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SPR Hydrostatic Column Model Verification and Validation

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Abstract

A Hydrostatic Column Model (HCM) was developed to help differentiate between normal "tight" well behavior and small-leak behavior under nitrogen for testing the pressure integrity of crude oil storage wells at the U.S. Strategic Petroleum Reserve. This effort was motivated by steady, yet distinct, pressure behavior of a series of Big Hill caverns that have been placed under nitrogen for extended period of time. This report describes the HCM model, its functional requirements, the model structure and the verification and validation process. Different modes of operation are also described, which illustrate how the software can be used to model extended nitrogen monitoring and Mechanical Integrity Tests by predicting wellhead pressures along with nitrogen interface movements. Model verification has shown that the program runs correctly and it is implemented as intended. The cavern BH101 long term nitrogen test was used to validate the model which showed very good agreement with measured data. This supports the claim that the model is, in fact, capturing the relevant physical phenomena and can be used to make accurate predictions of both wellhead pressure and interface movements.

Acknowledgments

Funding for this work was provided by the U.S. Strategic Petroleum Reserve.

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NOMENCLATURE

BH	Big Hill SPR site
BHF	Braden head flange
CCL	Casing collar locator
CS, CSD	Casing shoe depth
DCS	Distributed control system
DOE	Department of Energy
FFPO	Fluor Federal Petroleum Operations – SPR M&O contractor
FD	Finite difference
HCM	Hydrostatic Column Model
HS	Hanging string
ID	Internal diameter
LT	Long term (abbreviation used for extended nitrogen test)
MIT	Mechanical integrity test, a specific application of a NIT
MMB	Million barrels, volume
N2 or N_2	Nitrogen gas
NIT	Nitrogen integrity test
NOI	Nitrogen oil interface
OBI	Oil brine interface
OD	Outer diameter
SNL	Sandia National Laboratories
SPR	Strategic Petroleum Reserve
SQA	Software quality assurance
TD	Total depth
WH	West Hackberry SPR site

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1 EXECUTIVE SUMMARY

This report provides a detailed description of a numerical model, namely the Strategic Petroleum Reserve (SPR) Hydrostatic Column Model (HCM), developed at Sandia to interpret wellhead pressure time series data under nitrogen testing conditions.

The need for the HCM model arose during 2013-2014 as data streams from extended nitrogen monitoring of selected SPR wells showed behavior that was reproducible, yet distinct, from the more familiar mechanical integrity test (MIT) data that are collected routinely around SPR. Internal debate on the SPR project arose around how to interpret the new data, and in particular whether the wells under extended monitoring were leaking or not. The early discussion revolved around qualitative analyses of the new data, and Sandia decided to develop a relatively simple hydrostatic column model to calculate what type of pressure behavior should be expected under tight and leak conditions in the extended test configuration and the more familiar MIT configuration. Sandia and Fluor Federal Petroleum Operations (FFPO) also performed a pair of control tests in which "tight" cavern wells were tested under extended nitrogen conditions to establish what a no-leak case looked like.

The HCM was developed as a 1-dimensional representation of the well and is implemented with a finite difference approach. Currently it can accommodate both single and double well cavern configurations and it can be operated in a variety of modes to predict wellhead pressures and nitrogen oil interface (NOI) depths. The HCM underwent a formal software quality assurance (SQA) process which is described in this report. The model implementation has been verified and it has shown that the program runs correctly and it is implemented as intended. SPR cavern BH101 was chosen as a control experiment to validate the hydrostatic column model predictions for pressure and coupled interface movement values. The cavern passed its state-required 5 year MIT in Oct 2014 and initialization of the special extended nitrogen test was conducted on Nov 19, 2014. The model prediction for relative pressurization rate for well A during the test is 0.71, which is statistically identical to the rate measured. Similarly for well B the relative rate was predicted to be 0.93. The relative pressurization rates both measured and predicted are shown in Table 1-1.

Table 1-1: Relative pressurization rates for BH101 wells during the long term nitrogen monitoring test. Both the measured and the model predictions are shown.

	BH101A N_2	BH101B N_2	BH101B Brine
Relative Rate [psi/psi] (model)	0.71	0.93	1
Relative Rate [psi/psi] (experiment)	0.72	0.94	1

The very close correlation between measured and modeled data supports the claim that the model is, in fact capturing the relevant physical phenomena and can be used to make accurate predictions of both wellhead pressure and NOI movements for SPR caverns under nitrogen monitoring conditions.

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2 INTRODUCTION

2.1 Background

Nitrogen is used as a diagnostic tool to test pressure integrity of cavern wells at the U.S. Strategic Petroleum Reserve (SPR). A test methodology for SPR was published in the 1980's (Goin 1981; PB-KBB 1985) that remains largely the same today (Eldredge 2014) in its basic implementation. This method also meets regulatory requirements imposed by the states where the oil storage facilities are operated, and has been recognized as the most common means to test well integrity in storage caverns along the U.S. Gulf Coast (Skaug, Ratigan et al. 2011). The only substantial difference between the approach in the 1980's and current day is that there is no current conversion of nitrogen gas leak rate to oil leak rate, which is simply a post-processing step after the physical test sequence is completed.

Due to ever more stringent environmental laws and increased management attention to early leak detection and leak prevention, nitrogen is periodically used at SPR as an early mitigation and diagnostic tool when behavior suggestive of an early leak is observed at oil storage wells. Nitrogen provides several benefits in this scenario:

- as 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.

The continuous use of nitrogen over periods of months or more on given wells is relatively new at SPR, and has drawn management attention for several reasons. First, wells under nitrogen are exposed to a different pressure profile than normal operating conditions, and present an operating scenario that must be carefully reviewed for safety and possible negative impacts to the wells and stored product. Second, wells under nitrogen are not immediately ready for drawdown, and must be drained of nitrogen and re-piped in order to produce oil.

U.S. Strategic Petroleum Reserve is currently holding 2 caverns (4 wells) under long term nitrogen monitoring at Big Hill storage facility due to small-leak suspicion. The caverns have been under special nitrogen monitoring starting in Nov 2012 for BH112 and Dec 2013 for BH107 and indicate steady, yet distinct, pressurization rates for different wells within the same cavern. The wells under nitrogen (slick well and static annulus) pressurize at about 2/3 the rate of a well under liquid (hanging string). Modeling of the cavern system has indicated that the differences are due to basic fluid physics in a non-leaking system, with behavior driven by the several order-of-magnitude disparities in fluid compressibility between gas and liquid in a cavern system subjected to constant creep closure during the test period.

A hydrostatic column model has been developed that predicts the pressure profile in the cavern as well as the location of the nitrogen/oil interface (NOI). To assure model accuracy, relevance, and traceability, software quality assurance (SQA) principles are being applied as the framework for software development modification and documentation. The process consists of four basic developmental phases that specify: software requirements, design, verification and validation, and instructions on use.

2.1.1 SPR Cavern Pressure Monitoring System

The pressure of SPR caverns, typically oil and brine, is continuously recorded and collected at the wellhead. A typical two well configuration under normal operating conditions is shown in Figure 2-1(a). In this particular schematic well A is the designated 'slick' well which is use to move oil in and out of the cavern. The oil wellhead pressure monitored in this point is labeled **P(A,Oil).** The well that contains the hanging string, (in this case B) is used for brine and/or water movements and has 2 monitoring points, one for the brine inside the hanging string **P(B,brine),** the other the oil pressure in the static annulus **P(B,oil)**.

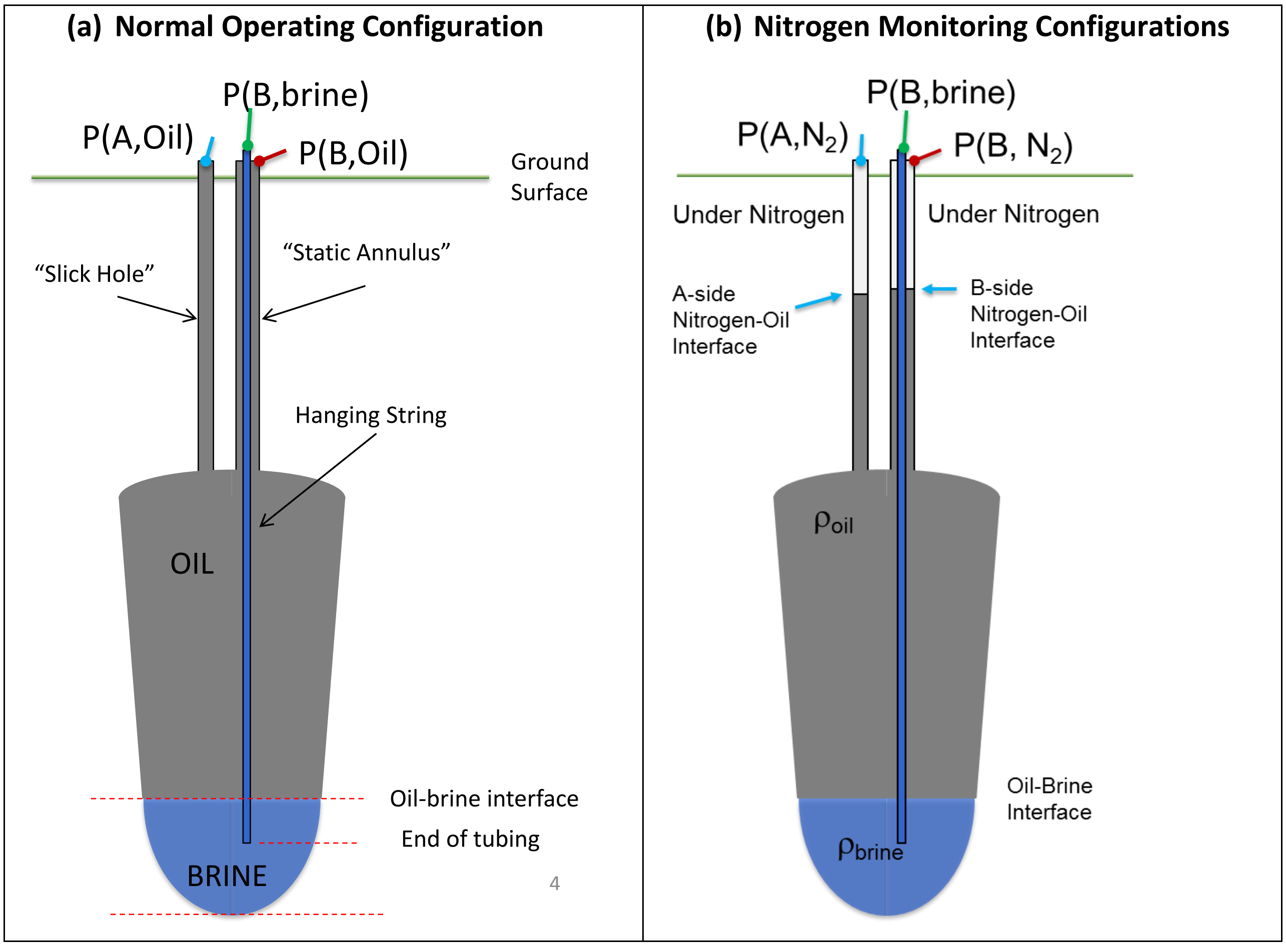

Figure 2-1: Schematic of typical pressure monitoring configuration for SPR two-well cavern in (a) normal operations, and (b) under nitrogen monitoring.

When a well is under nitrogen monitoring, either for a regularly scheduled mechanical integrity test (MIT) or due to suspicious pressure behavior, nitrogen is pumped into both wells to move the oil interface to the desired depth. A schematic of a typical two wells system under nitrogen configuration is shown conceptually in Figure 2-1(b). In this case the wellhead pressures are now **P(A,N_2)** and **P(B,N_2),** respectively, while the brine pressure in the hanging string is still indicated by **P(B,brine)**. The volume of nitrogen used to pressurize the wells is normally 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.

2.2 Software QA Background

This report documents verification and validation of the Sandia developed Hydrostatic Column Model (HCM) as part of an ongoing effort of Sandia National Laboratories to baseline software critical to its mission on the Strategic Petroleum Reserve (SPR). Validation, in the context of this report, refers to both qualitative and quantitative comparisons to observed or measured data.

As clarification of terminology used in this document, verification is the process of showing that equations, models and data are coded and solved correctly and validation shows that the model does an acceptable job of simulating the physical process for which it was designed. This is accomplished by comparing simulation results with real world data. In the more formal Software Quality Assurance (SQA) lifecycle, these exercises are sometime performed together and referred to as software Verification and Validation (V&V). More simply put: verification – programmed properly; validation – comparison to measured/real world data.

This report is organized using typical SQA principles as a framework in which software is developed or modified following four basic developmental phases that specify the software's requirements, design, verification/validation and user instructions. Requirements (section 0) are the specific required functionalities, capabilities or attributes of the software or software modifications. The design (section 0) describes how the requirements are implemented and programmed. User interaction with the software is described in a user guide (not specifically provided but discussed in section) and verification/validation (section 5 and 6) demonstrates that the software correctly implements the requirements and validation demonstrates that the software adequately models the physical process for which it is designed.

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3 SUMMARY OF FUNCTIONAL REQUIREMENTS

The functionalities, capabilities and attributes of the SNL Hydrostatic Column Model are as follows:

R.1 Simulate wellhead pressures in two nitrogen monitoring configurations:

(1) slick well (oil with N_2 cap).
(2) brine well with hanging string (oil capped with N_2 in static annulus, brine in hanging string).

R.2 The gas phase to be modeled using non-ideal gas law $PV = ZnRT$ with user specifiable parameters.

R.3 The liquid phase to be modeled by the following:

$$\frac{\partial P}{\partial z} = \rho(T, z) \cdot g$$

ρ to include effects of thermal expansion and mechanical compressibility, with user specified coefficients for oil (β_{oil}, E_{oil}) and brine (β_{brine}, E_{brine}), and user specified oil (ρ_{oil}) and brine density (ρ_{brine}).

R.4 The temperature gradient with depth *T(z)* to be user specifiable and the model to accommodate different temperature profiles (cavern specific and/or at test initiation and finalization).

R.5 Well zone discretization to be user specifiable.

R.6 Model to calculate interface locations (NOI) and nitrogen mass injected (M_{N_2}) in well for given wellhead pressures (P_{N_2}).

R.7 Model to determines nitrogen wellhead pressure (P_{N_2}) and interface location (NOI) for given nitrogen mass (M_{N_2}) injected by iteration process.

R.8 Model to predict gas pressure history for specified nitrogen mass leak rate ($\dot{m}_{leak}$) – implemented but not verified/validated herein; waiting on a controlled leak test. Demonstration is available in (Rudeen and Lord 2015)

R.9 Model to be implemented in Excel spreadsheet using combination of spreadsheet functions and Visual Basic macros.

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4 MODEL DESIGN

4.1 Governing Equations

A numerical model has been developed to simulate static fluid pressure and density distributions in the cavern wells in order to provide a theoretical basis for analyzing the pressure relationships observed at the cavern wellheads during MIT/NIT test periods.

The basic equation for the hydrostatic column model is as follows:

$$\frac{dP}{dz} = \rho g \qquad \textbf{(4-1)}$$

or for finite-difference modeling:

$$\boldsymbol{P}(\boldsymbol{i}) = \boldsymbol{P}(\boldsymbol{i}-\mathbf{1}) + \Delta\boldsymbol{P}(\boldsymbol{i}-\mathbf{1}) \qquad \textbf{(4-2)}$$

where,

$$\Delta\boldsymbol{P}(i-1) = g\rho(i-1)\Delta z(\boldsymbol{i}-1) \qquad \textbf{(4-3)}$$

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.

4.1.1 Gas – N_2

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

$$\rho_{N_2} = \frac{P}{R_{N_2} T Z_{N_2}} \qquad \textbf{(4-4)}$$

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).

4.1.2 Liquid – Brine or Oil

For brine and oil, density is defined with:

$$\rho_{liq} = \frac{\rho_0}{\left(1-k\left(P-P_0\right)\right)\left(1+\beta\left(T-T_0\right)\right)} \qquad \textbf{(4-5)}$$

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.

4.1.3 Units

Input and output data are generally specified in standard field units: (barrels, psi, ^oF, feet) which are converted to metric units for model computations: (m^3, Pa, ^oK, m). However, there are exceptions, particularly mass which specified in kg and time which is in days.

4.1.4 Using Hydrostatic Model for Time Dependent Modeling

HCM calculates depth dependent density and pressure for a static column of fluid (gas, oil or brine). However, a "slow" time dependent or quasi-static process can be modeled by specifying a series of time dependent pressure boundary conditions where for each step the fluid column is assumed to be in static equilibrium. In the case of SPR well modeling, the time dependence comes from slow, salt-creep induced cavern closure or cavern volume shrinkage.

At SPR cavern closure produces a wellhead pressurization rate of ~1 psi/day for "tight" wells. The pressurization rate is site and cavern dependent and since cavern pressures are cycled between prescribed maximums and minimums, it also depends on time. For non-leaking wells both the brine and oil wellhead pressures should reflect the same creep closure induced pressurization rate. For leaking wells both the brine and oil wellhead pressure will reflect reduced or even negative pressurization rates. However, under MIT conditions, with oil wells capped with nitrogen and an intact brine string, brine pressurization should follow the creep closure rate, but the oil/N2 well head pressurization rate will be slightly reduced. The amount of reduction is related to the compressibility of nitrogen and well geometry in the region of the oil/nitrogen interface. Thus, for time dependent modeling of an MIT, brine wellhead pressure should be based on the brine pressurization rate just prior to the test or during the test if the hanging brine string is intact.

4.2 Model Data

This section describes all variables used in the model and categorizes them as:

- Default constants
- Problem dependent fluid parameters
- Problem dependent well geometry parameters
- Quasi-static parameters
- Boundary conditions
- Model calculated output data
- Post-processed output data

Default constants are listed below and the numerical value used in the model is also included.

$$
\begin{aligned}
&g = 9.81 \text{ m/s} && -\text{ gravity constant}\\
&\bar{P}_0 = \text{ 1 atm = 1.014e5 Pa} && -\text{ reference pressure}\\
&\bar{T}_0 = 60^{\text{o}}\text{ F = 288.706 K} && -\text{ reference temperature}\\
&E_{Br} = \text{2.14E9Pa = 3.10e5 psi} && -\text{ brine elastic modulus}\\
&E_{oil} = \text{ 1.38e9 Pa = 2.0e5 psi} && -\text{ oil elasitic modulus}\\
&\beta_{Br} = \text{ 1.15e-4 F}^{-1}\text{ = 2.07e-4 K}^{-1} && -\text{ brine thermal expansion coefficient}\\
&\beta_{oil} = \text{ 4.44e-4 F}^{-1}\text{ = 7.99e-4 K}^{-1} && -\text{ oil thermal expansion coefficient}\\
&R_{N2} = \text{ 296.8 N·m/kg·K} && -\text{ gas constant for nitrogen}
\end{aligned}
\tag{4-6}
$$

If fine tuning of the model is necessary, fluid properties (E and β) can be specified by the user.

Problem dependent fluid parameters:

$\rho_{Br}^{0}, \rho_{oil}^{0}$	– liquid reference densities
Z_{N_2}	– nitrogen non-ideal factor
$T(z,t)$	– temperature profiles

Problem dependent well geometry data:

$r_i(z),\ r_o(z)$	– inside and outside casing dimensions
$\Delta z(z)$	– variable zone sizes

Inside the hanging string and slick well, inner radii and Δz are used to calculate cell volumes. For the oil annulus surrounding the hanging string the outside radius of the hanging string, inside radius of inner cemented casing and Δz are used calculate the annular zone volume.

Quasi-static parameters:

$\dot{P}_k$	– baseline cavern pressurization rate
$\dot{M}$	– nitrogen mass loss rate
$\Delta t(t)$	– variable timestep

These parameters are used for time dependent predictions from a static initial state. For typical MIT calculations these are not used. Instead, separate static calculations at initialization and finalization are performed. The initialization step is used to tune or calibrate the model and to determine the mass of nitrogen in the system and the finalization state is calculated assuming $\dot{M}$ is zero.

Boundary Conditions:

$$P_{N_2}(0), P_{Br}(0), P_{oil}(0) \quad \text{– wellhead pressures} \tag{4-7}$$

Wellhead pressures are the boundary conditions for all static calculations. If unknown, the pressure BC is found by iteration until another known quantity is matched, such as nitrogen mass or the nitrogen interface depth.

Primary model calculated output data:

$P_{N_2}(z), P_{Br}(z), P_{oil}(z)$	– depth dependent fluid pressures
$\rho_{N_2}(z), \rho_{Br}(z), \rho_{oil}(z)$	– depth dependent fluid densities

Post-processed output data:

NOI, NBI – nitrogen oil interface, nitrogen brine interface

M_{N_2} – nitrogen mass above interface

The nitrogen interface is located at the depth where nitrogen pressure equals liquid (oil or brine) pressure. Nitrogen mass is calculated as the sum of the incremental mass for all zones above the nitrogen interface. Interpolation is used to locate the interface within a cell and to calculate the mass.

A work flow of the model is illustrated in Figure 4-1.

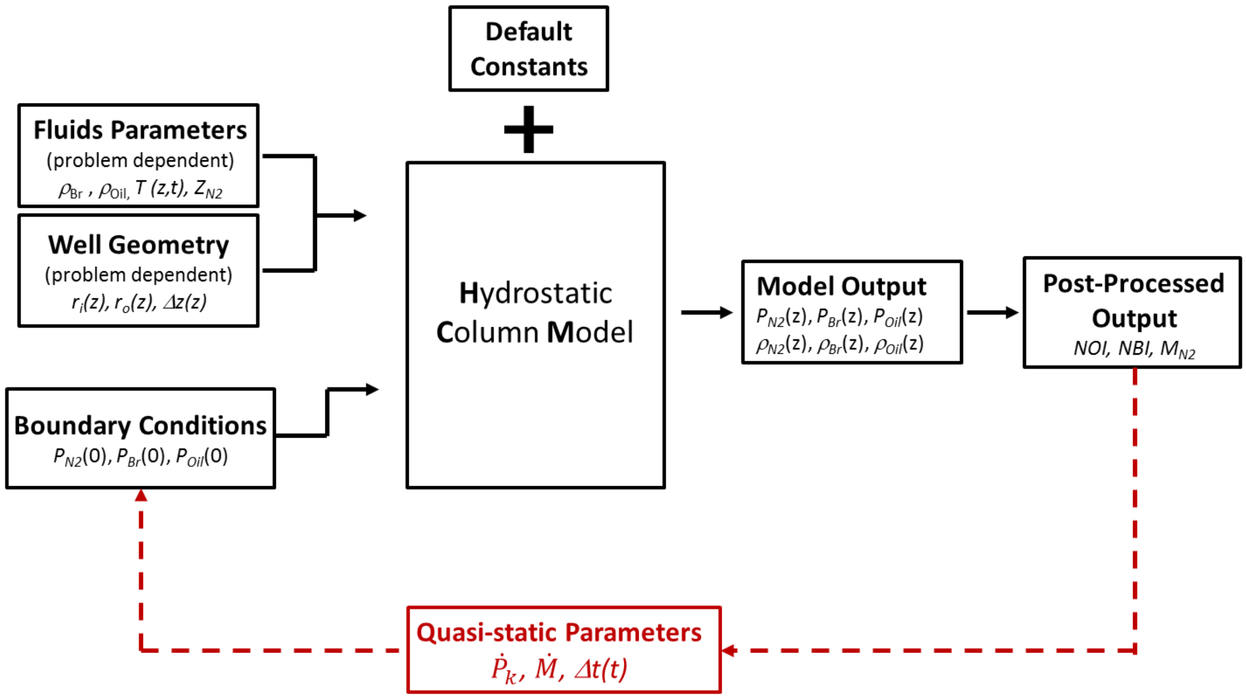


Figure 4-1: Workflow of data inputs and outputs for the HCM.

4.3 Model Structure

4.3.1 Model Domain

Each well is modeled separately using a finite difference approach. The well containing a brine string is treated as two wells - one for the brine string and one for the oil annulus. Each well is modelled using two independent single-fluid hydrostatic columns – one for the resident fluid (oil or brine) and one for nitrogen. Well internal diameters (ID) are estimated from nominal casing diameters in the cased sections, and from a combination of nitrogen injection and sonar data in the salt chimney and possibly cavern. The model is effectively one-dimensional with depth (z), and fluid properties (pressure, density, temperature) vary vertically but do not vary in the horizontal direction across the diameter of the domain. However, geometry (well radius) does vary with depth. Variable zone sizing (Δz) can be used so zone sizes can be refined over key depth zones where fluid interfaces (nitrogen-oil) occur. For a given well the geometry of both the nitrogen column and fluid column are identical. A logical sketch of the model domain for a representative well is given in Figure 4-2.

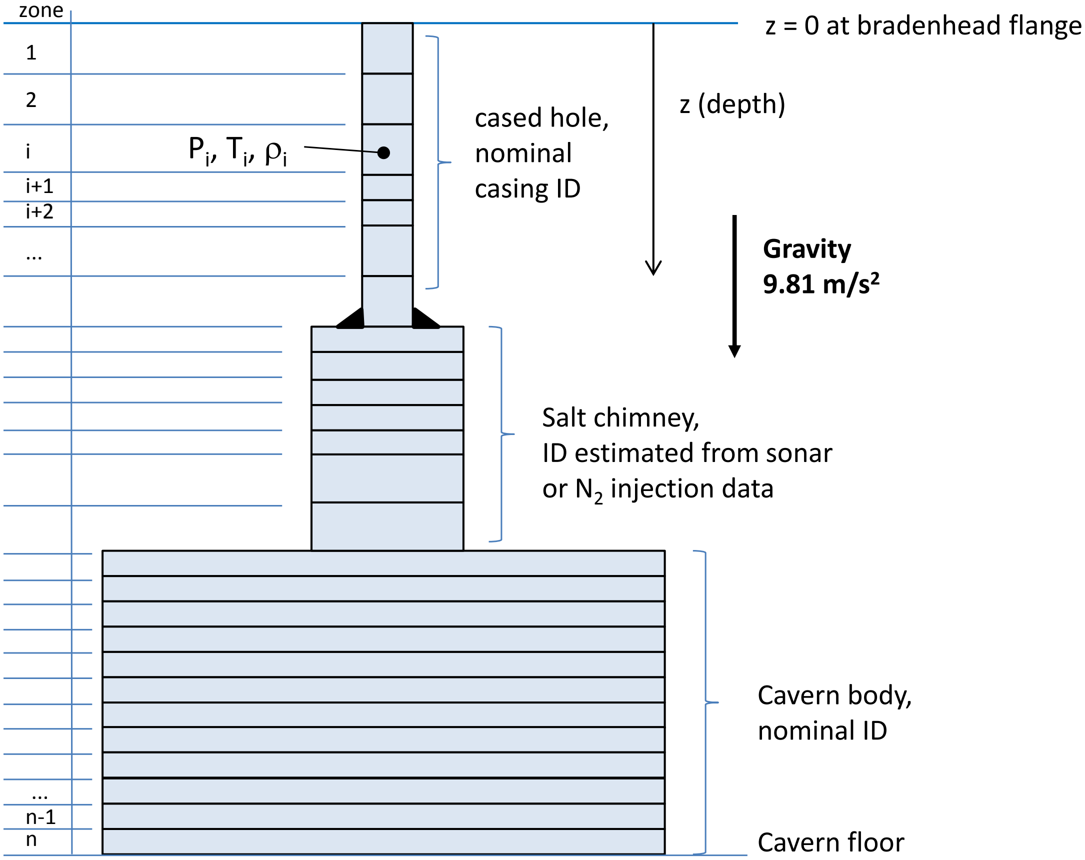


Figure 4-2: Schematic diagram of computational mesh used in hydrostatic column model.

4.3.2 Well Model Configuration

Cavern access wells at SPR fall into two general categories: "slick" wells with oil contained in the inner most cemented casing; and wells containing a brine-filled hanging string with oil located in the annulus between the hanging string and the inner most cemented casing. All caverns have at least one active hanging string well and most, but not all, have an active slick well. A few older caverns may have 3 or more wells. In order to efficiently cover the range of well configurations at SPR the HCM currently exists in two different configurations in two different MS Excel Workbooks: one is used to model a single hanging brine string well; the second is used to model a paired slick well and a hanging brine string well. Though each well (including the hanging string) are modeled independently, it is convenient to pair them this way because all wells at a site are implicitly coupled at the bottom of the hanging string where fluid pressures should all be equal and results for different wells can be easily compared.

The two workbooks are configured as follows:

HCM-1: The single-well workbook contains a hanging string model and an oil annulus model. The hanging string model contains a brine column and a nitrogen column. The HS nitrogen column is optional since the only time there is N_2 in the brine string is if there is a leak. The HS nitrogen column is turned off by specifying the target N_2 mass to zero. The oil annulus model contains an oil column and an N_2 column.

HCM-2: The two-well workbook contains a slick well model, a hanging brine string model and an oil annulus model. The slick well and oil annulus models both contain oil and N_2 hydrostatic columns. However, the hanging brine string model only contains a brine column. If nitrogen is present in the brine string of a two well cavern, the single well workbook will have to be used.

The two workbook configurations are summarized schematically in the following outline:

Single well cavern
(*HCM-1_V8.xlsb*)

- Hanging brine string model
  - *Brine column*
  - *N_2 column (optional)*
- Oil annulus model
  - *Oil column*
  - *N_2 column*

Two well cavern
(*HCM-2_V8.xlsb*)

- Slick well model
  - *Oil column*
  - *N_2 column*
- Brine well model
  - *Hanging brine string model*
  - *Brine column (if N_2 is present use (1))*
- Oil annulus model
  - *Oil column*
  - *N2 column*

A simple example of a paired oil and N_2 column is provided in section 4.5.1.

4.4 Numerical Model

In its most basic mode (Case-1) a single hydrostatic column model is solved using a finite-differences (FD) as follows:

1. Given a set constant parameters equations (4-6); and boundary pressures, equations (4-7) for oil, brine or N_2, the densities as a function of *z* are calculated as follows:

   For N_2:

$$\rho_{N_2}(i) = \frac{P(i)}{R_{N_2} T(i) Z_g}$$

   For oil or brine:

$$\rho = \frac{\rho_0}{\left(1 - k\left(P(i) - P_0\right)\right)\left(1 + \beta\left(T(i) - T_0\right)\right)}$$

2. Pressure is calculated as function of *z*:

$$P(i) = P(i-1) + \Delta P(i-1)$$

   where,

$$\Delta P(i-1) = g\rho(i-1)\Delta z(i-1)$$

For a paired set of oil (or brine) and N_2 columns (Case 2), the model calculates the NOI and N_2 mass as follows:

1. Using interpolation the model finds the depth where the nitrogen and oil pressure are equal (P_{N2}(i) – P_{oil}(i)) =0. This is the location of the N_2 interface, z_{if}.

2. Using interpolation on the cumulative mass of N_2 as a function of *z* the model determines the mass of N_2 above the interface, where cumulative mass is calculated as follows:

$$M(i) = M(i-1) + \Delta M(i)$$

$$\Delta M(i) = \rho(i) A(i) \Delta z(i)$$

   and $A(i)$ is the cross sectional area of the well

In summary, given wellhead pressures for oil, brine and N_2, the NIF and M_{N2} are calculated. Generally, under MIT conditions the oil column boundary pressure is not known, but the N_2 mass and interface are. In this case, iteration on boundary pressure (programed or manual) can be used until the desired N_2 mass or NIF is calculated, but generally not both.

4.5 Modes of Operation

Another common mode of operation (Case 3) builds on the basic solution discussed above. In this case, typical of an MIT initiation, the injected N_2 mass (or NOI) and wellhead N_2 pressure are known. The user manually iterates on the paired oil column pressure until the N_2 mass (or NOI) is achieved and the corresponding NOI (N_2 mass) is determined.

Similarly and typical of an MIT finalization (Case 4), assuming the oil boundary pressure is specified, the model can automatically iterate on the gas column boundary pressure until a target mass (mass injected) is calculated and the corresponding NOI is determined.

Finally, a quasi-static analysis can be performed (Case 5) where a series of oil column boundary pressures, target masses and baseline pressurization rate are provided. Here, the target mass can also be incrementally decreased by a user specified mass loss rate (kg/day) simulating a N_2 leak. HCM, using an automated iteration method similar to Case 3, calculates N_2 mass, N_2 pressure, and NIF histories. The parameters used for leak history modeling are described here:

P_{oil}^{0} – initial oil boundary pressure

M^{0} – initial N_2 mass, kg

$\dot{P}_k = psi/day$ – baseline cavern pressurization rate

$\dot{M} = f(t)$ – mass loss rate, kg/day

Calculated:

$P_{oil}^{n} = P_{oil}^{n-1} + \dot{P}_k \Delta t$ – oil boundary pressure history

$M^{n} = M^{n-1} + \dot{M}\Delta t$ – target N_2 mass hsitory

Iteration variable:

$P_{N_2}^{n}$ – N_2 boundary pressure history

Output:

$NIF(t), z_{if}(t)$ – N_2 interface history

Table 4-1 summarizes the various modes and parameters requirements of the HCM model.

Table 4-1: Summary of HCM operational modes.

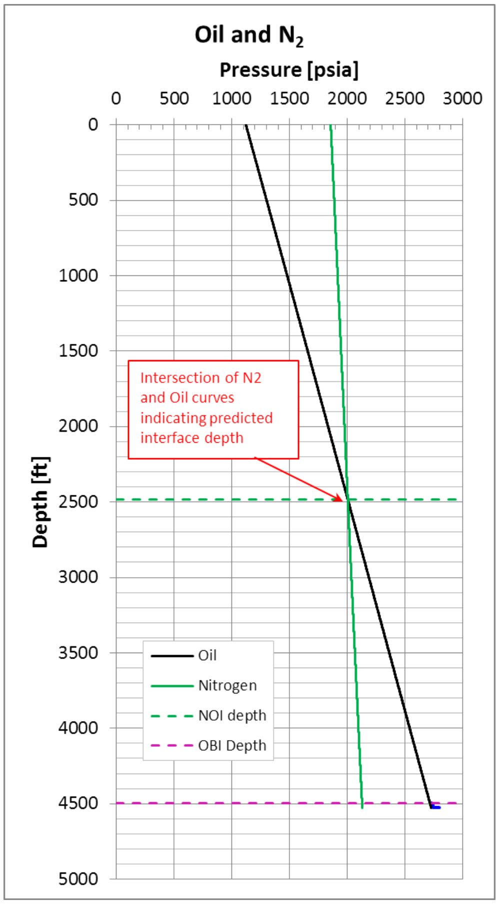
Case	Known Parameters	Iteration Variable[1]	Output	Description
Case 1	$P(0)$	-	$P(z)$, $\rho(z)$	Basic column model
Case 2	P_{oil}, P_{N2}	-	M, z_{if}	Basic IF case uses two instances of Case 1: oil and N_2
Case 3	z_{if} or M	P_{oil} or P_{N2} (M)	M , z_{if}	General NIF case
Case 3	P_{N2} and, M0 or z_{if}	P_{oil} (M)	P_{oil}, M, z_{if}	MIT initial
Case 4	P_{oil}, M0	P_{N2} (P)	P_{N2}, z_{if}	MIT final
Case 5 with leak	$P_{oil}(t)$, $M(t)$, $\dot{P}_k$, $\dot{M}$,	P_{N2} (P)	P_{N2} (t), z_{if} (t),	MIT with quasi-static leak history. See section 4.5.2 for details.

1. Iteration is either manual by user (M) or programmed into HCM (P).

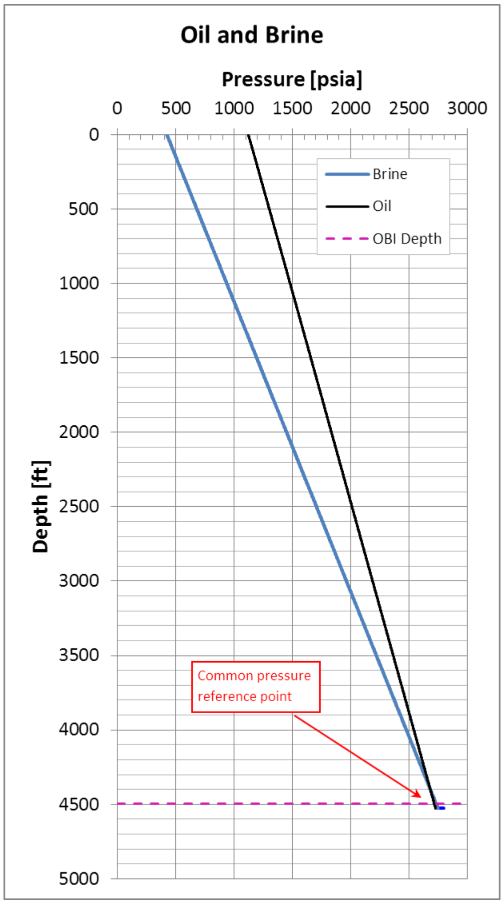
4.5.1 Sample Prediction of Nitrogen Interface Depth

A basic requirement of the model is to predict the nitrogen-oil interface (NOI) depth. The approach used is to simulate two parallel, uncoupled columns of fluid with specified wellhead pressures - one containing only oil, the other containing only nitrogen gas - and finding the depth at which the fluid pressures are equal. Sample graphical output from the model is shown in Figure 4-3(a). The model also calculates total mass of gas from BHF to the interface depth as one of the primary output variables.

Each cavern at SPR has both an oil well (slick or annulus) and a hanging string connected to a brine pool at the bottom of the cavern for which wellhead pressure is also continuously monitored. Given brine properties (density, compressibility and thermal expansion coefficient) and wellhead pressure, the pressure profile within the hanging string can also be calculated by the HCM. This profile can be used to calibrate (verify) the oil model since the two columns share a common reference pressure point at the bottom of the hanging string. Assuming the brine pool is the same for both the oil and brine columns, the fluid pressure at the OBI is a more convenient location to compare pressures because avoids a layered oil column. This common reference pressure point is illustrated in Figure 4-3(b).



(a) Intersection of oil and N_2 pressure histories determine NOI.



(b)Common pressure reference point at bottom of HS.

Figure 4-3: Graphical model output showing sample pressure profiles.

4.5.2 Predicting Pressure Change at the Gas Wellhead with Creep Closure

The model can also simulate the expected interface displacement and nitrogen wellhead pressure after the cavern has experienced a pressure rise due to creep closure. This is a variation on the interface calculation described above. An overview of the process is given below:

- Typically, brine pressure observed at the wellhead with a hanging string is taken as input and its slope represents the baseline cavern pressurization rate.
- The mass of gas in the system should remain constant with the assumption of a gas-tight well. This can be changed if a leak is suspected, in which case the mass of nitrogen can be incrementally decreased in a controlled manner.
- The oil-brine interface (OBI) depth is typically in the body of the cavern and can be used as a stationary reference point (z = constant) with the assumption that there is no liquid (brine or oil) movement in or out of the cavern. For a typical SPR cavern with a nominal 200 ft. diameter, a movement of ~5,600 bbl liquid is required in order to move the interface 1 foot, so this constant interface assumption is reasonable for typical SPR caverns.
- The brine string well is implicitly coupled with a nitrogen-capped oil well by maintaining the pressure at the end of tubing (EOT) depth in both wells. This is initially accomplished by tuning initial conditions and properties. This coupling is also utilized for modeling pressurization due to creep closure. First the brine wellhead is pressured up a known amount to reflect creep closure (say 10 psi for an example). In order to maintain a pressure balance at EOT, the oil wellhead pressure is incremented up accordingly, and experience shows that the pressure will increment by approximately the same amount (~10 psi in this example). The difference between calculated pressures at EOT is monitored for a minimum.
- The nitrogen wellhead pressure is calculated by the model assuming that a constant mass of nitrogen is maintained from the original configuration (prior to incrementing the brine well up 10 psi). The lower boundary on the nitrogen well domain, in reality, is the pressure at the oil-nitrogen interface, though its depth is currently unknown. The model iteratively adjusts N_2 pressure to find the wellhead pressure with the known (target) nitrogen mass above the intersection with the oil well pressure curve.

This process is demonstrated in detail and verified by the validation test case in section 0 and 5.

5 MODEL VERIFICATION

5.1 Plan

5.1.1 Gravity Constant Verification

A basic level of verification of the model programming will consist of a simple evaluation based on the fundamental hydrostatic column equation:

$$\frac{dP}{dz} = \rho g$$

or in finite-difference form:

$$\Delta P = \rho g \Delta z$$

Given that the model first calculates ρ as a function of depth dependent on fluid type, then calculates P incrementally as a function of ρ, g and Δz, a simple check would be to back calculate g using:

$$g = \frac{dP}{dz}\frac{1}{\rho}$$

or in FD form (6-1)

$$\text{g} = \frac{\left(P_{i+1/2} - P_{i-1/2}\right)}{\left(z_{i+1/2} - z_{i-1/2}\right)}\frac{1}{\rho_{i-1}}$$

Where i is the cell index and the i-1/2 subscript implies a zone interface value or the average of the values at i and i-1.

5.1.2 Constant Density and Temperature Verification

A second check uses analytic evaluation assuming constant T for gas and constant ρ and T for liquids. For oil and brine, assuming the compressibility is zero and temperature $T(z)$ is constant leads to the following analytical expression for pressure:

$$\frac{dP}{dz} = C\rho_0 g$$

Integrating gives:

$$P = C\rho_0 g z_i + P^0$$

where,

$$C = \frac{\rho_0}{\left(1+\beta\left(T_c - T_0\right)\right)}$$

and

$$\rho(z) = C\rho_0$$

$$T(z) = T_c$$

$$P^0 = \text{boundary (wellhead) pressure}$$

For N_2, assuming $T(z)$ is constant and equal to T_c leads to:

$$\rho = \frac{P(z)}{R_{N_2} T_c Z_g}$$

$$\frac{dP}{dz} = \rho g = \alpha P(z)$$

where,

$$\alpha = \frac{g}{R_{N_2} T_c Z_g}$$

Integrating gives:

$$P(z) = P^0 \, \mathrm{e}^{\alpha z}$$

Mass, m, as a function of depth, z, can be calculated for a constant cross sectional area, A, by integrating the following:

$$\rho = \frac{\Delta m}{\Delta V} = \frac{P(z)}{R_{N_2} T_c Z_g}$$

or,

$$\Delta m = \frac{P(z)}{R_{N_2} T_c Z_g} \Delta V = \frac{P^0}{R_{N_2} T_c Z_g} e^{\alpha z} A_c \Delta z$$

Integrating results in:

$$m = \frac{P^0 A_c}{R_{N_2} T_c Z_g} \frac{1}{\alpha} e^{\alpha z} \Big|_0^z = \frac{P^0 A_c}{g}\left(e^{\alpha z} - 1\right)$$

Results of the verification are provided in below.

5.2 Results

The spreadsheet coding of the density, pressure NOI and M_{N2} calculations (section 4.4) for all instances of a hydrostatic column in both HCM workbooks discussed in section 4.3.2 have been verified by adding extra columns that implement the equations in section 5.1.1 and 5.1.2. These columns have been clearly identified (highlighted in green) and can be readily checked by the user in order to insure the models have not been accidentally modified during use.

The BH101 MIT initiation described in section 0 (with modifications for constant temperature and liquid densities) was used for the verification described in this section. Because of the modifications, verification model results are slightly different than those reported in section 0. The specific workbooks (HCM-1_V8_V&V.xlsb, HCM-2_V8_V&V.xlsb) have been retained on the Sandia SPR data server, SPRDATA, for traceability.

Note that the extremely good validation results provided in section 6.4 also, implicitly, verifies that the model has been correctly implemented.

5.2.1 Results of Back-Calculating Gravity Constant

All back-calculations of the gravity constant, *g*, returned the inputted value of 9.81 ± 0.001.

5.2.2 Results for Constant Density and Temperature

5.2.2.1 Liquid Model

All instances of brine and oil hydrostatic columns in both HCM workbooks were verified by setting input parameters that created an incompressible, constant temperature liquid (compressibility $k = 0$ (E=1e199), $T_c = 80^{o}$F =299.82 K). Pressure calculated using the analytical expression from above was compared to pressure calculated by the HCM. Relative errors, ε, defined as follows:

$$\varepsilon = \frac{|Y_M - Y_A|}{Y_A}$$

Y_M = Model calculated value

Y_A = Analytical value

were less 1e-13 indicating very good agreement for the oil and brine columns.

5.2.2.2 Gas Model

All instances of N_2 gas columns in both HCM workbooks were verified by setting the gas temperature to a constant 80 ^{o}F (299.82 K). Pressure calculated using the analytical expression from above was compared to pressure calculated by the HCM. Relative errors were less 3e-6 and indicating very good agreement for the gas columns.

5.2.2.3 Interface Prediction

The depth of the interface was found by visual inspection of the analytical spreadsheet data. The interface is located where $P_{oil}(i)$ - $P_{N2}(i)$ switches sign. In all cases the analytically determined interface and the HCM calculated interface fell within the same zone. A zone size of 0.5 m and an interface depth ~2400 m implies a relative error of less than 2e-4, indicating very good agreement for NIF depth.

Two methods of verifying the mass above interface location were used depending on whether the hydrostatic gas column had a constant cross-sectional area or not. Total mass was calculated using the analytical expression from above in both cases. However, for constant area, the mass is calculated directly using P(0), A_c, and z = NOI. For columns with variable cross-sectional area, the mass is calculated using the equations above over the regions of constant area and summed down to the interface. P(0) is the pressure at the top of the region; A_c is the area of the region; and z relative to the top of the region. The first method was used in the slick well and in the hanging string. The second method was used when the interface was located in the chimney – typical of MIT configurations. In all cases the relative mass error was less than 3e-5 indicating very good agreement on the mass of N_2 injected.

6 MODEL VALIDATION: BH101 EXTENDED NITROGEN TEST

6.1 Cavern History

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. The cavern passed its 5 year MIT in October 2014 (McCoy 2014) after which Sandia submitted test plan for post-MIT nitrogen monitoring (Lord 2014). Figure 6-1 shows the wellhead pressure history of the cavern between Nov 2014 and Feb 2015. Nitrogen was injected on Sep 16, 2014 and the MIT conducted Sep 29 - Oct 23, 2014. Before the start of the post-MIT nitrogen test, the cavern was depressurized in order to assure that the cavern did not exceed recommended pressure range during the extended test duration. Initialization of the special nitrogen test was conducted on Nov 19, 2014 when the nitrogen interface of well A was also raised to 1702 ft. A table with the timeline of the various logs is given in Table 6-1.

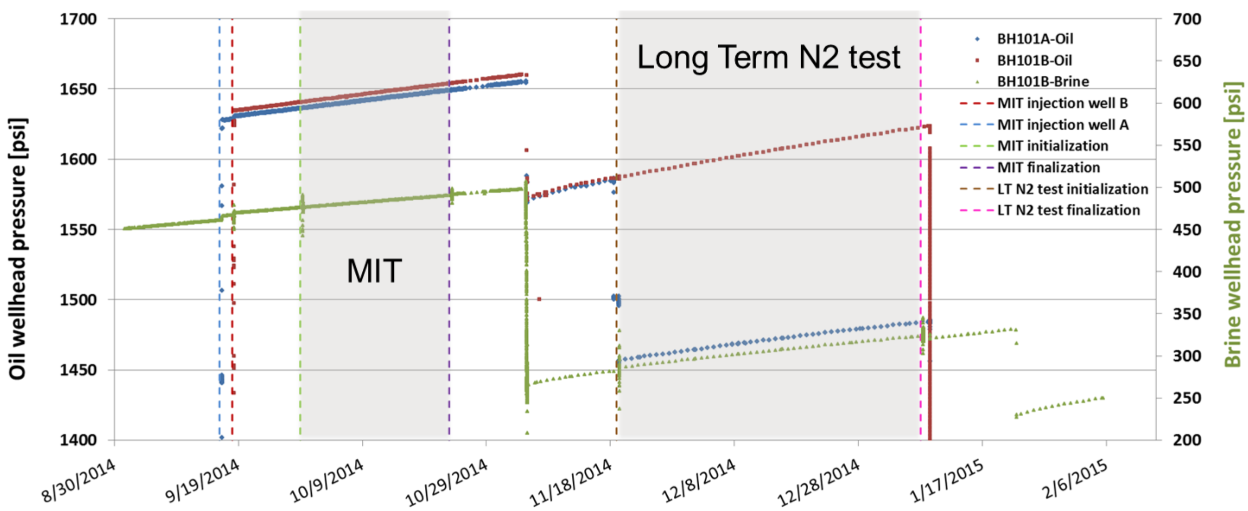


Figure 6-1: BH101 wellhead pressure history between Nov 2014 and Feb 2015.

Table 6-1: Timeline of logging events for BH101 between Nov 2014 and Feb 2015.

Well A			Well B		
Date	Event	Notes	Date	Event	Notes
9/16/2014	MIT injection well A		9/18/2014	MIT injection well B	
9/29/2014	MIT initialization		9/29/2014	MIT initialization	
10/23/2014	MIT finalization		10/23/2014	MIT finalization	
11/19/2014	LT N2 test initialization	NOI moved to 1702 ft	11/19/2014	LT N2 test initialization	Only interface log
1/7/2015	LT N2 test finalization	High res press. log	1/7/2015	LT N2 test finalization	High res press. log

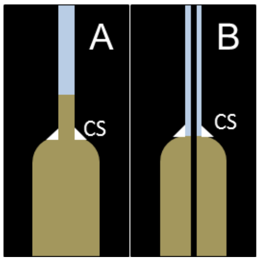
Note: LT is abbreviation for long term or extended N2 test.

6.2 BH101 Geometry

Big Hill cavern 101 is a two-well cavern with A being the 'slick' well and B containing the brine string; the well completion drawings are contained in APPENDIX A:. The location of the nitrogen-oil interface (NOI) at the beginning of the nitrogen test for well A was measured to be at 1702 ft, which is inside the well casing. A movement of 33 ft. was recorded for the duration of the test (see Table 6-2). On the other hand, the location of the NOI for well B was in the chimney just below the casing shoe (2143 ft), as normally placed during an MIT and was recorded to move 2 ft during the test.

Table 6-2: NOI locations recorded for the nitrogen test. (right) Cartoon representation of the wells with approximate NOI location.

	NOI well A	NOI well B
	[ft]	[ft]
Initial	1702	2143
Final	1669	2141



6.3 BH101 Test Results

6.3.1 Wellhead Pressures

The wellhead pressure for both wells was closely monitored for the duration of the test (Figure 6-2). On Nov 19, 2014, nitrogen was bled from well A in order to move the NOI from its original location below the casing shoe up to around 1702 ft. This effectively lowered the wellhead pressure about 150 psi. Pressurization rates for the test were calculated to be 0.554 psi/day for well A and 0.722 psi/day for well B, and they were found to be extremely linear. The baseline cavern pressurization rate was found to be 0.766 psi/day. According to our analysis well A was pressurizing at a relative rate of 0.72 with respect to the brine pressure rate, while well B at 0.94. Calculated values are summarized in Table 6-3.

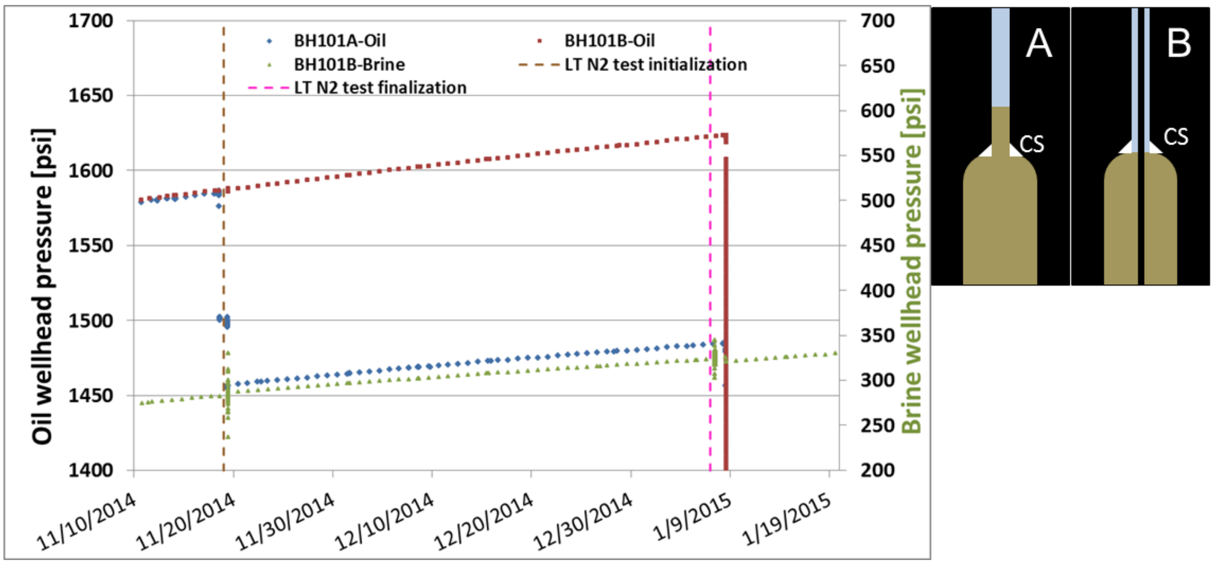


Figure 6-2: Wellhead pressure history for cavern BH101 for the duration of the nitrogen test. Schematic on the right illustrates that the NOI was placed in the casing for well A, while for well B it was right below the casing shoe, which results in different wellhead pressure magnitude for the wells.

Table 6-3: Calculated values of pressurization rates for BH101 cavern during the long term nitrogen test.

			BH101-Brine	BH101A-Oil	BH101B-Oil
Start Date	11/20/2014	Slope (psi/day)	0.766	0.554	0.722
End Date	1/6/2015	Rsq	0.998	0.998	0.998
		Relative Rate	1.00	**0.72**	**0.94**

6.3.2 Temperature

Temperature logs were taken at the time of finalization for both well A and B and are shown in Figure 6-3 as the N_2 test logs. The log for well B was taken inside the hanging string and it shows a slightly higher temperature than well A in the cased sections from surface down to about 2000 ft. For comparison, temperature logs from the MIT are also included in the figure. A temperature difference of about 5 degrees is found between the two sets of logs. This is believed to be due to instrument calibration issues and not reflective of the true temperature changes in the cavern.

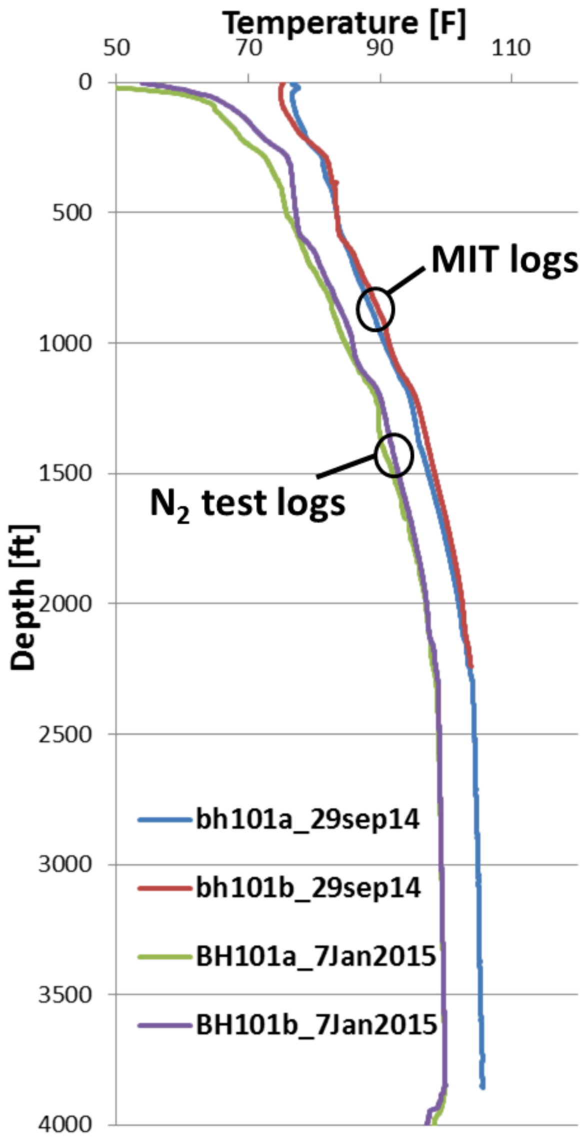


Figure 6-3: Temperature logs taken at finalization of the nitrogen test (Jan 7, 2015). For comparison the earlier logs, taken during the previous MIT (Sept 29, 2014) are also shown.

6.3.3 High Resolution Pressure Logs

High resolution pressure logs were collected at the test finalization on Jan 7, 2015 and are shown in Figure 6-4. The bend in the slope of the pressure in well A represents the change in the fluid density and therefore corresponds to the nitrogen oil interface. Pressure data from the logs were a direct input to the hydrostatic column model and used for calibration purposes.

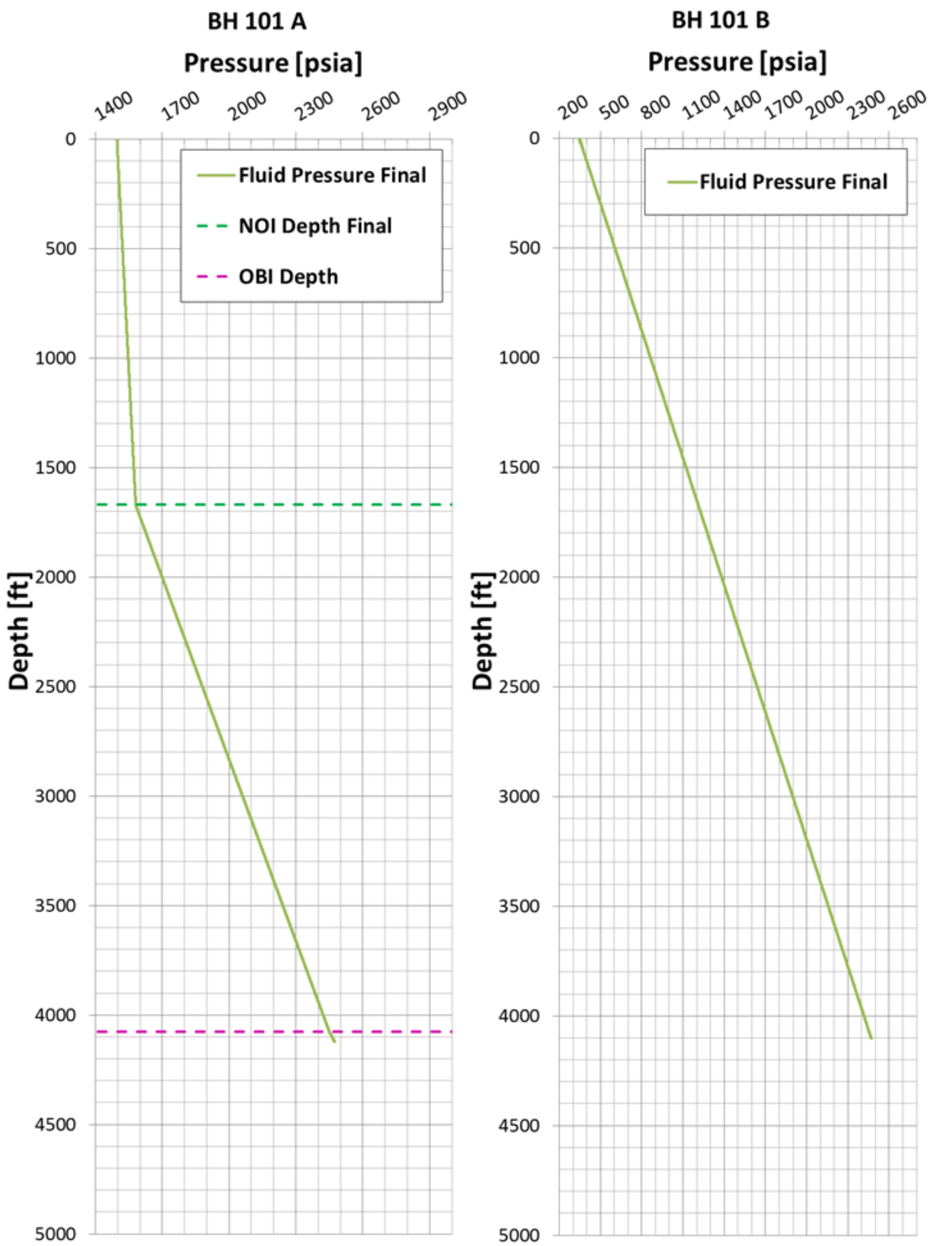


Figure 6-4: High resolution pressure logs for BH101 well A and B taken on Jan 7th 2015 as part of the finalization of the long term nitrogen test.

6.4 Model Performance for Test Case

6.4.1 Model Input Parameters

The model inputs used for BH101 are summarized in Table 6-4. The magnitude of the wellhead pressures were taken from the DCS, while the NOIs were taken by the interface log. In blue are the actual model output values for the finalization step. For process traceability, the lower part of the table includes the working parameters for each of the well.

Table 6-4: List inputs and outputs parameters for the HCM for the simulation of BH101 long term nitrogen test. In blue are the outputs of the model. Working parameters are also included.

Well A				Well B			
T 1		T2		T 1		T2	
Event:	Test initialization	**Event:**	Test finalization	**Event:**	Test initialization	**Event:**	Test finalization
Date:	11/19/14	**Date:**	1/7/15	**Date:**	11/19/14	**Date:**	1/7/15
P,N_2 [psi]	1457	**P,N_2 [psi]**	**1484**	**P,N_2 [psi]**	1587	**P,N_2 [psi]**	**1623**
				P,brine	283	**P,brine**	323
NOI [ft]	1702	**NOI [ft]**	**1669**	**NOI [ft]**	2143	**NOI [ft]**	**2141**
Working parameters							
P,oil	923.4	**P,oil**	963.4	**P,oil**	926	**P,oil**	965
M, $_{N2}$	4730	**M, $_{N2}$**	4730	**M, $_{N2}$**	3054	**M, $_{N2}$**	3054
ρ_{oil}	839	ρ_{oil}	839	ρ_{oil}	839	ρ_{oil}	839
				ρ_{brine}	1193	ρ_{brine}	1193

6.4.2 Pressure Prediction

As mentioned earlier, 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. Figure 6-5 is a plot of the magnitude of the difference in the measure 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.

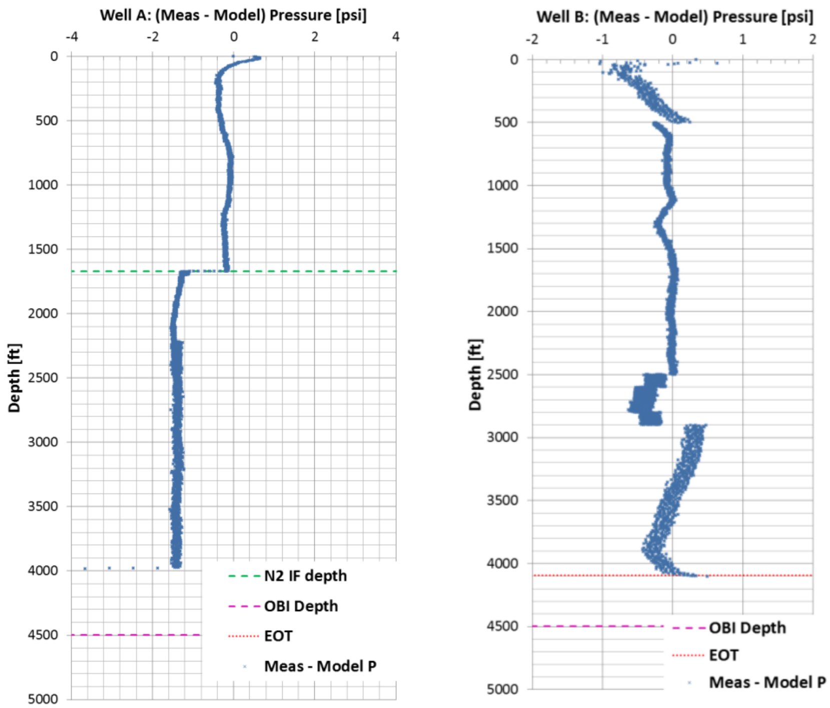


Figure 6-5: Illustration of the difference between measured and predicted pressure as a function of depth for both BH101 well A and well B.

The model also performed very well in predicting the oil/N_2 wellhead pressure as function of cavern brine pressure (and time). Figure 6-6 shows the measured values of pressure at the wellhead (from the DCS) 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 (see Table 6-3). Similarly for well B the relative rate was predicted to be 0.93. For reference the values of pressure both measured and predicted as well as the relative pressurization rates are given in Table 6-5.

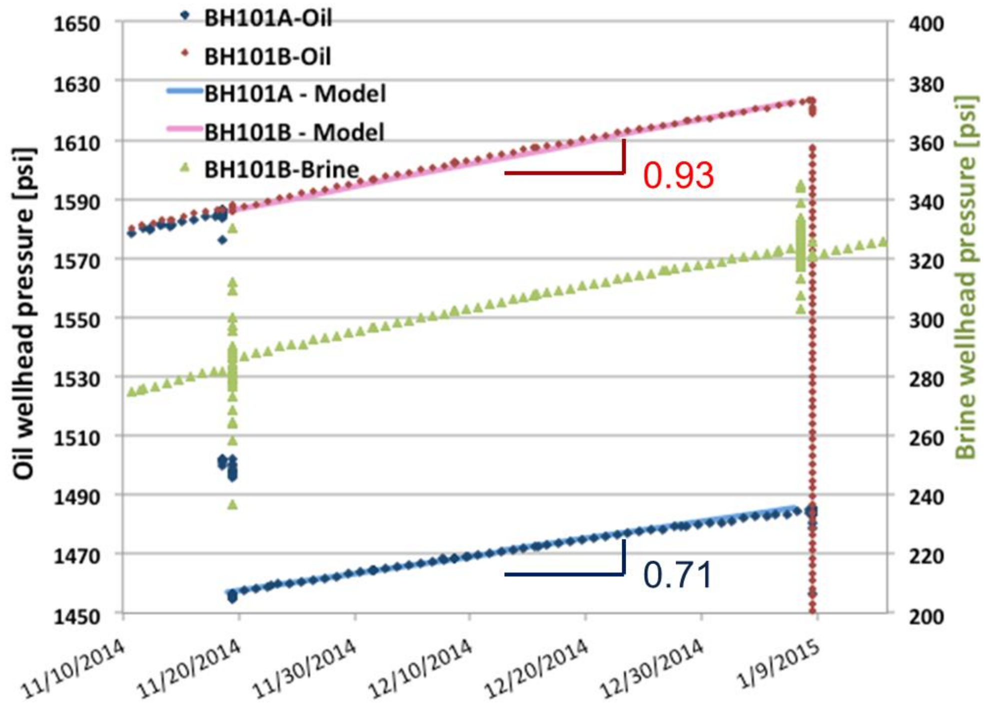


Figure 6-6: Pressure history for BH101 cavern during the long term nitrogen test. Solid lines represent model predictions after calibration. Annotated are also the relative pressurization rates predicted by the model.

Table 6-5: Comparison between measured and predicted pressure at initialization and finalization of the nitrogen test for BH101 cavern. Relative pressurization rates are also included.

	Well A			Well B		
	Initialization	Finalization	ΔP	Initialization	Finalization	ΔP
Pressure (model) [psi]	1457	1485.6	28.6	1587	1623	36
Pressure (experiment) [psi]	1457	1484	27	1587	1623	36
Relative Rate [psi/psi] (model)	0.71			0.93		
Relative Rate [psi/psi] (experiment)	0.72			0.94		

6.4.3 NOI Predictions

The model was able to accurately predict the NOI movements during the long term nitrogen test. Illustrated in Figure 6-7 are the model predictions for the NOI location for both wells. The interface of well B is located just below the casing shoe and large movements are therefore not expected. The interface of well A, on the other hand, is located in the casing and a NOI movement of about 32 ft was expected. Wireline measurements confirmed the predicted locations of the NOI. Table 6-6 contains the measured and predicted values for the NOI locations for this test.

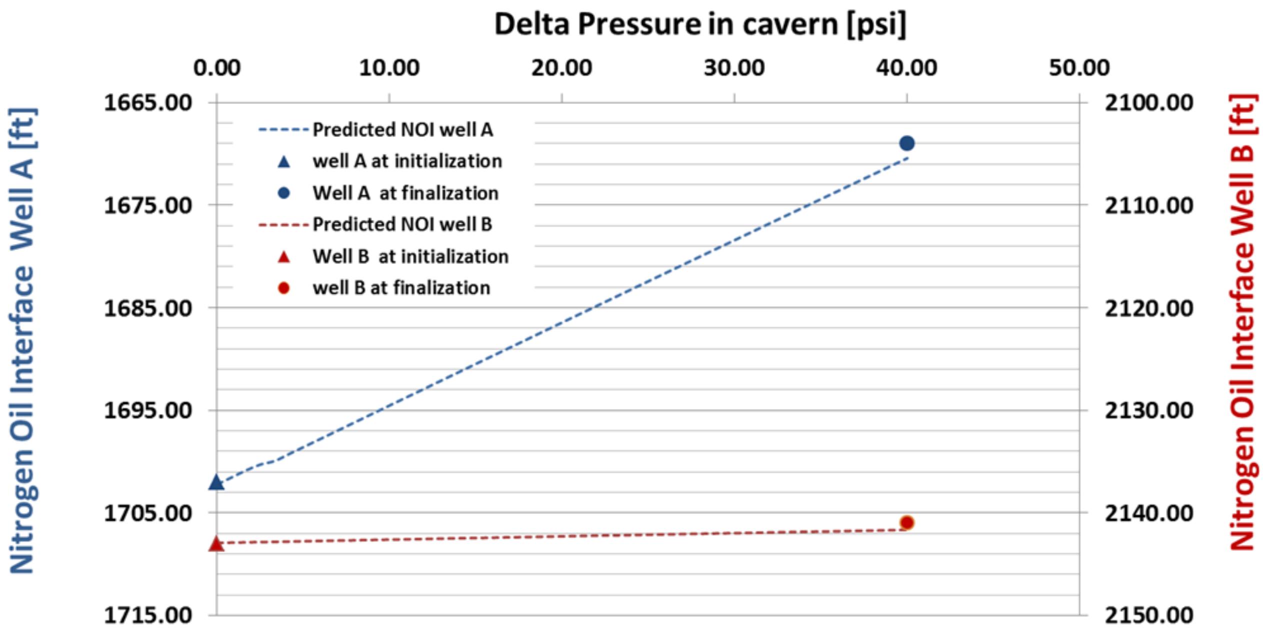


Figure 6-7: Model NOI predictions for BH101 cavern during nitrogen test.

Table 6-6: Location of nitrogen oil interfaces as recorded by the test logs as they compare to the model predictions for BH101 wells.

	Well A			Well B		
	Initialization	Finalization	ΔH	Initialization	Finalization	ΔH
NOI Model [ft]	1702.2	1670.4	31.8	2142.9	2141.1	1.8
NOI Experiment [ft]	1702	1669	33	2143	2141	2

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7 APPLICATION OF THE MODEL: BH101 MIT

An example of an application of this model during a routinely schedule MIT is given in this section. In most of the cases temperature and pressure logs will not be available, and are not necessary for the running of the model. The only inputs for the model for this simulation were the wellhead pressures and NOIs at initialization, the brine change in pressure between MIT initialization and finalization and a pre-test temperature log.

Table 7-1: List of inputs and result for the model of BH101 MIT of Oct 2014. In blue are the model inputs.

	Well A Initial	Well A Final		Well B Initial	Well B Final	
Date of log	Sep 29, 2014	Oct 23, 2014	Delta	Sep 29, 2014	Oct 23, 2014	Delta
$P(N_2)$ [psi] Experim.	1636	1649	13	1641	1654	13
$P(N_2)$ [psi] model	**1636**	1649.3	13.3	**1641**	1654.2	13.2
P(brine) [psi]				**476**	**491**	15
NOI [ft] Experim.	2134	2131.3	2.7	2141	2141	0
NOI [ft] model	**2133.6**	2131.2	2.4	**2141**	2140.5	0.5

As shown on the table, the model was able to predict the wellhead pressure and the NOI at finalization reasonably well.

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8 CONCLUSIONS

This report describes the Hydrostatic Column Model, its functional requirements, the model structure and the verification and validation process. All model functional requirements were met and a description of the various mode of operation is included.

Model verification has shown that the program runs correctly and it is implemented as intended. Cavern BH101 long term nitrogen test was used to validate the model and it has shown very good agreement with measured data. This supports the claim that the model is, in fact capturing the relevant physical phenomena and can be used to make accurate predictions of both wellhead pressure and NOI movements.

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APPENDIX A: WELL COMPLETION DRAWINGS

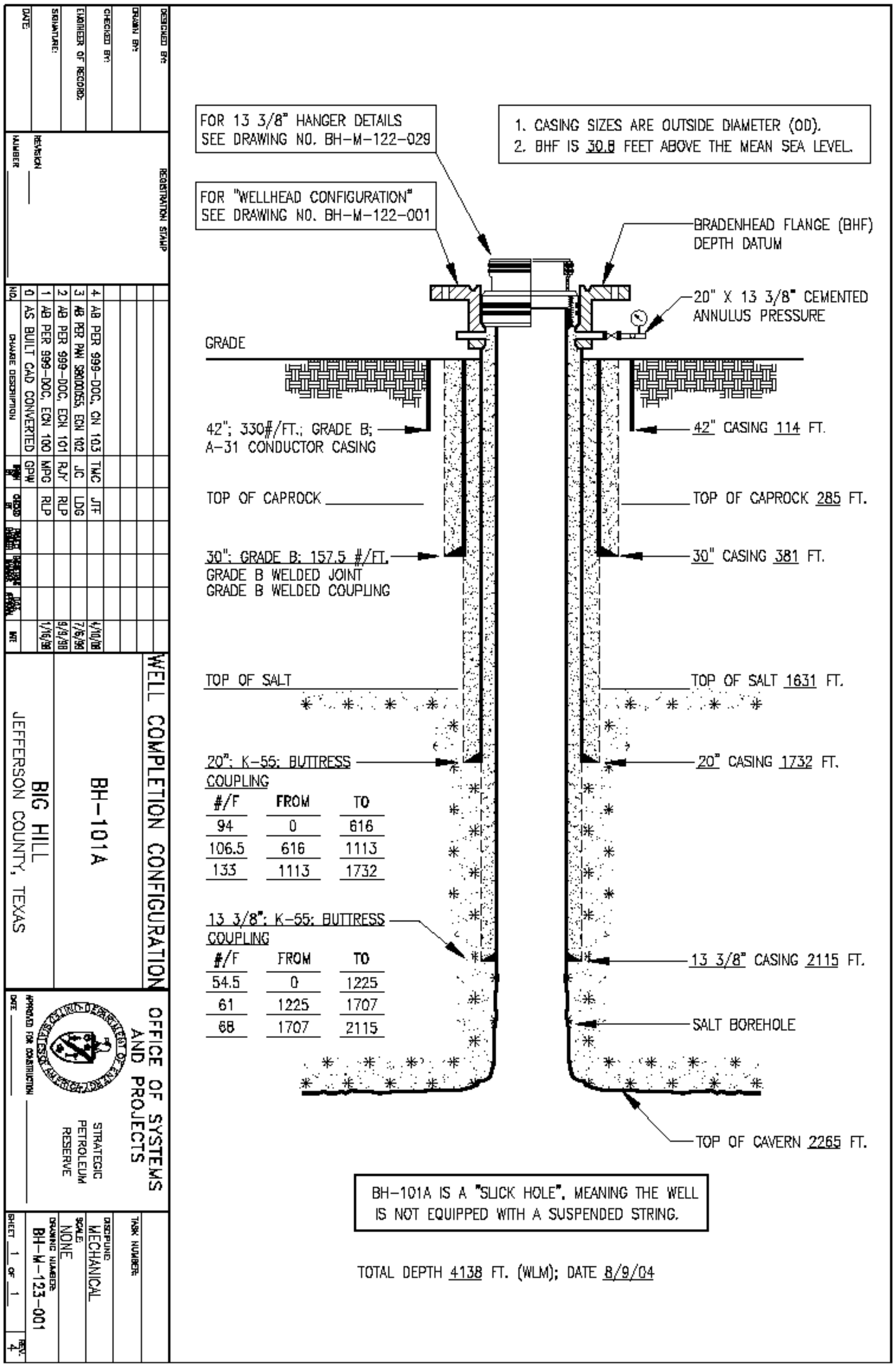

Figure A-1: BH101A well configuration drawing.

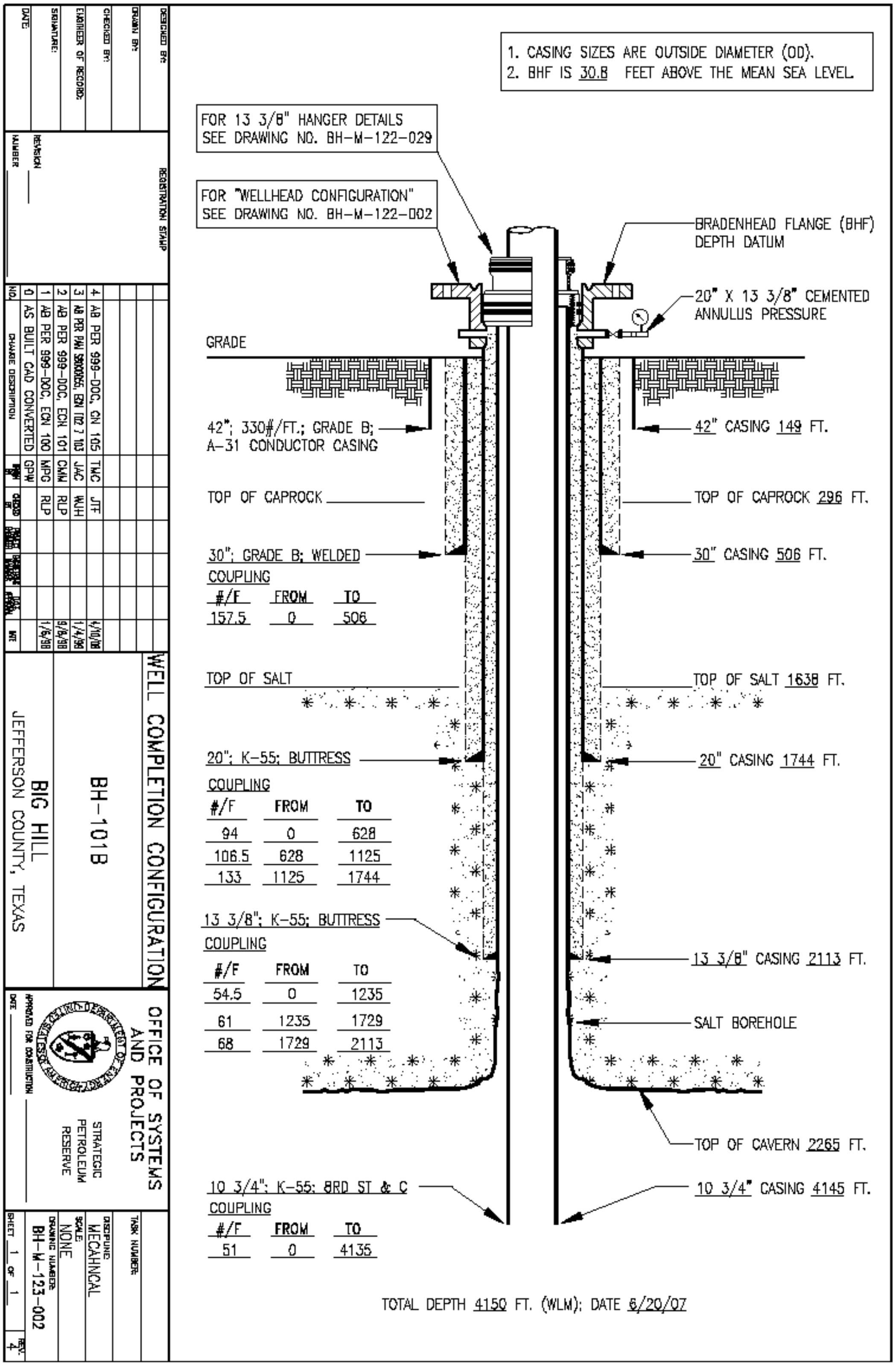

Figure A-2: BH101B well configuration drawing.

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