. Streams labeled with a OK-GOR exhibit a BPP > 14.7, but a GOR < 0.6 scf/bbl, and are suitable for drawdown under presidential order. Note that this condition is identified for many of the streams during the summer months. Streams labeled with Note 4 are suitable for drawdown under presidential order if pipeline cooling is incorporated into the drawdown model. Streams labeled with Note 3 are suitable for drawdown under presidential order if pipeline cooling and selective blending are incorporated into the drawdown model. Selective blending implies that caverns are selected to optimize the resultant BPP of the stream so that it meets delivery criteria and maximum drawdown rates. This entails utilizing lower BPP caverns for summer drawdown and higher BPP caverns for winter drawdown. Degasification will be required at WH and BC after BM is completed in order to bring those streams to an OK status for all months.

Projected Seasonal Vapor Pressure Impacts
As of November 2009

Streams	Oct-09	Nov-09	Dec-09	Jan-10	Feb-10	Mar-10	Apr-10	May-10	Jun-10	Jul-10	Aug-10	Sep-10
BM SW		OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
BM SO		OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
BH SW		OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
BH SO		OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
WH SW		OK	OK	OK	OK	OK	OK-GOR	OK-GOR	Note 4	Note 3	Note 3	OK-GOR
WH SO		OK	OK	OK	OK	OK	OK-GOR	OK-GOR	OK-GOR	Note 4	Note 4	OK-GOR
BC SW		OK	OK	OK	OK	OK	OK	OK-GOR	OK-GOR	OK-GOR	OK-GOR	OK-GOR
BC SO		OK	OK	OK	OK	OK	OK-GOR	OK-GOR	OK-GOR	OK-GOR	OK-GOR	OK-GOR

Streams	Oct-10	Nov-10	Dec-10	Jan-11	Feb-11	Mar-11	Apr-11	May-11	Jun-11	Jul-11	Aug-11	Sep-11
BM SW	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
BM SO	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
BH SW	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
BH SO	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
WH SW	OK-GOR	OK	OK	OK	OK	OK	OK-GOR	OK-GOR	Note 3	Note 3	Note 3	Note 4
WH SO	OK-GOR	OK	OK	OK	OK	OK	OK-GOR	OK-GOR	OK-GOR	Note 4	Note 4	OK-GOR
BC SW	OK-GOR	OK	OK	OK	OK	OK	OK	OK-GOR	OK-GOR	OK-GOR	OK-GOR	OK-GOR
BC SO	OK-GOR	OK	OK	OK	OK	OK	OK-GOR	OK-GOR	OK-GOR	OK-GOR	OK-GOR	OK-GOR

Streams	Oct-11	Nov-11	Dec-11	Jan-12	Feb-12	Mar-12	Apr-12	May-12	Jun-12	Jul-12	Aug-12	Sep-12
BM SW	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
BM SO	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
BH SW	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
BH SO	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
WH SW	OK-GOR	OK	OK	OK	OK	OK	OK-GOR	OK-GOR	Note 5	Note 3	Note 3	OK-GOR
WH SO	OK-GOR	OK	OK	OK	OK	OK	OK-GOR	OK-GOR	Note 4	Note 4	Note 4	OK-GOR
BC SW	OK-GOR	OK	OK	OK	OK	OK	OK	OK-GOR	OK-GOR	OK-GOR	OK-GOR	OK-GOR
BC SO	OK-GOR	OK	OK	OK	OK	OK	OK-GOR	OK-GOR	OK-GOR	OK-GOR	OK-GOR	OK-GOR

	Historical Data
OK	BP <= 14.7 psi
OK-GOR	BP > 14.7 psi GOR <= 0.6 scf/bbl
MBD	GOR >= 0.6 scf/bbl

Note 1: Current projections include effects of Degas II as currently budgeted and projected fill.
Note 2: Can be drawn down non proportionally to achieve max rates
Note 3: Includes pipeline cooling and selective blending drawdown to achieve max rates
Note 4: Includes pipeline cooling to achieve max rates
Note 5: Includes pipeline cooling to achieve max rates, Degas WH105 complete.

Figure 7-1. Seasonal Vapor Pressure Projections as Reported by the Vapor Pressure Committee in November 2009.

7.2 Sampling Recommendations for FY11

The sampling program for FY11 is designed to address two main objectives: (i) regain sampling, and (ii) EOS model calibration. The regain sampling portion of the program will remain at a minimum necessary level, focusing on high priority caverns for sampling on a 2-3 year period, and low-priority caverns moved to a longer period. The EOS calibration sampling will take the form of selected Grabner TVP tests, liquid chromatography for heavy ends analysis, and parallel sampling during degas. More details on these proposed methods are given in the annual sampling recommendations from Sandia to the vapor pressure committee (Lord and Rudeen, 2009c).

7.3 Regain Monitoring

A total of 13 downhole and 10 flowing samples are recommended in order to support the regain analysis in FY11. The numbers by site basis are shown below in Table 7-1. The vapor pressure committee should also recommend special samples of opportunity that arise due to events such as well *workovers* in single-well caverns or special samples due to anomalous events or degas schedule changes. Estimated costs associated with the regain sampling activities are shown in Table 7-2.

Table 7-1. Regain Sampling Summary.

Site	Downhole	Flowing TVP
Big Hill	3	0
Bayou Choctaw	2	0
Bryan Mound	6	1
West Hackberry	2	9
TOTAL	13	10

Table 7-2. Regain Sampling Estimated Costs.

Test Type	Each	Extended
Downhole	$ 32,345	$ 420,485
Flowing	$ 8,255	$ 82,550
SUM		$ 503,035

7.4 EOS Model Calibration Sampling

With one cavern (BM112) scheduled to start degassing in FY11, there will be one opportunity to collect parallel flowing TVP-95 and Grabner temperature test data at the degas plant. Also, a *C30+* analysis is recommended for every cavern test, to total 19 in FY11. Table 7-3 summarizes these tests by site. Note that *parallel sampling* with degas entails four flowing tests for each cavern.

Table 7-3. Parallel Flowing and C30+ Sampling Summary.

Site	Parallel Flowing TVP	C30+
Big Hill	0	3
Bayou Choctaw	0	2
Bryan Mound	4	8
West Hackberry	0	11
TOTAL	4	24

Cost data for calibration sampling are given in Table 7-4. Grabner temperature tests do not have direct costs as they only require temporarily programming the Grabner unit to operate at nonstandard conditions for several days while Allen Energy monitors the tests. DM and Sandia typically coordinate with Allen Energy to observe the Grabner tests.

Table 7-4. Parallel Flowing and C30+ Estimated Costs.

Test Type	Each	Extended
Flowing	$ 8,255	$ 33,020
C30+	$ 685	$ 16,440
SUM		$ 49,460

There are no specific schedule constrains; the sampling may be completed anytime during FY11 as other Operational and Maintenance activities may dictate.

7.5 BC102, BC103 and BC104 Impacts

The retirement of Cavern 20 at BC and the associated space purchased in BC Cavern 102 will be monitored for impact on the degas project. Currently per Rev 7 of the Degas Plan (DeLuca, 2010), West Hackberry will finish degassing in early 2017. The November 2009 EOS model has the current BC sour inventory drop dead date for degas (where the GOR hits 0.6 scf/bbl) occurring in 2020. The November 2009 EOS model shows that the current Bayou Choctaw sweet stream does not need degassing for GOR in the immediate future. Both streams would benefit greatly today from a reduction in Vapor Pressure as they both require H_2S scavenger addition approximately half the year (See Figure 7-1). Additional inventory at historical bubble points of 17.5 to 18.5 psia will have a negative impact on the need to degas at Bayou Choctaw. This must be included in the planning for degassing Bayou Choctaw. Possible new caverns 103 &104 will add additional higher vapor pressure crude oil to BC and will again have to be factored into degas planning for Bayou Choctaw.

7.6 Impacts of Remedial Leach on Vapor Pressure

Creep closure steadily reduces the long-term storage capacity at SPR, and some level of cavern expansion and associated leaching (solution mining) will be required to maintain a 20 year cavern creep allowance at the SPR. Leaching is relevant to vapor pressure because the salt dissolved in the leaching process releases gases to the cavern which may accumulate in the oil to increase vapor pressure. This may ultimately be realized as higher bubblepoint pressures or gas-

oil ratios in oil at delivery. The vapor pressure committee must incorporate any remedial leach activities or crude oil movements into its future analyses and planning.

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Glossary

1-Plant Model. Quarterly SPR program planning tool that presents status of crude oil deliverability on site/stream basis against program published emissions criteria. The model assumes there is one degas plant operating to mitigate gassy oil, and looks ahead up to 15 years in order to plan the long-term degasification schedule.

Bubble point pressure (BPP): The pressure at which gas bubbles begin to evolve from a single-phase liquid crude oil. In SPR systems, this condition may be encountered when containment pressure on a crude oil is reduced from cavern storage pressure to near atmospheric pressure, resulting in the evolution of a mixture of gases (N_2, CH_4, C_2H_6, etc., benzene, H_2S). BPP will increase with geothermal heating of caverns and gas intrusion into cavern oil. Units: *psia*

C30+: A compositional analysis of a crude oil sample where compounds of up to 29 carbon atoms are separately discriminated with the remainder combined into a fraction termed C30+. Light ends are likely under estimated because samples are typically not pressurized and are exposed to atmospheric conditions. Molecular weight and specific gravity are also determined.

Degas Plant: A crude oil processing plant used to mitigate gassy oil, resulting in an outlet liquid crude oil stream that exhibits a bubble point pressure several psi lower than the inlet stream. The primary process removes light gases (nitrogen, methane, ethane, propane, butane, pentane) by passing the crude oil through a pressure-controlled gas-liquid separator and incinerating the off-gas. The plant is portable and is moved to each SPR site according to needs defined by the vapor pressure committee.

DynMcDermott Petroleum Operations: Maintenance and operations contractor to the U.S. Strategic Petroleum Reserve.

Equation of state model (EOS): Model used to predict phase behavior of crude oil based on thermodynamic principles. EOS model output includes BPP and GOR of crude oils as a function of temperature and pressure. EOS models underlie all deliverability forecasting at SPR and are embedded in the HYSYS degas plant process simulator. EOS models are also used to build whole oil compositions for each cavern based on TVP-95 vapor pressure, GOR, and flash experiments. The Soave-Redlich-Kwong (SRK) version of the cubic EOS is used by the VP project to model two phase vapor/liquid equilibrium problems. The SRK EOS is implemented in Microsoft Excel using spreadsheet functions and Visual Basic macros as part of the VP database and as a standalone FORTRAN MS Windows program called D2EOS.

Gas-oil ratio (GOR): The volume (standard cubic feet) of gas evolved (N_2, CH_4, C_2H_6, etc., benzene, H_2S) per barrel of liquid oil at selected conditions, usually evaluated at atmospheric pressure. GOR is zero for oils contained at pressure greater than their bubble point pressure. GOR is positive and nonzero for oils contained at pressure below their bubble point pressure. GOR value will increase with geothermal heating of caverns and gas intrusion into cavern oil. Units: *scf/bbl*

Grabner: The Grabner TVP Analyzer, abbreviated sometimes as the Grabner, refers to a test cell that measures the pressure of a fixed-mass, two-phase crude oil sample as a function of controlled volume and temperature. The test sequence creates points in pressure-volume-

temperature (PVT) space that can be used for curve-fitting to determine bubble point pressure and gas-oil ratio.

Gross Observed Volume (GOV): The total volume of all petroleum liquids and sediment and water, excluding free water, at observed temperature and pressure. See GSV.

Gross Standard Volume (GSV): 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. See GOV.

H_2S scavenging: One mitigation strategy used to minimize risk of worker exposure to hydrogen sulfide (H_2S) in crude oil emissions is to add an H_2S scavenger to the crude stream when it is sent to various delivery points, including external customers. The H_2S scavenger is a liquid that is injected into an oil delivery stream on SPR property that chemically binds with the H_2S in the oil and reduces downstream H_2S emissions to below federal occupational safety and health administration (OSHA) exposure limits.

HYSYS: Commercial software contracted from AspenTech that simulates oil and gas physical behavior in the SPR process environment. SPR has HYSYS models of each SPR site and the degasification plant. The models are used to predict the properties of oil and gas streams (i.e., phase behavior) as well as optimize plant performance.

Parallel testing: A test configuration in which the TVP-95 and TVP-2000 instrument systems are run side-by-side using flowing source oil from the same stream, typically at the degas plant.

Pencor: Oilfield services contractor that collects and analyzes crude oil samples for the vapor pressure program at SPR. Pencor owns and operates the TVP-95 instrument that is used to analyze all cavern oil samples for vapor pressure, GOR, and flash analysis.

Pencor Reports: Pencor sampling results are reported in Excel workbooks containing a cover letter summary, BPP test data and plot, BPP gas chromatography results, GOR test data and plot and GOR gas chromatography results. Reports are delivered to Collins Lanier of DM, who maintains a library of test reports and distributes them to the project. A set of Pencor reports is also stored in the SNL SPR digital library maintained by Sam Wallace. The report naming convention is: SSNNN-yy-mm-dd-comment-nnnn-nnnnnnnnnn.xls, where SS is site abbreviation (BC, BH, BM, WH), NNN is cavern number, yy-mm-dd is the date of sampling event, comment is an abbreviated test comment (*DH=downhole sample; F=flowing sample*; UP = unpressurized test; C30+= C30+ compositional analysis; the remainder is Pencor coding).

Red-yellow-green (RYG) charts: Quarterly SPR program planning tool that presents status of crude oil deliverability on site/stream basis against program published emissions criteria. The chart looks forward 3 years from date of publication. Results are color coded in green (OK for delivery), yellow (OK with H_2S scavenging), or red (not OK for delivery).

Regain (also called vapor pressure regain): Term used within SPR program for the rate-of-change in cavern representative BP pressure in units of psi/yr. It is determined from linear

regression analysis of measured BPP as a function of time. Historically, this change in BP pressure was thought to be caused by in the influx of volatile gases from the surrounding host salt, primarily methane with small amounts of nitrogen, ethane, propane and butane. This interpretation was influenced by the large quantities of gas produced during cavern development by leaching. As both the quantity and quality of VP data increased with time, apparent regain rates have been reduce to essentially zero except for a few isolated caverns. Because of the method used, calculated regain rates also include the effects of compositional changes due to oil movements in and out of the caverns. New incoming 18 psi oil when mixed in a cavern with a 15 psi degassed oil will result in a oil with an intermediate BP pressure. Much of the current apparent regain is significantly influenced by these oil movements. The regression calculated regain rates also contain sampling errors because the data is obtained from very small samples located at single locations within very large caverns.

Stream: At SPR, the term "stream" implies commingled crude oil, originating from one or more caverns at a given SPR site that is intended for delivery to market. For vapor pressure program planning purposes, streams are built nominally from volume-weighted averages of all sweet or all sour caverns at a given site. Each site has a sweet stream and a sour stream that has a set of published properties and assay data that are used in negotiating sales.

Sweet and Sour crude oils: Sweet and sour crude oil designations specific to SPR refer to allowable total sulfur limits in the crude stream. Sweet oil must have less than 0.5 mass % total sulfur, and sour oil must have less than 2.0 mass % total sulfur. Sweet and sour oils are not commingled at SPR, hence they are stored, marketed and transported separately.

Tool and Flowing Samples: Tool and flowing refer to crude oil sample collection methods. A tool sample (tool test) is obtained by sending a tool downhole on a wireline into a storage cavern to gather a discrete sample of oil from a prescribed depth. The tool is then brought to the surface and the sample is transferred to the TVP-95 for analysis. Flowing samples are obtained by connecting the TVP-95 instrument system directly to a cavern wellhead or flowing transport line through a sampling port. The oil is then flowed continuously through the test chamber for as long as the test needs to be run.

TVP-2000: A crude oil measurement system (gas-liquid separator, constant mass expansion tool (Grabner), gas chromatograph, and data loggers) that obtains phase behavior and compositional data, co-located with the degas plant. The TVP-2000 is used to monitor the BP pressures and flash gas compositions of the inlet and outlet streams of the degas plant for monitoring and tuning degas plant operations. The flash chamber is typically run at ~120° F and 15 psia in order to produce sufficient gas for volume flow rate determination and proper GC operations.

TVP-95: A portable set of vapor pressure VP test equipment (flash chamber, gas-liquid separator, gas chromatograph, measurement transducers and data loggers), housed in a trailer and operated by Pencor Laboratory for the SPR program. The TVP-95 is used by the SPR to measure vapor pressure and flash gas compositions of oil samples taken from SPR caverns on a semi-regular scheduled basis. The data are primarily used to establish a baseline BP pressure, corresponding GOR, flash gas composition, and vapor pressure regain rates from historical data. Typically, two tests are run for a sampling event: (1) a BPP pressure test where flash conditions are T=100° F, gas phase volume is small, and pressure is measured and (2) a GOR test where

T=100° F, P = 14.7 psia and gas volume is measured. Flash is actually performed using flowing samples so volumes are actually fluxes (volume-rates).

Vapor pressure database: Also called quarterly vapor pressure spreadsheets. The VP database is a set of four Microsoft Excel workbooks, one for each SPR site, and a set of utilities programmed with Visual Basic macros. Each site workbook contains a worksheet for each cavern at the site and each cavern worksheet contains a column of data for each sampling/test event for the cavern. A column of data represents a tabulation of the data from a Pencor Report: vapor pressure test conditions (temperature, pressure and GOR), gas chromatography results (mole fractions), and a whole oil description calculated by the EOS, and VP regain rate calculated using linear regression of screened data. The VP database is updated each time a Pencor Report is received and snapshots of the database are released to the project quarterly.

The production versions of the quarterly VP database files currently reside on the SPR project server in New Orleans, which requires a SPR network account to access. On the SPR network, the files can be accessed by running the KONFIG application. Data are organized in folders on KONFIG, with the pathname for quarterly VP data as follows:

"SPR Project Library > Engineering > Process Analysis > Process Models > Quarterly Data"

The four current Excel vapor pressure database files can also be obtained from the DynMcDermott Operational Systems Engineering Department, as they are responsible for quarterly reporting to project management.

Workover: Oilfield term applied at SPR that refers to a process in which the well(s) that connect a cavern with the ground-level infrastructure are opened and serviced for a variety of reasons.

Appendix A1

Bryan Mound Performance to Date

Actual Start Date	Cavern	Cumulative Degassed by Cavern MMB(GOV)	Actual Cavern Average Rate	Cavern Average TVP Actual	Cavern Average C3+ Recovery Actual	Cavern Average Shrinkage % Actual
9/1/2007	BM105	12.20	123,863	9.91	99.26%	0.07%
12/8/2007	BM115	10.98	127,713	11.81	99.07%	0.08%
3/3/2008	BM102	12.74	128,669	9.34	98.57%	0.08%
6/10/2008	BM104	12.60	104,099	9.21	97.39%	0.11%
10/9/2008	BM4	24.28	120,314	11.45	95.81%	0.12%
4/29/2009	BM116	11.40	105,676	11.19	97.31%	0.12%

Bryan Mound Degassing Plan (Plan A6)

Cavern	Actual/Forecast Start Date	Cumulative Degassed by Cavern MMB(GOV)	Planned Degassing Rate MBD	Processing Days
BM108	8/15/2009(actual)	13.27	112.5	118
BM114	01/02/2010	9.21	112.5	82
BM106	03/25/2010	14.93	112.5	133
BM111	08/05/2010	13.83	112.5	123
BM112	12/16/2010	13.71	112.5	122
TOTAL BM (Actual +Planned)		149.15		

Appendix A2

West Hackberry Degassing Plan (Plan A6)

Cavern	Forecast Start Date	Cumulative Degassed by Cavern MMB(GOV)	Planned Degassing Rate MBD	Processing Days
WH105	01/28/2012	12.72	112.5	113
WH111	05/20/2012	10.57	112.5	94
WH102	08/22/2012	11.78	112.5	105
WH117	12/04/2012	13.26	112.5	118
WH101	04/01/2013	12.09	112.5	108
WH115	07/18/2013	11.98	112.5	106
WH108	11/11/2013	12.21	112.5	109
WH112	03/21/2014	12.00	112.5	107
WH110	07/05/2014	12.60	112.5	112
WH114	10/25/2014	12.16	112.5	108
WH116	02/20/2015	12.41	112.5	110
WH109	06/11/2015	12.71	112.5	113
WH104	10/02/2015	12.32	112.5	110
WH106	01/19/2016	11.98	112.5	107
WH7	05/26/2016	13.62	112.5	121
WH6	10/04/2016	7.51	112.5	67
TOTAL WH (plan)		191.91		

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