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Rock Fracturing Using High-Pressure Ethylene/Nitrous Oxide Detonations
(Tests conducted at EMTRC, Socorro, New Mexico)

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ABSTRACT

The present work investigates high initial pressure detonations of a stoichiometric mixture of ethylene and nitrous oxide (C2H4 + 6N2O) as a method of fracturing rock beneath the ground surface. These tests were conducted at a test site operated by the Energetic Materials Research and Testing Center (EMRTC), Socorro, New Mexico. The volume under the surface used for testing (called the Down Hole Assembly) consists of a 0.438 in. ID x 50 ft. long stainless-steel tube running down from the test site to a well bore which is 3 in. ID x 10 ft. long and the rock in the well bore is exposed to the propagating combustion wave. The testing carried out at Zucrow Laboratories in the smaller, alloy steel combustion vessel provided a scaling of pressures expected in the well bore. The combustion is initiated by energizing an EBW (Exploding Bridge Wire) above the ground surface. The experimental setup accommodates one high pressure (100,000 psia) transducer to measure the pressure peak and is placed approximately 5 ft. above the ground surface and 5 ft. downstream of the EBW. The focus of this series of experiments is to investigate the dependence of fracture to the rock beneath the surface on initial pressures of the mixture of ethylene and nitrous oxide. Experiments were carried out at initial pressures varying between 125 psia and 300 psi. The transducer recorded elevated pressures, which were 2.3 to 2.6 times in excess of the CJ values. The experimental results are discussed and explained in this report.

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ACRONYMS AND DEFINITIONS

Abbreviation	Definition
ID	Inner Diameter
EBW	Exploding Bridge Wire
in	Units of length in inches
CJ	Chapman Jouguet
psia	Units of pressure in pounds per square inch (absolute)
P&ID	Plumbing and Instrumentation Diagram
EMRTC	Energetic Materials Research and Testing Center, New Mexico
NP	Nitrogen Pressurization
ENP	Ethylene and Nitrous oxide Pressurization
s	Units of time in seconds
lbm	Units of mass in pounds mass
ft^3	Units of volume in cubic feet
^oF	Units of temperature in Fahrenheit
R	Units of temperature in Rankine
γ	Ratio of Specific Heats
T	Temperature
P	Pressure
dp/dt	Rate of change of pressure with time
R_u	Universal Gas Constant
min	Units of time in minutes
det	Detonation

1. INTRODUCTION

The present work investigates the high initial pressure detonations of a stoichiometric mixture of ethylene and nitrous oxide ($C_2H_4 + 6N_2O$) as a method of fracturing rock beneath the ground surface. These tests were conducted at a test site operated by the Energetic Materials Research and Testing Center (EMRTC), Socorro, New Mexico. The tests were conducted over two phases: first phase from the 4th to 7th of March 2013 and the second phase from the 24th to the 25th of June.

The test site was located on top of a mountain where multiple well bores were dug out and connected to the surface using stainless steel tubes set in concrete. The volume in which these detonations were setup consisted of a 0.438 in. ID x 50 ft. long stainless-steel tube running down from the ground surface to a well bore which is 3 in. ID x 10 ft. long and the rock in the well bore is exposed to the propagating combustion wave. This volume is referred to as the "Down Hole Assembly" or simply the "Well Bore" throughout this document. The stainless-steel tube was set in concrete and the extended about 4.5 ft. above the ground surface. The tube was attached to the "Tree" panel (schematic shown in the next section) above the surface which branched out to the ethylene, nitrous oxide and nitrogen lines. The combustible mixture in the above-mentioned volume was ignited by energizing an EBW (Exploding Bridge Wire), fitted at the top of the "Tree" panel about 10 ft. above the ground surface.

The experimental setup, apart from the well bore, consisted of two panels: the "Tree" panel and the regulator panel. Both the panels were fabricated and assembled at Zucrow Laboratories, Purdue University. The regulator panel consisted of the regulators, sonic venturis, thermocouples and pressure gages used to set the required pressures of ethylene, nitrous oxide and nitrogen. The regulator panel was connected to the ethylene, nitrous oxide and nitrogen cylinders using 40 ft. flexible metal hoses.

Experiments were carried out at initial pressures varying between 125 psia and 300 psia. The experimental setup accommodates one high frequency, high pressure (100,000 psia) transducer from PCB Piezotronics, Inc (PCB 109C11) to measure the pressure peaks during these tests. It was placed about 5 ft. above the ground surface and 5 ft. downstream of the EBW on the "Tree" panel as indicated in Figure 2-1. The pressures sensed by the transducer were observed on an oscilloscope and a Sandia National Laboratories personnel was responsible for recording these values. These values were about 2.3 to 2.6 times in excess of the CJ values. The experimental results from these tests are discussed and explained in this report.

The report includes sections about the test rig hardware, pressure and mass analysis of data obtained and finally a discussion about the damage on the rock due to these tests.

2. EMERTC TEST RIG HARDWARE

The EMRTC experimental setup consisted of 6 high pressure cylinders, 2 each for ethylene, nitrous oxide, and nitrogen. These cylinders were connected to the panels using 40 ft. flexible metal hoses. The metal hoses were connected to the regulator panel and each gas pathway consisted of pressure gages, a sonic venturi, a thermocouple, a solenoid valve, and related fittings to set the required pressures and mass flow rates for each test. The regulator panel was connected to the "Tree" panel using 0.25-in flexible metal hose for the ethylene line and 0.50-in flexible metal hose for nitrous oxide and nitrogen. The "Tree" panel consists of a central flow path that connects to the well bore assembly. Ethylene and nitrous oxide flow into this central flow path from opposing directions, aiding in mixing of the gases. Also, nitrogen can be injected into the central flow path as well for pre- and post-combustion investigation of leaks in the well bore.

Sonic venturis were used to maintain a set mass flow rate of the gases introduced into the well bore. The throat diameters for the venturis were selected based on the gas mixture ratio. Hence, the diameter of the venturi on the nitrous oxide line is higher than that on the ethylene line. The sonic venturis are choked by setting an upstream pressure about 1.3 times that of the desired gas pressure. Based on these requirements the following throat diameters were selected from those available:

1. Ethylene: 0.022 in.
2. Nitrous oxide: 0.062 in.
3. Nitrogen: 0.062 in.

The second panel ("Tree" panel) is placed directly over the well bore at the test site and consists of the necessary check valves and tubing to control the flow of gases into the well bore. All the plumbing fittings on this panel are Autoclave products except the unions used to connect the flexible metal hoses to the Tree panel, which are Parker tube fittings. The design and arrangement of the Tree panel are described in detail in the following three sections. The pressure ratings of the fittings are listed in Section 2.1, a schematic of the panel layout is given in Section 2.2, and the detailed plumbing and instrumentation diagram (P&ID) is given in Section 2.3.

2.1. Pressure Rating of Fittings on the Tree Panel

All the fittings used on the Tree panel are listed below as shown on the schematic in Section 2.2. The part numbers are highlighted in green and the pressure rating for each part is highlighted in yellow. All the fittings used for testing on the setup at Zucrow Laboratories were rated to a maximum, steady-state pressure of 20,000 psi and pressures in excess of 40,000 psi for some tests were recorded. In order to avoid any damage to equipment and personnel at the test site fittings rated to higher pressures were selected for locations where combustion gases are expected to be present.

2.1.1 Nitrous Oxide Inlet Line (moving away from the tree):

1. 1" Male to 9/16" Female adapter (43M169B40): 43,000 Psi (Male) & 40,000 Psi (Female)
2. 9/16" x 4" Nipple (40CN9904-316): 40,000 Psi
3. 9/16" O-Ring Check Valve (40CKO9900): 40,000 Psi

4. 9/16" Male to 1/2" NPT Female Adapter (15M98G8): 40,000 Psi (Male) & 15,000 Psi (Female)
5. 1/2" NPT to 1/2" Seal-Lok 8-8 FLO-SS: 12,000 Psi
6. 1/2" ID Flexible Metal Hose (SS-FM8VF8VF8-96): 1,800 Psi

2.1.2 *Ethylene Fuel Inlet (moving away from the tree):*

1. 1" Male to 3/8" Female adapter (43M166B3): 43,000 Psi (Male) & 60,000 Psi (Female)
2. 3/8" x 4" Nipple (CN6604-316): 60,000 Psi
3. 3/8" O-Ring Check Valve (CKO6600): 60,000 Psi
4. 3/8" Male to 1/4" NPT Female Adapter (15M64B8): 60,000 Psi (Male) & 15,000 Psi (Female)
5. 1/4" NPT to 1/4" Seal-Lok 4-4 FLO-SS: 12,000 Psi
6. 1/4" ID Flexible Metal Hose (SS-FM4VF4VF4-96): 3,100 Psi

2.1.3 *Nitrogen Inlet (moving away from the tree):*

1. 1" Male to 3/8" Female adapter (43M166B3): 43,000 Psi (Male) & 60,000 Psi (Female)
2. 3/8" x 4" Nipple (CN6604-316): 60,000 Psi
3. 3/8" O-Ring Check Valve (CKO6600): 60,000 Psi
4. 3/8" Male to 1/4" NPT Female Adapter (15M64B8): 60,000 Psi (Male) & 15,000 Psi (Female)
5. 1/4" NPT to 1/2" Seal-Lok 4-8 FLO-SS: 12,000 Psi
6. 1/2" ID Flexible Metal Hose (SS-FM8VF8VF8-96): 1,800 Psi

2.1.4 *Isolation for Low-Pressure Fill Process Pressure Transducer (moving away from the tree):*

1. 1" Male to 1/4" Female adapter (43M164B3): 43,000 Psi (Male) & 60,000 Psi (Female)
2. 1/4" x 3" Nipple (CN4403-316): 60,000 Psi
3. Needle valve with Air-to-Open Actuator (60VM4071-O1S): 60,000 Psi
4. 1/4" Male to 1/4" NPT Female Adapter (15M44B8): 60,000 Psi (Male) & 15,000 Psi (Female)
5. 1/4" NPT to 1/4" Seal-Lok 4-4 FLO-SS: 12,000 Psi
6. 1/4" ID Flexible Rubber Hose: 300 Psi

2.1.5 *High-Pressure Low-Frequency Pressure Transducer (moving away from the tree):*

1. 1" Male to 1/4" Female adapter (43M164B3): 43,000 Psi (Male) & 60,000 Psi (Female)
2. 1/4" x 3" Nipple (CN4403-316): 60,000 Psi
3. Honeywell Model HP Pressure Transducer: 50,000 Psi

2.1.6 Central Tree (moving from top to down):

1. 1” Plug Adapter for Igniter (43CP160): 43,000 Psi
2. 1” Cross (43CX16): 43,000 Psi
3. 1” x 6” Nipple (43CN1606-316): 43,000 Psi
4. 1” Cross (43CX16): 43,000 Psi
5. 1” x 6” Nipple (43CN1606-316): 43,000 Psi
6. 1” Cross (43CX16): 43,000 Psi
7. 1” x 6” Nipple (43CN1606-316): 43,000 Psi
8. 1” Cross (43CX16): 43,000 Psi
9. 1” x 6” Nipple (43CN1606-316): 43,000 Psi
10. 1” Coupling (43F16): 43,000 Psi
11. 1” x 20’ Tubing (MS15-199)
12. 1” Coupling (43F16): 43,000 Psi
13. 1” x 20’ Tubing (MS15-199)

2.2. Plumbing and Fittings Layout on the Tree Panel

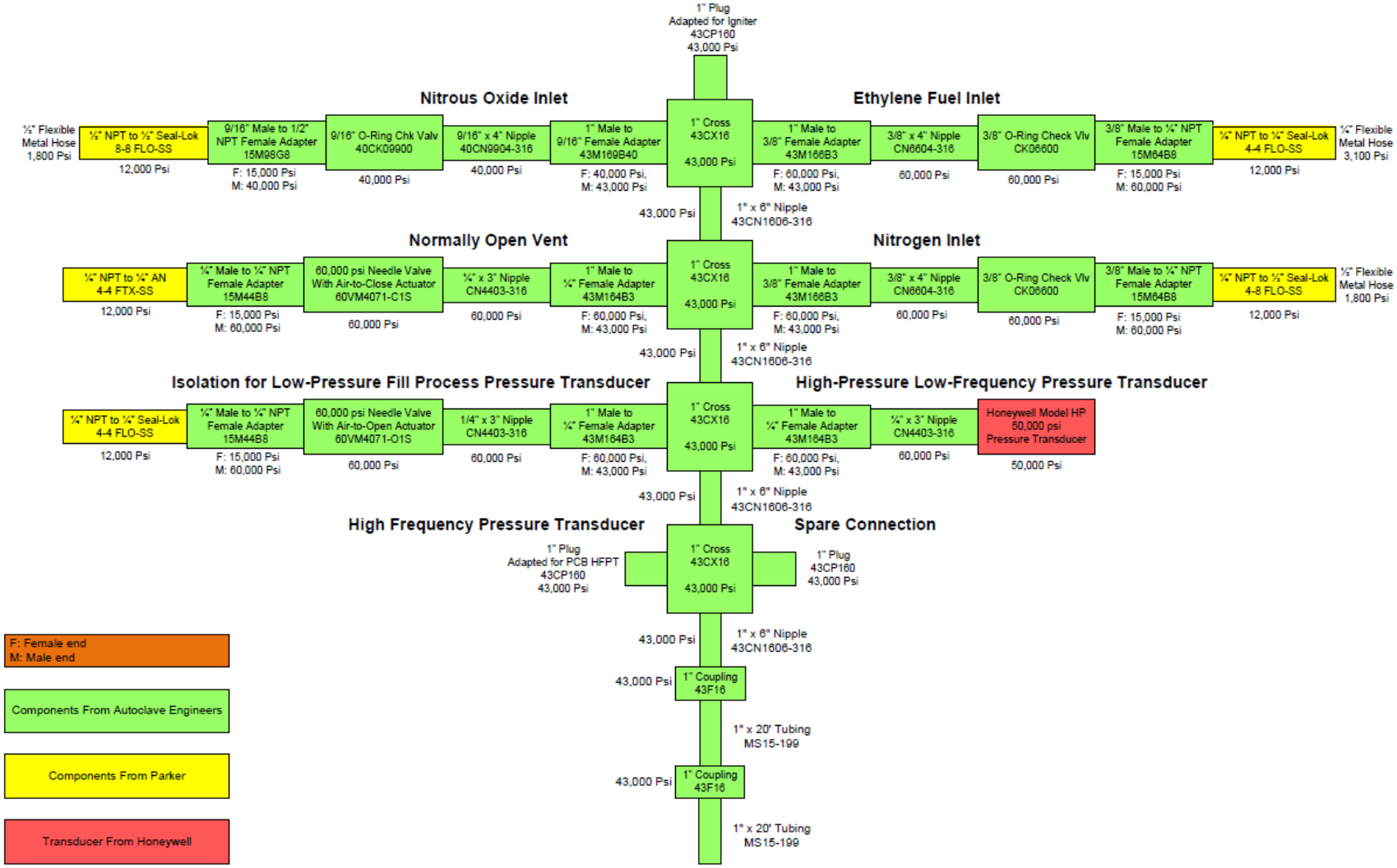

Figure 2-1. Plumbing and Fittings Layout.

2.3. Plumbing and Instrumentation Diagram for the EMRTC Test Setup

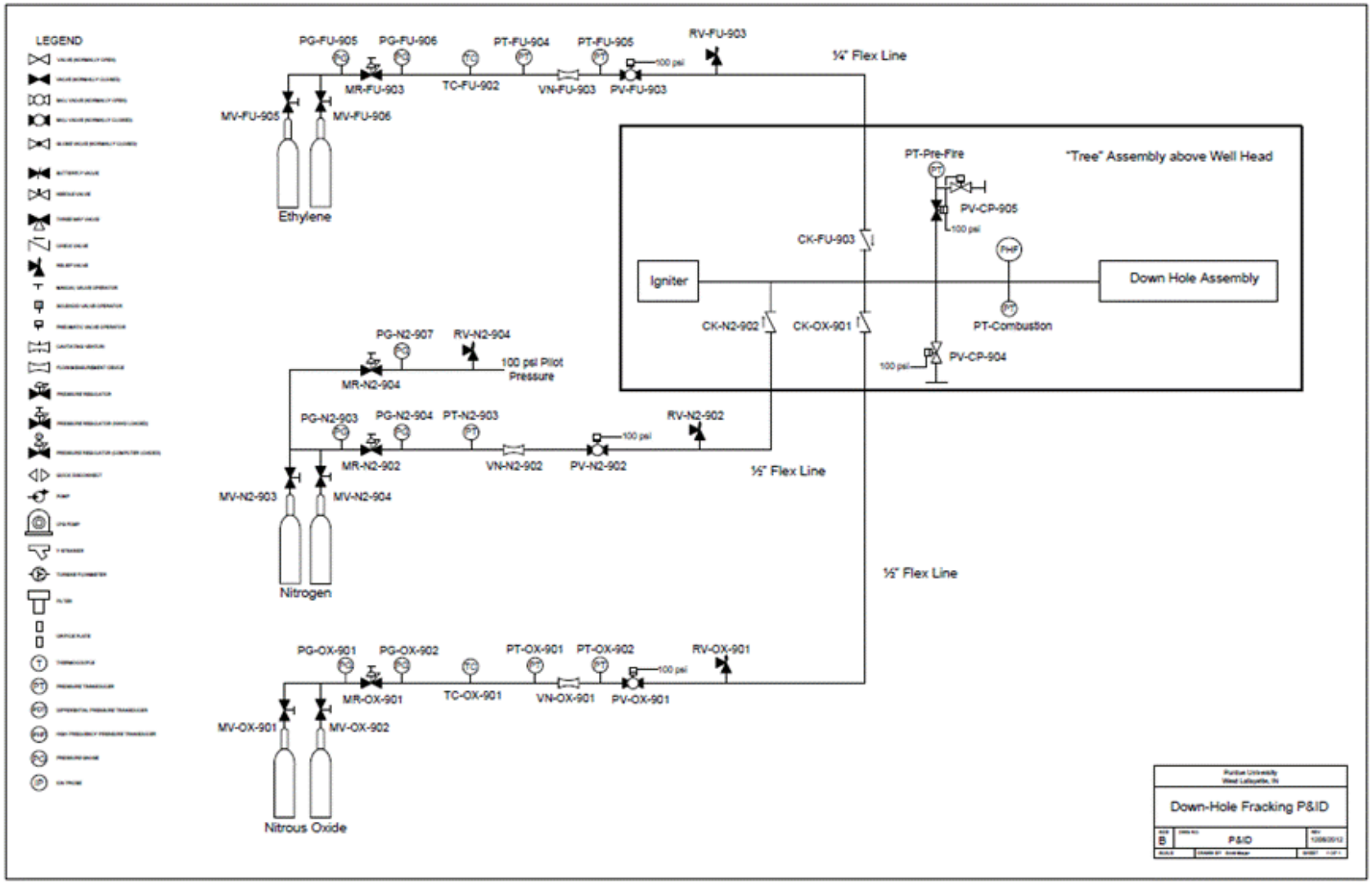

Figure 2-2. Plumbing and Instrumentation Diagram for the Down-Hole Setup at EMRTC.

3. PRESSURE AND MASS ANALYSIS OF EMRTC TEST DATA

Data obtained from each test run at the EMRTC site was analyzed to estimate the mass of nitrogen, ethylene and nitrous oxide introduced into the well bore. Pressure in the well bore, mass of gases introduced, and calculated volume of the well bore are plotted against time for these tests. The ethylene and nitrous oxide mixtures were ignited and combustion was observed during seven of the tests. For the remaining tests, the first few nitrogen pressurization tests were used to verify that the down hole assembly could maintain a constant pressure without any leaks. The other nitrogen pressurization tests were post-detonation cycles to observe the amount of gas leakage and thereby the extent of rock fracture. The un-ignited ethylene-nitrous oxide pressure tests in June were used to check the extent of leakage after each combustion test. After a certain duration of data acquisition, the gas mixture from the un-ignited pressurization cycles carried out before each combustion cycle was vented. Thus, these pressure cycles also served the purpose of ensuring that the well bore was at an atmospheric pressure containing primarily the ethylene-nitrous oxide mixture. Throughout the presentation of the test results, the following abbreviations are used to denote the gas(es) used in each test:

NP: Nitrogen Pressurization

ENP: Ethylene-Nitrous Oxide Pressurization

3.1. Mass Calculation for Gases

The pressures of nitrogen, ethylene, and nitrous oxide upstream of the venturis was recorded for each test. A National Instruments USB data acquisition device (NI USB-6341) was used for acquiring data from the components on the panels. A LabVIEW virtual interface (VI) was used to monitor and record the pressures and temperatures of the gases. The data was recorded at a sampling rate of 100 samples/s/channel. High pressure data from the PCB transducer was recorded on an oscilloscope operated by Sandia National Laboratories at a sampling rate of 1 million samples/s/channel.

The venturis were installed to maintain a set mass flow of gases based on the upstream pressure P_u. The mass flow rate of the gases is calculated at each time step using Equation 1:

$$\dot{m}_t = \frac{C_d A P_u}{\sqrt{\frac{R_u T}{(MW)\, g}}} \sqrt{\left(\gamma \frac{2}{\gamma + 1}\right)^{\frac{\gamma+1}{\gamma-1}}} \qquad \text{Equation 1}$$

which uses the following nomenclature:

C_d: Coefficient of discharge
A: Venturi cross sectional area
P_u: Pressure upstream of venturi
R_u: Universal gas constant
T: Temperature of the gas
MW: Molecular weight
g: Acceleration due to gravity
γ: Ratio of specific heats

Figure 3-1 shows the mass flow rate of nitrogen flowing into the well bore versus time for the 6th nitrogen pressurization test conducted in March 2013. The pressure upstream of the venturi was maintained at approximately 199 psia for this test. The plot represents an example of mass flow rate changes during the gas filling process. The mass flow rate is approximately constant apart from the initial sudden drop. The small fluctuations seen as time progresses are due to the minor unsteadiness observed in the upstream pressure.

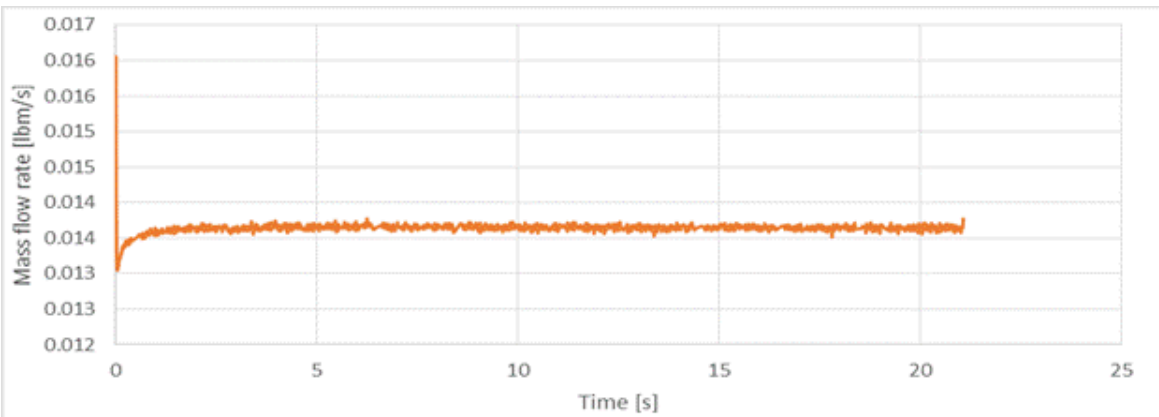

Figure 3-1. Plot of the measured mass flow rate of nitrogen for the 6th nitrogen pressurization test.

The product of this mass flow rate and the time step gives the increase in mass of the gas (Δm_t) in the down hole at each time step (Δt), i.e.,

$$\Delta m_t = \dot{m}_t \Delta t \qquad \text{Equation 2}$$

This increase in mass is integrated at each time step over the duration of gas flow into the down hole to calculate the total mass of gas (M_t) introduced into the well bore for each test as shown in Equation 3:

$$M_t = M_{t-1} + \Delta m_t \qquad \text{Equation 3}$$

The initial amount of gas present in the down hole at atmospheric pressure is accounted for when calculating the final mass. The well bore volume was estimated using Equation 4 at each time step and plotted along with the ideal well bore volume to observe changes in the volume:

$$V_t = \frac{M_t R_u T_g}{(MW)\,P} \qquad \text{Equation 4}$$

where T_g is the temperature of the ground and P is the recorded well bore pressure at time step t.

These plots are given in Appendix A. The method of volume calculation was refined at a later time to use the equilibrium pressure in Equation 4 instead of the instantaneous pressure. These results are presented along with the data analysis in Section 5.

3.2. Well Bore Pressure Measurement

The pressure in the well bore was observed in real-time during testing and recorded for data analysis. This data was essential for assessing the rate at which the gas mixture was filled into the well bore and understand how this filling rate was affected by the fracture of rock. The first nitrogen pressurization test is shown in Figure 3-2 as an example of the recorded well bore pressure.

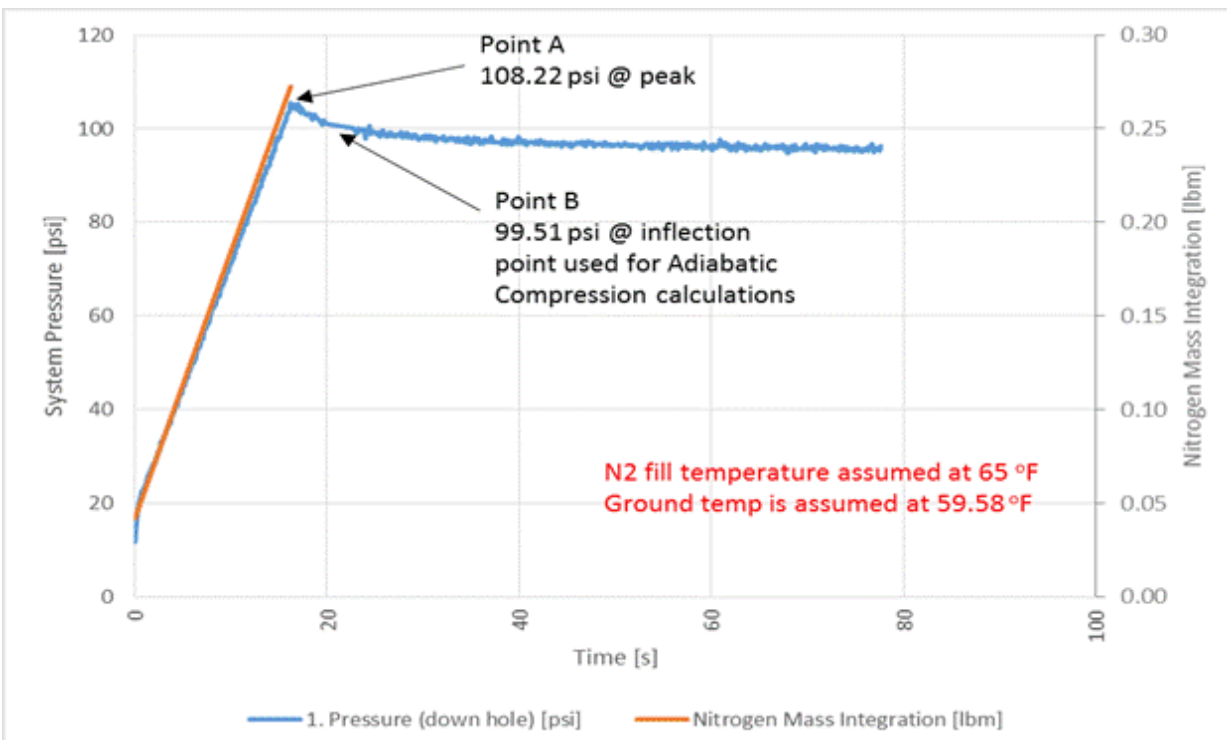

Figure 3-2. Plot of the measured pressure in the well bore and the calculated mass of nitrogen vs. time for test NP1.

As the gases flow into the well bore they are adiabatically compressed over the duration of the flow while simultaneously losing heat to the surrounding ground. When flow into the well bore is stopped, there is a drop in pressure in the well bore as shown in Figure 3-2 from point A to point B. This rapid pressure drop is principally attributed to the gases losing heat to the ground. In this pressurization cycle nitrogen in the well bore reaches a peak pressure of 108.22 psia (point A) and decreases to an approximately constant pressure of 99.51 psia (point B).

Assuming a ground temperature of 59.58°F (519.25 R) corresponding to point B in Figure 3-2, the temperature of the gases at point A can be determined using the adiabatic relation:

$$\frac{T_A}{T_B} = \left(\frac{P_A}{P_B}\right)^{\frac{\gamma-1}{\gamma}} \qquad \text{Equation 5}$$

where γ =1.4 for nitrogen. Using the assumed ground temperature (T_B) and the pressures at points A and B, the temperature of the gas at point A is estimated to be:

$$T_A = 519.25\left(\frac{108.22}{99.51}\right)^{\frac{1.4-1}{1.4}} = 531.85\ R = 295.47\ K = 72.18°\text{F} \qquad \text{Equation 6}$$

This temperature is higher than the temperature of the well bore and the temperature of the surroundings at the test site. The rapid drop in the well bore pressure from 108 to 99 psia upon stopping the nitrogen flow is easily explained by the gas temperature decreasing from 72°F to 59°F. The pressure continues to decrease slowly beyond point B which indicates a small leak in the well bore. The mass flow rate of this leak can be estimated based on the rate of the pressure decrease in Figure 3-2 and is discussed in more detail in a later section.

The pressure and mass data from the March and June tests are split into subsections 3.3 and 3.4, respectively. The plots from all ENP tests conducted in March only show pre-combustion data of the gas mixture and the pressure was recorded up to the peak pressure only. Data was not recorded beyond this point, and thus the final "equilibrium" pressure in the well bore is unknown. The plots from all NP tests and ENP tests from June show both pre- and post-combustion data. The pressure data recording was stopped/paused by closing the valve PV-CP-905 shown in the P&ID in Figure 2-2 and thereby shutting off the pressure transducer, PT-Pre-Fire, used to measure pressure in the well bore during all tests. For the combustion tests from June the valve PV-CP-905 was opened after a short duration post-combustion to resume data recording from the pressure transducer, PT-Pre-Fire. For all tests, the mass in the well bore is calculated by integrating the mass added at each time step during the filling process, as explained in Section 3.1. Each subsection includes data about the target pressure and the final "equilibrium" pressure achieved for each test after a certain duration of gas holding in the well bore.

3.3. Plots of Pressure and Mass Data from March 2013 Tests

All the plots are arranged in chronological order beginning with the first nitrogen pressure test conducted on the well bore on 03/04/2013. The initial nitrogen pressurization cycles were used to assess the ability of the well bore to maintain constant pressure and to identify any leaks in the well bore before the combustion cycles. The ENP tests were used to initiate combustion in the well bore to fracture rock, and the subsequent NP tests were used to assess the extent of rock fracture. The March tests are summarized in Table 3-1, and subsections 3.3.1 to 3.3.12 include plots of the bore pressure and the corresponding mass estimates.

Table 3-1. Summary of tests from March 2013.

Pressure cycle	Date of test	Target pressure [psia]	Equilibrium pressure [psia]	Fill time [s]	Mass of gases injected [lbm]	Combustion?
NP1	03/04/13	107.79	96.32	16.21	0.27	No
NP2	03/04/13	124.50	107.76	19.40	0.32	No
NP3	03/05/13	123.81	108.45	19.90	0.32	No
NP4	03/07/13	121.05	108.62	19.86	0.31	No
ENP1	03/07/13	141.77	-	25.12	0.53	Yes
NP5	03/07/13	124.70	95.17	22.30	0.36	No
ENP2	03/07/13	175.25	-	25.25	0.66	Yes
NP6	03/07/13	122.37	70.04	21.08	0.37	No
ENP3	03/07/13	281.48	-	25.22	1.08	Yes
NP7	03/07/13	123.45	51.52	91.71	1.34	No
NP8	03/07/13	291.87	179.62	213.07	7.90	No
NP9	03/07/13	291.08	218.43	256.92	10.44	No

3.3.1 Nitrogen Pressurization 1 (NP1)

Date: 03/04/2013
Duration of gas filling: 16.21 s
Target pressure: 105.46 psia
Equilibrium pressure: 96.32 psia
Data file name: 20130304_165043_.txt

This test was conducted to assess the ability of the well bore to maintain a constant pressure higher than atmospheric pressure and to verify that all equipment was functioning properly. As shown in Figure 3-3, the mass of nitrogen introduced into the well bore, calculated using the procedure outlined in Section 3.1, is 0.272 lbm.

In all the plots the blue line represents the well bore pressure and corresponds to the axis on the left and the orange line represents the mass of gas injected into the well bore and corresponds to the right axis.

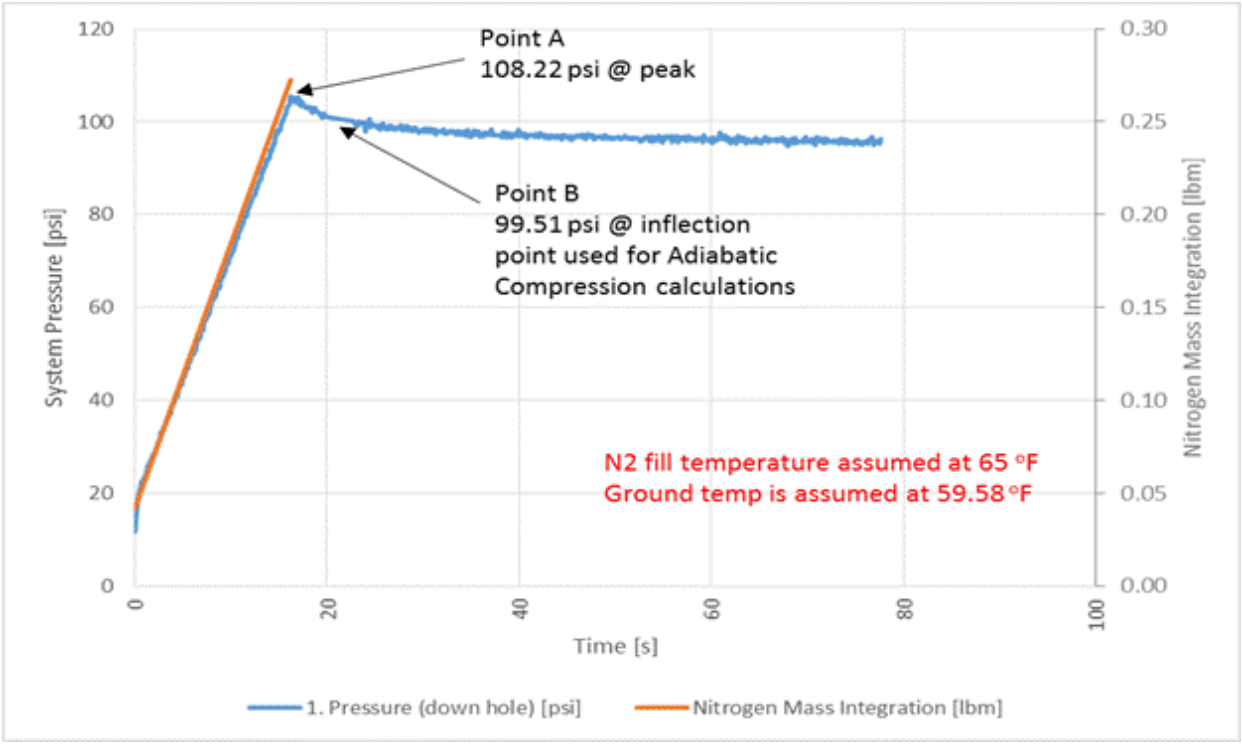

Figure 3-3. Plot of the measured pressure in the well bore and the calculated mass of nitrogen vs. time for test NP1.

3.3.2 Nitrogen Pressurization 2 (NP2)

Date: 03/04/2013
Duration of gas filling: 19.40 s
Target pressure: 124.50 psia
Equilibrium pressure: 107.76 psia
Data file name: 20130304_174527_.txt

The pressure drop observed in Figure 3-4 is due to the initial adiabatic compression of the gas followed by leakage out of the well bore. The mass of nitrogen introduced into the well bore is calculated to be 0.316 lbm.

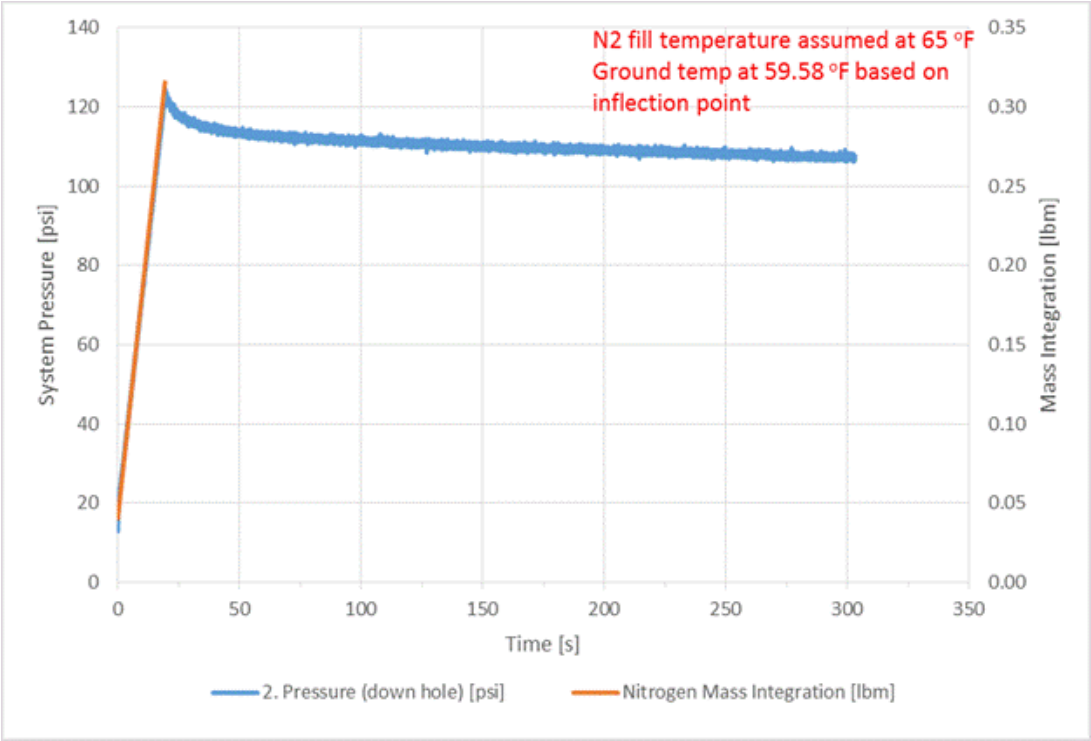

Figure 3-4. Plot of the pressure in well bore and mass of nitrogen (calculated) vs. time for test NP2.

3.3.3 Nitrogen Pressurization 3 (NP3)

Date: 03/05/2013
Duration of gas filling: 19.90 s
Target pressure: 123.81 psia
Equilibrium Pressure: 108.45 psia
Data file name: 20130305_182930_.txt

The mass of nitrogen introduced into the well bore was 0.316 lbm as shown in Figure 3-5. The well bore pressure equalizes at 108.45 psia, which is approximately the same as the previous test (NP2).

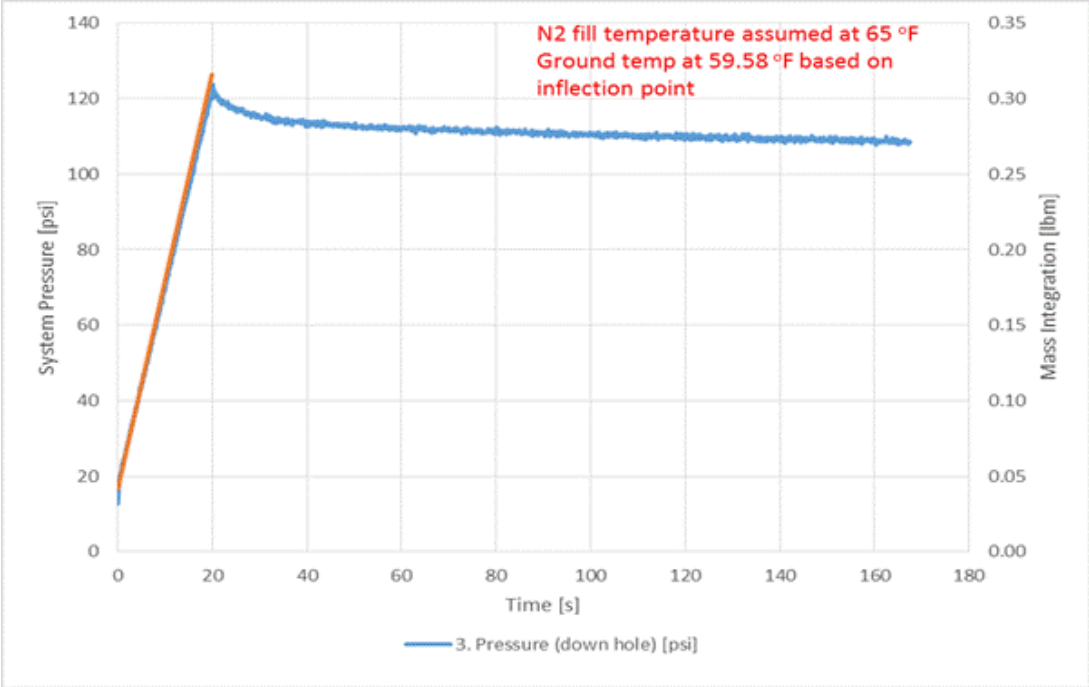

Figure 3-5. Plot of the pressure in well bore and mass of nitrogen (calculated) vs. time for test NP3.

3.3.4 Nitrogen Pressurization 4: Pre-Test Pressurization (NP4)

Date: 03/07/2013
Duration of gas filling: 19.86 s
Target pressure: 120.56 psia
Equilibrium pressure: 108.62 psia
Data file name: 20130307_131525_.txt

The mass of nitrogen introduced into the well bore was 0.314 lbm as shown in Figure 3-6. This nitrogen pressurization test was conducted on the 7th of March just before the first ENP test so ensure nothing in the well bore had changed since the nitrogen test on the 5th of March. Both the mass and the equilibrium pressure were approximately the same as the previous two NP tests, as expected.

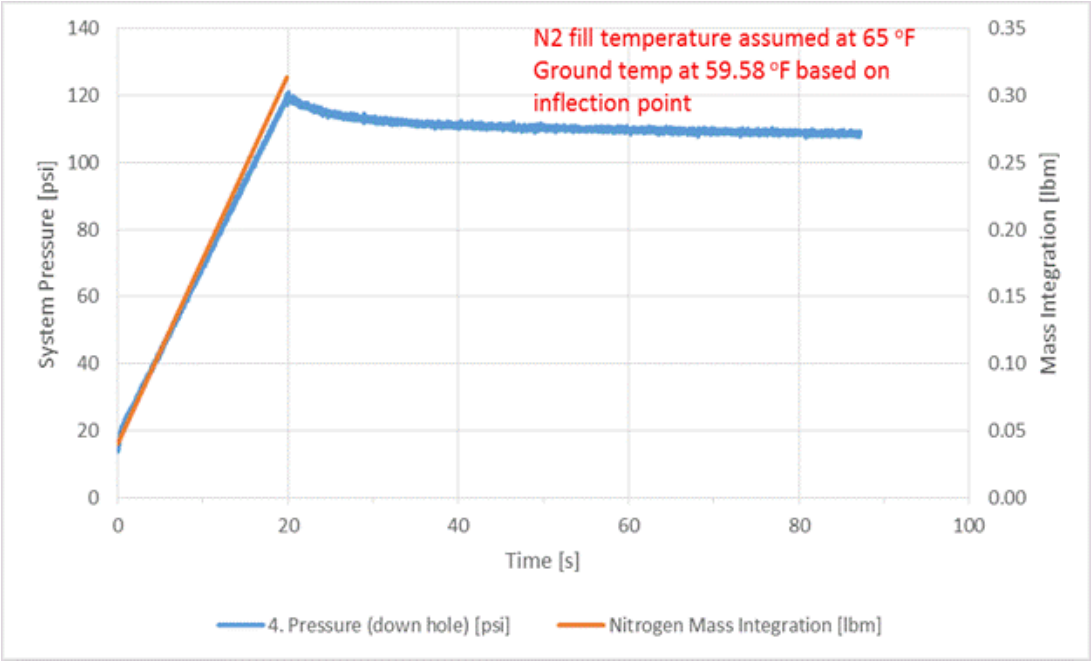

Figure 3-6. Plot of pressure in well bore and mass of nitrogen (calculated) vs. time for test NP4.

3.3.5 Ethylene/Nitrous Oxide Pressurization 1 with Combustion (ENP1)

Date: 03/07/2013
Duration of gas filling: 25.12 s
Target pressure: 141.77 psia
Data file name: 20130307_131525_.txt

ENP1 was the first pressurization test using a stoichiometric ethylene-nitrous oxide mixture. The mixture was ignited remotely using an EBW and the pressure from the PCB transducer was recorded on an oscilloscope by Sandia personnel. Post-combustion, the gases were allowed to cool down for several seconds before opening the vent valve.

The mass of gas mixture introduced into the well bore was 0.528 lbm as shown in Figure 3-7. The figures from all ethylene-nitrous oxide pressurization (ENP) tests conducted in March only show pre-ignition data for the test mixture, and the pressure is not measured once the gas filling has stopped and hence the final equilibrium pressure cannot be determined. The only data recorded after this point in the test was the combustion pressure, which was done by Sandia personnel. The calculated mass values for the ENP cycles are based on the integration method explained in the earlier subsection.

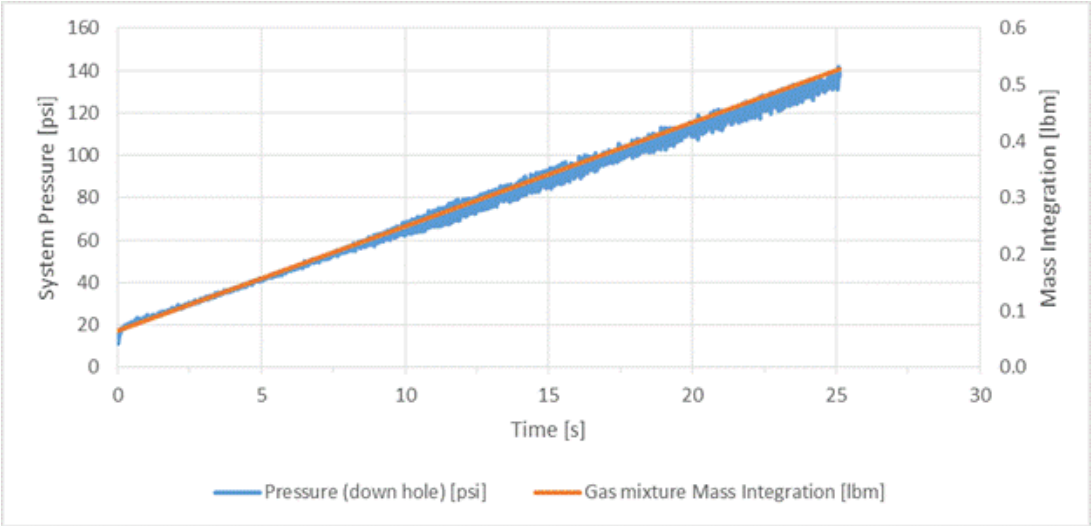

Figure 3-7. Plot of pressure in well bore and mass of gas mixture (calculated) vs. time for test ENP1.

3.3.6 Nitrogen Pressurization 5: Post-Test Pressurization (NP5)

Date: 03/07/2013
Duration of gas filling: 22.30 s
Target pressure: 124.70 psia
Equilibrium pressure: 95.17 psia
Data file name: 20130307_131525_.txt

After each ethylene-nitrous oxide combustion cycle the well bore was pressurized with nitrogen to investigate leakages, if any, in the well bore. These tests provided information about the extent to which the rock was fractured during combustion. Post-combustion, the mass of nitrogen introduced during this cycle into the well bore was calculated to be 0.356 lbm as shown in **Figure 3-8**. The mass of nitrogen in the well bore increased slightly from the values obtained in the previous nitrogen pressurization test (NP4), suggesting that the well bore volume increased due to fracturing of the rock.

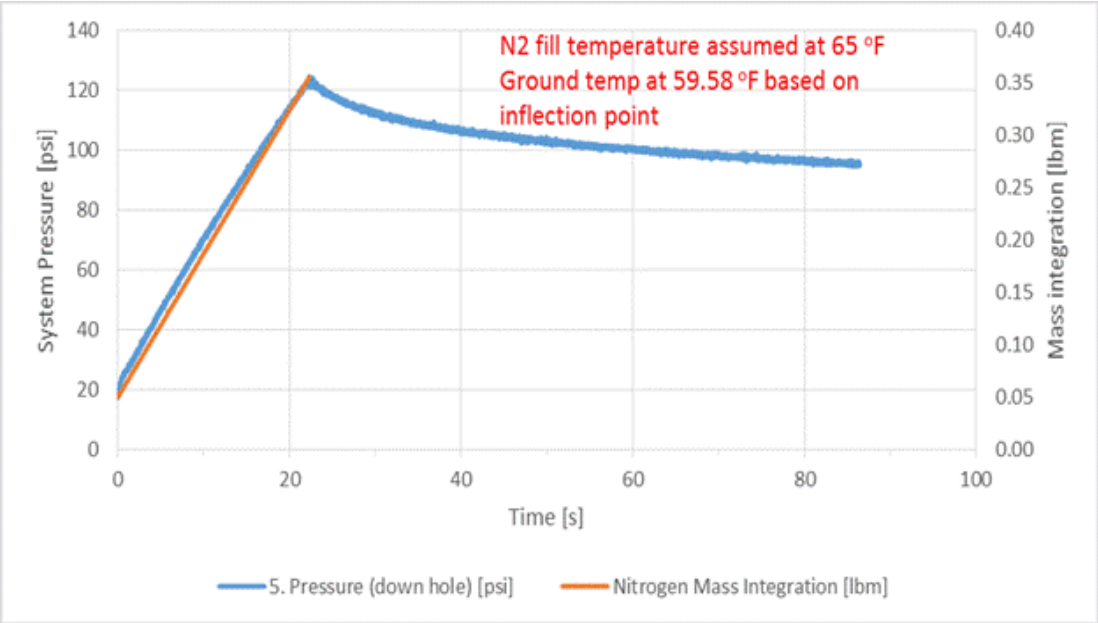

Figure 3-8. Plot of pressure in well bore and mass of nitrogen (calculated) vs. time for test NP5.

3.3.7 Ethylene/Nitrous Oxide Pressurization 2 with Combustion (ENP2)

Date: 03/07/2013
Duration of gas filling: 25.25 s
Target pressure: 175.25 psia
Data file name: 20130307_163027_.txt

This was the second ENP test and the gas mixture was again ignited using an EBW. The mass of gas mixture introduced into the well bore was 0.656 lbm as shown in Figure 3-9. The increase in mass compared to the previous test (NP5) is due to the significantly higher filling pressure (175.25 psia vs. 124.7 psia). For this higher filling pressure, a fill time of 25 s is similar to the fill time for NP5 (22 s), indicating that the rock might not have fractured during the process of filling. Any fracturing in the rock during the filling process would have likely increased the gas fill time for an increased target pressure.

Also, as with the first combustion test (ENP1), the pressure was not measured after stopping the gas filling and hence the final equilibrium pressure is unknown.

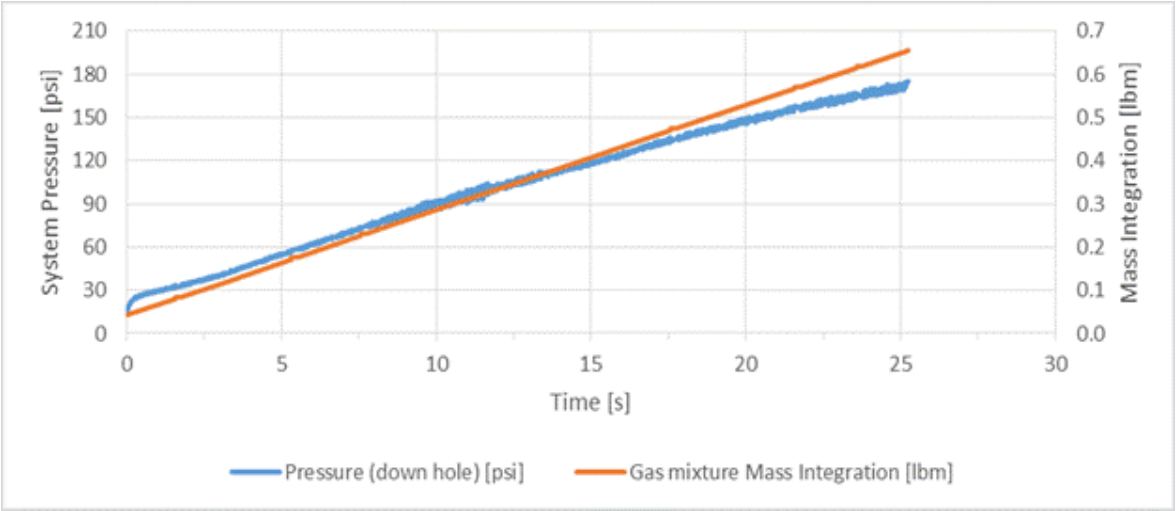

Figure 3-9. Plot of pressure in well bore and mass of gas mixture (calculated) vs. time for test ENP2.

3.3.8 Nitrogen Pressurization 6: Post-Test Pressurization (NP6)

Date: 03/07/2013
Duration of gas filling: 21.08 s
Target pressure: 122.37 psia
Equilibrium pressure: 70.04 psia
Data file name: 20130307_163027_.txt

The mass of nitrogen introduced into the well bore was 0.365 lbm as shown in Figure 3-10. The mass of nitrogen injected into the well bore did not increase in comparison to the previous pressurization test (NP5) in spite of a combustion test before this pressurization cycle. On comparison, the post-fill pressure drops to approximately the same value after a time duration of 80 s for both NP4 and NP5 tests. The NP4 data could have provided a better estimate of equilibrium pressure and thereby an understanding of possible rock fracture if pressure data was recorded for a longer duration as was done during the NP5 test.

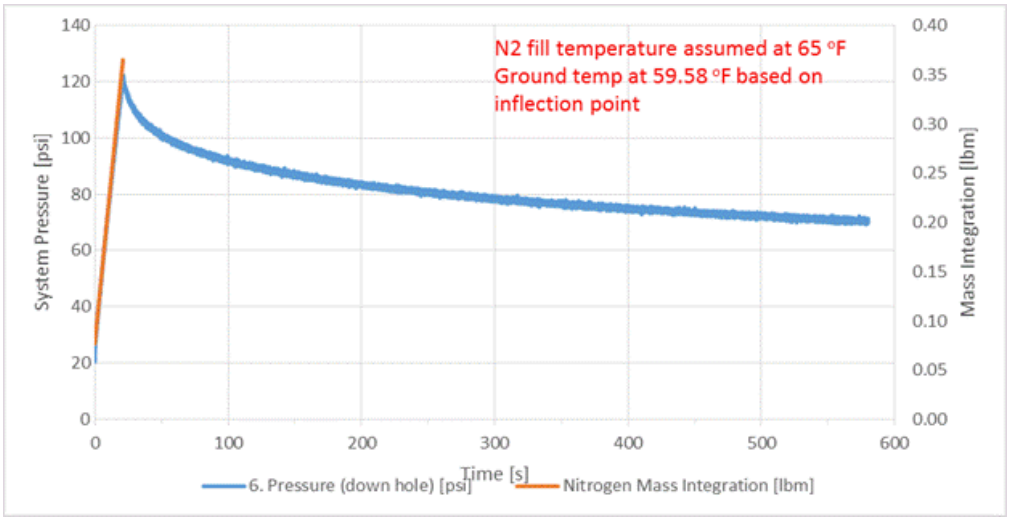

Figure 3-10. Plot of pressure in well bore and mass of Nitrogen (calculated) vs. time for test NP6.

3.3.9 Ethylene/Nitrous Oxide Pressurization 3 with Combustion (ENP3)

Date: 03/07/2013
Duration of gas filling: 25.22 s
Target pressure: 281.48 psia
Data file name: 20130307_175034_.txt

The mass of gas mixture introduced into the well bore was 1.075 lbm as shown in Figure 3-11. The mass of the gas injected into the well bore is approximately 3 times larger than the previous test due to the much higher initial pressure (282 vs. 122 psia).

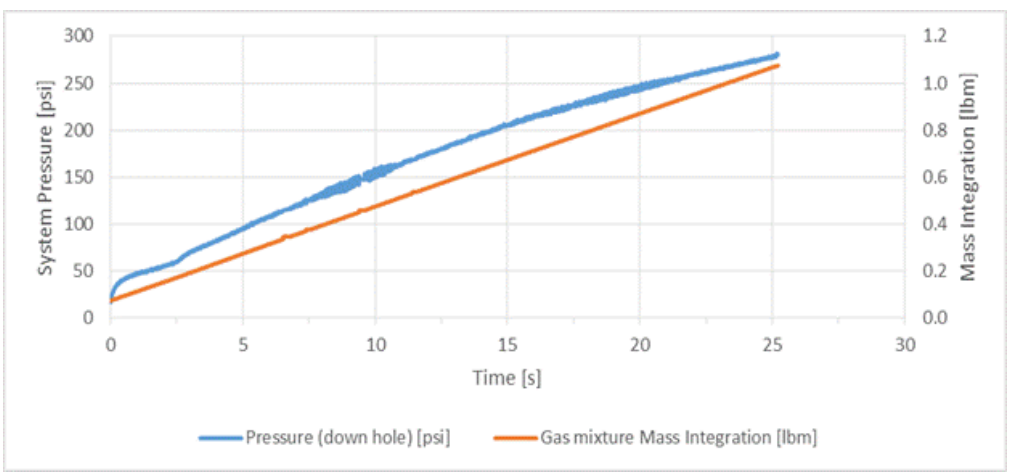

Figure 3-11. Plot of pressure in well bore and mass of gas mixture (calculated) vs. time for test ENP3.

3.3.10 Nitrogen Pressurization 7: Post-Test Pressurization (NP7)

Date: 03/07/2013
Duration of gas filling: 91.71 s
Target pressure: 123.45 psia
Equilibrium pressure: 51.52 psia
Data file name: 20130307_175034_.txt

The mass of nitrogen introduced into the well bore was 1.336 lbm as shown in Figure 3-12. The mass of nitrogen injected into the well bore has significantly increased from 0.365 lbm for the NP6 test (at approximately the same fill pressure) due to dramatic fracturing of the rock during the previous combustion test (ENP3) which had a high target pressure of 281.48 psia.

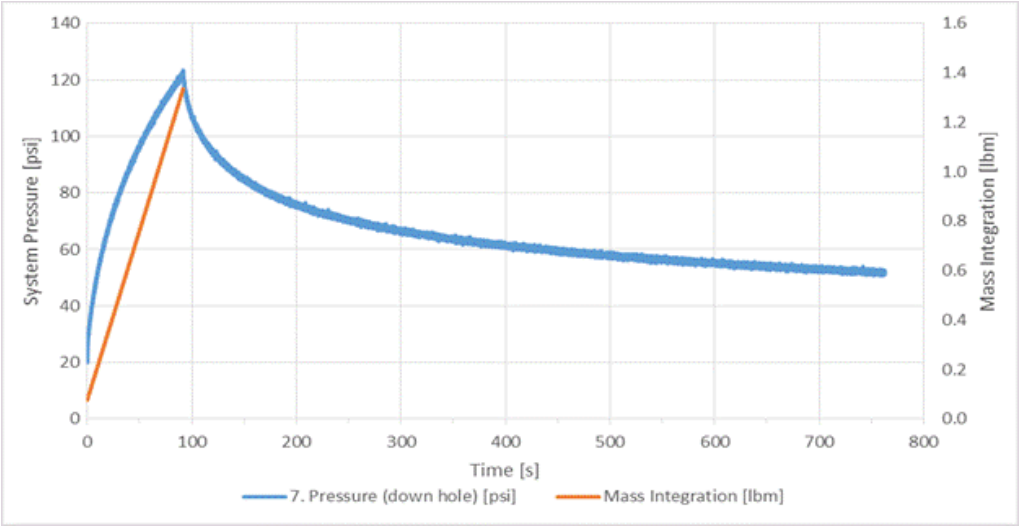

Figure 3-12. Plot of pressure in well bore and mass of nitrogen (calculated) vs. time for test NP7.

3.3.11 Nitrogen Pressurization 8 (NP8)

Date: 03/07/2013
Duration of gas filling: 213.07 s
Target pressure: 291.87 psia
Equilibrium pressure: 179.62 psia
Data file name: 20130307_192852_.txt

The mass of nitrogen introduced into the well bore was 7.899 lbm as shown in Figure 3-13. The primary reason for the large increase in nitrogen mass from test NP7 is the higher initial pressure for the test. It is also possible that the increased initial pressure may have widened existing cracks, further expanding the bore volume.

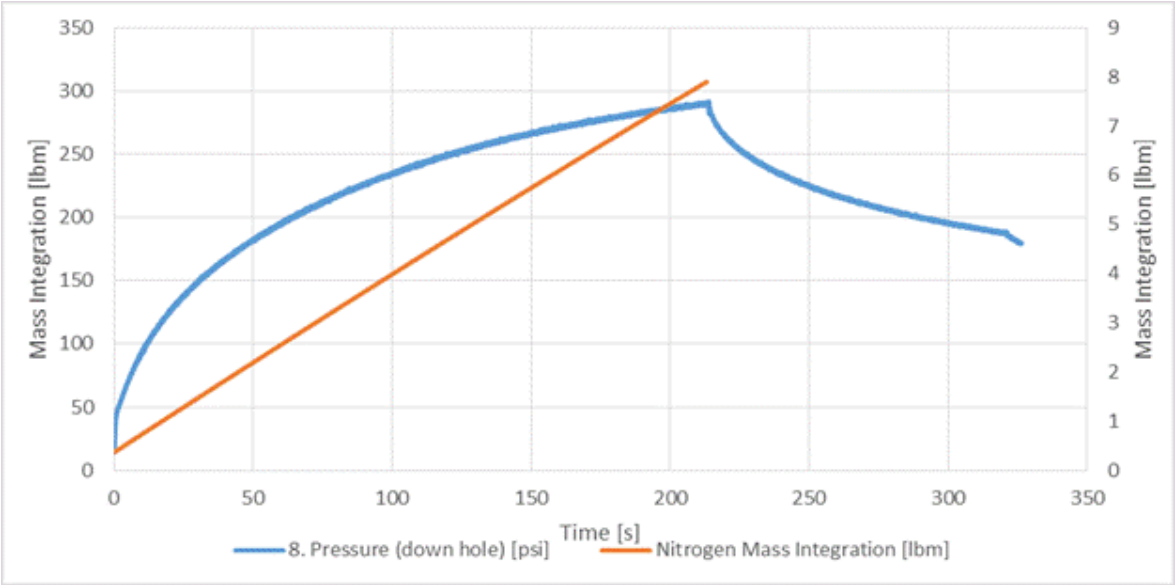

Figure 3-13. Plot of pressure in well bore and mass of nitrogen (calculated) vs. time for test NP8.

3.3.12 Nitrogen Pressurization 9 (NP9)

Date: 03/07/2013
Duration of gas filling: 256.92 s
Target pressure: 291.08 psia
Equilibrium pressure: 218.43 psia
Data file name: 20130307_194342_.txt

The mass of nitrogen introduced into the well bore was 10.444 lbm as shown in Figure 3-14. For the NP9 test the well bore was pressurized before it reached an ambient pressure after the previous test. Hence, the pressure plot for NP9 shows an initial pressure of approximately 90 psia. The main aim of this pressure test was to access the well bore's ability to hold pressure close to 400 psia before conducting a combustion test at this high initial pressure.

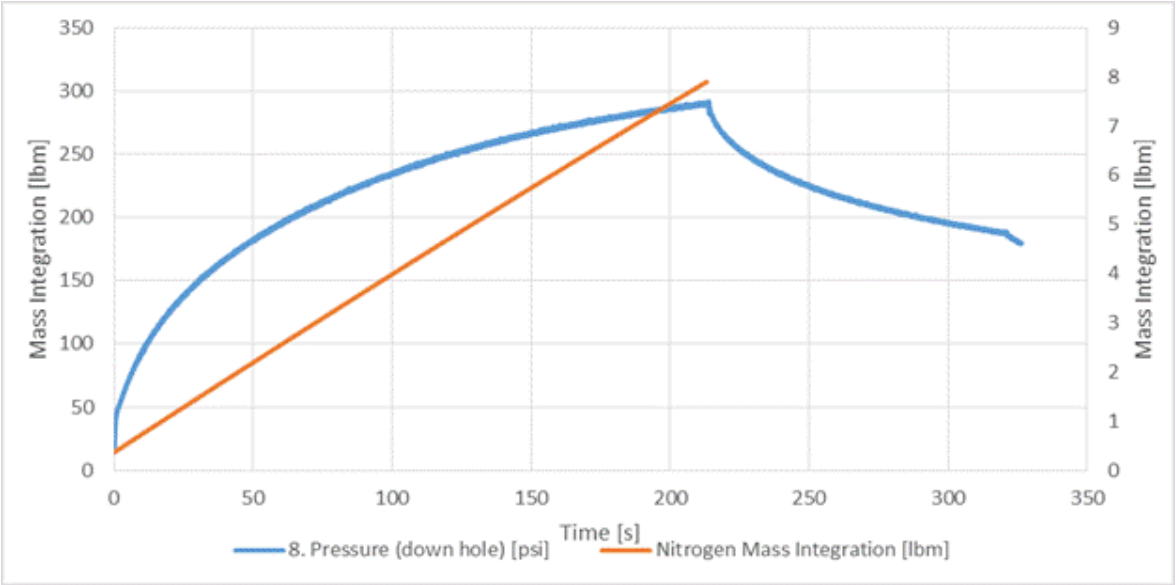

Figure 3-14. Plot of pressure in well bore and mass of nitrogen (calculated) vs. time for test NP9.

The pressure data for tests NP8 and NP9 are plotted together on **Error! Reference source not found.** for comparison. The figure shows that the pressure rise during filling for the NP9 test was slower than that for NP8. The main reason for this was the insufficient nitrogen cylinder pressure available during this test and therefore the leak rate of gas was likely comparable to the fill rate of nitrogen into the well bore. Thus, the pressure plot for NP9 plateaus at approximately 200 s. However, the filling process was stopped more than 50 s later and this resulted in a larger mass of nitrogen filled in the well bore as compared to NP8 (10.44 lbm vs. 7.89 lbm).

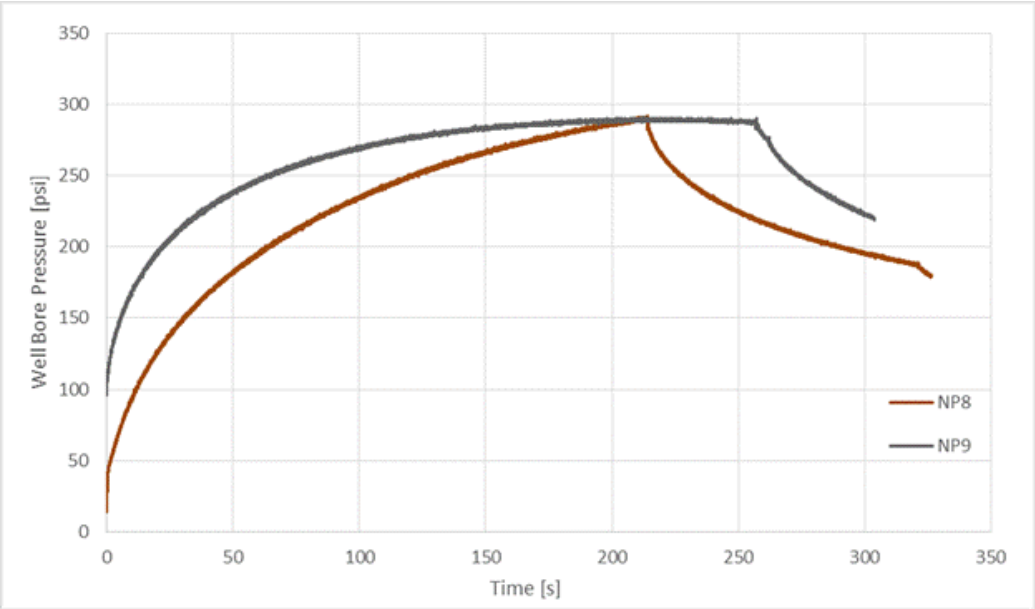

Figure 3-15. Plot of pressure comparison in well bore vs. time for tests NP8 and NP9.

3.4. Plots of Pressure and Mass Data from June 2013 Tests

The second phase of tests were conducted June 24-25, 2013. The recorded ambient temperature for these tests was 85°F and a ground temperature of 79.58°F was assumed for all analysis of the June test data. This set of tests included only 2 nitrogen pressure cycles and the rest were ENP tests. All the ENP tests with initial pressures of approximately 125 psia were not ignited, while the tests with higher initial pressures were ignited and combustion was observed. The un-ignited ethylene-nitrous oxide pressure tests were used to check the extent of leakage after each combustion test. After a certain duration of data acquisition, the gas mixture from the un-ignited pressurization cycles carried out before each combustion cycle was vented. Thus, they also served the purpose of ensuring the well bore was at an atmospheric pressure containing mainly ethylene-nitrous oxide mixture and reducing the dilution of the gas mixture. The June tests are summarized in Table 3-2 and the pressure and mass data are presented in the following subsections.

Table 3-2. Summary of tests from June 2013.

Pressure cycle	Date of test	Target pressure [psia]	Equilibrium pressure [psia]	Fill time [s]	Mass of gases injected [lbm]	Combustion?
ENP4	06/24/13	124.80	34.26	15.42	1.43	No
ENP5	06/24/13	239.48	-	106.37	5.94	Yes
ENP6	06/24/13	124.18	36.49	14.12	1.39	No
ENP7	06/24/13	285.76	-	191.72	10.45	Yes
NP10	06/24/13	308.35	162.00	464.38	17.72	No
ENP8	06/25/13	130.33	34.16	28.76	2.10	No
ENP9	06/25/13	257.43	-	439.52	20.81	Yes
ENP10	06/25/13	133.32	44.36	38.30	2.95	No
ENP11	06/25/13	251.91	-	656.78	26.27	Yes
NP11	06/25/13	305.26	169.1	499.85	20.63	No

3.4.1. Ethylene/Nitrous Oxide Pressurization 4 without Combustion (ENP4)

Date: 06/24/2013
Duration of gas filling: 15.42 s
Target pressure: 124.8 psia
Equilibrium pressure: 34.26 psia
Data file name: 20130624_150237_.txt

A target pressure of 124.8 psia was used for the ENP4 test. The mass of gas mixture introduced into the well bore was 1.425 lbm as shown in Figure 3-16. This mass is similar to the mass calculated for NP7 at a similar target pressure and indicates that the well bore volume was consistent with tests from

March. ENP4 was the first pressurization test that was conducted in June. The gas mixture was not ignited and the test was used to assess the state of the well bore since the last test in March.

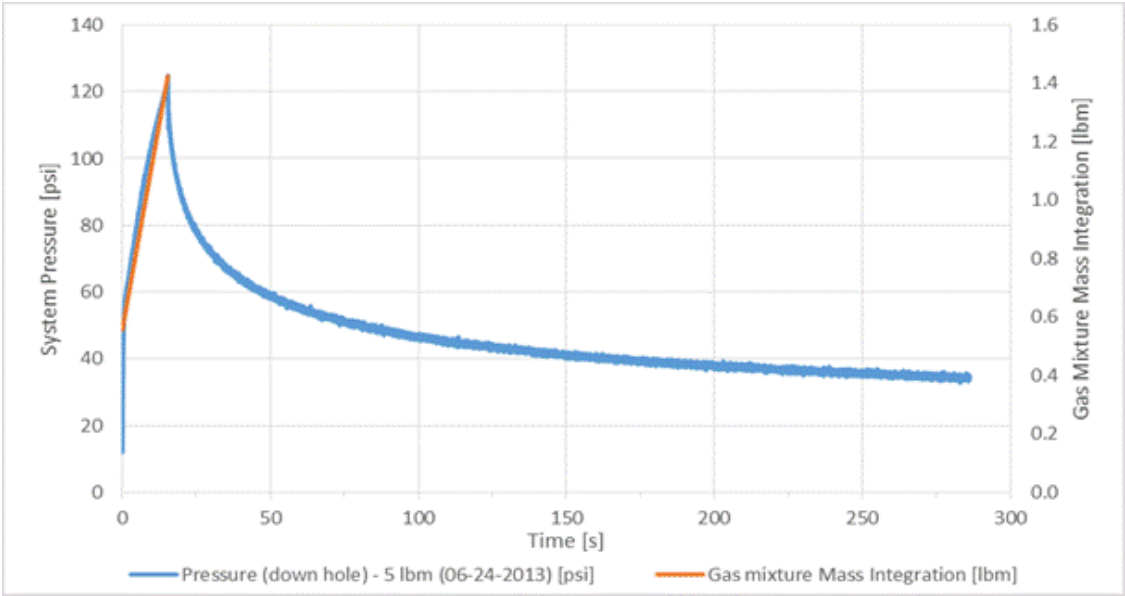

Figure 3-16. Plot of pressure in well bore and mass of gas mixture (calculated) vs. time for test ENP4.

3.4.2. Ethylene/Nitrous Oxide Pressurization 5 with Combustion (ENP5)

Date: 06/24/2013
Duration of gas filling: 106.37 s
Target mass of gas mixture: 5 lbm
Actual mass of gas mixture: 5.9336 lbm
Well bore pressure: 239.48 psia
Data file name: 20130624_150237_.txt

All the combustion tests carried out in June were aimed at introducing a certain mass of gas mixture into the well bore, rather than reaching a particular well bore pressure, before igniting the mixture. This was monitored by adding a "mass injected" readout on the VI which calculated the mass injected into the well bore by the mass integration method.

The ENP5 test was the first combustion test where a target mass was used instead of a target pressure when filling the well bore. A target mass of 5 lbm was used for the ENP5 test. To verify this target mass the gas mixture mass integration shown in Figure 3-17 only accounts for the mass introduced into the well bore and excludes the mass of the gases already present. This analysis is carried out for each of the combustion tests in this subsection. The mass of gas mixture introduced in to the well bore was 5.936 lbm which is higher due to the increased initial pressure as compared to test ENP4 (240 vs. 125 psia).

In this test, the valve PV-CP-905 was opened after approximately 200 s and pressure data recording by PT-Pre-Fire was resumed. In addition to this the vent valve, PV-CP-904, was opened after 900 s to access the rate of pressure drop due to both venting and leaking into the cracks. The vent valve, PV-CP-904, was closed after 1500 s and the pressure drop only includes the leak rate of the combustion gases. This cycle of opening and closing the vent valve was carried out multiple times during all combustion tests. This provided a quick comparison between the rate of pressure drop due to leaking into the cracks and rate of pressure drop with both venting and leaking.

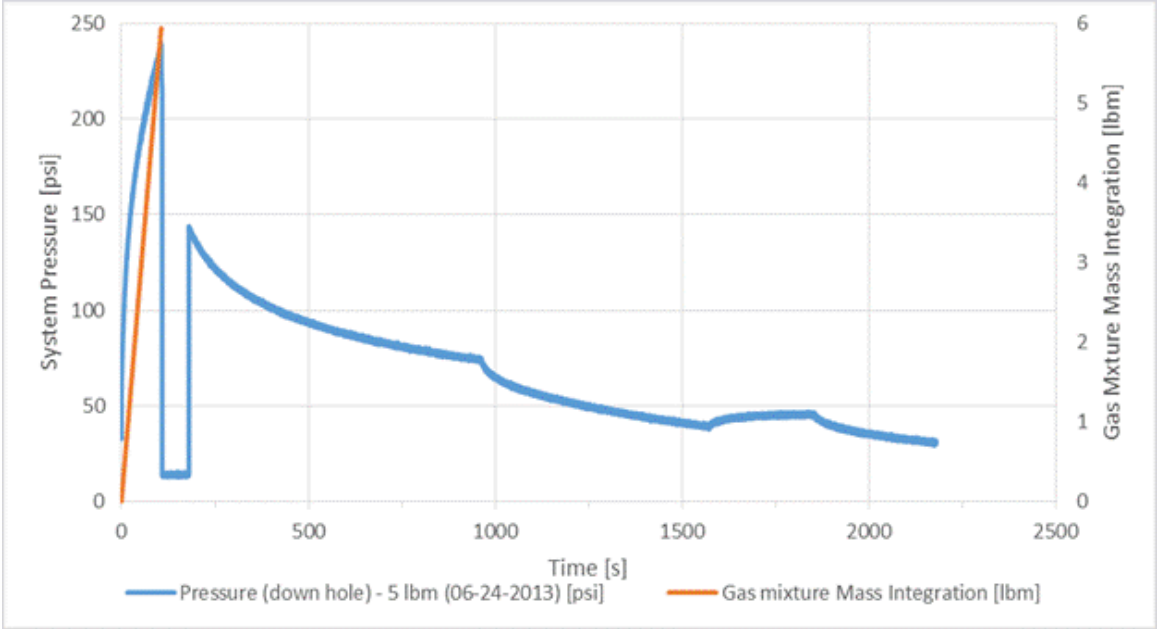

Figure 3-17. Plot of pressure in well bore and mass of gas mixture (calculated) vs. time for test ENP5.

3.4.3. Ethylene/Nitrous Oxide Pressurization 6 without Combustion (ENP6)

Date: 06/24/2013
Duration of gas filling: 14.12 s
Target pressure: 124.18 psia
Equilibrium pressure: 36.49 psia
Data file name: 20130624_172709_.txt

A target pressure of 124.18 psia was used for the ENP6 test. The mass of gas mixture introduced into the well bore was 1.391 lbm as shown in Figure 3-18. There was no appreciable increase in the gas mixture mass in comparison to the ENP4 test (same fill pressure of 124 psia).

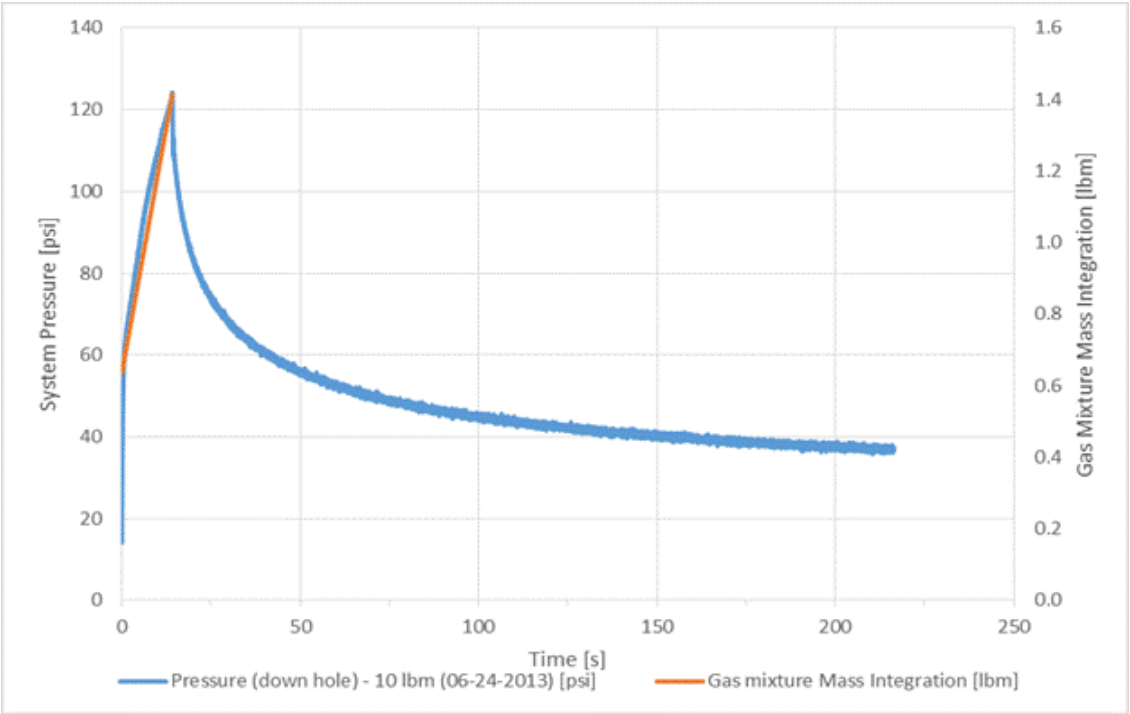

Figure 3-18. Plot of pressure in well bore and mass of gas mixture (calculated) vs. time for test ENP6.

3.4.4. Ethylene/Nitrous Oxide Pressurization 7 with Combustion (ENP7)

Date: 06/24/2013
Duration of gas filling: 191.72 s
Target mass of gas mixture: 10 lbm
Actual mass of gas mixture: 10.446 lbm
Well bore pressure: 285.76 psia
Data file name: 20130624_172709_.txt

A target mass of 10 lbm was used for the ENP7 test. The mass of gas mixture introduced into the well bore was 10.446 lbm as shown in Figure 3-19. The large increase in the mass is primarily due to the much higher initial pressure vs. test ENP6. The vent valve was opened and closed in this test multiple times post-combustion. After closing the vent valve for the final time, the pressure was not allowed to reach equilibrium before pressure data recording was stopped. Therefore, this test does not have a defined equilibrium pressure.

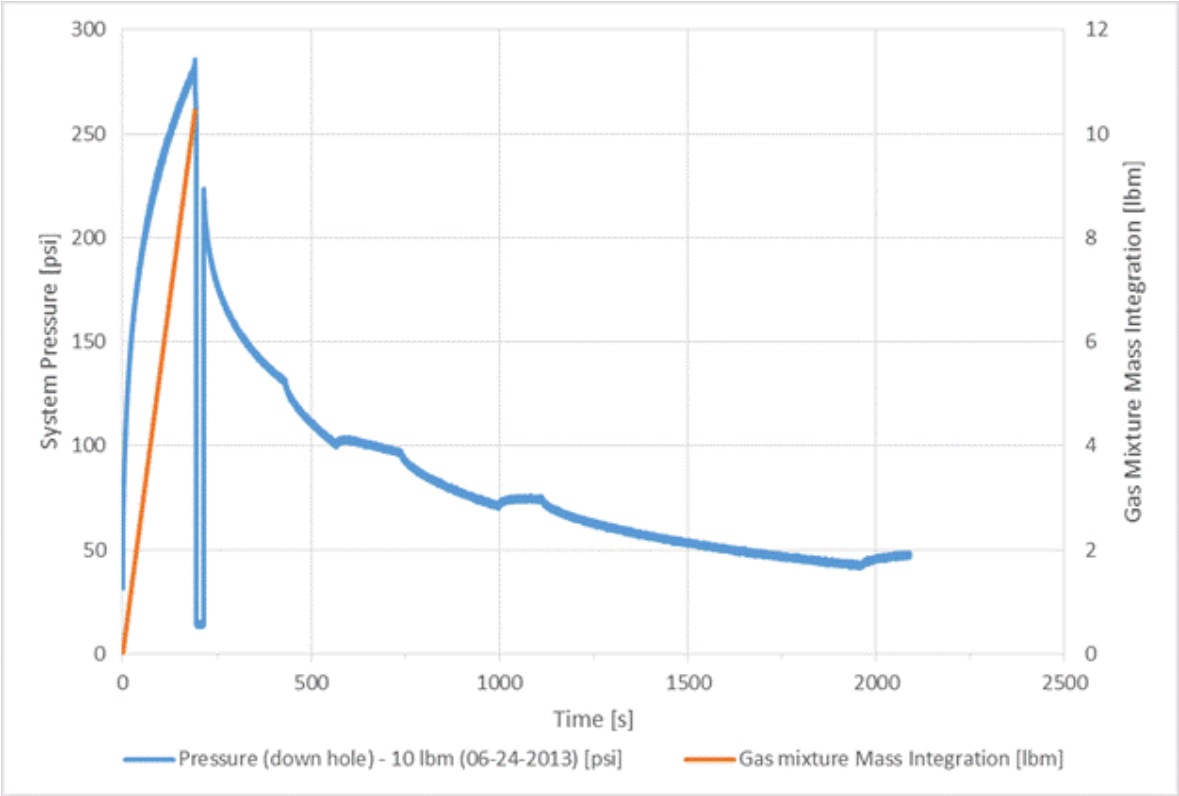

Figure 3-19. Plot of pressure in well bore and mass of gas mixture (calculated) vs. time for test ENP7.

3.4.5. Nitrogen Pressurization 10 (NP10)

Date: 06/24/2013
Duration of gas filling: 464.38 s
Target pressure: 308.35 psia
Equilibrium pressure: 162.00 psia
Data file name: 20130624_183908_.txt

A target pressure of 308.35 psia was used for the NP10 test. The mass of nitrogen introduced into the well bore was 17.721 lbm as shown in Figure 3-20. This was the last pressurization test conducted on the 24th of June. The well bore was pressurized with nitrogen to investigate the rate at which pressure decreased after filling, i.e., to assess the leak rate of the bore.

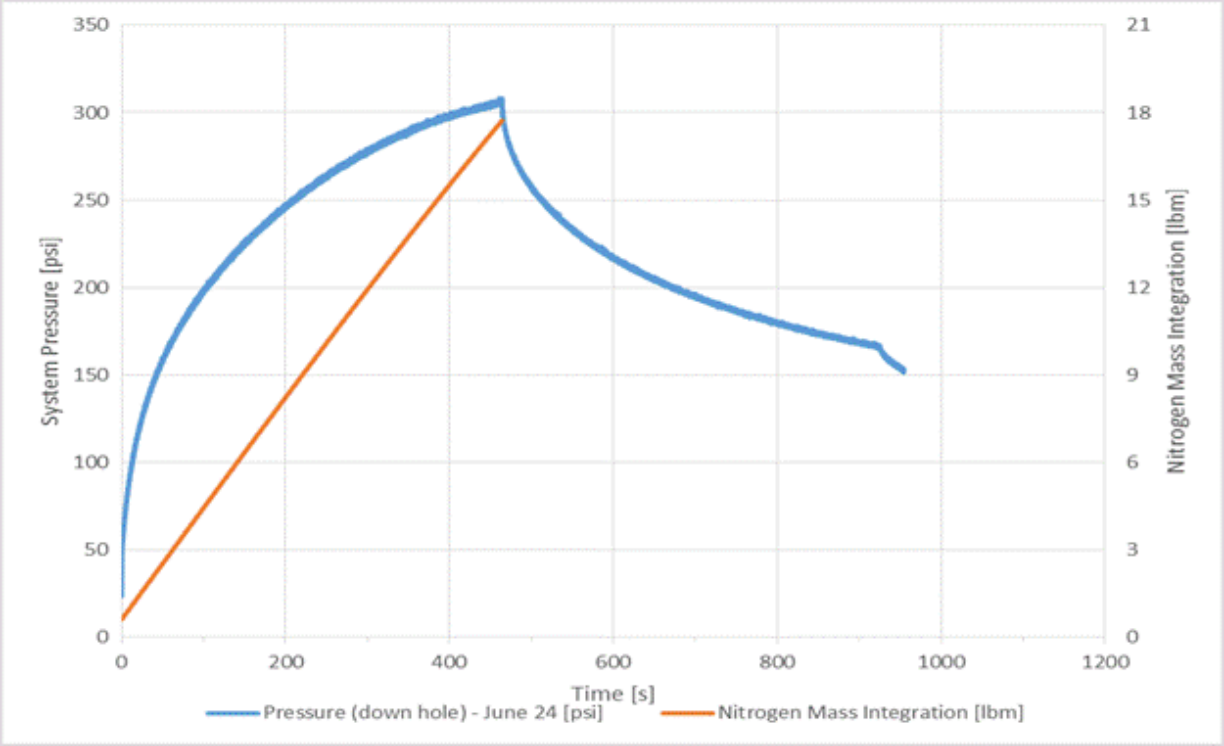

Figure 3-20. Plot of pressure in well bore and mass of nitrogen (calculated) vs. time for test NP10.

3.4.6. Ethylene/Nitrous oxide Pressurization 8 without Combustion (ENP8)

Date: 06/25/2013
Duration of gas filling: 28.76 s
Target pressure: 130.33 psia
Equilibrium pressure: 34.16 psia
Data file name: 20130625_125704_.txt

A target pressure of 130.33 psia was used for the ENP8 test. The mass of gas mixture introduced into the well bore was 2.10 lbm as shown in Figure 3-21. This was the first pressurization test on June 25th. When compared with the last test at the same fill pressure (ENP6), the mass of gas mixture introduced into the well bore has increased significantly (2.10 lbm vs. 1.39 lbm for ENP6). This increase is due to possible fracture of rock during the ENP7 test, where the gas mixture was ignited.

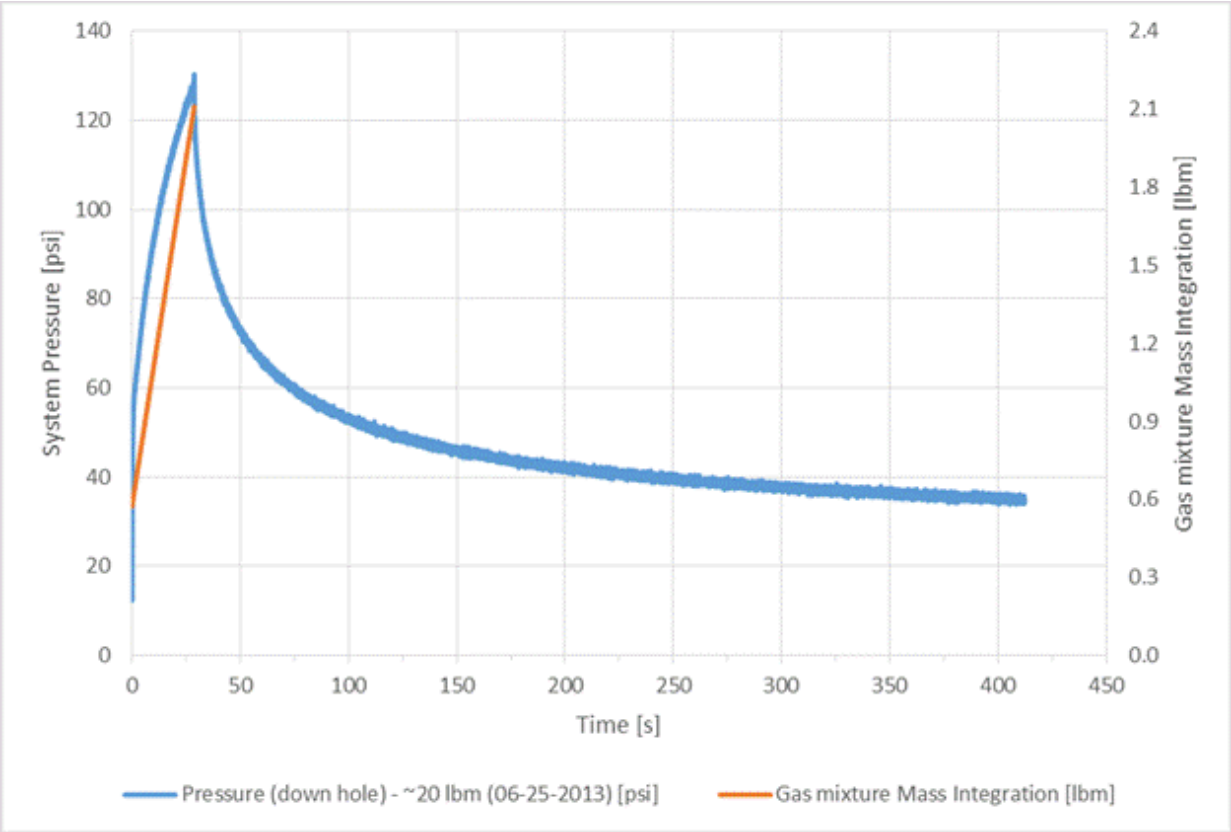

Figure 3-21. Plot of pressure in well bore and mass of gas mixture (calculated) vs. time for test ENP8.

3.4.7. Ethylene/Nitrous Oxide Pressurization 9 with Combustion (ENP9)

Date: 06/25/2013
Duration of gas filling: 439.52 s
Target mass of gas mixture: 20 lbm
Actual mass of gas mixture: 20.806 lbm
Well pressure: 257.43 psia
Data file name: 20130625_125704_.txt

A target mass of 20 lbm was used for the ENP9 test. The mass of gas mixture introduced into the well bore was 20.806 lbm as shown in Figure 3-22. The test was aimed at introducing approximately 20 lbm of gas mixture before ignition. However, when compared to ENP7 the well bore pressure is lower and this can indicate an increase in fracture of the rock, creating a larger volume to accommodate an increased mass of gas mixture. This increase in volume is primarily caused by the previous combustion test, ENP7. In addition, the rock might have opened up further when filling the well bore during this test and the NP10 cycle.

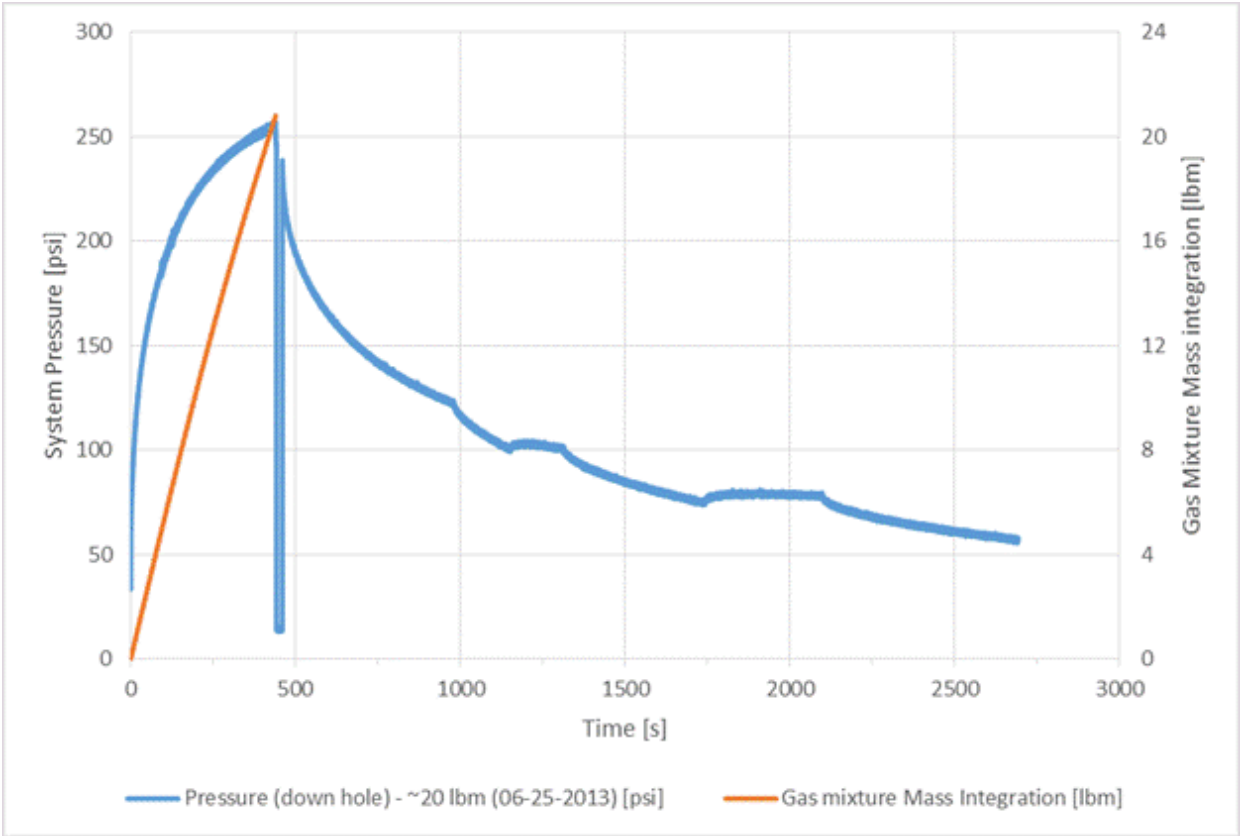

Figure 3-22. Plot of pressure in well bore and mass of gas mixture (calculated) vs. time for test ENP9.

3.4.8. Ethylene/Nitrous Oxide Pressurization 10 without Combustion (ENP10)

Date: 06/25/2013
Duration of gas filling: 38.30 s
Target pressure: 133.32 psia
Equilibrium pressure: 44.36 psia
Data file name: 20130625_165720_.txt

A target pressure of 133.32 psia was used for the ENP10 test. The mass of gas mixture introduced into the well bore was 2.948 lbm as shown in Figure 3-23. The combustion of gas mixture during the ENP9 test would have widened the cracks in the rock and thus, the mass of gas mixture introduced into the well bore has further increased when compared to ENP8 (2.948 lbm vs. 2.10 lbm for ENP8). The combustion from the ENP9 test must have fractured the rock further thereby widening existing cracks and increasing the bore volume.

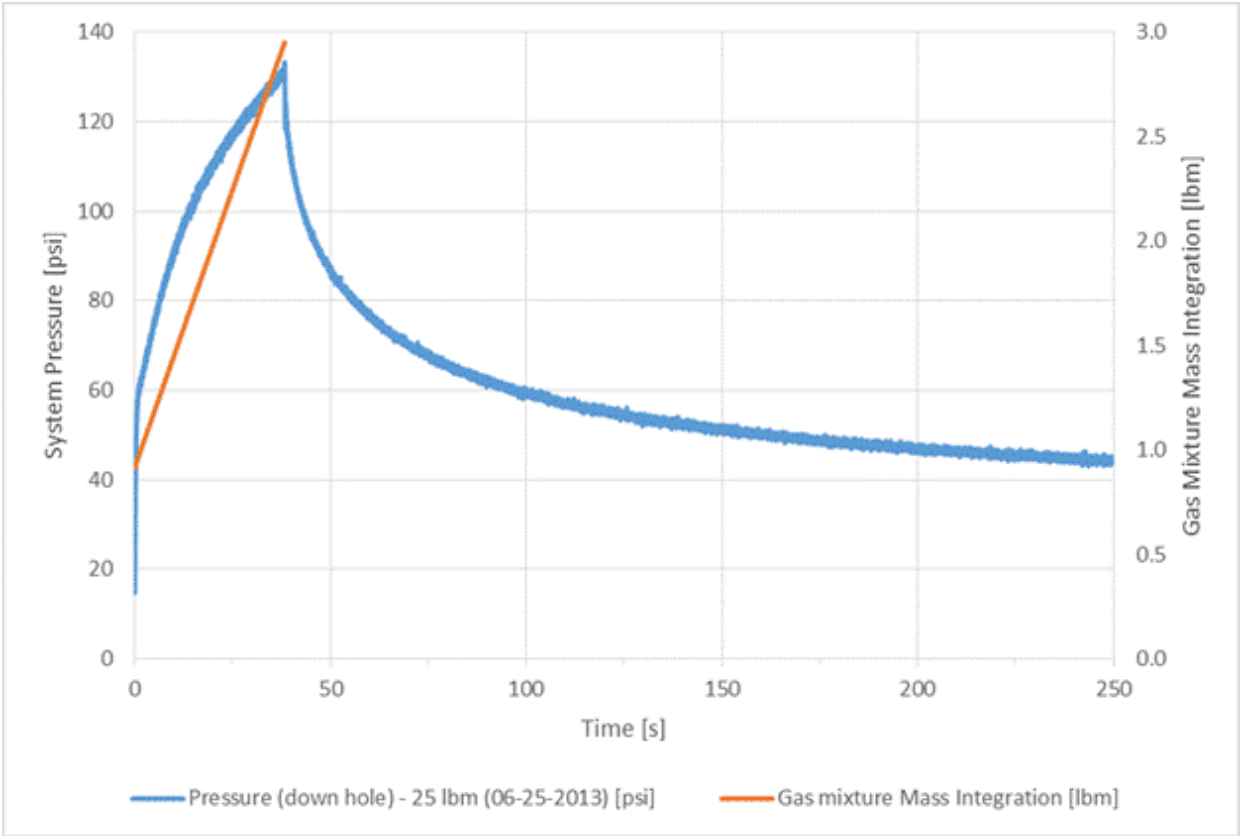

Figure 3-23. Plot of pressure in well bore and mass of gas mixture (calculated) vs. time for test ENP10.

3.4.9. Ethylene/Nitrous Oxide Pressurization 11 with Combustion (ENP11)

Date: 06/25/2013
Duration of gas filling: 656.78 s
Target mass of gas mixture: 25 lbm
Actual mass of gas mixture: 26.269 lbm
Well bore pressure: 251.91 psia
Data file name: 20130625_165720_.txt

A target mass of 25 lbm was used for the ENP11 test. The aim of this test was to introduce approximately 25 lbm of gas mixture. The mass of gas mixture introduced into the well bore was 26.269 lbm as shown in Figure 3-24, resulting in a pressure of 252 psia. This pressure is very close to that used in test ENP9, but the mass has increased by approximately 5 lbm due to fracturing of the rock during ENP9.

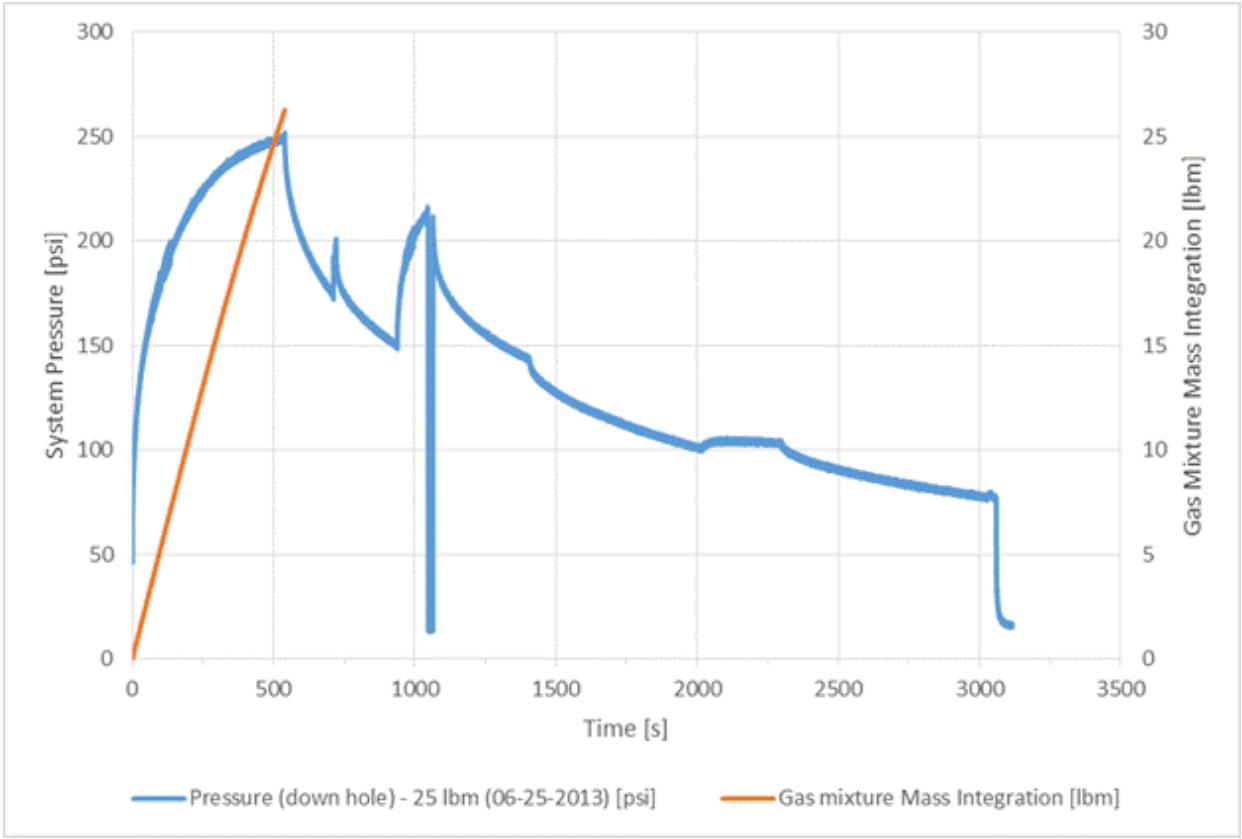

Figure 3-24. Plot of pressure in well bore and mass of gas mixture (calculated) vs. time for test ENP11.

3.4.10. Nitrogen Pressurization 11 (NP11)

Date: 06/25/2013
Duration of gas filling: 499.85 s
Target pressure: 305.26 psia
Equilibrium pressure: 169.1 psia
Data file name: 20130625_181505_.txt

A target pressure of 305.26 psia was used for the NP11 test. The mass of nitrogen introduced into the well bore was 20.625 lbm as shown in Figure 3-25. The mass of nitrogen introduced has increased since the last nitrogen pressure cycle (20.625 lbm vs. 17.721 lbm for NP10). It was also observed that the pressure of the gases in the cylinders was reducing and thus, the mass flow rate of nitrogen entering the line was reducing as well. This is observed in Figure 3-25 when the pressure starts dropping beyond the peak pressure. The mass flow rate of nitrogen leaking into the cracks might be slightly higher than the mass flow rate of nitrogen injection into the well bore causing this pressure drop beyond the peak pressure.

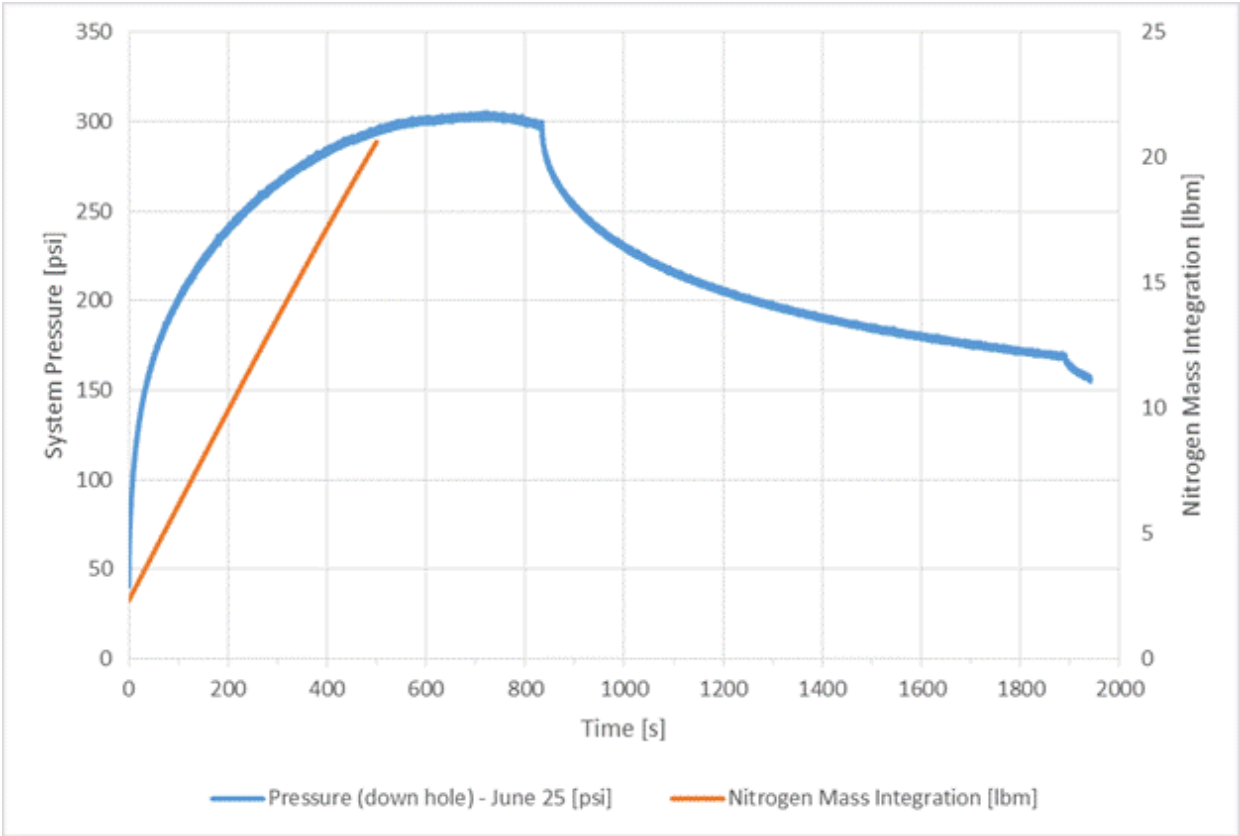

Figure 3-25. Plot of pressure in well bore and mass of nitrogen (calculated) vs. time for test NP11.

4. COMBUSTION PRESSURES AND TEMPERATURES BASED ON CANTERA CALCULATIONS

The theoretical pressures and temperatures for a range of initial pressures of the well-bore are calculated using the Shock and Detonation Toolbox [1] in Cantera [2] to compare with the experimental pressure measurements. Calculations were first conducted for the following conditions:

1. Constant Volume Combustion
2. Constant Pressure Combustion – provides the adiabatic flame temperatures
3. CJ Detonation

These calculations are made for the following fuel-oxidizer combinations:

1. Ethylene – nitrous oxide (combination used in the experiments)
2. Ethylene – air
3. Ethylene – oxygen

The combustion calculations with air and oxygen are presented here for comparison and to understand the effect of different oxidizers. The results of the calculations are given in Tables 4-1, 4-2 and 4-3.

Table 4-1. Constant Volume Combustion Calculations.

Initial Pressure [psia]	Ethylene - Nitrous oxide		Ethylene - Air		Ethylene - Oxygen	
	Pressure [psia]	Temperature [°F]	Pressure [psia]	Temperature [°F]	Pressure [psia]	Temperature [°F]
14.7	283.47	5961.09	137.13	4461.69	246.48	6255.26
50	1000.60	6291.63	475.74	4581.47	876.53	6696.27
100	2041.60	6479.82	961.18	4644.13	1796.71	6960.58
150	3097.23	6589.64	1449.81	4678.89	2733.34	7119.75
200	4162.16	6667.27	1940.40	4702.66	3680.53	7234.59
250	5233.89	6727.25	2432.39	4720.58	4635.49	7324.70
300	6310.96	6776.08	2925.46	4734.88	5596.60	7398.95
350	7392.43	6817.22	3419.40	4746.72	6562.75	7462.15
400	8477.61	6852.74	3914.07	4756.80	7533.21	7517.19
450	9566.02	6883.97	4409.37	4765.55	8507.39	7565.96
500	10657.26	6911.82	4905.21	4773.27	9484.85	7609.75
550	11751.04	6936.94	5401.53	4780.16	10465.25	7649.49
600	12847.11	6959.82	5898.29	4786.37	11448.31	7685.88
650	13945.26	6980.80	6395.44	4792.02	12433.77	7719.43
700	15045.32	7000.18	6892.94	4797.20	13421.45	7750.57
750	16147.14	7018.18	7390.78	4801.97	14411.18	7779.61

Table 4-2. Constant Pressure Combustion Calculations.

Initial Pressure [psia]	Ethylene - Nitrous oxide		Ethylene - Air		Ethylene - Oxygen	
	Pressure [psia]	Temperature [°F]	Pressure [psia]	Temperature [°F]	Pressure [psia]	Temperature [°F]
14.7	14.7	4968.31	14.7	3805.26	14.7	5252.53
50	50	5210.65	50	3878.30	50	5570.94
100	100	5349.66	100	3915.13	100	5761.55
150	150	5431.26	150	3935.10	150	5876.49
200	200	5489.18	200	3948.56	200	5959.56
250	250	5534.09	250	3958.59	250	6024.84
300	300	5570.76	300	3966.53	300	6078.73
350	350	5601.72	350	3973.06	350	6124.67
400	400	5628.52	400	3978.58	400	6164.74
450	450	5652.13	450	3983.35	450	6200.29
500	500	5673.22	500	3987.53	500	6232.27
550	550	5692.28	550	3991.25	550	6261.32
600	600	5709.66	600	3994.59	600	6287.96
650	650	5725.63	650	3997.62	650	6312.55
700	700	5740.39	700	4000.38	700	6335.40
750	750	5754.13	750	4002.92	750	6356.74

Table 4-3. CJ Detonation Calculations.

Initial Pressure [psia]	Ethylene - Nitrous oxide			Ethylene - Air			Ethylene - Oxygen		
	Pressure [psia]	Temperature [°F]	Velocity [m/s]	Pressure [psia]	Temperature [°F]	Velocity [m/s]	Pressure [psia]	Temperature [°F]	Velocity [m/s]
14.7	561.47	6359.67	2205.24	267.65	4802.89	1823.84	487.63	6620.48	2373.41
50	1983.04	6737.14	2251.19	928.88	4953.10	1846.68	1734.55	7112.27	2432.34
100	4045.29	6952.17	2276.27	1876.92	5033.03	1858.67	3557.18	7408.05	2465.34
150	6133.48	7077.34	2290.53	2831.39	5077.87	1865.34	5413.08	7586.36	2484.37
200	8243.67	7166.33	2300.45	3789.75	5108.75	1869.92	7289.90	7715.01	2497.71
250	10371.88	7235.49	2308.03	4750.88	5132.15	1873.38	9183.30	7816.04	2507.93
300	12500.00	7290.90	2314.13	5713.59	5150.83	1876.14	11088.34	7899.23	2516.20
350	14642.24	7338.00	2319.24	6678.51	5166.42	1878.44	13004.97	7970.12	2523.13
400	16791.89	7378.65	2323.61	7644.88	5179.73	1880.39	14929.11	8031.78	2529.08
450	18947.94	7414.39	2327.43	8612.50	5191.32	1882.10	16862.68	8086.51	2534.28
500	21109.65	7446.26	2330.82	9581.20	5201.56	1883.60	18803.42	8135.66	2538.90
550	23276.40	7475.01	2333.86	10550.85	5210.72	1884.94	20691.38	8177.58	2543.05
600	25447.70	7501.17	2336.61	11521.37	5219.00	1886.15	22688.65	8220.50	2546.81

Initial	Ethylene - Nitrous oxide			Ethylene - Air			Ethylene - Oxygen		
650	27623.14	7525.17	2339.13	12492.66	5226.54	1887.25	24671.10	8259.15	2550.25
700	29802.38	7547.34	2341.45	13464.65	5233.47	1888.27	26578.58	8292.07	2553.42
750	31985.13	7567.92	2343.59	14437.30	5239.86	1889.20	28538.68	8324.52	2556.34

The calculations were carried out at an initial temperature of 80.3°F (300 K). For all cases, the combustion pressure increases linearly with increasing initial pressure in the vessel. As expected, the pressures calculated for the CJ detonation are significantly higher than those for the constant volume combustion. The theoretical combustion pressures for the CJ detonation and constant volume combustion conditions are highest with nitrous oxide as the oxidizer and lowest with air as the oxidizer; the increase in the combustion pressure when changing from oxygen to nitrous oxide is relatively small, approximately 11-13%. The theoretical combustion temperatures with oxygen as the oxidizer are higher than those calculated with nitrous oxide and air as oxidizers. As mentioned previously, both the constant volume combustion and CJ detonation pressures are significantly lower than the couple of pressure values observed in the experiment. This discrepancy is believed to occur because the detonation achieved in the well bore is not a CJ detonation but rather an unstable, overdriven detonation.

For comparison with the experiment pressures recorded at the test site, reflected detonation calculations were also performed. The theoretical pressures and temperatures for the CJ and reflected detonation waves are tabulated in Table 4-4 and the reflected detonation pressure vs. initial pressure is plotted in Figure 4-7. The reflected detonation pressure is approximately 2.5 times larger than the CJ pressure, as expected from basic reflected shock theory. These theoretical reflected pressures were compared to the pressures measured at the end wall on the Zucrow combustion vessel and are still significantly lower than the measured pressures. These results further suggest that the detonation is in fact unstable and overdriven, and so simple one-dimensional, steady shock and detonation theory cannot capture the complete physics.

Finally, calculations of overdriven detonations were performed to investigate if the predicted pressures would more closely match the experimental pressures. The theoretical pressures for stoichiometric ethylene-nitrous oxide were calculated for initial pressures of 14.7 to 500 psia and overdrive factors of 1 to 1.9. The resulting theoretical overdrive pressures are given in Table 4-5 and plotted in Figure 4-8; in some cases, the code would not converge for larger overdrive factors, as indicated by the empty cells in the table. Once again, these theoretical overdriven detonations pressures were compared to the pressure recorded during testing at Zucrow Laboratories and this comparison is also presented in the Zucrow report. It is not surprising that the simplified detonation theory cannot exactly predict the experimental pressures, however, the results of these calculations do provide insight on the various physical phenomena involved.

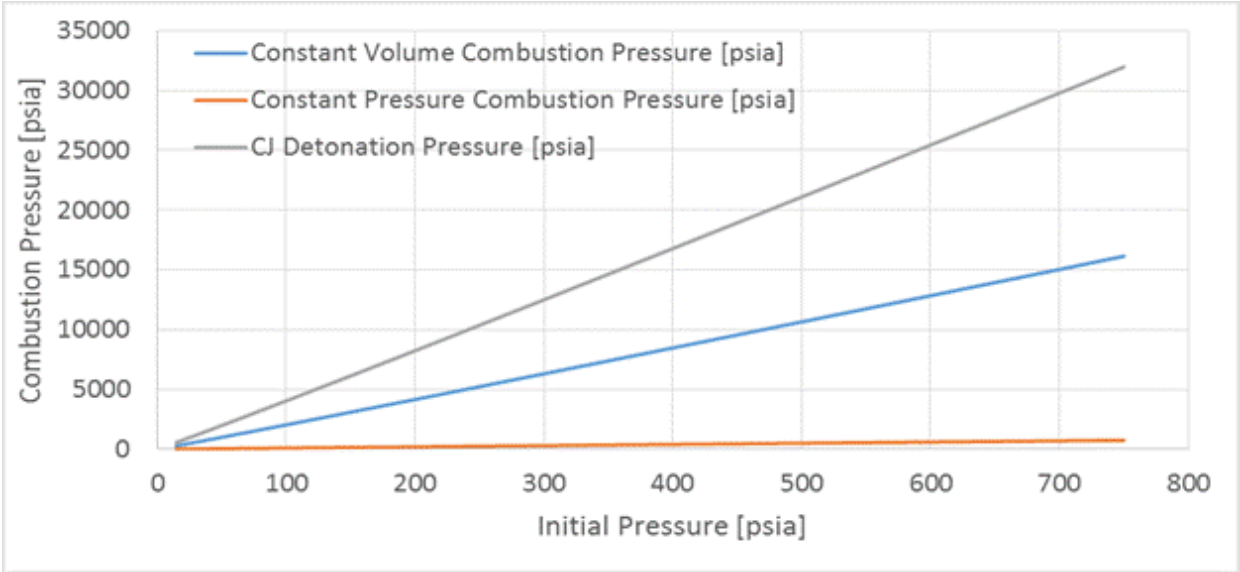

Figure 4-1. Theoretical combustion pressures for stoichiometric ethylene-nitrous oxide vs. initial pressure.

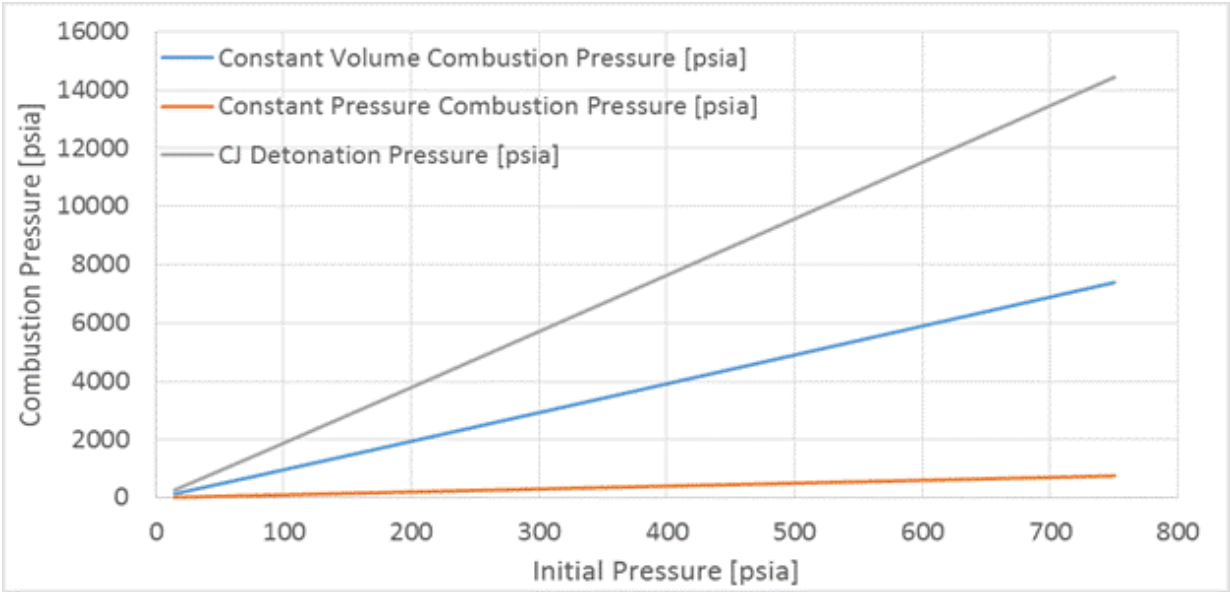

Figure 4-2. Theoretical combustion pressures for stoichiometric ethylene-air vs. initial pressure.

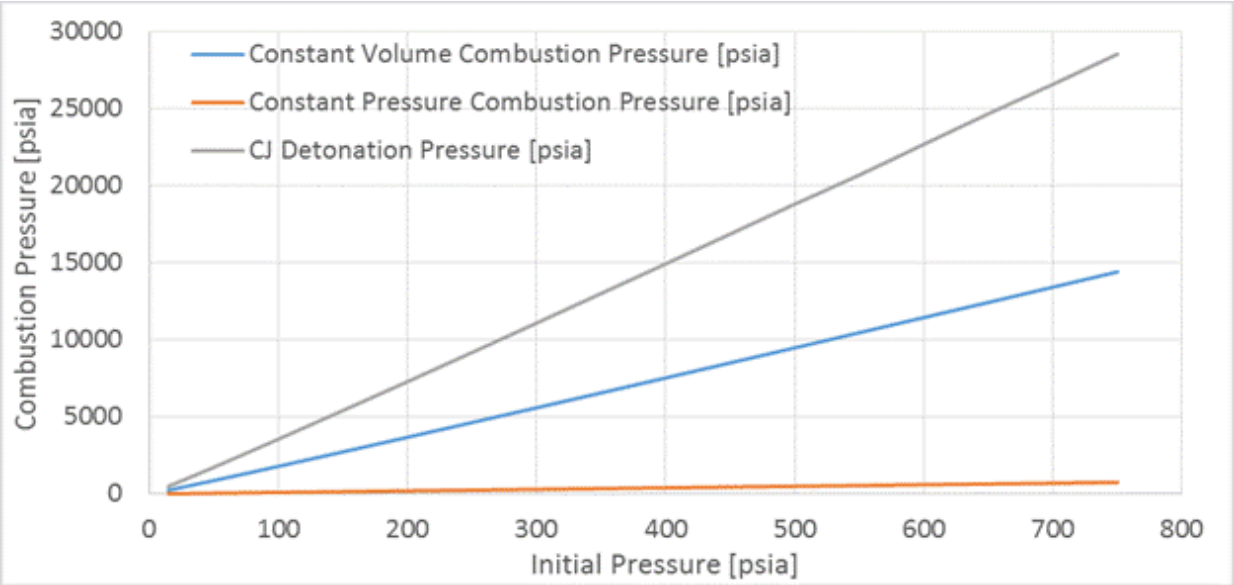

Figure 4-3. Theoretical combustion pressures for stoichiometric ethylene-oxygen vs. initial pressure.

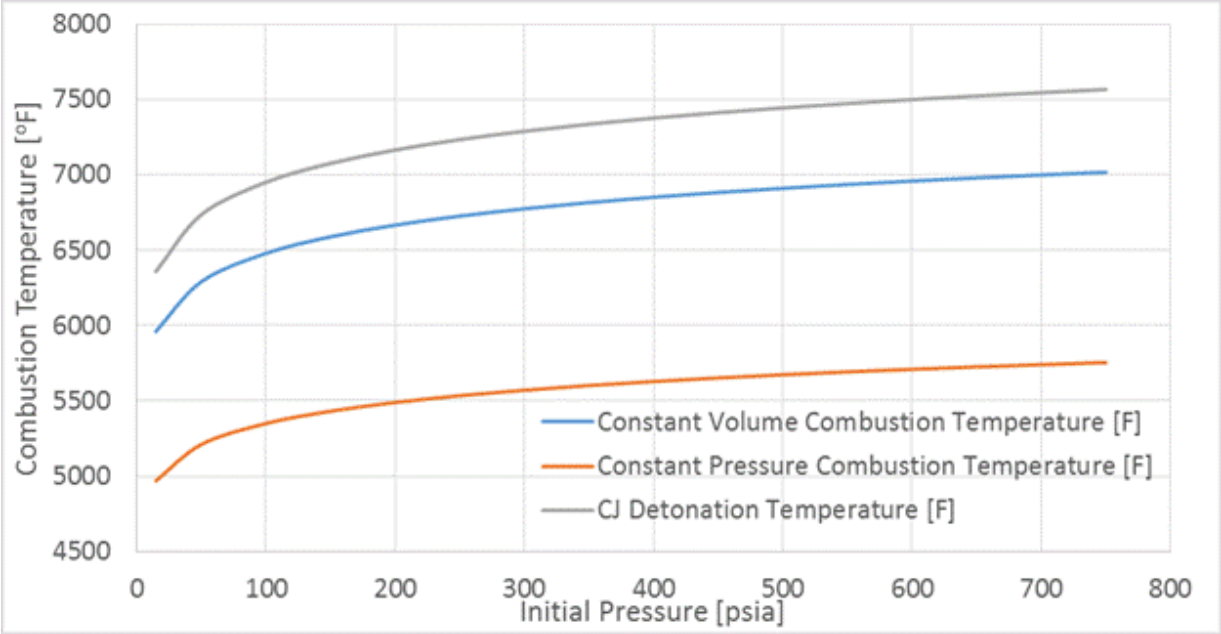

Figure 4-4. Theoretical combustion temperatures for stoichiometric ethylene-nitrous oxide vs. initial pressure.

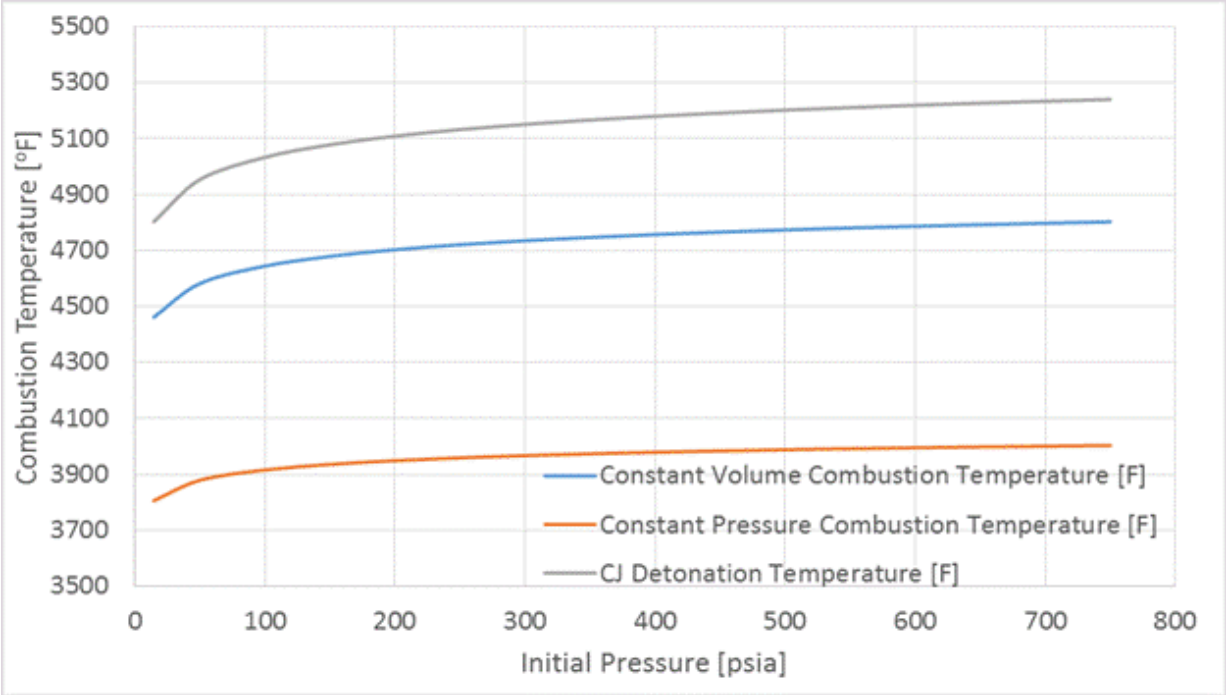

Figure 4-5. Theoretical combustion temperatures for stoichiometric ethylene-air vs. initial pressure.

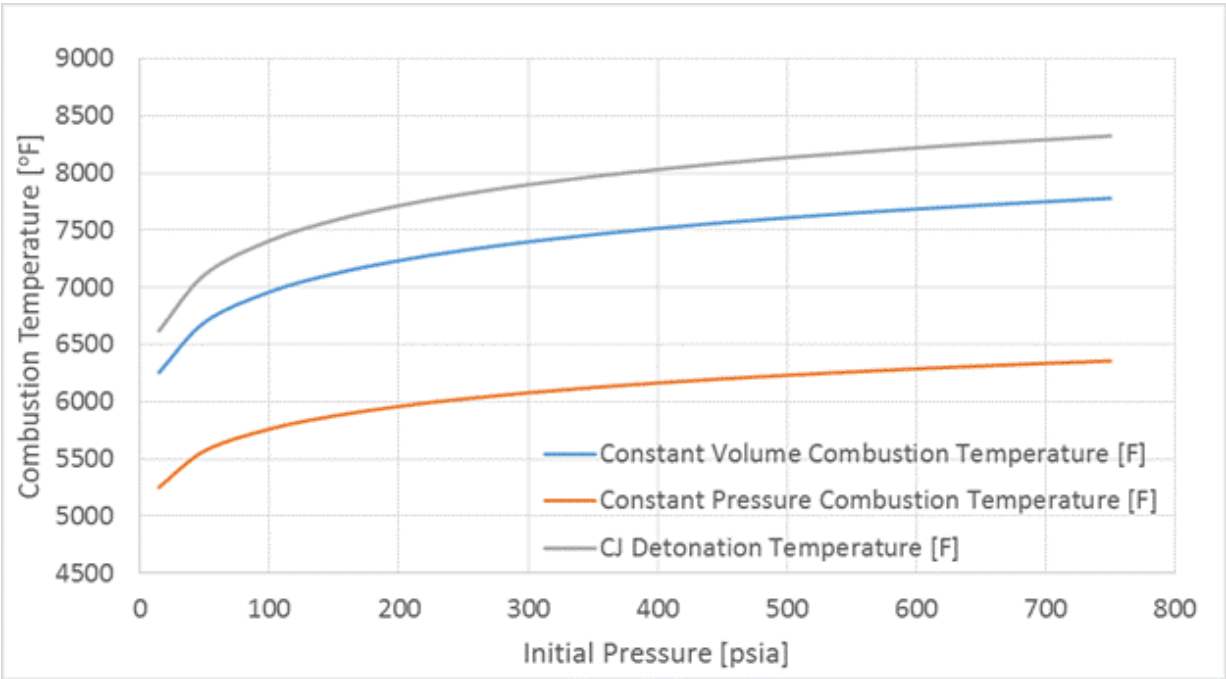

Figure 4-6. Theoretical combustion temperatures for stoichiometric ethylene-oxygen vs. initial pressure.

Table 4-4. Comparison of theoretical pressure and temperature calculations for a CJ detonation and reflected detonation wave at increasing initial pressures.

Initial Pressure [psia]	CJ Detonation		Reflected Wave	
	Pressure [psia]	Temperature [°F]	Pressure [psia]	Temperature [°F]
14.7	561.47	6359.67	1410.40	7141.26
50	1983.04	6737.14	4984.03	7628.30
100	4045.29	6952.17	10165.65	7907.20
150	6133.48	7077.34	15406.25	8069.42
200	8243.67	7166.33	20709.44	8185.40
250	10371.88	7235.49	26067.15	8275.98
300	12500.00	7290.90	31402.70	8347.52
350	14642.24	7338.00	36784.79	8408.77
400	16791.89	7378.65	42185.46	8461.62
450	18947.94	7414.39	47602.23	8508.06
500	21109.65	7446.26	53033.15	8549.45
550	23276.40	7475.01	58476.72	8586.75
600	25447.70	7501.17	63931.69	8620.68
650	27623.14	7525.17	69397.03	8651.79
700	29802.38	7547.34	74871.88	8680.50
750	31985.13	7567.92	80355.51	8707.14

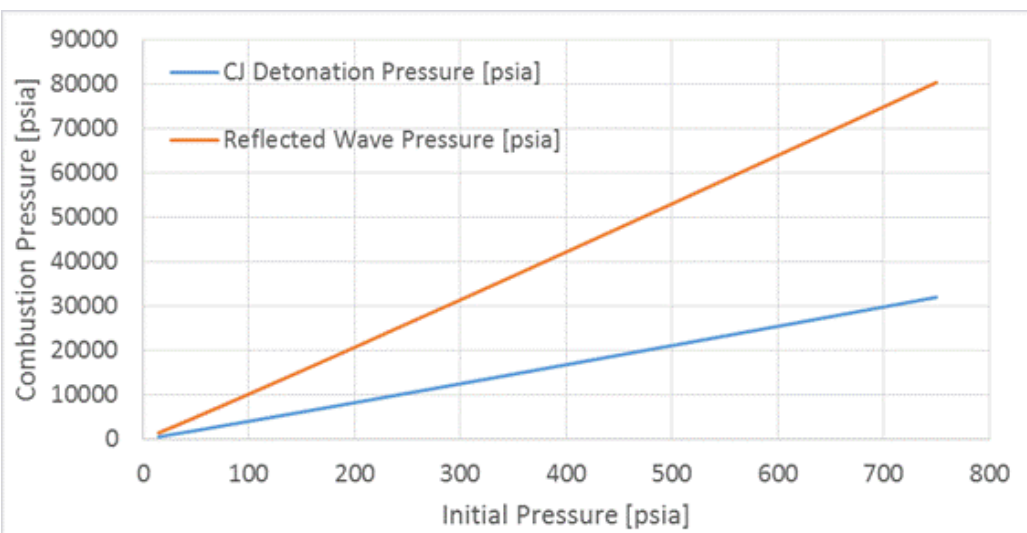

Figure 4-7. Comparison of theoretical CJ detonation and reflected detonation pressures for stoichiometric ethylene-nitrous oxide vs. initial pressure.

Table 4-5. Overdriven detonation calculations for a range of intial pressures.

Overdrive ↓	Initial Pressures [psia] →	14.7	50	100	150	200	250	300	350	400	450	500
1.0		561	1983	4045	6133	8244	10372	12500	14642	16792	18948	21110
1.1		960	3389	6916	10491	14099	17729	21378	25042	28718	32405	36102
1.2		1251	4415	9008	13665	18363	23092	27844	32615	37403	42206	47021
1.3		1548	5462	11144	16906	22718	28567	34446	40349	46273	52214	58172
1.4	Overdrive n Pressures [psia] →	1860	6562	13388	20301	27292	34319	41381	48473	55589	62727	69884
1.5		2189	7725	15760	23908	32127	40399	48713	57062	65439	73842	82268
1.6		2538	8956	18270	27715	37243	46832	56470	66148	75860	85602	95370
1.7		2907	10255	20921	31736	42646	53628	64664	75747	86869	98025	109211
1.8		3295	11625	23715	35974	48425	60789	73300	85864	98471	111118	123798
1.9		3703	13065	26652	40430	54423	68319	82379	96498	110667	124879	139129

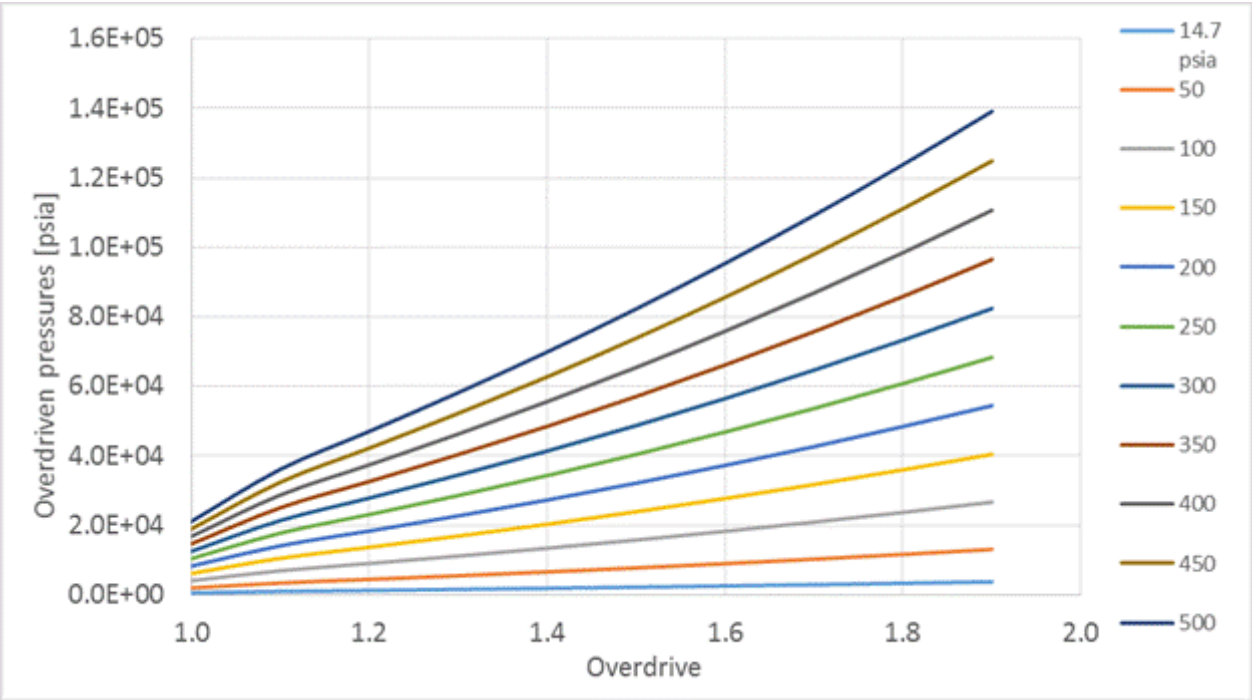

Figure 4-8. Theoretical overdriven detonation pressures for stoichiometric ethylene-nitrous oxide vs. initial pressure for initial pressures ranging from 14.7 psia to 750 psia.

5. ANALYSIS ON VOLUME INCREASE AND RELATED DISCUSSION

The following analysis assumes that the well bore remains a closed system pre- and post-combustion and the gas that is pumped into it does not escape to the surface. This assumption is based on the observation that, once the gas flow into the bore has stopped, the change in the well bore pressure with time (i.e., dp/dt) asymptotes to zero. This was observed only on tests where pressure data was recorded for a long duration of time without venting the gases. This behavior is shown on the dp/dt vs. t plots shown in Figure 5-2 and Figure 5-3 below. This behavior is also observed in Figure 5-1 (a repeat of the NP6 plot) with the recorded pressure shown to asymptote, which we believe is due to the gas pressure reaching an equilibrium state. These three figures are examples representing similar trends seen in the rest of the data. In addition, there was no leakage of gas to the surface or record of pressure rise on the gauges attached to the adjacent well bores (this is based on what was noticed at the test site).

As shown in Table 5-1 below, there was a combustion cycle between the nitrogen pressurization cycles NP6 and NP7. Based on the above assumption, the cracks formed after each combustion cycle contribute to an increase in volume of the well bore but it still remains a closed system. Once the fill valve is closed, the drop in pressure observed can be associated to the gas "leaking" into these cracks and the pressure dropping to an equilibrium pressure. This equilibrium pressure is reached when the change in pressure (dp/dt) asymptotes to zero. Using this equilibrium pressure and the mass of gas inserted into the well bore, the volume of the well bore can be estimated using the following equation:

$$\text{Volume} = \frac{(\text{Mass of gas})(R_u)(\text{Ground temperature})}{(\text{Molecular mass})(\text{Equilibrium pressure})} \qquad \text{Equation 7}$$

After calculating this volume for each cycle, a percentage increase in volume in comparison (vs. the pre-combustion volume) is calculated and tabulated in Table 5-1.

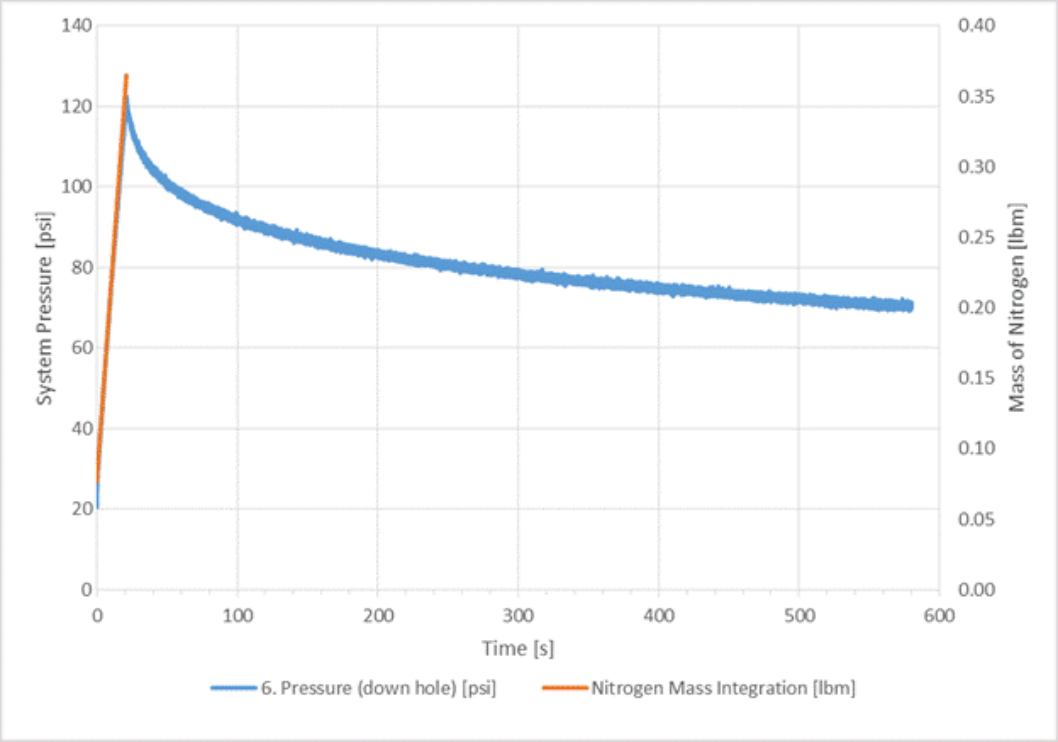

Figure 5-1. Recorded pressure and mass plot for test NP6.

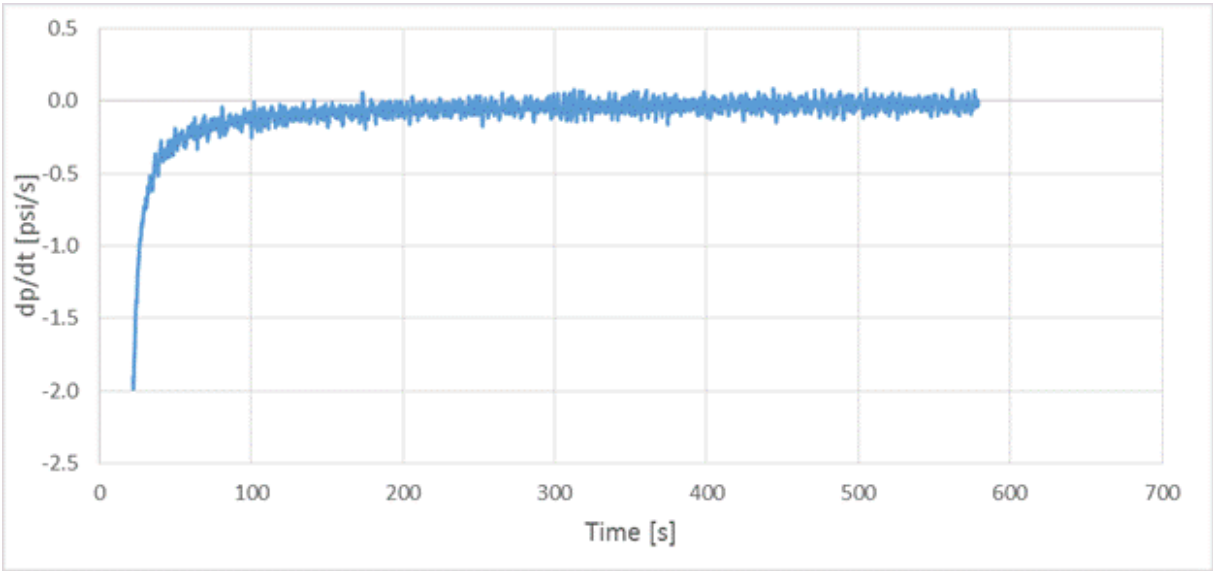

Figure 5-2. Post-fill change in pressure (*dp/dt*) vs. time for NP6.

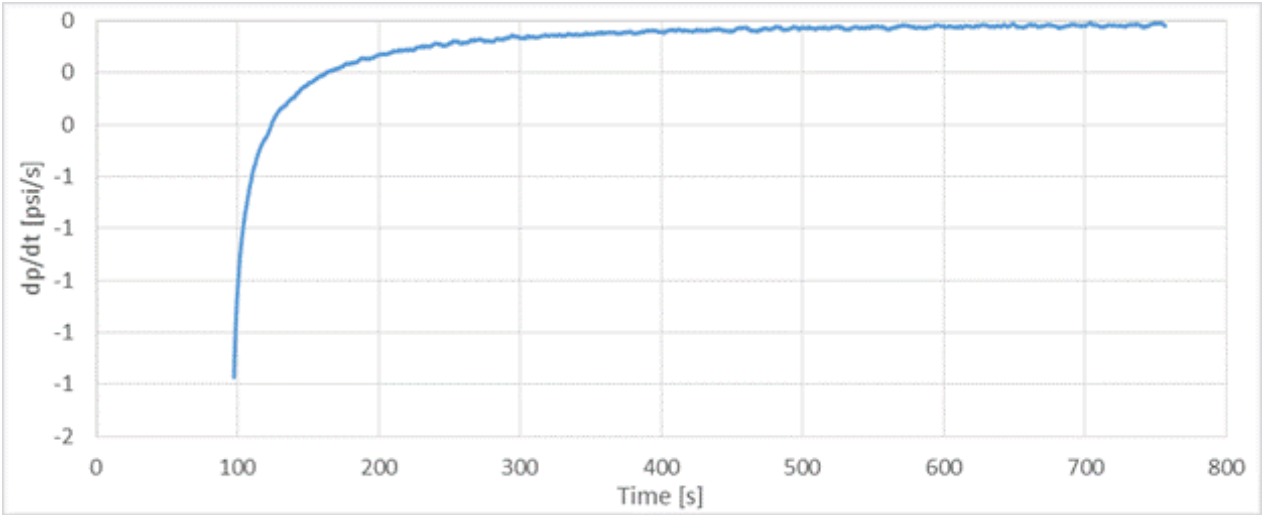

Figure 5-3. Post-fill change in pressure (*dp/dt*) vs. time for NP7.

Table 5-1. Compiled data from all tests – March and June 2013.

Pressure Cycle	Well Bore Target Pressure	Fill Time [s]	Equilibrium Volume [ft^3]	Percentage increase in volume	Avg. Mass Flow Rate [lbm/s]	Mass of gas/gases [lbm]	Cross section area of cracks [in^2]	Gas Holding Time [min]	Remarks
MARCH 2013									
NP1	107.79	16.21	0.56	-	0.014	0.27	-	1.0	
NP2	124.50	19.40	0.58	-	0.014	0.32	-	4.7	
NP3	123.81	19.90	0.58	-	0.014	0.32	-	2.5	
NP4	121.05	19.86	0.57	-	0.014	0.31	-	1.1	
ENP1	141.77	25.12	-	-	0.016	0.53	-	-	
NP5	124.70	22.30	0.74	27.6	0.014	0.36	0.001105	1.1	dp/dt does not go to 0; pressure data recording stopped
ENP2	175.25	25.25	-	-	0.024	0.66	-	-	
NP6	122.37	21.08	1.03	39.2	0.014	0.37	0.001145	9.3	
ENP3	281.48	25.22	-	-	0.040	1.08	-	-	
NP7	123.45	91.71	5.15	400.0	0.014	1.34	0.004705	11.2	
NP8	291.87	213.07	8.75	69.9	0.035	7.90	0.005911	1.7	dp/dt does not go to 0; pressure data recording stopped
NP9	291.08	256.92	9.51	8.7	0.031	10.44	0.007761	0.7	dp/dt does not go to 0; pressure data recording stopped
JUNE 24, 2013									
ENP4 (no det.)	124.80	15.42	5.61	-	0.056	1.43	0.013229	4.5	
ENP5 (det.)	239.48	106.37	-	-	0.056	5.94	0.008419	-	
ENP6 (no det.)	124.18	14.12	5.20	Negative	0.055	1.39	0.013061	3.4	Data recording stopped before pressure equalizes

Pressure Cycle	Well Bore Target Pressure	Fill Time [s]	Equilibrium Volume [ft^3]	Percentage increase in volume	Avg. Mass Flow Rate [lbm/s]	Mass of gas/gases [lbm]	Cross section area of cracks [in^2]	Gas Holding Time [min]	Remarks
ENP7 (det.)	285.76	191.72	-	-	0.054	10.45	0.006951	-	
NP10	308.35	464.38	22.59	329.4	0.037	17.72	0.008063	7.7	
JUNE 25, 2013									
ENP8 (no det.)	130.33	28.76	8.35	Negative	0.053	2.10	0.013941	6.4	
ENP9 (det.)	257.43	439.52	-	-	0.047	20.81	0.006314	-	
ENP10 (no det.)	133.32	38.30	8.99	7.3	0.053	2.95	0.015149	3.5	Data recording stopped before pressure equalizes
ENP11 (det.)	251.91	656.78	-	-	0.048	26.27	0.006737	-	
NP11	305.26	499.85	25.19	179.8	0.036	20.63	0.007174	23.2	

Table 5-1 summarizes data from all tests conducted at the EMRTC site in March and June 2013 and includes a column with percentage increase in well bore volume between consecutive tests. The values under the "Equilibrium Volume" column in red and the values under the 'Percentage increase in volume" column in green do not follow the expected volume increase trend. The initial volume based on the well bore dimensions is calculated to be 0.54 ft^3 and the equilibrium volumes calculated for tests NP1 to NP4 are close to this value. This suggests that there was no fracture in the rock before the first combustion test.

The well bore volume increases by 27.6% after the first combustion test with a charge pressure of 140 psia. The dp/dt plot for this case does not asymptote to zero, but the pressure could have reached equilibrium if pressure data was recorded for a longer duration. Based on this argument the estimated increase in volume could have been higher for this case. The next percentage increase in well bore volume is 39.2%, which is larger than the previous increase due to the higher initial pressure of gas for the combustion test ENP2 as compared to ENP1. The 400% volume increase for the NP7 test is also due to the much higher initial pressure. The detonation pressure is largely dependent on the initial pressure of the gases in the well bore and influences the extent to which cracks are opened up. The volume estimates for NP8 and NP9 are relatively higher than that of NP7 and the high initial pressure possibly opened up the cracks further. However, pressure data is not recorded long enough to allow the gas to reach equilibrium and thus these values are highlighted in red to indicate that they might be different from the actual volume of the well bore at that time.

For easier comparison of tests with similar conditions the data from Table 5-1 is separated into Tables Table 5-2 to Table 5-5 according to the following test categories:

1. Nitrogen Pressure Data at ~125 psia
2. Nitrogen Pressure Data at ~300 psia
3. Ethylene and Nitrous oxide Pressure Data at ~130 psia
4. Ethylene and Nitrous oxide Pressure Data at ~250 psia

Tables Table 5-2 to Table 5-5 can be used to compare tests where the well bore was pressurized with the same gases to similar pressures. Organizing the data in this manner makes it easier to investigate the increase in the well bore volume and cross-sectional area of the cracks from test to test.

Table 5-2 shows all the nitrogen pressurization tests with target well bore pressures of approximately 125 psia. All these tests have a similar average fill mass flow rate, but the fill time increases significantly between NP6 and NP7 for similar well bore pressures indicating a dramatic increase in well bore volume. The estimated equilibrium volume values also indicate a large increase in the bore volume due to rock fracturing during combustion. The high percentage increase in volume shown for NP7 can be attributed to the high initial pressure used for the ENP3 combustion test.

Table 5-3 summarizes the nitrogen pressurization tests with a target well bore pressure of approximately 300 psia. The tests in this table were conducted before testing was ended for a particular day. The NP8 and NP9 tests were conducted on the last day of testing in March, the NP10 test was conducted at the end of June 24, 2013 and the NP11 test was conducted at the end of June 25, 2013. It was observed at the test site that the NP9 and NP11 tests did not have sufficient nitrogen cylinder

pressure to fill the bore to 300 psi and hence the pressure plots show a plateauing trend. Also, the tests did not include a sufficient gas holding time and therefore an accurate estimate of equilibrium pressure was not possible for these tests. However, the table shows an increasing well bore equilibrium volume when from NP8 to NP11 which is further demonstrated by a longer fill duration for similar target pressures.

Table 5-4 shows all the ethylene-nitrous oxide pressurization tests with target well bore pressures of approximately 130 psia. The tests in this table from March were combustion tests and those from June were only fill cycles conducted between two combustion tests. The tests in this series show a general increasing trend with respect to the estimated well bore volume except for the ENP6 test. Once again, this trend is also demonstrated by the increased fill time for tests with a similar target pressure and fill mass flow rate. A longer duration of data recording for the ENP6 and ENP10 tests could have provided a better estimate of well bore volume which may have resulted in a higher estimate of well bore volume for ENP6 in comparison to ENP4.

The ENP4, ENP6, ENP8 and ENP10 tests between the combustion tests in Table 5-5 were simply filling tests and were conducted to assess the well bore's ability to maintain pressure. There was no observed increase in volume due to these low-pressure filling cycles. Table 5-5 shows that the combustion tests ENP5 and ENP7 have similar fill mass flow rates, but ENP7 has a target gas mixture mass of nearly twice as much as ENP5. However, this only yields a well bore pressure rise of approximately 45 psia. This can possibly be attributed to the widening of cracks in the well bore after the ENP5 test thereby creating a larger volume. A similar phenomenon is observed between the combustion tests ENP9 and ENP11. The goal of the ENP11 test was to fill the well bore with gas mixture mass approximately 5 lbm higher than ENP9, but this is done over a considerably longer duration and therefore a lower well bore pressure is achieved in comparison to ENP9. This is a good indication that the well bore volume has increased after the ENP9 combustion test.

Table 5-2. Nitrogen Pressure Data at ~125 psia.

Pressure Cycle	Well Bore Target Pressure	Fill Time [s]	Equilibrium Volume [ft^3]	Percentage increase in volume	Avg. Mass Flow Rate [lbm/s]	Mass of gas/gases [lbm]	Cross section area of cracks [in^2]	Gas Holding Time [min]	Remarks
MARCH 2013									
NP1	107.79	16.21	0.56	-	0.014	0.27	-	1.0	
NP2	124.50	19.40	0.58	-	0.014	0.32	-	4.7	
NP3	123.81	19.90	0.58	-	0.014	0.32	-	2.5	
NP4	121.05	19.86	0.57	-	0.014	0.31	-	1.1	
NP5	124.70	22.30	0.74	27.6	0.014	0.36	0.001105	1.1	dp/dt does not go to 0; pressure data recording stopped
NP6	122.37	21.08	1.03	39.2	0.014	0.37	0.001145	9.3	
NP7	123.45	91.71	5.15	400.0	0.014	1.34	0.004705	11.2	

Combustion

Combustion

Combustion

Table 5-3. Nitrogen Pressure Data at ~300 psia.

Pressure Cycle	Well Bore Target Pressure	Fill Time [s]	Equilibrium Volume [ft^3]	Percentage increase in volume	Avg. Mass Flow Rate [lbm/s]	Mass of gas/gases [lbm]	Cross section area of cracks [in^2]	Gas Holding Time [min]	Remarks
MARCH 2013									
NP8	291.87	213.07	8.75	69.9	0.035	7.90	0.005911	1.7	dp/dt does not go to 0; pressure data recording stopped
NP9	291.08	256.92	9.51	8.7	0.031	10.44	0.007761	0.7	dp/dt does not go to 0; pressure data recording stopped
JUNE 24, 2013									
NP10	308.35	464.38	22.59	329.4	0.037	17.72	0.008063	7.7	

Combustion

Pressure Cycle	Well Bore Target Pressure	Fill Time [s]	Equilibrium Volume [ft^3]	Percentage increase in volume	Avg. Mass Flow Rate [lbm/s]	Mass of gas/gases [lbm]	Cross section area of cracks [in^2]	Gas Holding Time [min]	Remarks
JUNE 25, 2013									
NP11	305.26	499.85	25.19	179.8	0.036	20.63	0.007174	23.2	Combustion

Table 5-4. Ethylene & Nitrous oxide Pressure Data at ~130 psia.

Pressure Cycle	Well Bore Target Pressure	Fill Time [s]	Equilibrium Volume [ft^3]	Percentage increase in volume	Avg. Mass Flow Rate [lbm/s]	Mass of gas/gases [lbm]	Cross section area of cracks [in^2]	Gas Holding Time [min]	Remarks
MARCH 2013									
ENP1	141.77	25.12	-	-	0.016	0.53	-	-	
ENP2	175.25	25.25	-	-	0.024	0.66	-	-	
JUNE 24, 2013									
ENP4 (no det.)	124.80	15.42	5.61	-	0.056	1.43	0.013229	4.5	Combustion
ENP6 (no det.)	124.18	14.12	5.20	Negative	0.055	1.39	0.013061	3.4	Data recording stopped before pressure equalizes Combustion
JUNE 25, 2013									
ENP8 (no det.)	130.33	28.76	8.35	59.4 *Comparing to ENP6*	0.053	2.10	0.013941	6.4	
ENP10 (no det.)	133.32	38.30	8.99	7.3	0.053	2.95	0.015149	3.5	Combustion Data recording stopped before pressure equalizes

Table 5-5. Ethylene & Nitrous oxide Pressure Data at ~250 psia.

Pressure Cycle	Well Bore Target Pressure	Fill Time [s]	Equilibrium Volume [ft^3]	Percentage increase in volume	Avg. Mass Flow Rate [lbm/s]	Mass of gas/gases [lbm]	Cross section area of cracks [in^2]	Gas Holding Time [min]	Remarks
MARCH 2013									
ENP3	281.48	25.22	-	-	0.040	1.08	-	-	
JUNE 24, 2013									
ENP5 (det.)	239.48	106.37	-	-	0.056	5.94	0.008419	-	
ENP7 (det.)	285.76	191.72	-	-	0.054	10.45	0.006951	-	
JUNE 25, 2013									
ENP9 (det.)	257.43	439.52	-	-	0.047	20.81	0.006314	-	
ENP11 (det.)	251.91	656.78	-	-	0.048	26.27	0.006737	-	

The data presented indicates that the gas in the well bore required a certain holding time before reaching equilibrium pressure (i.e., dp/dt reached zero). This phenomenon can possibly be attributed to relatively small openings to the cracks that were formed post-combustion tests. Using the pressure and mass of the gas mixture, an attempt was made to estimate the cross-sectional area of cracks formed in the well bore during each test.

The dp/dt curve on for each test (after the first combustion test) is comprised of two components: the expected pressurization rate and the leak rate. The expected pressurization rate is the rate at which pressure in the well bore is expected to rise based on the fill mass flow rate for each test. The leak rate is the rate at which the gas leaks into the cracks during the fill process. The pressure data provides the actual pressure rise (dp/dt_{actual}) and the expected pressure rise ($dp/dt_{expected}$) can be calculated using the average mass flow rate of the gas during filling. Thus, using these two pressure-rates the leak rate (dp/dt_{leak}) can be estimated.

Using the dp/dt_{leak} value corresponding to the final fill time, the average leak mass flow rate can be estimated as:

$$\dot{m}_{leak} = \frac{dM}{dt} = \left(\frac{dp}{dt}\right)_{leak} \frac{\mu V}{R_u T} \qquad \text{Equation 8}$$

where:

M: Mass of gas [lbm]
μ: Molecular mass [lbm/lbmol]
V: Volume of original well bore [ft^3]
T: Ground temperature [R]

The leak rate, $\dot{m}_{leak}$, estimated from Equation 8 is used in Equation 1 and rearranged to obtain the cross-sectional area of the cracks. In this method we assume that the flow of gas into the cracks is choked. The estimated crack cross sectional areas are shown in Table 5-1 to Table 5-5 as an additional way to investigate the increase in rock fracture between tests. The crack cross sectional areas in Table 5-2 and Table 5-4 show an increasing trend, suggesting an increase in rock fracture after each combustion test.

6. COMPARISON PLOTS

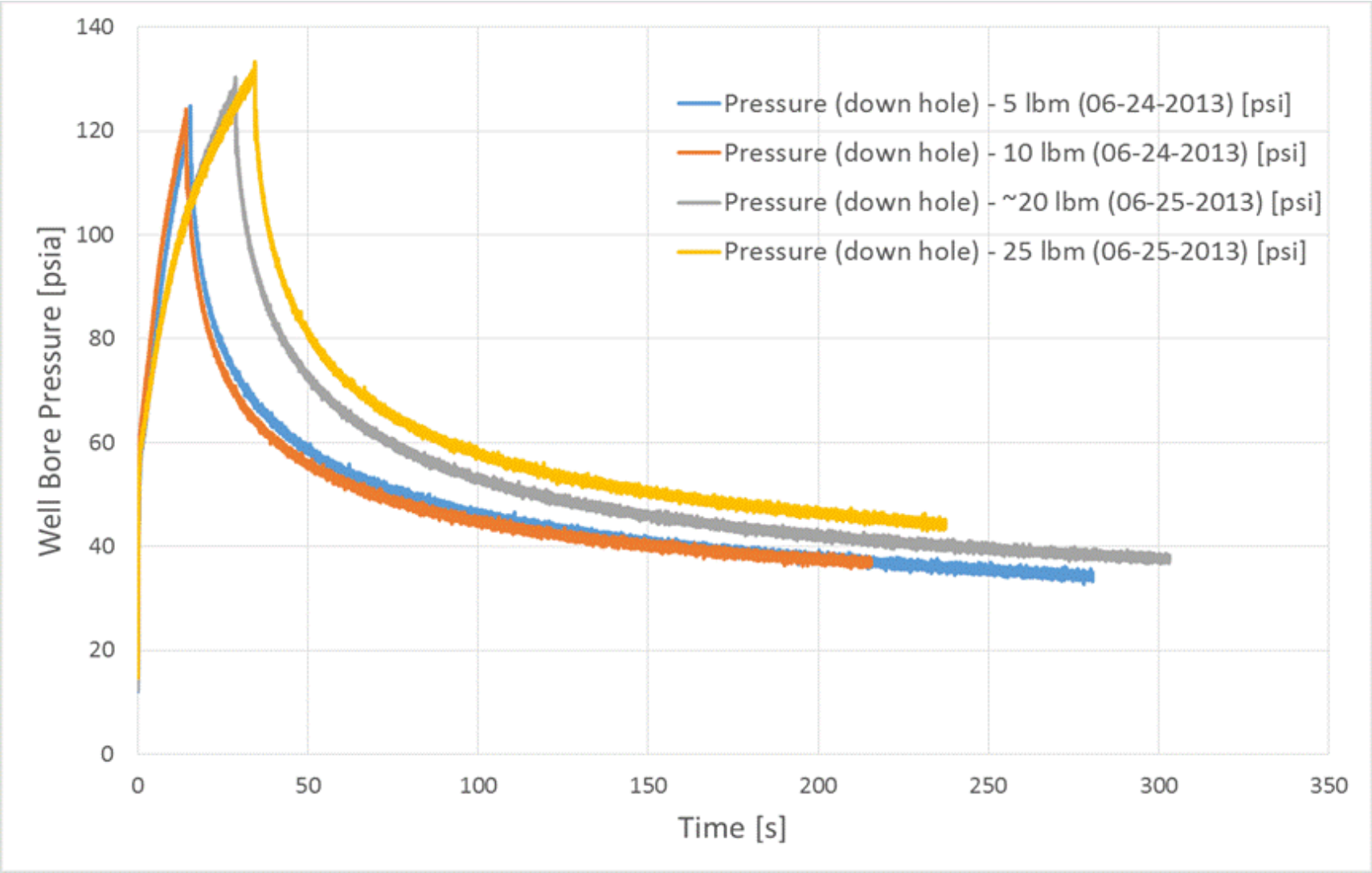

Figure 6-1. Ethylene and Nitrous oxide Mixture 100 psia Leak Tests.

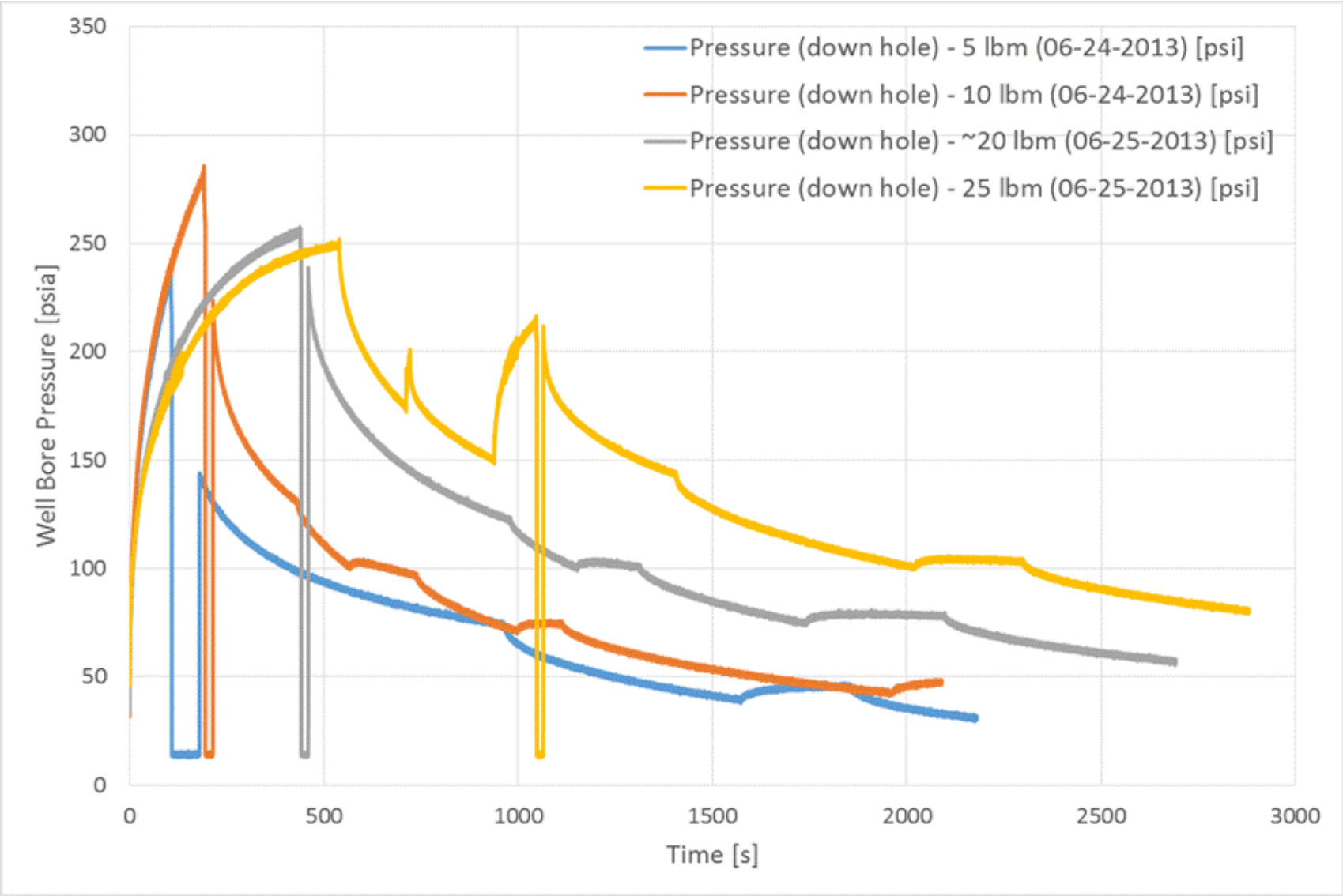

Figure 6-2. Ethylene and Nitrous oxide Mixture at 250 psia - Hot Fires.

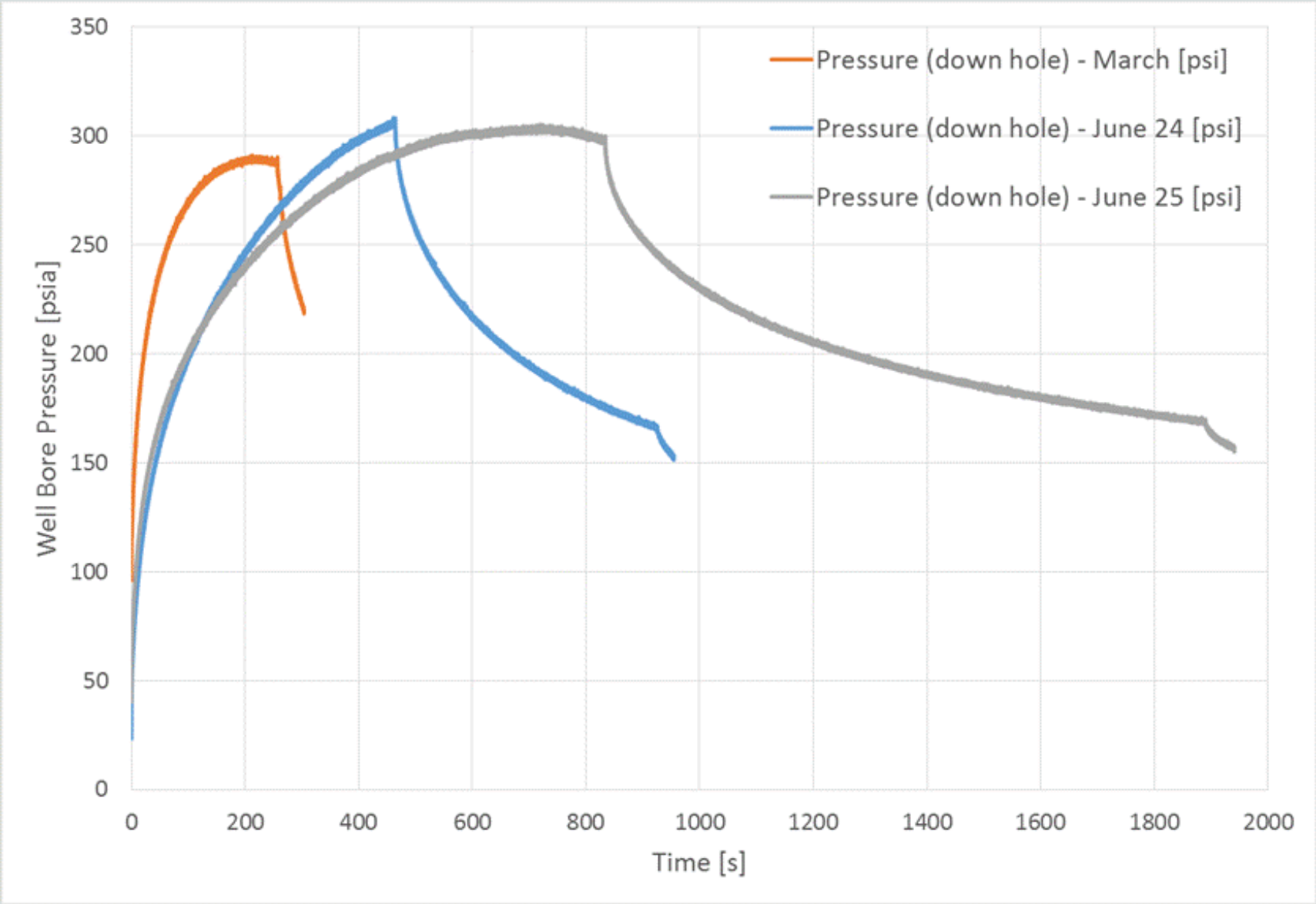

Figure 6-3. Nitrogen Pressurization Cycle Comparison (March & June 2013).

REFERENCES

[1] Browne, S., Shepherd, J.E. and Ziegler, J.L. Shock and Detonation Toolbox, 2005. URL www2.galcit.caltech.edu/EDL/public/cantera/html/SD_Toolbox/index.html.

[2] Goodwin, D. Cantera: Object-oriented Software for Reacting Flows. Technical report, California Institute of Technology, 2005. URL www.code.google.com/p/cantera.

APPENDIX A. VOLUME OF WELL BORE

The *ideal well volume* is defined as the volume of the 3-inch ID x 10 ft. long well bore and the 0.438-inch ID x 50 ft. long tube added together. The *calculated well volume* for each test cycle is calculated using the ideal gas law with the measured well bore pressure and the integrated mass of gas injected into the well bore at every instant of time. This calculated well bore volume is plotted along with the ideal well bore volume to observe the changes in volume. Plots comparing the *calculated* and *ideal* well bore volumes are shown in Figures **Error! Reference source not found.** to **Error! Reference source not found.** .

A.1. Nitrogen Pressurization 1 (NP1)

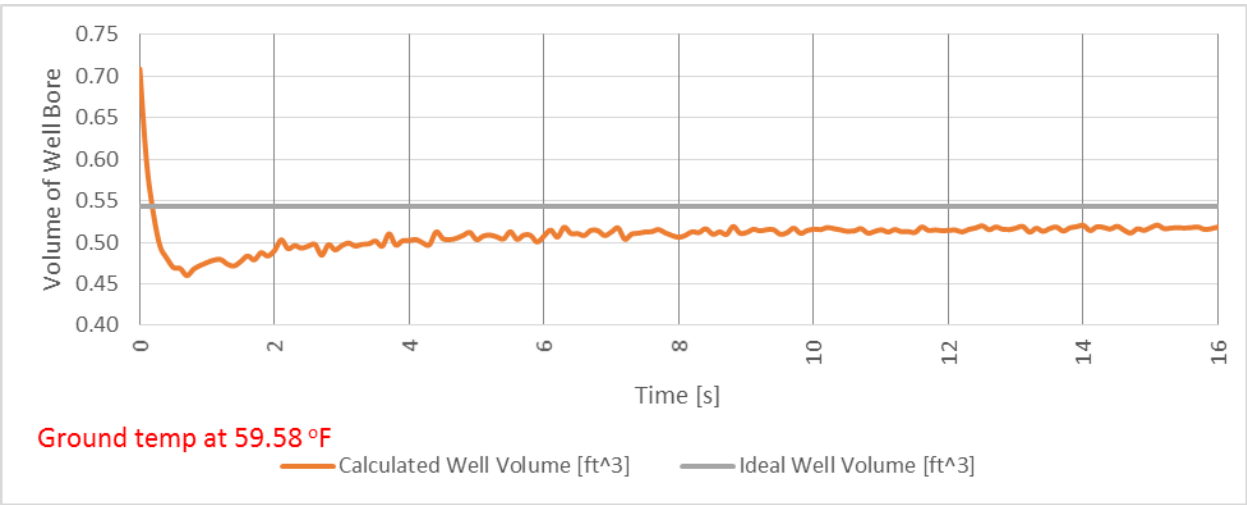

Figure A-1. Comparison of calculated and ideal well bore volumes for test NP1.

A.2. Nitrogen Pressurization 2 (NP2)

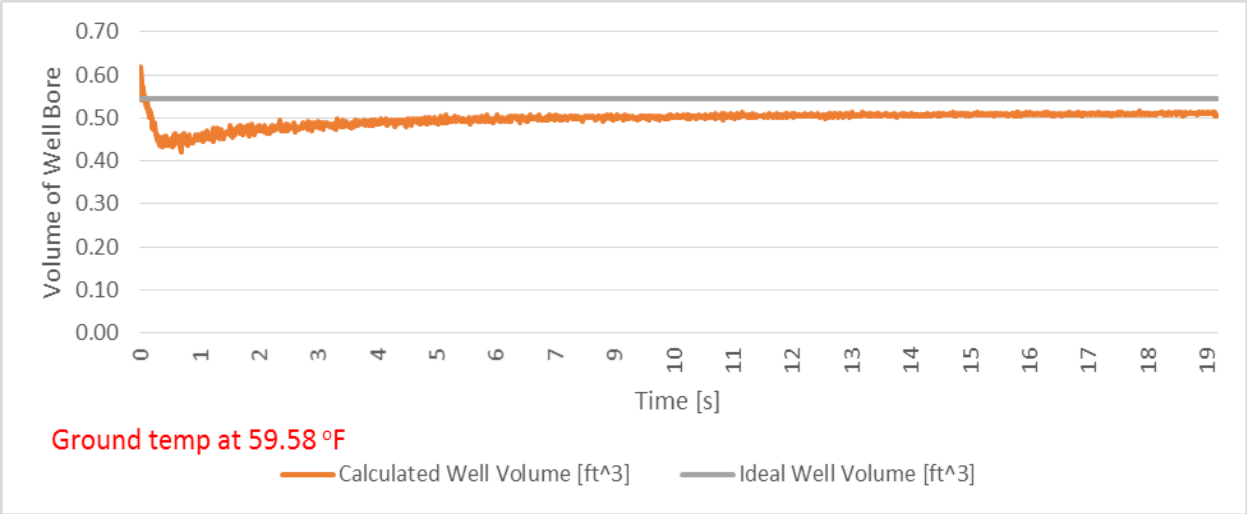

Figure A-2. Comparison of calculated and ideal well bore volumes for test NP2.

A.3. Nitrogen Pressurization 3 (NP3)

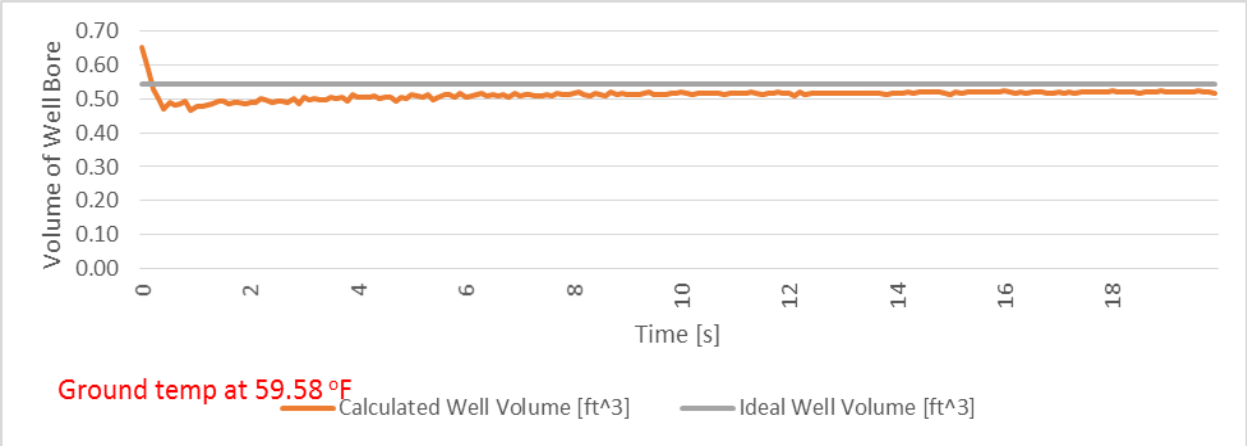

Figure A-3. Comparison of calculated and ideal well bore volumes for test NP3.

A.4. Nitrogen Pressurization 4: Pre-Test Pressurization (NP4)

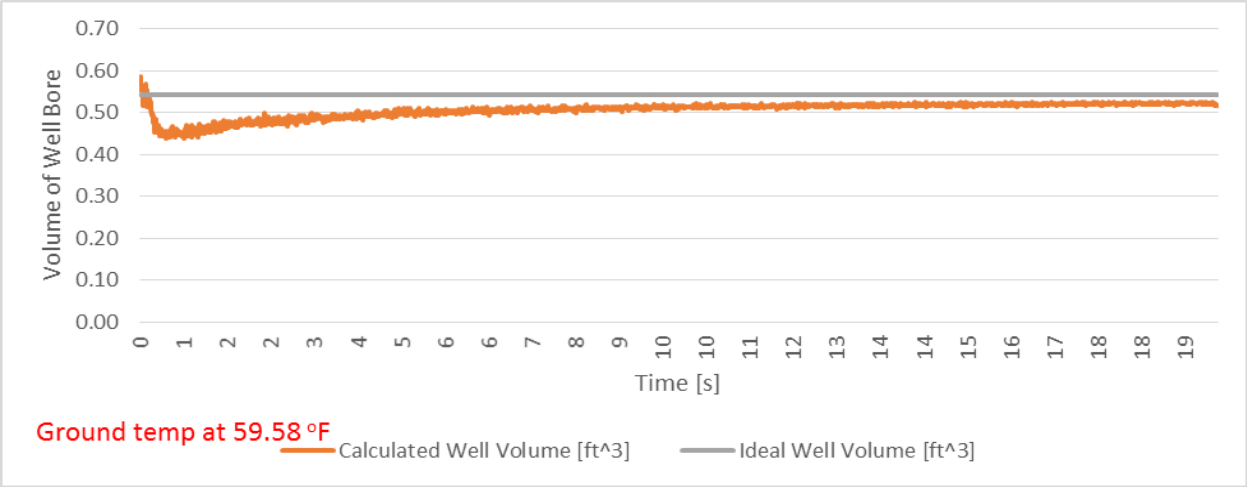

Figure A-4. Comparison of calculated and ideal well bore volumes for test NP4.

A.5. Ethylene/Nitrous Oxide Pressurization 1 with Combustion (ENP1)

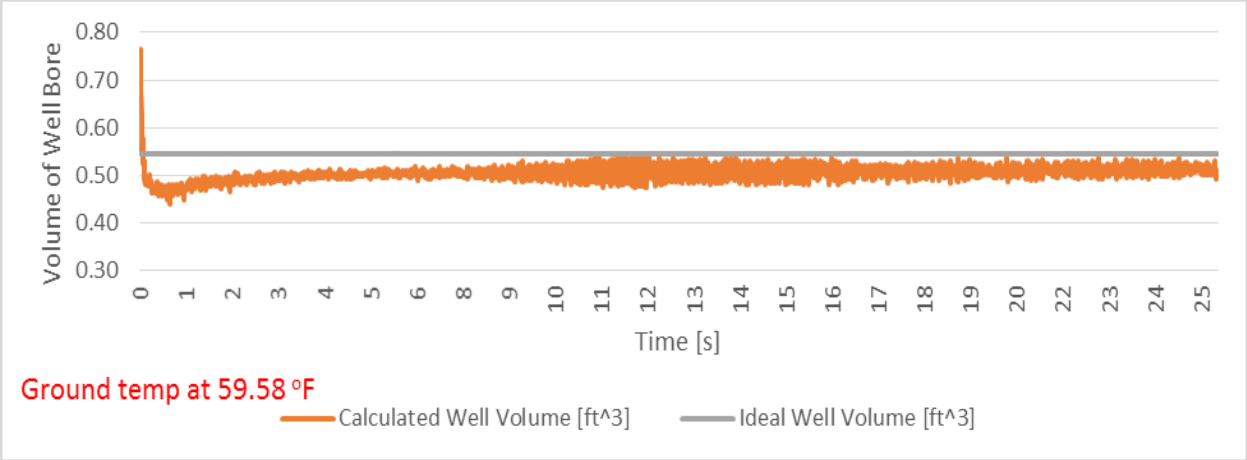

Figure A-5. Comparison of calculated and ideal well bore volumes for test ENP1.

A.6. Nitrogen Pressurization 5: Post-Test Pressurization (NP5)

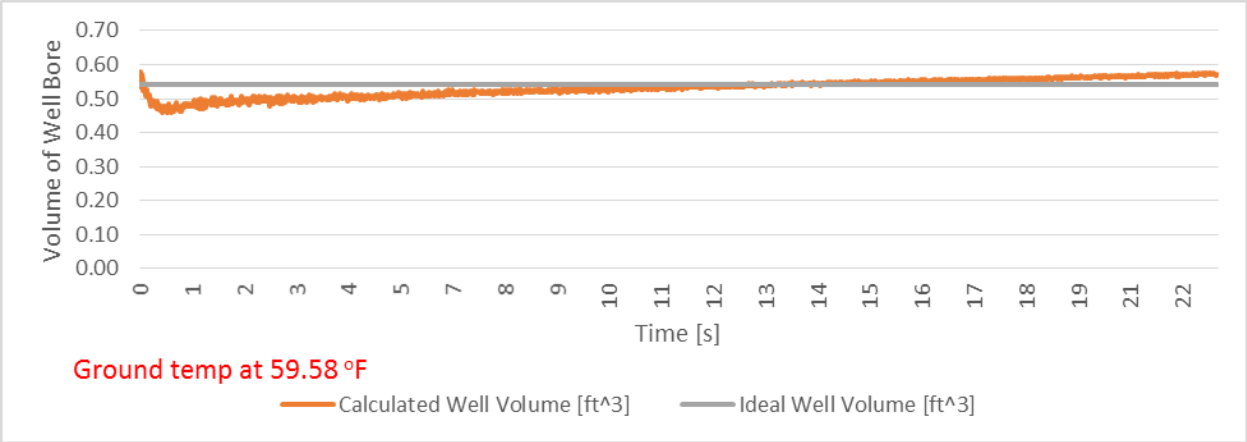

Figure A-6. Comparison of calculated and ideal well bore volumes for test NP5.

A.7. Ethylene/Nitrous Oxide Pressurization 2 with Combustion (ENP2)

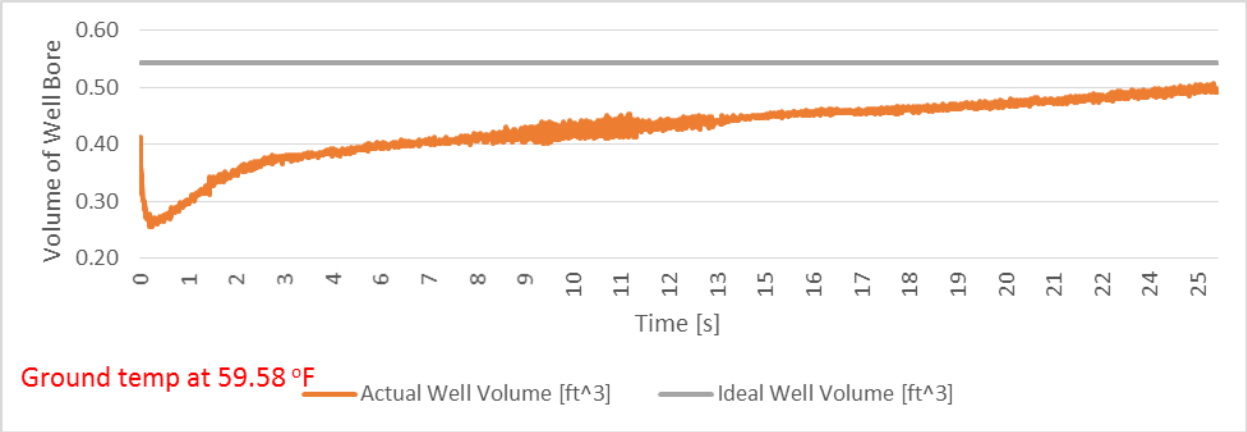

Figure A-7. Comparison of calculated and ideal well bore volumes for test ENP2.

A.8. Nitrogen Pressurization 6: Post-Test Pressurization (NP6)

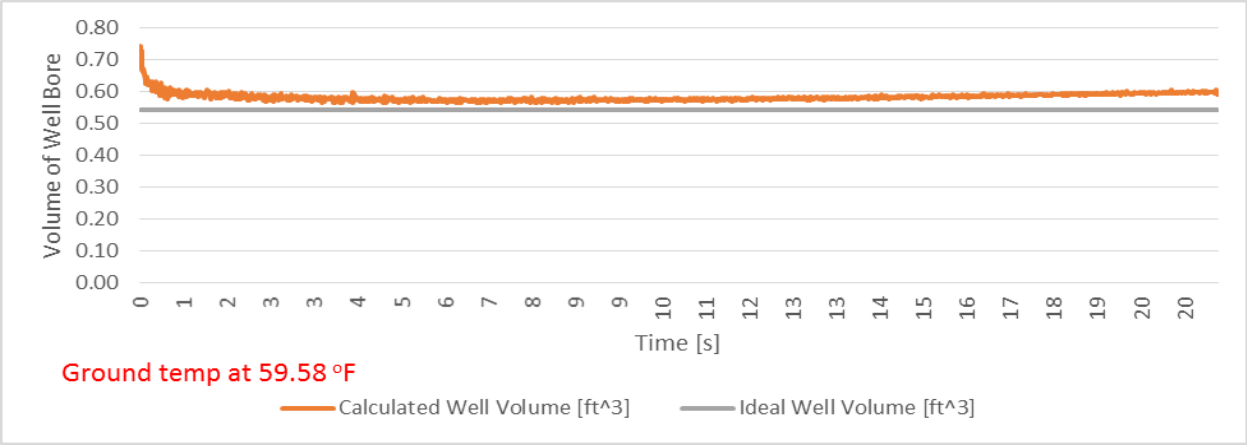

Figure A-8. Comparison of calculated and ideal well bore volumes for test NP6.

A.9. Ethylene/Nitrous Oxide Pressurization 3 with Combustion (ENP3)

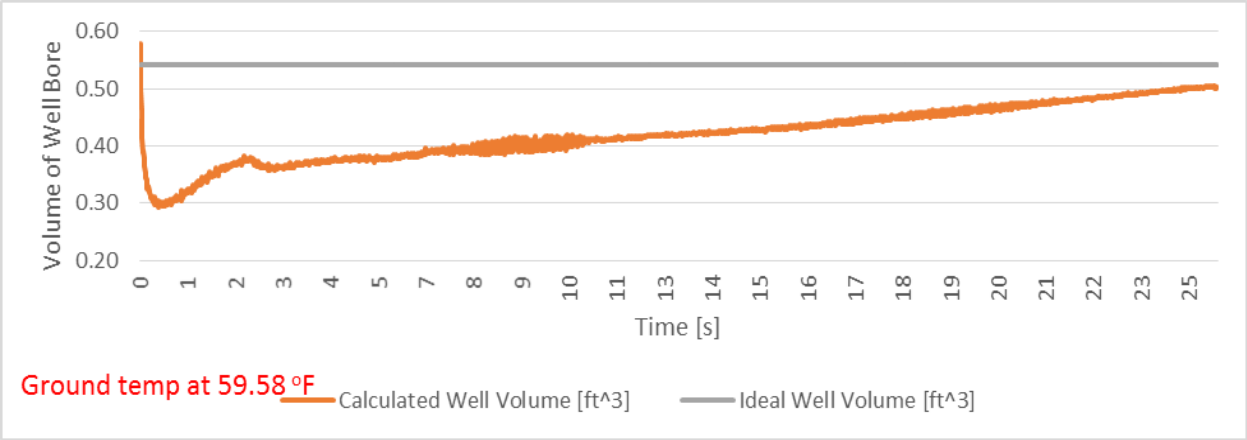

Figure A-9. Comparison of calculated and ideal well bore volumes for test ENP3.

A.10. Nitrogen Pressurization 7: Post-Test Pressurization (NP7)

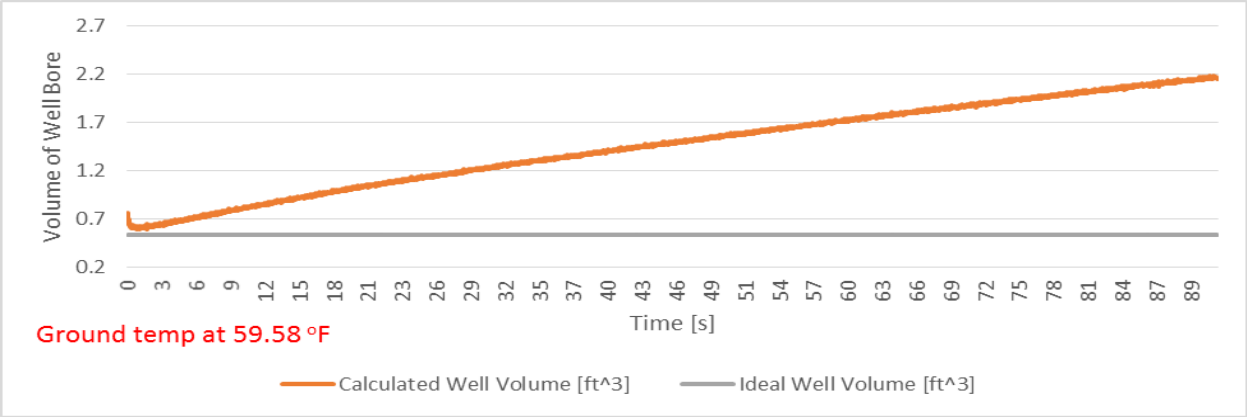

Figure A-10. Comparison of calculated and ideal well bore volumes for test NP7.

A.11. Nitrogen Pressurization 8 (NP8)

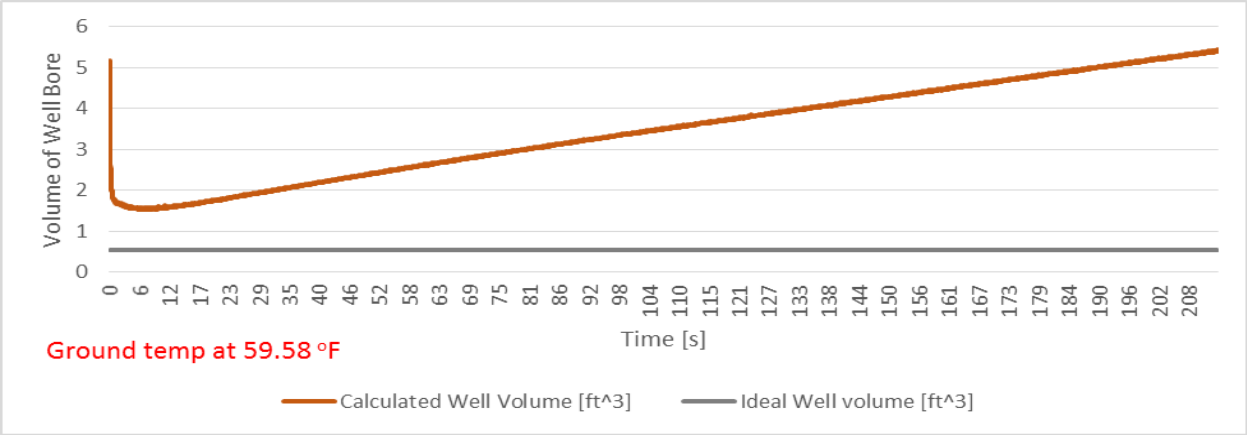

Figure A-11. Comparison of calculated and ideal well bore volumes for test NP8.

A.12. Nitrogen Pressurization 9 (NP9)

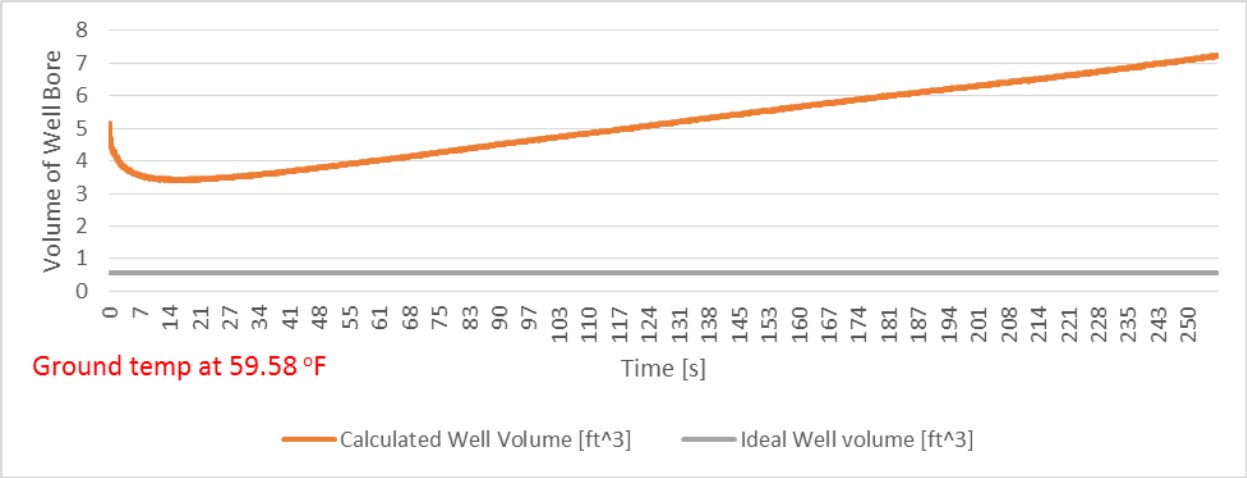

Figure A-12. Comparison of calculated and ideal well bore volumes for test NP9.

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