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Modeling the behavior of caverns under nitrogen

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Abstract

A Hydrostatic Column Model (HCM) was developed at SANDIA to help differentiate between normal "tight" well pressure behavior and small-leak behavior under nitrogen for testing the pressure integrity of crude oil storage wells at the U.S. Strategic Petroleum Reserve. HCM was used to model extended nitrogen monitoring and Mechanical Integrity Tests (MITs) by predicting wellhead pressures along with nitrogen interface movements. A set of field experiments were also conducted where wellhead pressure and high resolution temperature and density logs were used to validate the model assuring that the relevant physical phenomena were adequately captured. This effort was motivated by steady, yet distinct, pressure behavior of a series of Big Hill wells that were placed under nitrogen for extended periods of time following anomalous pressure behavior. The wells exhibited reproducible pressure cycles with a creep-driven nitrogen pressurization rate of about 70% that of brine wells. The analysis shows that the differences in compressibility between nitrogen and the cavern liquids in a manometer configuration drives the nitrogen wellhead pressure to rise at a lower rate than a liquid filled well, even with no leak. The study also concluded that the theoretical relative pressure rate, for no leak conditions, depends on the well configuration, pressure and the location of the nitrogen-oil interface and varies from well to well. This consequently implies that wells under long term nitrogen monitoring do not necessarily pressurize with a relative rate (PN2/Pbrine) of 1.

Key words: Cavern Testing, Caverns for Liquid Storage, Computer Modeling, Gulf Coast of the U.S. and Mexico, Mechanical Integrity, MIT (Mechanical Integrity Test), Strategic Petroleum Reserves

Introduction

Several crude oil cavern storage wells at the U.S. Strategic Petroleum Reserve (SPR) Big Hill (BH) facility have been maintained under nitrogen caps for extended periods of months to years following anomalous events observed during routine wellhead pressure monitoring. An example of these anomalous pressure behaviors is shown in Figure 1 for BH103, where the cavern wellhead pressure stalled for a period of about 7 days. At the present there is still no explanation on the reason for such pressure anomaly. The nitrogen was placed over the wells as a precautionary measure because it provides:

- a buffer fluid that separates the product (crude oil) from the possible leak zone and loss to the environment, and
- as a sensitive diagnostic to identify the presence and location of a leak.

In total there have been 3 caverns that exhibited similar pressure behavior and were placed under long-term nitrogen monitoring BH103, BH107 and BH112.

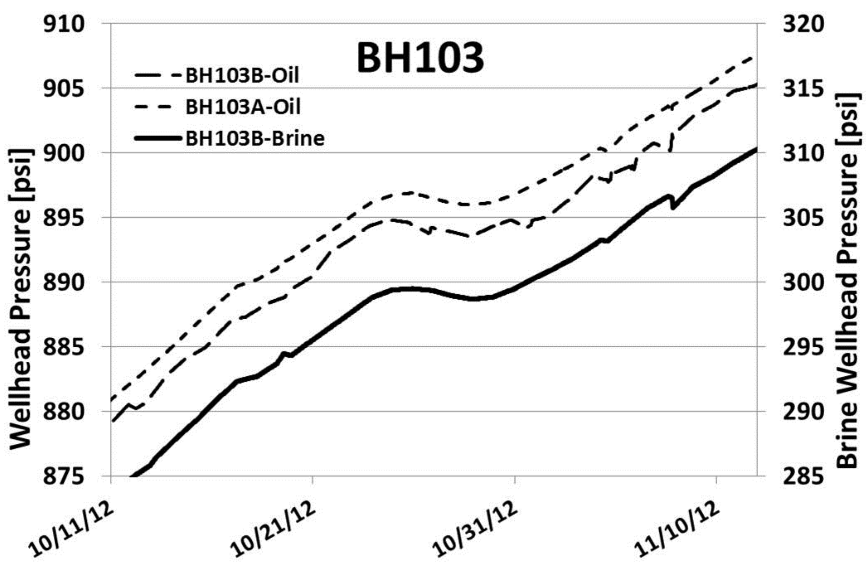


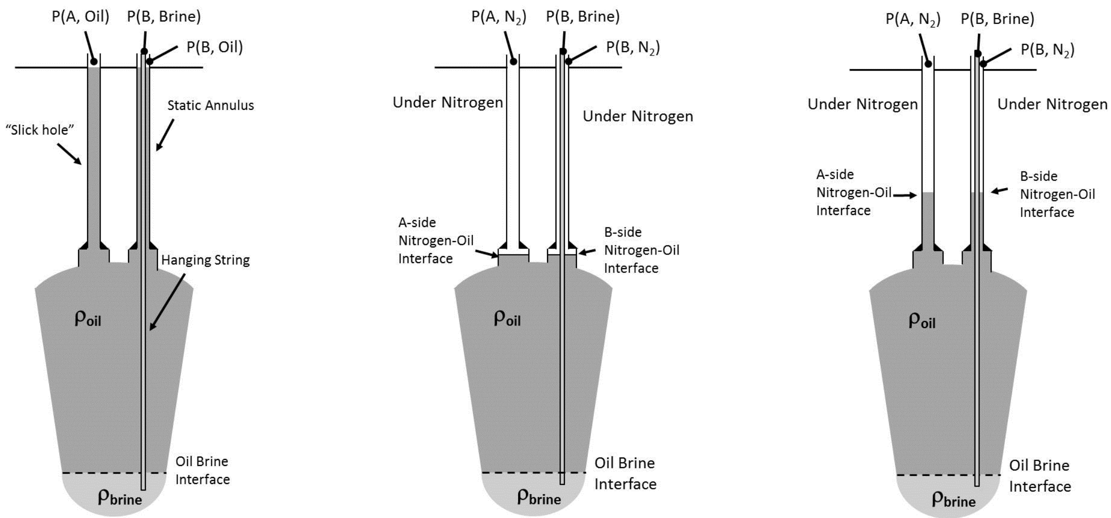
Figure 1: BH103 pressure behavior anomaly recorded in Oct. 2012.

Table 1: Listing of Big Hill caverns under extended nitrogen monitoring during the period Nov 2012 – Aug 2015.

Cavern Wells	Start	Comment	End	Comment
BH112-A,B	Nov, 2012	N_2 injected due to abnormal cavern pressurization behavior in Oct 2012	Ongoing	Still under N_2 monitoring
BH103-A,B	Nov, 2012	N_2 injected due to abnormal cavern pressurization behavior in Oct 2012	Dec, 2013	Installed cemented liner in B-well.
BH107-A,B	Dec, 2013	N2 injected due to abnormal cavern pressurization behavior in Dec 2013	Jan 2016	Installed cemented liner in B-well.

Cavern configurations

A typical SPR oil storage cavern containing two wells has continuous product and brine wellhead monitoring under normal operating conditions as shown in Figure 2(a). Oil is typically moved in and out of the cavern through the “slick hole” well that does not contain a hanging string, and this oil pressure is indicated by P(A,Oil). Brine and/or water is moved in and out of the cavern through the hanging string, with pressure indicated by P(B,Brine) in Figure 2(a). Oil is also contained and monitored in the annular space between the hanging string and cemented casing in well B, sometimes called the “static annulus” with pressure P(B,Oil).



(a) Normal operation

(b) Typical MIT configuration

(c) Typical Big Hill nitrogen monitoring configuration

Figure 2: Schematic of typical pressure monitoring configuration for SPR two-well cavern in (a) normal operations, (b) under MIT, (c) under nitrogen monitoring.

The same two-well SPR cavern under MIT configuration is depicted conceptually in Figure 2(b), where nitrogen has been pumped into one or both the slick hole and the static annulus, with pressure indicated by P(A,N_2) and P(B,N_2) respectively. Brine pressure in the hanging string is indicated by P(B,Brine). Generally speaking, the volume of nitrogen used to pressurize the wells is small enough that the brine pressure P(B,Brine) and oil-brine interface depth (OBI) are insensitive to this change. Conversely, the product wellhead pressures rise markedly as nitrogen is injected to displace oil down the wellbore, reflecting the effect of the significantly less dense nitrogen gas. During an MIT the nitrogen-oil interface (NOI) is placed below the lowest cemented casing in order to test the casing shoe, while during an extended nitrogen test the NOI is placed just below the zone of interest, often a judgment by the cavern engineer. In many cases at Big Hill, the zone of interest is the salt-caprock interface depth, where several wells failed in the past (Lord, Roberts et al. 2012). As such, many of the Big Hill cavern wells have been monitored with the NOI set several feet below the top of salt, see Figure 2(c).

Cavern behavior during MIT

Compliance with State regulators requires periodic well integrity testing which provides a large amount of data demonstrating normal pressure behavior during an MIT. An observation throughout many years of MIT testing at SPR is that the nitrogen pressurization rate is comparable to the brine pressurization rate, thus yielding an expected relative pressurization rate of about 1. The relative pressurization rate is defined as follows:

$$\textit{Relative Rate of Pressurization} = \frac{\textit{Nitrogen pressurization rate}}{\textit{Brine Pressurization rate}}$$

Figure 3 shows a compilation of MIT data for all of the Big Hill wells during a period 2009-2015, expressed in terms of relative pressurization rates of the A-well nitrogen and B-well nitrogen vs. brine. These data support the general notion that relative pressurization rates during MIT are near 1. There is a subtle difference between wells, however, with A wells (slick) pressurizing with an average relative rate to brine of 0.88 and B wells (with the hanging string) pressurizing at an average rate of 0.93.

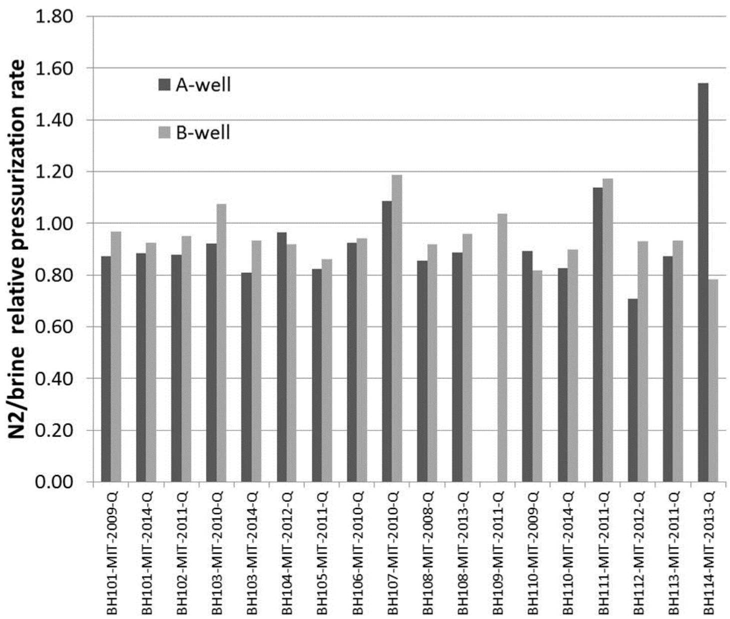


Figure 3: Relative rate of pressurization for all Big Hill caverns under MIT.

<u>Cavern behavior during long term nitrogen monitoring at BH</u>

During the monitoring of the 3 BH caverns under nitrogen a steady, yet distinct, pressure behavior was observed. A plot of BH103 cavern pressure history for the entirety of the monitoring period is shown in Figure 4. The figure also illustrates the time of each log recording. The cavern went through 6 pressure cycles before undergoing a remediation in Jan 2014, due to large deformation at the caprock/salt interface as recorded by a multi-arm caliper (MAC) survey. A pressure cycle in the context of an SPR cavern is a period during which average cavern fluid pressure rises steadily due to a combination of cavern creep closure and thermal expansion of the oil from geothermal heating. Pressure rise rates at SPR typically range from ~0.5-1.0 psi/day under normal circumstances. Note the cavern is “shut in” during this period to retain a constant mass of fluid in the cavern. The cycle is punctuated by (i) a start date when cavern pressure is placed into the lower end of its normal operating range by prescribed fluid movement in or out to reach a target starting pressure, and (ii) an end date when fluid pressure is relieved by draining fluid (typically brine) to reach a target starting pressure, coinciding with the start of the next cycle.

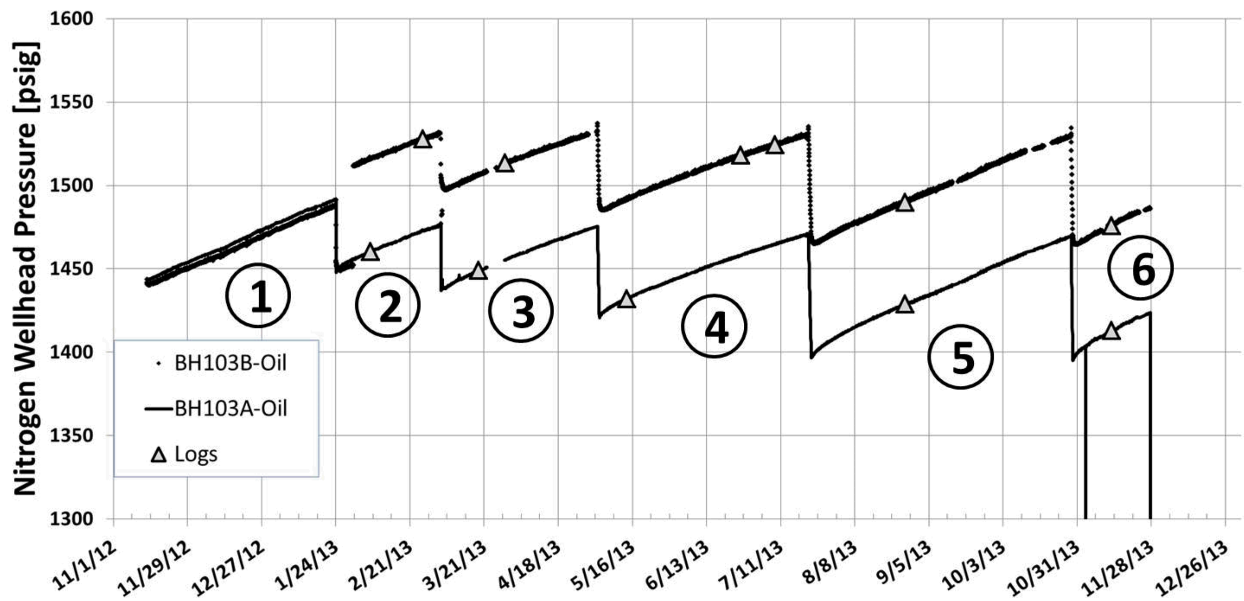


Figure 4: BH103 pressure history during nitrogen monitoring. The plot shows 6 distinct pressure cycles.

The rate of pressure rise for both nitrogen and brine for each of the 6 pressure cycles was evaluated by linear curve fitting. The slope of the pressure curve was evaluated between the start and end date of the pressure cycle. The rate of brine pressurization was found to slightly vary from cycle to cycle due to the cavern salt creep. It was found that in the 12 months of nitrogen data, the relative rate is very consistent from cycle to cycle and averages 0.69 for well A and 0.68 for well B. Similar calculations were carried out for BH107 and BH112. Results for average relative pressurization rate vs. the latest MIT are shown in Table 2.

Table 2: Relative pressurization rates for Big Hill caverns 103, 107 and 112.

Relative Pressurization Rates						
	BH103		**BH107**		**BH112**	
	Well A	**Well B**	**Well A**	**Well B**	**Well A**	**Well B**
MIT (latest before monitoring)	0.92	1.08	1.09	1.19	0.71	0.93
Average Long term nitrogen monitoring	0.69	0.68	0.68	0.68	0.69	0.70

Methodology

Model

A numerical model has been developed to simulate static fluid pressure and density distributions in the cavern wells. The basic equation for the hydrostatic column model is as follows:

$$\frac{dP}{dz} = \rho g \qquad (1)$$

where, ρ is density, g is gravity constant, P is pressure and z is depth. Density is both pressure and temperature, T, dependent and the relationship is also fluid dependent.

For gas, density is given by the non-ideal gas law:

$$\rho_{N_2} = \frac{P}{R_{N_2} T Z_{N_2}} \qquad (2)$$

where, R_{N2}=297 (Pa m^3 $K^{-1}kg^{-1}$) is the gas constant for nitrogen, T is temperature and Z_{N2} is the non-ideal factor (1 for ideal gas).

For brine and oil, density is defined with:

$$\rho_{liq} = \frac{\rho_0}{\left(1 - k\left(P - P_0\right)\right)\left(1 + \beta\left(T - T_0\right)\right)} \qquad (3)$$

where k is fluid compressibility ($k=1/E$, E is the elastic modulus), β is the thermal expansion coefficient and ρ_0 is the density at P_0 and T_0.

Model verification

SPR cavern BH101 was chosen as a control experiment to validate the hydrostatic column model predictions for pressure and coupled interface movement values. This cavern was chosen because it is believed to be fluid and gas tight, and has a historical record of stable and predictable creep closure-driven wellhead pressure rise. Big Hill cavern 101 is a two-well cavern with A being the ‘slick’ well and B containing the brine string. The interface of the slick well was chosen to be placed inside the casing near the caprock/salt interface, while the interface for well B was placed below the casing shoe as depicted in Figure 5.

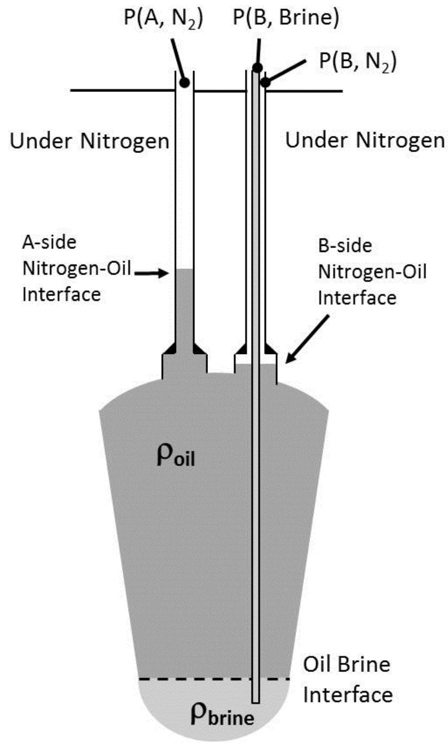


Figure 5: Configuration of BH101 during control test for model validation.

The log data and the initialization wellhead pressures were used to tune the model which was able to accurately predict the wellhead pressures for both wells as well as the pressure profile as a function of depth. A list of the parameters used in the predictive model and their values is included in Table 3. Figure 6is a plot of the magnitude of the difference in the measured and predicted pressure as a function of depth for both wells. For this simulation the difference never exceeds 2 psi and supports the validity of the model.

Table 3: List of parameters used in the hydrostatic column model.

Fluid	Symbol	Value	Units	Description
oil	β	4.44E-04	1/F	liquid thermal expansion coefficient
	E	2.00E+05	psi	liquid bulk modulus of elasticity
	ρ_o	853	kg/m^3	density at standard pressure (P_o) and temperature (T_o)
Unsaturated Brine	β	1.15E-04	1/F	liquid thermal expansion coefficient
	E	3.10E+05	psi	liquid bulk modulus of elasticity
	ρ_o	1176	kg/m^3	density at standard pressure (P_o) and temperature (T_o)

Fluid	Symbol	Value	Units	Description
Brine	β	1.15E-04	1/F	liquid thermal expansion coefficient
	E	3.10E+05	psi	liquid bulk modulus of elasticity
	ρ_o	1200	kg/m^3	density at standard pressure (P_o) and temperature (T_o)
Nitrogen	Z_{N2}	1.02	kg/m^3	Nitrogen non-ideal factor
	R_{N2}	296.8	N*m/kg*K	Gas constant for nitrogen

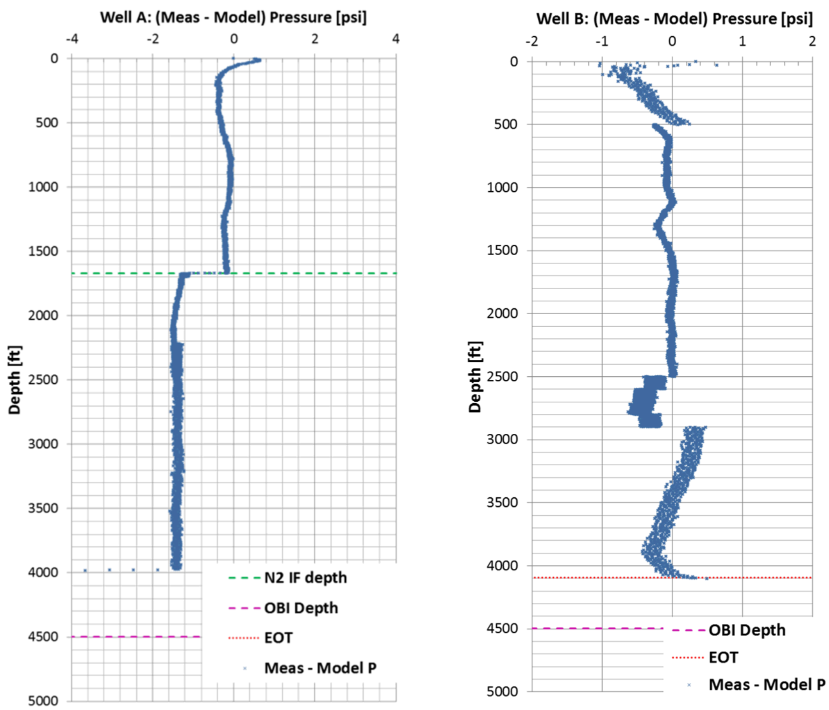


Figure 6: Illustration of the difference between measured and predicted pressure as a function of depth for both BH101 well A and well B.

The model also performed very well in predicting the oil/N_2 wellhead pressure as function of cavern brine pressure (and time). Figure 7 shows the measured values of pressure at the wellhead (from the Data historian) for the duration of the test. The solid lines correspond to the model predictions and strong agreement with measured data is observed. As annotated in the figure the model prediction for relative pressurization rate for well A is 0.71, which is statistically identical to the rate measured. Similarly for well B the relative rate was predicted to be 0.93. Additional details are contained in (Bettin, Lord et al. 2015).

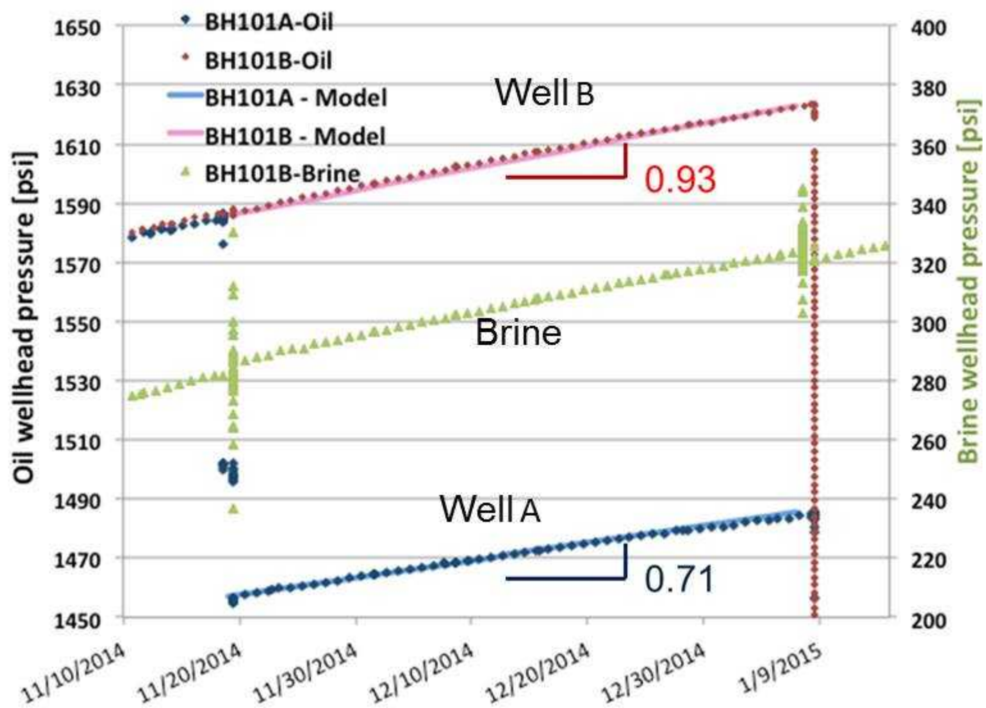


Figure 7: Pressure history for BH101 cavern during the long term nitrogen test. Solid lines represent model predictions after calibration. Annotated are also the relative pressurization rates predicted by the model.

The validation and verification of the model with the field test was successful in concluding, that in fact, the model does capture the relevant physics of the problem and can be used to accurately predict the pressure behavior of a cavern under nitrogen. This analysis also concluded that wells under nitrogen monitoring with the NOI up in the relatively narrow cased hole do not pressurize with a relative rate (P(N2)/P(brine)) of 1 but in fact the differences in compressibility between nitrogen and the cavern filled with liquid causes the nitrogen pressure to rise at a lower rate. It was found that the relative rate of pressurization depends on the well configuration, pressure and location of the NOI and varies from well to well. For the case when the NOI in below the casing shoe, geometry (particularly the diameter of the chimney) plays a significant role in the rate of pressurization. For the BH caverns this rate was found to be around 0.9 which is consistent with the historical data as presented in Figure 3.

Big Hill caverns results

Big Hill cavern 103

BH103 pressure behavior was modelled for the duration of the nitrogen monitoring. The values of the pressure and the interface depth values recorded during the logging events were used to calibrate and determine the mass of nitrogen injected into the wellbore. For well A (slick) the mass of nitrogen was calculated to be 4545 Kg. Similarly, for well B the mass was estimated to be 2790 Kg.

Very good agreement was found by comparing the model predictions to measured data for each cycle as shown in Figure 8. The first cycle for well B was not modelled because no logs were available for that time period and nitrogen was bled off to bring the interface to the desired depth. The average values of relative pressurization rates for each cycle as they compared to the model predictions are shown in Table 4. An average relative rate of pressurization of 0.68 (well A) and 0.69 (well B) was found to be consistent with the model average prediction of 0.71 (well A) and 0.70 (well B). Additionally very good agreement was found with the predicted NOI movements and the values recorded during the logs. This is illustrated in Figure 9.

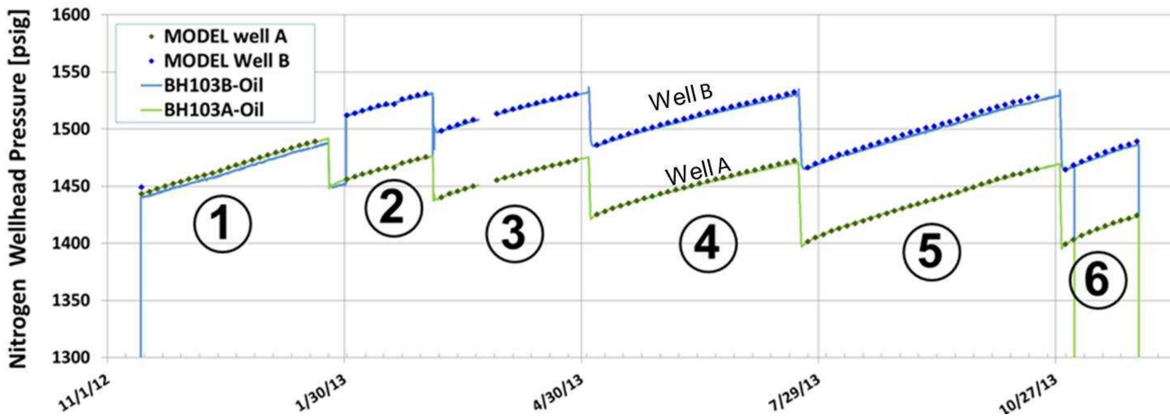


Figure 8: Pressure model predictions for BH103 compared to measured data.

Table 4: BH103 rates of pressurization for each cycle compared to the model predictions.

Cycle #	Start date	End date	Pressurization Rate [psi/day]		Relative Pressurization Rate [psi/psi]	
			BH103A		BH103B	
			DCS	MODEL	DCS	MODEL
1	11/13/2012	1/19/2013	0.702	0.716	0.697	
2	01/29/13	3/4/2013	0.693	0.715	0.665	0.703
3	3/5/2013	4/26/2013	0.717	0.714	0.686	0.701
4	5/3/2013	7/22/2013	0.678	0.714	0.678	0.697
5	7/22/2013	10/28/2013	0.689	0.711	0.666	0.694
6	10/29/2013	11/25/2013	0.670	0.708	0.662	0.688
		Average	**0.69**	**0.71**	**0.68**	**0.70**

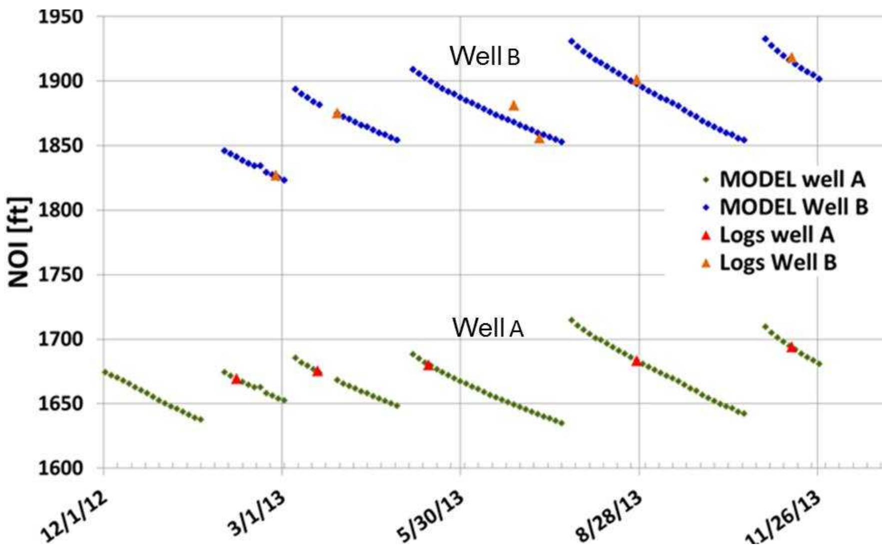


Figure 9: NOI model predictions for BH103 compared to log data.

Big Hill cavern 107

The pressure behavior of BH107 cavern has been modelled and analyzed for the duration of the monitoring. Similar to the procedure used for BH103, the log data was used to calibrate and determine the mass of nitrogen injected into the wellbore. For well A (slick) the mass of nitrogen was calculated to be 5068 Kg. Similarly, for well B the mass was estimated to be 1302 Kg.

Very good agreement was found by comparing modeled predictions to measured data for each cycle, see Figure 10. The average values of relative pressurization rates for each cycle as they compared to the model predictions are shown in Table 5. An average relative rate of pressurization of 0.68 was found to be consistent with the model average prediction of 0.71. Additionally, very good agreement was found with the predicted NOI movements and the values recorded during the logs.

Figure 10: Pressure model predictions for BH107 compared to measured data.

Table 5: Average BH107 rates of pressurization as they compare to the model predictions.

Pressurization Rate [psi/day]		Relative Pressurization Rate [psi/psi]	
BH107A		BH107B	
Average DCS	Average MODEL	Average DCS	Average MODEL
0.68	0.71	0.68	0.71

Big Hill cavern 112

The pressure behavior of BH112 cavern has also been modelled and analyzed. Similar to the procedure used for BH103, the log data was used to calibrate and determine the mass of nitrogen injected into the wellbore. For well A (slick) the mass of nitrogen was calculated to be 4645 Kg. Similarly, for well B the mass was estimated to be 1239 Kg. Very good agreement was found by comparing modeled predictions to measured data for each cycle as it is shown in Figure 11. An average relative rate of pressurization of 0.69 (well A) and 0.70 (well B) was found to be consistent with the model average prediction of 0.72. Additionally very good agreement was found with the predicted NOI movements and the values recorded during the logs.

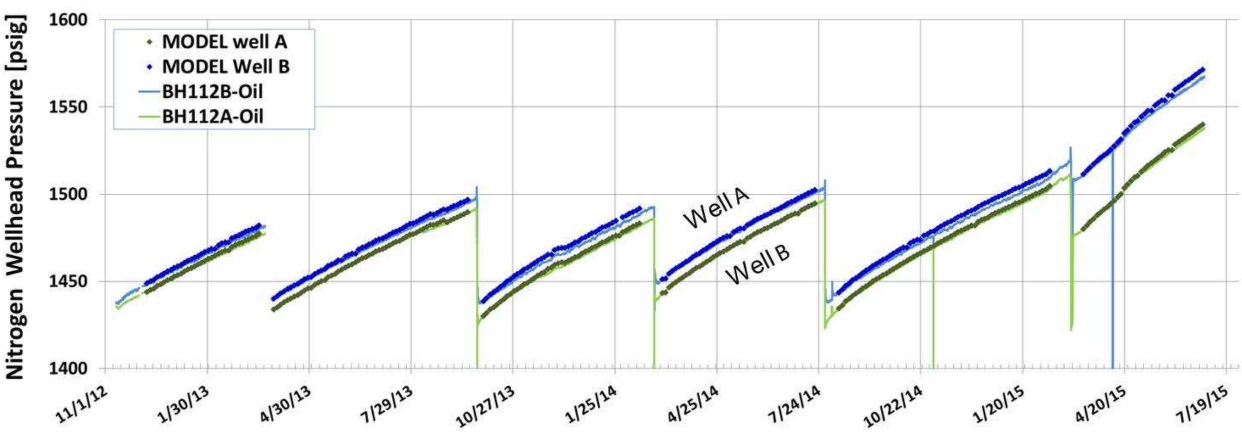


Figure 11: Pressure model predictions for BH112 compared to measured data.

Table 6: Average BH112 rates of pressurization as they compare to the model predictions.

Pressurization Rate [psi/day]		Relative Pressurization Rate [psi/psi]	
BH112A		BH112B	
Average DCS	Average MODEL	Average DCS	Average MODEL
0.69	0.72	0.70	0.72

Conclusions

The current study reviewed a range of field data and model results related to the pressure integrity of selected cavern wells at the Big Hill SPR site after they showed brief periods (1-2 weeks) of anomalous behavior.

1. Big Hill caverns 103, 107, and 112 exhibited no evidence of active leaks of oil or nitrogen during the period December 2012 – June 2015
2. The root causes for the anomalous behavior in each of the above wells that originally drew attention and nitrogen monitoring to them has not been determined
3. The relative rate of pressurization depends on the well configuration, pressure and location of the NOI and varies from well to well and is not necessarily expected to even in a “tight” well.
4. The relative pressurization rate of nitrogen to brine of ~0.7 observed in all three caverns during extended nitrogen monitoring is in fact an outcome of the monitoring configuration for a mass-tight system
5. For the case when the NOI in below the casing shoe the relative pressurization rate was found to be around 0.9 which is consistent with the historical data.

The model offers the capability to predict relative pressurization rate and interface movement for system with known geometry, fluid properties and N_2 mass loss rate equal to zero. Current work is underway to extend capabilities and validate the HCM for N_2 leak cases by comparing field data for controlled N_2 mass loss rate tests.

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