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Sensitivity Analysis of Salt Storage Cavern Mechanical Integrity Test Parameters

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ABSTRACT

This report examines the sensitivity of salt cavern Mechanical Integrity Tests (MIT) to uncertainties in key test parameters. MIT's are used by cavern operators to detect and quantify leak rates in access wells in underground salt storage caverns and involve a suite of measured and assumed parameters that have a direct impact on the sensitivity of the testing to detect actual leaks from the cavern storage system. Determining the sensitivity of the testing to these different parameters provides a basis for understanding the results from, and informing the design criteria for, this type of testing. Without fully understanding the sensitivity of the test to the testing parameters, it is possible that the test results may not accurately reflect the integrity of the cavern system; an actual leak may be missed, or an intact system may be interpreted as leaking. This report reviews the main parameters included in MITs and examines how selected changes in their values can impact test results. The deviations used in the sensitivity analyses were designed to be within the ranges believed to be similar to those which may be encountered during testing. The results show that small, plausible fluctuations in some of the parameters measured values can have a significant impact on the testing results. Of the parameters studied here, the sensitivity analyses showed the order of importance to be (from highest to lowest): nitrogen-oil interface depth measurement, well bore temperature, well head pressure, and finally the internal geometry of the testing interval.

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EXECUTIVE SUMMARY

This report presents the results from a series of sensitivity analyses on several parameters related to mechanical integrity tests (MIT) for cavern storage wells. The parameters investigated were: measurement of the depth of the nitrogen-oil interface, temperature, pressure, and geometry of the test interval.

Sensitivity testing was performed by altering baseline conditions for a hypothetical MIT analysis scenario that may be encountered at the U.S. Strategic Petroleum Reserve. The alterations represented changes that might be possible during an MIT. For some parameters multiple scenarios were investigated. The impact of these alterations was assessed by looking at the effect the changes had on the nitrogen volume in the testing interval and how any volumetric changes related to the minimum detectable leak rate (MDLR) computed for that scenario.

Of the parameters studied in this report, accurate measurement of the NOI depth has the greatest impact on the MIT results having an influence of approximately 100% of the MDLR. This is because this parameter is incorporated into many of the calculations necessary for a MIT. The sensitivity analysis revealed that fluctuations in the temperature profile of the testing interval has the next greatest influence on an MIT. Small (1 °F) changes in the temperature profile can have an impact of up to 90% of the MDLR. Small (1.4 PSI) changes in well head pressure were shown to have a less impact on the MIT nitrogen volumes, on the order of 50% of the MDLR with larger (3.4 PSI) pressure fluctuations driving that rate to greater than 100% of MDLR. The final parameter, test interval geometry, appears to have the smallest impact on the response variable. For the geometries investigated here, the maximum influence was only about 33% of the MDLR.

Because actual MITs involve real world conditions and actual cavern geometries, assumptions and simplifications necessary for the type of sensitivity analysis reported here must be considered when interpreting the results. In addition, alteration of other factors such as the test interval geometry, duration of the test, etc. from those used here may alter the sensitivity results. Regardless, the results presented here are considered to be generally representative of the sensitivity of MITs to changes in the main input parameters and reflect the magnitude of impact expected in typical testing conditions. It is recommended that any efforts to improve the reliability and accuracy of nitrogen-liquid interface mechanical integrity testing focus on the parameters presented here and in the order of significance determined in this report.

ACRONYMS AND DEFINITIONS

Abbreviation	Definition
AWC	average well conditions
BBL	barrel (volumetric measurement)
CLR	calculated leak rate
CF	cubic feet
EVCR	equivalent volumetric change rate
°F	degrees Fahrenheit
ft	foot
HST	hydraulic stabilization test
MDLR	minimum detectable leak rate
MIT	mechanical integrity test
NIT	nitrogen interface test
NOI	nitrogen oil interface
PSI	pounds per square foot
°R	degrees Rankine
SCF	standard cubic foot (at 14.7 psia and 60 F°)
SPR	Strategic Petroleum Reserve
yr.	year

1. INTRODUCTION

Mechanical Integrity Tests (MIT) for salt storage caverns are used to determine the condition of the cavern access wells and the integrity of the fluid storage system. Although there are several types of MITs (Jordan, 2019), the type under consideration for this report is strictly the Nitrogen Interface Test (NIT). For liquid filled caverns, this type of MIT involves pressurizing the well bore with nitrogen which then pushes the nitrogen-liquid interface down the well bore. Typically, the interface is pushed some distance below the lowest well casing shoe where it is kept for some period of time. After the nitrogen temperature has equilibrated with the well bore environment, an initial measurement of the depth to the nitrogen-liquid interface is made. Then, after some additional time, another interface depth measurement is made. Comparisons of the two depth measurements provides an indication of the well's integrity. If the two measurements are sufficiently close, then the well is considered to have passed the MIT; significant differences in the measurements indicates the well is not gas-tight and may be leaking liquids to the surrounding environment.

The NIT type tests involve a suite of measured and assumed parameters. These parameters have a direct impact on the sensitivity of the testing to detect actual leaks from the cavern storage system. Determining the sensitivity of the testing to these different parameters provides a basis for understanding the results from, and informing the design criteria for, this type of testing. Without fully understanding the sensitivity of the test to the testing parameters, it is possible that the test results may not accurately reflect the integrity of the cavern system; an actual leak may be missed, or an intact system may be interpreted as leaking. This report examines the main parameters included in MITs and examines how subtle changes in their values can impact test results. The deviations used in the sensitivity analyses were designed to be within the range of plausible errors. The results show that small, plausible fluctuations in the parameters measured values can have a significant impact on the testing results.

Because Sandia National Laboratories is the geotechnical advisor to the Department of Energy's Strategic Petroleum Reserve (SPR), this report is aligned with the general procedures and measurements used for SPR MIT testing. This report should not be considered an evaluation of these procedures. Instead, it is intended to inform about the relative importance and influence of various parameters involved in in MIT NIT testing. For background information, a general review of SPR MIT procedures as of this report date is provided below.

1.1. General SPR MIT Procedures

The SPR consists of 62 solution-mined storage caverns contained in four separate salt domes along the Gulf Coast of the United States. Each cavern is accessed by from one to three wells; there are 116 wells in total. The following description applies generally to all the SPR wells, but, because of differing well completions and cavern shapes the exact procedure used at any specific well may differ slightly. This description is derived from a MIT procedure report for two specific wells at the Bryan Mound SPR site (Strategic Petroleum Reserve, 2019b) and by the SPR MIT procedure manual (Checkai, 2015).

In general, the MIT procedures at the SPR are as follows:

1. An initial Hydraulic Stabilization Test (HST) is performed by increasing the pressure in the cavern via liquid injection and observing the pressure response over time. This process is designed to identify possible liquid leaks in the cavern system. Aspects of this portion of the testing are not considered here.
2. Following the HST, a baseline temperature measurement (well log) of the well from well head to the casing shoe is made. Following this, the initial nitrogen injection is performed. This is done in a manner which minimize the thermal disequilibrium between the nitrogen and the well bore and to allow for the careful measurement of the injected nitrogen. Sufficient nitrogen is injected to push the nitrogen-liquid interface to a depth approximately 10 feet below the lowest well casing shoe. After confirmation via well log that the interface is near the desired depth, a waiting period of 4-6 days is initiated to allow for thermal equilibration of the injected gas.
3. After nitrogen thermal equilibration, the MIT is initialized by measuring the interface depth and temperature profile of the nitrogen.
4. A specified waiting period is then initiated. This period is sufficiently long to allow for detectable movement of the nitrogen-liquid interface if a leak above a given threshold (750 BBL/yr.) is present. The actual waiting period is a function of the cavern and well geometry, and the resolution of the interface logging tool.
5. The MIT is then finalized by running another interface and temperature log.
6. All the interface depth, temperature measurements, along with other data are used to compute a Calculated Leak Rate (CLR). If the CLR is less than the minimum detectable leak rate (MDLR) computed for the test, then the well is deemed to have passed the MIT. The MDLR is computed individually for each MIT and is a function of the cavern and well geometry, the resolution of the interface logging tool, and the duration of the test. CLR and MDLR calculation methodologies are discussed below.

2. MIT CALCULATION PROCEDURE

These calculation procedures are as presented in the SPR MIT procedure manual (Checkai, 2015) with additional guidance provided by examples of SPR calculation spreadsheets.

The Minimum Detectable Leak Rate is the smallest rate of nitrogen loss from the cavern system which would be detectable given the cavern's geometry, current testing technology, and duration of the test. The equation used in determining the MDLR is provided below. In this equation, the unit well volume is the volume of the testing environment swept by a one-foot change in the nitrogen oil interface (NOI). It is a function of the geometry of the cavern in the interval over which any movement of the nitrogen oil interface will take place. The interface log resolution represents the vertical accuracy to which the NOI depth can be determined from a well log. It is typically taken as 0.5 feet based on industry guidance. Commonly, a cap of 750 BBL/yr. is used for the maximum allowable MDLR (Checkai, 2015), and then this value used to determine the test duration. For most cavern geometries, a test duration of 2 days provides a MDLR below the 750 BBL/yr. cap. For caverns with larger test interval diameters, and hence larger unit well volumes, the test duration must be increased.

Minimum Detectable Leak Rate

$$MDLR = \frac{CV * r * [365\left(\frac{days}{yr}\right)]}{t}$$

where:

$MDLR =$ Minimum Detectable Leak Rate (BBL/yr.)

$CV =$ Unit Well Volume (BBL/ft)

$r =$ Interface Log resolution (feet)

$t =$ Test Duration (days)

The Calculated Leak Rate is the volume of nitrogen loss per unit time. The final units are typically given as barrels-per-year. The calculation involves a comparison between the initial and final total nitrogen volumes. These volumes are computed using the temperature and pressure regime of the well casing and are then converted to Standard Cubic Feet (SCF). The final reported volume is then adjusted to average well conditions (temperature and pressure) and converted from cubic feet to barrels. The duration of the test is used to compute the actual rate on a per annum basis.

Calculated Leak Rate

$$CLR_{SCF} = \frac{(V_{initial} - V_{final}) * 365}{t}$$

where:

$CLR_{SCF} =$ the calculated leak rate in standard cubic feet

$$V_{initial} = \left(\frac{P_{initial}}{atmospheric}\right) * \left(\frac{520°R}{460°R + T_{initial°F}}\right) * \left(\frac{1}{Z}\right) * (Hole\ volume\ to\ I/F\ Ft^3)$$

$$V_{final} = \left(\frac{P_{final}}{atmospheric}\right) * \left(\frac{520°R}{460°R + T_{final°F}}\right) * \left(\frac{1}{Z}\right) * (Hole\ volume\ to\ I/F\ Ft^3)$$

$$SCF/BBL = \left(\frac{P_{final}}{atmospheric}\right) * \left(\frac{520°R}{460°R + T_{final°F}}\right) * \left(\frac{1}{Z}\right) * (5.6146\ Ft^3/bbl\ )$$

$$CLR_{BBLS} = \frac{CLR_{SCF}}{SCF/BBL}$$

where:

$t =$ test duration (days)

$V_{initial} =$ Initial wellbore volume filled with nitrogen (SCF)

$V_{final} =$ Final wellbore volume filled with nitrogen (SCF)

$P_{initial} =$ Average initial nitrogen pressure (psia)

$P_{final} =$ Average initial nitrogen pressure (psia)

$T_{initial} =$ Average initial nitrogen temperature (°R)

$T_{final} =$ Average final nitrogen temperature (°R)

$Z =$ Compressibility of Nitrogen for a given pressure and temperature

$CLR_{SCF} =$ Calculated Leak Rate (in SCF)

$CLR_{BBLS} =$ Calculated Leak Rate (in BBLS at average well conditions)

The hole volume to I/F is calculated as shown below:

$$Hole\ volume\ to\ I/F = \sum_{i=1}^{n} (\pi r_i^2 l_i)$$

where:

$r_i =$	radius for casing/chimney section i
$l_i =$	Length of casing/chimney section i
$n =$	Number of different radius casing/chimney sections from top to interface depth

3. SENSITIVITY ANALYSIS PROCEDURE

The focus of this report is to investigate the sensitivity of MIT results to changes in the parameters involved in the testing. The procedure adopted for doing this involves making changes to the input parameters, then observing the changes in a response variable. For most of the analysis presented here, the response variable will be the change in the volume of nitrogen contained in the MIT testing interval. The choice of input variables considered for analysis here are discussed below.

3.1. Sensitivity analysis variables

There are a multitude of variables that can impact the results of a nitrogen interface MIT. For this report, we only consider those that have an impact on the parameters directly used in computing the CLR and others that impact the computation of MDLR. MDLR variables are considered because they impact the criteria against which the CLR are compared to determine if the given well passes or fails the MIT.

3.1.1. Interface depth measurement

The depth measurement of the nitrogen-oil interface is fundamental in the MIT procedure; it is the primary measurement used to determine the results of the MIT. Movement of the NOI is used as an indicator of gas loss from the system and is directly used in the computation of the indicated leak rate. As such, it is an important parameter to include in this sensitivity analysis.

3.1.2. Temperature measurement

Because of its critical importance in the MIT calculations, temperature of the injected nitrogen is included in parameters of interest. Temperature is a critical measurement in determining the CLR. Accurate and precise determination of the nitrogen temperature is important since the mass contained in a given volume for a gas is temperature dependent. To accurately compute any changes in nitrogen mass during the MIT, the temperature of the gas at the initial and final test stages must be known.

3.1.3. Chimney geometry

To compute any changes in nitrogen volume during an MIT the geometry of the test interval (diameter as a function of depth) must be known. The geometry provides the critical second dimension in the nitrogen volume calculation. This parameter is critical for both the CLR and the MDLR determinations. Therefore, it is included in this sensitivity analysis.

3.1.4. Well head pressure measurements

The CLR depends on the pressure of the system. It is used to compute the initial and final nitrogen volumes and so is an important parameter in the MIT process. It is included here to study the impact of small fluctuations in pressure measurements.

3.1.5. Response variable

As mentioned above, the response variable in most scenarios considered here will be related to changes in the volume in the MIT testing interval. Because the response variable involves a gas volume, we must compare those volumes at a consistent pressure and temperature for the comparisons to be meaningful. Because of this, all final comparison volumes will be adjusted to the average well bore temperature and pressure for the scenario under consideration. This is consistent with the calculations presented in actual SPR MIT spreadsheets.

Most of the sensitivity scenarios presented below will be evaluated using a value coined here as the equivalent volumetric change rate. The equivalent volumetric change rate (EVCR) represents the rate at which the volume of nitrogen in the well test interval could be changing based on the sensitivity test scenario and the duration of the test scenario computed for average well conditions. If this were an actual MIT, and this volumetric change was identified, this could be considered a leak rate. Scenario evaluations will also compare the EVCR to the MDLR as a means of representing the relative importance of the testing deviations presented in that scenario. In this comparison an EVCR value greater than or equal to the MDLR indicates that testing scenario presents a deviation which could result in a false-positive or false-negative MIT result. That is, that scenario deviation could result in a misinterpretation of the MIT results.

4. ANALYSIS

This section presents the general calculation methodology and scenarios investigated for the sensitivity analysis. In some cases, the analysis of a single parameter may involve more than one scenario in order to assess the impact of another characteristic (i.e. test interval geometry). In some cases the analysis results are presented with respect to a MDLR value. This is to give a more direct frame of reference of the gas volume changes.

4.1. Considerations of average well conditions

Any change in nitrogen volume in the well is reflected and measured by a change in the depth of the nitrogen-oil interface. A vertical change in the NOI will sweep a specific volume of the casing or chimney. The volume represented by the NOI depth change is dependent on the casing or chimney geometry. The volume of nitrogen actually contained in the swept volume is dependent on the pressure and temperature in that region. A significant change in the NOI depth indicates a loss of nitrogen from the well system. In calculating the volume of nitrogen lost, the temperature and pressure at the leak point must be considered. In general, this information is not available, because the actual leak point is unknown (the leak may be occurring anywhere in the well system). To address this in the leak volume calculation, average well temperature and pressure conditions are assumed. These average well conditions are computed using volume-based weighting.

It is important to keep in mind that the assumption of average temperature and pressure are a necessary convenience for calculating a leak rate and that there is likely no single depth in the well where these average temperature and pressure values exist simultaneously. This is because the natural geothermal gradient in the depth range covering SPR caverns is linear, but the pressure increase in the well is non-linear due to compressibility of the nitrogen. Computing average values from linear and non-linear functions across the same depth range will result in each average value occurring at a different depth. For example, in the hypothetical testing well presented below, the average temperature occurs at a depth of 1020.25 feet while the average pressure is seen at a depth of 1015 feet. Although this is not a large difference in depths, these differences can become important when looking at calculated leak rates. These differences can also be accentuated in areas with anthropogenically altered geothermal gradients, such as the Bryan Mound SPR site where sulfur mining in the caprock has disturbed the temperature profile (Kirby and Lord, 2015).

4.2. General calculation methodology

To find changes in the nitrogen volume response variable, we need to compute the volume of nitrogen in the test interval as we alter a single test parameter. There are several approaches to computing this volume including full hydrostatic column modeling. The approach used here adopts a less complex methodology similar to what is used in actual MIT calculation spreadsheets. This provides a more constrained environment which is more appropriate for sensitivity analysis.

The sensitivity analysis calculations presented here concentrate on the parameters primarily associated with the nitrogen and the nitrogen-oil interface associated with a MIT. To model the conditions of the nitrogen as a function of depth, a standard set of calculations are used as presented below:

$$P_z = (P_w + P_{atm})\, e^{\alpha} \ ,$$

where $$\alpha = \frac{z}{R_{N_2}\, T_z}$$

with $P_z =$ absolute pressure at depth z (psia)

$P_w =$ gauge pressure at well head (psia)

$P_{atm} =$ atmospheric pressure (psia)

Z = depth (ft)

$R_{N_2} =$ nitrogen gas constant (54.99 ft/°R)

$T_z =$ temperature at depth z (°R)

The depth-varying temperature and pressure data are then used to compute average well conditions, which are then used to convert the nitrogen volume to standard conditions. The adjustment of the volume to standard conditions allows for a systematic calculation of differences between analysis scenarios. The nitrogen volume at standard conditions (V_{SCF}) is computed as shown below. A similar calculation can be used to adjust volumes to other temperature and pressure regimes such as average well conditions.

$$V_{SCF} = \frac{P_{avg}}{P_{sc}} \frac{T_{sc}}{T_{avg}} \frac{1}{N_Z} V_c$$

Where

P_{avg} = average well pressure (psia)

P_{sc} = pressure at standard conditions (14.696 psia)

T_{avg} = average well temperature (°R)

T_{sc} = temperature at standard conditions (60 °R)

N_Z = nitrogen compressibility factor (unitless)

V_c = volume of MIT test interval above the NOI (ft^3)

4.3. Interface measurement

One of the most critical determinations made during MIT's is the measurement of the nitrogen-oil interface depth. This measurement is a direct indicator of potential loss of nitrogen from the well bore system.

Typically, it is assumed that this measurement can be made with an accuracy of 0.5 feet using current technologies and procedures. This means that the true interface depth should be within 0.5 feet of the reported measurement. Testing the significance of interface measurement errors on the computed nitrogen volume is relatively straight forward as the volume calculations are not complex; in general, the volume response is a function of the radius of the vertical test section.

For MITs where the region of the well/cavern system over which the NOI movement occurs has a constant radius, the change in nitrogen volume per unit change in NOI depth is very close to constant. The actual change in vessel volume between the different depth measurements is constant, but the volume of nitrogen at standard conditions does not change perfectly linearly due to compressibility of the nitrogen and temperature and pressure effects. The impact of these effects is typically very small (<<0.001%) for most MIT testing conditions.

In test sections where the radius is not constant, the change in nitrogen volume per unit change in NOI depth is a function of the geometry of the chimney or cavern. Test sections with greater radial change per vertical foot will show greater sensitivity than those with less radial change. Compounded on top of these changes are the relatively minor contributions of pressure and temperature over the test section of NOI movement.

4.3.1. Vertical wall chimney configuration

The first scenario considered for NOI movement assumes that the NOI movement occurs in a 3 foot diameter chimney with vertical walls. This geometry basically represents a cylinder. The details of the parameters used in the calculations for this scenario are provided in Table 4-1.

Table 4-1. Assumed well configuration and parameters for vertical wall chimney example.

Assumed Temperature Gradient	0.019 °F/ft
Initial Top Temperature	75 °F
Gauge Pressure	1370 PSI
RN2	54.99
Compressibility Factor	1.0158
Well Casing Length	2000 ft
Well Casing ID	1.04 ft
Chimney Length	10 ft
Chimney Diameter	3.0 ft
Nitrogen Oil Interface Depth	2005 ft
Average Well Temperature	94.5 F°
Average Well Pressure	1731.6 PSI

A 3-foot chimney diameter gives a chimney volume rate of 633.8 standard cubic feet of nitrogen per foot of NOI change for the test section within the chimney. This is computed using temperature and pressure conditions near the NOI and then adjusting that mass to standard conditions (14.7 psia and 60 °F). Adjusting SCF to average well conditions (AWC) gives 6.9 cubic feet per foot of NOI change.

The volume rate of 6.9 AWC CF per foot of test section means that if the nitrogen oil interface is misread by 0.5 feet (6 inches), then a nitrogen volume difference of 3.5 AWC CF could be unrecognized. Over a 2-day test period this would be equivalent to a volumetric change rate of 113.2 BBL/yr. at AWC. This value is approximately 100% of the MDLR for this size chimney assuming a 2 day test duration. The equivalent volumetric change rate (EVCR) represents the rate at which the volume of nitrogen in the test interval could be changing based on the sensitivity test scenario and the duration of the test scenario computed for average well conditions. If this were an actual MIT, and this volumetric change was identified, this could be considered a leak rate.

If this well contained a hanging brine string, then the overall volume of nitrogen in the test interval must be reduced by the volume displaced by the brine string. A 10 ¾" brine string occupies 0.64 cubic feet per 1-foot length of brine string ($\pi * 0.45\ ft^2$), which would be 0.32 cubic feet for a 0.5 foot interface misread. Subtracting this from the chimney volume to give the actual nitrogen volume at depth, then converting this volume to average well conditions gives a value of 3.2 CF at AWC. For this chimney containing a brine string, over a 2-day MIT period, a NOI misread of 0.5 feet would be equivalent to a volumetric change rate of 103 BBL/yr, which could lead to either false-positive or false-negative leak identification.

Table 4-2 below shows how differing chimney diameters impact the EVCR resulting from a 0.5 foot error in determining the depth of the NOI. This would represent not identifying a 0.5 foot change in the NOI when in fact the NOI had shifted that amount. The lower portion of the table provides results for the same chimney diameters, but with the presence of a brine string.

Table 4-2. Potential volume change from 0.5' error in NOI determination.

Chimney Diameter (ft)	Equivalent Vol. Change Rate AWC (BBL/yr.)*
2	50.3
2.5	78.6
3.0	113.2
3.5	154.0
4	201.2
With 10 ¾" Brine String	
2	40.1
2.5	68.4
3.0	103.0
3.5	143.8
4	191.0

*This is the equivalent volume change per year that could occur due to a 0.5 foot error in reading the NOI based on a 2 day MIT for average well conditions.

Because the volume values for all the diameter examples provided in Table 4-2 reflect a 0.5 foot change in NOI, which is the same as the logging resolution used in computing the MDLR, they are approximately equivalent to 100% of the MDLR assuming a test duration of 2 days.

4.3.2. Sloping wall chimney configuration

In this example of looking at NOI measurement error, the chimney is assumed to have sloping walls so that the chimney diameter increases with depth at a constant rate. The chimney diameter at the casing shoe is 3 feet (same as the constant radius example above) and increases by 1.0 foot per foot of depth increase. Using a 10 foot chimney length, this gives a final chimney diameter of 13 feet where the chimney enters the cavern. The chimney diameter is 8 feet at the nitrogen oil interface.

Table 4-3. Assumed well configuration and parameters for sloping wall chimney example.

Assumed Temperature Gradient	0.019 °F/ft
Initial Top Temperature	75 °F
Gauge Pressure	1370 PSI
R_N2	54.99
Compressibility Factor	1.0158
Well Casing Length	2000 ft
Well Casing ID	1.04 ft
Chimney Length	10 ft
Top Chimney Diameter	3.0 ft
Bottom Chimney Diameter	13.0 ft
Nitrogen Oil Interface Depth	2005 ft
Average Well Temperature	95.4 °F
Average Well Pressure	1433.8 PSI

Because of the sloping walls (varying diameter), the volume rate of the chimney is depth dependent. Figure 4-1 below shows the relationship between chimney diameter and chimney volume for the assumed chimney configuration in Table 4-3. In the region of the nitrogen oil interface (midway down the chimney), raising the NOI by one foot sweeps a volume of 44.2 CF. This volume filled with nitrogen at NOI pressure and temperature would occupy 43.4 CF at AWC. The lower volume at AWC is due to the lower temperature at AWC as compared to conditions at the NOI. Here, the temperature affect is greater than the volumetric change due to lower AWC pressure.

At this volume rate, misreading the NOI depth by 0.5 feet means a volume difference of 23.2 AWC CF could be misinterpreted. Over a 2 day test period this would give a EVCR of 753.5 AWC BBL/yr. which is approximately 105% of the MDLR.

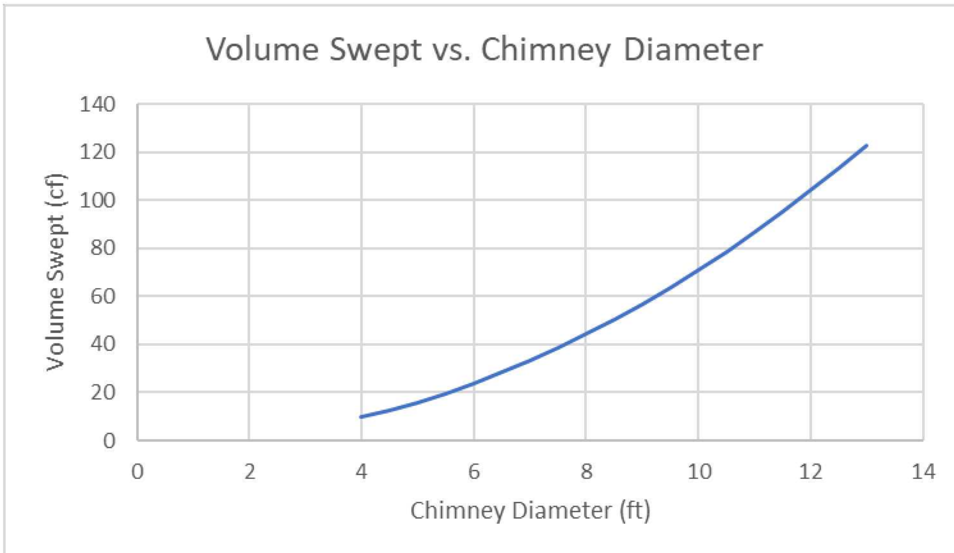

Figure 4-1. Volume swept per foot of interface movement as a function of chimney diameter for sloping wall chimney example.

If this well contained a 10 ¾" brine string, then, using calculations similar to those shown above, the volume rate at the chimney would be 42.8 per foot of chimney at AWC. This would result in a volume of 22.9 CF AWC for a 0.5 foot error in reading the NOI. Over a 2-day MIT, this represents the EVCR of 743.3 BBL/yr. AWC, which is again about 105% of the MDLR.

4.4. Temperature

The MIT process accounts for temperature effects at the time of the MIT. This sensitivity analysis is targeted at looking at the potential impacts from unidentified temperature fluctuations, the type of error that may occur from instrument miscalibration or bias.

Investigation of potential temperature measurement deviations are investigated by applying slight changes to an assumed well temperature profile. These minor changes are intended to represent the potential measurement errors that might be experienced during the multiple logging sessions over which the initial and final MIT temperature measurements are made.

The general procedure for this analysis is to assume a well head temperature (75 °F) and incremental temperature change (0.019 °F/ft) as a function of depth. This generates a linear temperature profile as shown in Figure 4-2. Then small changes are applied to the initial well head temperature to simulate fluctuations in the logging procedure which then shifts the entire temperature profile. This analysis will be done using two different chimney configurations, one with a constant diameter, and the other with sloping chimney wall where the diameter increases with depth. Common parameters for this analysis are presented in Table 4-4.

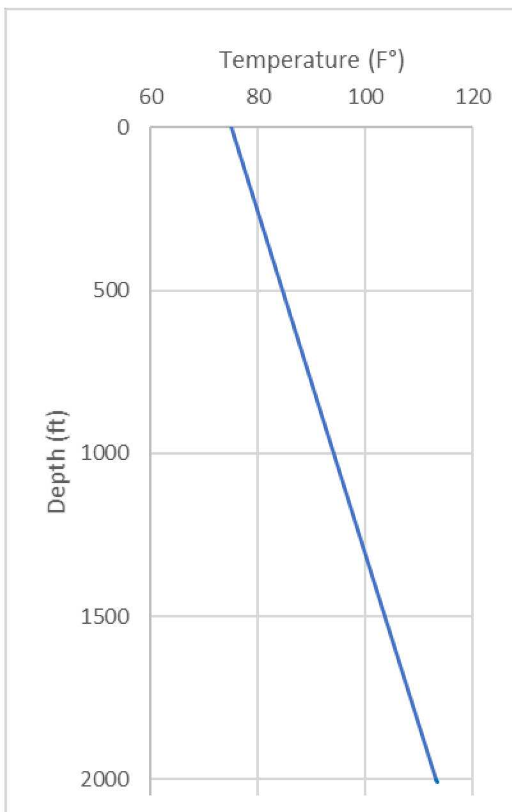

Figure 4-2. Assumed initial borehole-chimney temperature profile.

Table 4-4. Assumed well configuration and parameters for temperature effects scenario.

Assumed Temperature Gradient	0.019 °F/ft
Initial Top Temperature	75 °F
Gauge Pressure	1370 PSI
R_N2	54.99
Compressibility Factor	1.0158
Well Casing Length	2000 ft
Well Casing ID	1.04 ft
Chimney Length	10 ft
Nitrogen Oil Interface Depth	2005 ft

4.4.1. Constant diameter chimney scenario

In this temperate effects scenario, the chimney diameter is fixed at 3 feet. The NOI is located in the chimney. For this investigation, three different temperature change scenarios were used: 1 degree, 2 degree, and 3 degree total temperature range difference. All temperatures are in degrees Fahrenheit. For each scenario, the temperature range difference was centered on the default initial top temperature listed in Table 4-4. For example, for the 1 degree temperature range scenario, the initial top temperatures would be 74.5 and 75.5 °F. For each of these initial top temperatures, the total volume of nitrogen contained in the well system was calculated and adjusted to AWC. It is assumed that there is no perceptible change in the NOI depth and so, the same NOI is used for all scenarios. The well configuration for this scenario consists of a 1.04 foot inner diameter well casing with a constant 3 foot diameter chimney into the salt. The NOI is assumed to be located 5 feet below the end of the casing and in the chimney. The only difference between all these scenarios is the temperature profile of the well bore.

Table 4-5 lists the parameters and results from each of the three temperature range scenarios given above. In this table, the "Vol. Change AWC" column presents the volumetric change in nitrogen between the two temperature endpoints adjusted to average well conditions for that scenario. The EVCR provides the annual rate of change represented by the volumetric change assuming the temperature measurements spanned a 2-day time period. That is, if, during a 2-day MIT, an unrecognized temperature difference was experienced, then that difference could mask a potential volumetric change rate of this magnitude. The potential change rate is provided in barrels per year for comparison against the MDLR. The MDLR was computed using the equation listed in Section 2 of this report and assumes a 2-day MIT. The final column in Table 4-5 lists the EVCR as a percentage of the calculated MDLR. This gives insight into the relative magnitude of the EVCR. The results show that even for minor temperature excursions, there is the potential to mask a leak which is a significant percentage of the MDLR. For a one-degree error between temperature logs could mask a loss rate which is 90% of the MDLR; this goes up to 270% of MDLR for a 3-degree error. As seen in the results, the impact of temperature appears to scale linearly for the ranges considered here.

Table 4-5. Test parameters and results for temperature sensitivity investigation for constant diameter chimney geometry.

Temp. Range (°F)	Low Temp. (°F)	High Temp. (°F)	Vol. Change AWC (BBL)	EVCR (BBL/yr.)	MDLR (BBL/yr.)	EVCR % of MDLR
1	74.5	75.5	0.57	103.84	114.98	90.3%
2	74	76	1.14	207.68	114.98	180.6%
3	73.5	76.5	1.71	311.52	114.98	270.9%

4.4.2. Increasing diameter chimney scenario

In the above investigation of temperature impact, the NOI was assumed to reside in a chimney of constant diameter. Now we will look at the same temperature impact for a NOI occurring in a chimney with sloping walls.

In this scenario, the chimney has an initial diameter of 3 feet at the top of the chimney, then increases at a rate of 1 foot per foot of depth increase. This gives a chimney diameter of 8 feet at the NOI depth of 2005 feet. The three temperature range scenarios used here are exactly as seen in Section 4.4.1; only the chimney geometry is changed.

The results from this temperature investigation are presented in Table 4-6. As seen in the MDLR column, the MDLR computed for this geometry is much larger than the previous constant diameter chimney. This is because the larger diameter at the NOI reduces the sensitivity of the MIT. In fact, the duration of the MIT for this geometry must be increased to 4.3 days to drop the MDLR below the maximum allowable value of 750 BBL/yr. Therefore, the calculations here assumed a 4.3 day MIT as well.

Although the AWC volumetric change values for this chimney geometry are almost identical to those in the constant diameter chimney scenario (Table 4-5), the potential loss rate as a percentage of MDLR is dramatically lower due to the larger MDLR. This provides a good example of the interdependency of MIT test results on test region geometry. The reason that volume changes are so similar to those in the constant diameter example is that only a small portion (~0.1%) of the total nitrogen volume is contained in the chimney, the vast majority of the volume is contained in the well casing.

Table 4-6. Test parameters and results for temperature sensitivity investigation for increasing diameter chimney geometry.

Temp. Range (°F)	Low Temp. (°F)	High Temp. (°F)	Vol. Change AWC (BBL)	EVCR (BBL/yr.)	MDLR (BBL/yr.)	EVCR % of MDLR
1	74.5	75.5	0.57	48.23	746.98	6.5%
2	74	76	1.14	96.46	746.98	12.9%
3	73.5	76.5	1.70	114.69	746.98	19.4%

The results from the temperature sensitivity investigation show that relatively small offsets in the temperature profile can generate significant changes in the total test interval nitrogen volume. This demonstrates the possibility of changes in the nitrogen volume that could be hidden by small fluctuations in the temperature profile.

4.5. Pressure

The MIT process accounts for pressure effects at the time of the MIT. This sensitivity analysis is targeted at looking at the potential impacts from unidentified pressure fluctuations, the type of error that may occur from instrument miscalibration or bias.

Investigation of potential pressure measurement errors are investigated by applying small changes to an assumed wellhead pressure. These minor changes are applied to investigate the impact that wellhead gauge pressure errors might have.

The general procedure for this analysis is to assume a nominal well head pressure. This wellhead pressure is used to compute the total wellbore nitrogen volume in a manner similar to what was done in Section 4.4 above. Small changes are then applied to the wellhead pressure and the nitrogen volumes recalculated. It is assumed that there is no perceptible change in the NOI depth during this process. Like the temperature analysis, this investigation will be done using two different chimney configurations, one with a constant diameter, and the other with sloping chimney wall where the diameter increases with depth.

4.5.1. Constant diameter chimney scenario

In this pressure effects scenario, the chimney diameter is fixed at 3 feet. The NOI is located in the chimney. The other parameters for this investigation are the same as those presented in Table 4-4 above.

For this testing a series of five pressure changes were investigated (Table 4-7). The pressures were chosen as a combination of absolute and relative pressure differentials. The 1 PSI pressure change was selected to represent a very small change in the well head pressure. The other four pressure changes were chosen as a relative percentage of the original well head pressure. The results from this analysis are presented in Table 4-7 below. The results columns are the same as those described for Table 4-5.

Table 4-7. Test parameters and results for pressure sensitivity investigation for constant diameter chimney geometry.

Press. Change (PSI)	Press. Change (%)	Low Press. (PSI)	High Press. (PSI)	Vol. Change AWC (BBL)	EVCR (BBL/yr.)	MDLR (BBL/yr.)	EVCR % of MDLR
1	0.73	1369.5	1370.5	0.22	40.32	114.98	35.1%
1.4	0.1	1369.3	1370.7	0.30	55.23	114.98	48.0%
3.4	0.25	1368.3	1371.7	0.76	137.97	114.98	120.0%
6.8	0.5	1366.6	1373.4	1.50	274.16	114.98	238.5%
13.7	1	1363.2	1376.9	3.03	552.35	114.98	480.4%

As the results show, relatively small deviations in well head pressure from the nominal pressure can have a notable impact on the potential loss rate. For example, if there was a 3.4 PSI change in the well head pressure during an MIT which was unrecognized (due to gauge or environmental issues), this could mask a potential nitrogen loss that is 120% of the MDLR.

4.5.2. Increasing diameter chimney scenario

Similar to the scenario presented in Section 4.4.2, this section presents pressure change results for a chimney with a diameter that increases with depth. In this scenario, the chimney has an initial diameter of 3 feet at the top of the chimney, then increases at a rate of 1 foot per foot of depth increase. This gives a chimney diameter of 8 feet at the NOI depth of 2005 feet. The pressure range scenarios used here are exactly as seen above; only the chimney geometry is changed.

Table 4-8 shows the results from this analysis. Because of the larger diameter of this chimney geometry, the MDLR is much larger than the constant geometry scenario, and the duration of the test must be increased to 4.3 days in order stay under the 750 BBL/yr. MDLR constraint.

Table 4-8. Test parameters and results for pressure sensitivity investigation for increasing diameter chimney geometry.

Press. Change (PSI)	Press. Change (%)	Low Press. (PSI)	High Press. (PSI)	Vol. Change AWC (BBL)	EVCR (BBL/yr)	MDLR (BBL/yr)	EVCR % of MDLR
1	0.73	1369.5	1370.5	0.22	18.91	746.98	2.5%
1.4	0.1	1369.3	1370.7	0.31	25.91	746.98	3.5%
3.4	0.25	1368.3	1371.7	0.76	64.76	746.98	8.7%
6.8	0.5	1366.6	1373.4	1.52	128.58	746.98	17.2%
13.7	1	1363.2	1376.9	3.05	259.05	746.98	34.7%

The results in Table 4-8 show that the absolute volume change at average well conditions (Vol. Change AWC) is not that different from the constant chimney diameter scenario for most of the pressure change ranges. However, these values represent a smaller percentage of the MDLR because the absolute MDLR value is significantly larger due to the larger diameter of the testing interval; a reduction in the MDLR would require a substantially longer test duration which is unlikely in most circumstances.

4.6. Chimney geometry

The geometry, or more specifically, the diameter of the testing interval is critical in a MIT in both the calculation of the MDLR and the CLR, because both of these values rely on knowing the volume of the testing interval as a function of depth. The depth to the NOI can be measured and the vertical movement of the interface provides one dimension of the volume measurement. The other required value is the diameter or radius of the testing interval. In practice, it is only important to know this diameter for the region of the NOI movement (Roberts, 2017).

The challenge is that determining the testing interval diameter accurately is difficult since we cannot make direct, physical measurements of the internal chimney diameters. Although we have indirect measurements of the cavern geometry via sonar surveys (Munson, 2000), the accuracy and resolution of these may not be sufficient for use in MITs. Instead, the cavern geometry in the MIT testing area is determined indirectly via measurements of NOI movement as a known mass of gas is injected. Using these techniques, axisymmetric (constant radius) estimates of the cavern diameter can be made. These are typically done at specific depth increments resulting in a representation of the cavern geometry as a series of stacked cylinders, each having a constant diameter.

As an example, Figure 4-3 below shows the stacked cylinders model using actual injection determined diameters of the lowest 4 injection segments for a MIT run on well BH-110A. As seen in this figure, there can be relatively significant diameter differences between the injection intervals. The change in diameters is a function of the cavern geometry and the height of the injection interval.

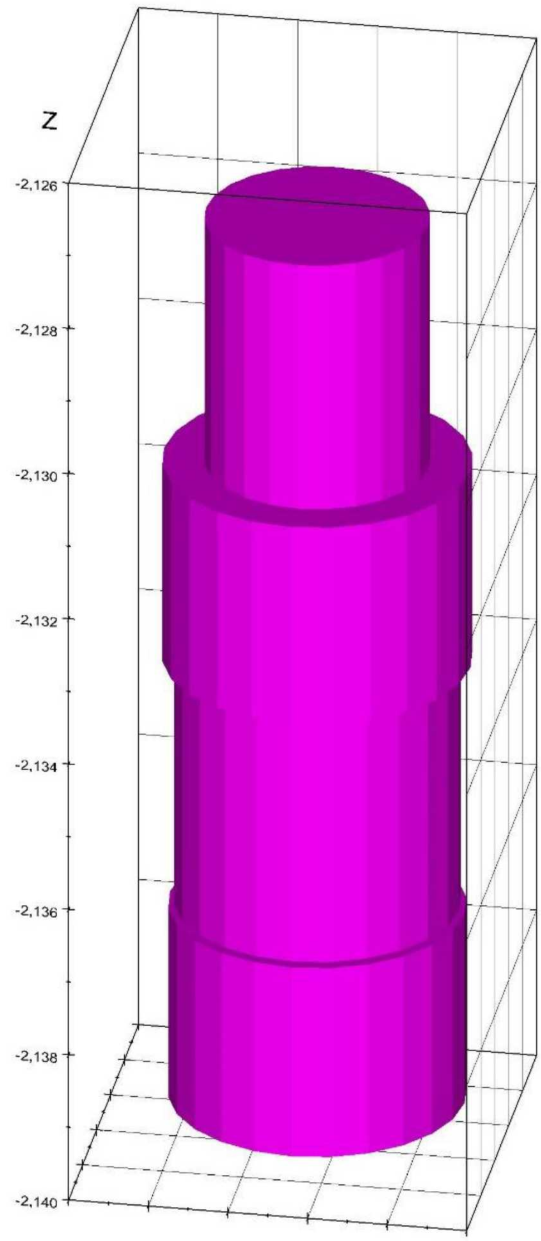

Figure 4-3. Stacked disk volume model developed from injection data for BH-110A MIT. Units are feet, horizontal gridlines at one-foot spacing.

To make an evaluation of the impact of the test section geometry (the interval over which any NOI movement takes place), the assumed cylinder-shaped test interval will be compared to a frustum shaped interval. The frustum is the same height as the cylinder, but the upper and lower radii have been computed to give the same volume as the cylinder geometry. This provides a testing geometry which would generate similar nitrogen injection data.

The dimensions of the assumed cylinder geometry are taken directly from the results of an actual MIT (Strategic Petroleum Reserve, 2019a) and are represented by the bottom cylinder in Figure 4-3.

This cylinder has a diameter of 3.85 feet, a height of 2.7 feet, and holds a volume of 31.54 cubic feet. Details of the cylinder and frustum geometries are listed in Table 4-9.

A visual comparison between the cylinder and frustum geometries is provided in Figure 4-4. As shown in this figure, the magnitude and sign of the difference of radii between the vertical and sloping wall configurations depends on what section of the test interval you are looking at. If your NOI movement occurs in the lower section of the geometry (below mid-point), then the cylinder geometry will under-estimate the volume of gas displaced relative to the frustum geometry. If the NOI movement is in the upper section, then the cylinder geometry over-estimates. In typical cases the NOI is at the bottom of the last segment of the nitrogen injection, and so, any NOI movement would occur near the base. This would suggest that the cylinder geometry would under-estimate the volume of gas displaced relative to the frustum geometry. Under-estimation of the gas volume could lead to a false-negative result – a missed leak.

The magnitude of the difference between the cylinder and frustum geometries is a function of the angle of the frustum walls; larger angles lead to larger differences. Note that the volume differences for the lower-half and upper-half of the geometries are not equal.

Table 4-9. Configuration of geometries used in geometry sensitivity analysis study. Color column refers to geometry colors seen in Figure 4-4

Geometry	Top Radius (ft)	Bot. Radius (ft)	Vol. (cu. Ft.)	Color
Cylinder	1.93	1.93	31.54	Black
Frustum 1	1.83	2.03	31.54	Gray
Frustum 2	1.73	2.12	31.54	Orange
Frustum 3	1.63	2.21	31.54	Green
Frustum 4	1.53	2.30	31.54	Purple

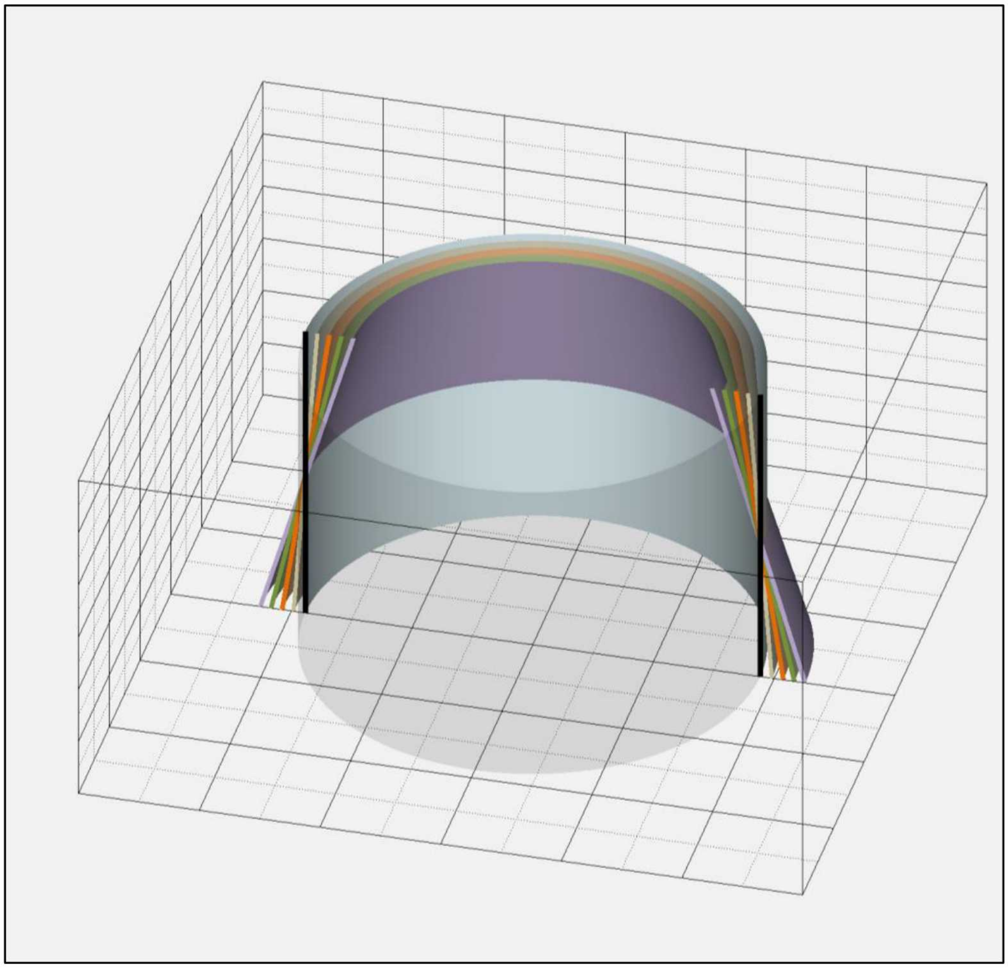

Figure 4-4. 3D rendering showing the assumed cylinder configuration and alternate frustum geometries investigated. Details provided in Table 4-9.

For the sensitivity analysis, it was assumed that the NOI was located at the bottom of the frustum geometry as would be the case in an actual MIT. This maximizes the volume differences between the frustum and cylinder geometries; NOI movement nearer the mid-height of the frustum would exhibit smaller volume differences.

Results from the cylinder to frustum comparison for the lowest section of the test segment are shown in Table 4-10 below. The geometry volumes shown are for a 0.5 foot rise of the NOI from the base of the test segment and are strictly based on the geometry of the test section swept by the 0.5 rise in the NOI. The "Vol. N_2 AWC" column shows the volume that nitrogen would occupy if the geometric volume was moved from the testing conditions to average well conditions. As shown in this table, the volumes gradually increase as the angle of the frustum wall increases.

Table 4-10. Dimensions and volumes of geometries covered by a 0.5 foot rise in the NOI.

Geometry	Top Radius (ft)	Bot. Radius (ft)	Geometry Vol. (BBL)	Vol. N_2 AWC (BBL)
Cylinder	1.93	1.93	1.04	1.02
Frustum 1	1.99	2.03	1.13	1.11
Frustum 2	2.05	2.12	1.22	1.19
Frustum 3	2.11	2.21	1.31	1.28
Frustum 4	2.16	2.30	1.39	1.37

Table 4-11 shows calculated volumetric change rates for each of the geometries calculated from a 0.5 foot rise in the NOI and assuming a 2 day test interval. The "Delta" columns show the change in the EVCR compared to the cylinder geometry both in BBL/yr. and as a percentage of the MDLR. As the table shows, the impact from changes from the assumed cylindrical geometry are relatively minor but do become more significant as the sidewall angle increases.

Table 4-11. Calculated volumetric change rates computed for different test segment geometries.

Geometry	EVCR* (BBL/yr)	EVCR Delta (BBL/yr.)	Delta (% MDLR**)
Cylinder	186.47	0.0	0%
Frustum 1	202.29	15.82	8.33%
Frustum 2	218.11	31.64	16.65%
Frustum 3	233.91	47.44	24.97%
Frustum 4	249.66	63.19	33.22%

*computed assuming 0.5 foot NOI rise and 2 day test duration

**MDLR computed as 190.01 BBL/yr for cylinder geometry assuming 0.5 foot log resolution and 2 day test duration.

5. CONCULSIONS

The focus of this report is investigating the sensitivity of MIT results to changes in the parameters involved in the testing. The procedure adopted for doing this involved making changes to the input parameters, then observing the changes in a response variable. The response variable for the testing focused on changes to nitrogen volumes in the testing interval. The responses were presented both as an absolute volume and as a percentage of the MDLR. The MDLR comparison is provided to give a frame of reference for the relative impact of the changes in the response variable.

A total of four MIT parameters were investigated. These are believed to represent the parameters which would have the greatest impact on the MIT and also parameters which may be subject to error or fluctuation during the testing. For most of the analysis parameters, alternate testing interval geometries were investigated. This was done to provide additional insight into the analysis. Discussion of the results for each testing parameter are provided below.

5.1. Discussion of results

The following sections discuss results from each of the sensitivity analysis scenarios. Figure 5-1 shows a comparative summary of the results. In this figure, the increasing diameter chimney and constant diameter chimney scenarios are labeled as "I.D." and "C.D." respectively. The interface measurement scenarios are shown as a single dot at 100%. It is useful to keep in mind that the primary reason the increasing diameter scenarios have lower percent MDLR values is because of the larger MDLR value associated with this geometry. The base case for each scenario is described in Table 4-1.

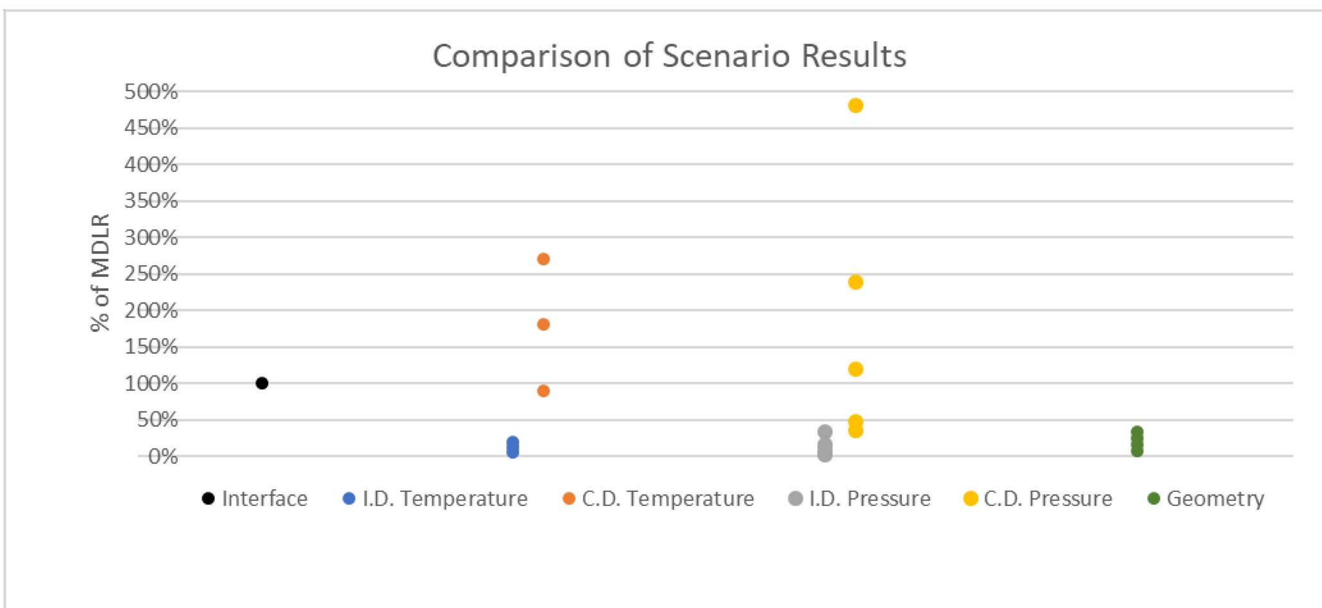

Figure 5-1. Comparison of different scenario results shown as percentage of the MDLR for that scenario.

5.1.1. Interface measurement sensitivity results

This analysis looked at how plausible errors in determining the NOI depth could impact MIT results. The results, assuming a 0.5 foot error in reading the interface depth are equivalent to approximately 100% of the MDLR regardless of the test interval configuration. This shows the critical importance in accurate and repeatable determination of the NOI depth. Errors in this measurement have a direct impact on the accuracy of the MIT.

5.1.2. Temperature sensitivity results

In this analysis, the impact of relatively minor errors in measuring the temperature profile of the testing environment were investigated. The MIT process accounts for temperature effects at the time of the MIT. This analysis is targeted at looking at the potential impacts from unidentified temperature fluctuations, the type of error that may occur from instrument miscalibration or bias.

Results from this analysis show that small fluctuations in the temperature profile can have impacts that are a significant percentage of the MDLR. For example, Table 4-5 shows that for a constant diameter chimney, a one-degree fluctuation in the temperature profile could cause a change in the nitrogen content of the testing system which is 90% of the MDLR. This goes up to 181% and 271% for temperature deviations of 2 and 3 degrees respectively. The EVCR for the increasing diameter chimney scenario are much smaller in absolute volume and as a percentage of the MDLR (Figure 5-1). This is because the larger diameter of the testing region around the NOI requires a longer test duration to meet the maximum MDLR allowable value. This longer duration lowers the annual change rate (EVCR) because the change in volume occurred over a longer test duration. And, the EVCR represents a smaller percentage of the MDLR simply because the MDLR is much larger than in the constant diameter scenario.

5.1.3. Pressure sensitivity results

This analysis scenario investigated the impact of small deviation in the well head pressure during a MIT. Although the well head pressure and down hole pressure environment is accounted for in the MIT calculations, the scenarios presented here represent the potential impacts of pressure fluctuations that were not identified due to some instrumentation error.

The results from this analysis show that seemingly small changes in well head pressure can have significant impacts. As Table 4-7 shows, for a constant diameter chimney, a 3.4 PSI change in the well head pressure could result in a significant change in the nitrogen content of the system. Computing a volumetric change rate from this would result in an EVCR that is 120% of the MDLR. This pressure change represents only 0.25% of the well head pressure. The results for the increasing diameter scenario are similar in volumetric magnitude, but, like the temperature sensitivity results, the EVCR and EVCR as percent of MDLR values are much lower than in the constant diameter chimney scenario (Figure 5-1). This is for the same reasons as discussed under the temperature sensitivity analysis results.

5.1.4. Cavern geometry results

In this analysis, impacts from assumptions regarding the cavern geometry are investigated. Specifically, this analysis looks at technique of determining the testing interval geometry (diameter values) from nitrogen injection data. In this process, the testing interval geometry is assumed to be cylindrical in shape. This analysis looked at the impact of differing geometries, specifically frustums, on testing results.

The test results, as shown in Table 4-11 and Figure 5-1, indicate that the assumption of a cylindrical geometry has relatively little impact on the testing results. That is, deviations from the assumed cylindrical geometry are not likely to change the test results dramatically at least for the range of geometries investigated here. This would likely not hold if the NOI movement was sufficient to span multiple injection intervals (cylinders shown in Figure 4-3), and these intervals had significantly different diameters. In this case, more consideration would need to be given to the analysis results, and special treatment necessary.

5.1.5. *Summary of testing results*

Of the testing parameters investigated here, it appears that accurate measurement of the NOI depth has the greatest impact on the MIT results. This is not surprising as this measurement, or derivatives from it, are fundamental in virtually all the MIT calculations. Although other scenario results can have larger deviations with respect to the MDLR, errors in the interface measurement have ramifications throughout the MIT process, and so, have the greatest impact on the accuracy of MIT results.

Next in order of importance would be the influence of temperature. The results show that seemingly innocuous changes in the temperature profile (1 F°) can have a significant influence on the MIT results (up to 90% of MDLR). Potential errors from mis-calibration or instrumentation bias may have detrimental impact MIT results and interpretation.

Well head pressure would be the next parameter in order of importance of those reviewed here. Results from the sensitivity analysis indicate that very small errors in well head pressure readings would have only minor impact on MIT results. But these impacts increase as the pressure variance increases. With a 3.4 PSI pressure variance, the impact can be as high as 120% of the MDLR.

The final parameter investigated here, test interval geometry, appears to have the least potential impact on MIT results. Even with fairly significant deviations from the assumed cylindrical geometry, the impact was only about one-third of the MDLR. Although these results are highly dependent on the actual geometries of the testing interval, they are considered representative of the magnitude of impact expected in typical testing conditions.

Because actual MITs involve real world conditions and actual cavern geometries, assumptions and simplifications necessary for this type of sensitivity analysis must be considered when interpreting the results. For many of the analyses presented here, it is assumed that other MIT parameters do not change as the analysis variable is changed. This is necessary to isolate the effect of the analysis variable but may not be representative of actual real-world MIT conditions. In addition, alteration of other factors such as the test interval geometry, duration of the test, etc. from those used here may alter the sensitivity results. Regardless, the results here are considered to be generally representative of the sensitivity of MITs to changes in the main input parameters. It is recommended that any efforts to improve the reliability and accuracy of nitrogen-liquid interface mechanical integrity testing focus on the parameters presented here and in the order of significance discussed above.

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