# DEPARTMENT OF ENERGY (DOE) ENHANCED GEOTHERMAL SYSTEMS (EGS) PROJECT

# WELLFLO SIMULATIONS REPORT

# **STEP 5: DRILLING 20,000 WELLS**

# WITH SUPERCRITICAL STEAM, NITROGEN

# AND

# **CARBON DIOXIDE**

by

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18-11-2010

#### **EXECUTIVE SUMMARY**

The scope of this report is to provide simulation results for drilling 20,000 ft wells utilizing supercritical fluid; Nitrogen. The WellFlo Version 8.013 (by SPT) under balanced drilling hydraulic program was used to perform all modeling runs.

Three different well profile were used to create operational envelopes, pressure and temperature profiles. For the first cases, 1.25'' coiled tubing and 2.25'' hole size was used to drill vertical 20,000 wells. In the second cases, 1.25'' coiled tubing was used to drill 20,000 wells which have casing for the first 19,000 ft. For the third cases, well deviated 30° from its vertical path after 19,000 ft depth of the well and has different size of casings for the first 18.000 ft. In the second and third part, in order to analyze cutting transport efficiency, different size of cuttings was also used.

Operational envelopes were created based on erosion velocity limit which is 1800 ft/min. Runs were made with using supercritical nitrogen as the drilling fluid. Also, some of the runs were made with adding different flow rates of water with the supercritical nitrogen. Liquid fractions after the nozzle were shown on the operational envelope graphs.

Hydrate formation did not occur in 20,000 ft simulations. Higher temperature drop occurred at the nozzle for nitrogen with water addition cases. For nitrogen only cases, temperature drop at the nozzle was not significant.

Increasing casing and cutting sizes affect cutting transport efficiency negatively. For lower injection flow rates, cutting transport became impossible in the annulus.

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#### **1. Overall Approach**

Drilling vertical 20,000 ft. wells were modeled using supercritical fluid: nitrogen under different conditions to create operational envelopes, pressure-temperature profiles and to analyze cutting transport efficiencies for such operations. SPT 's WellFlo version 8.0.13 program was used for this effort.

Runs were performed for three main cases: 1) Simulations with 1.25'' Coiled Tubing-2.25'' Hole Size, 2) Simulations with Different Casing and Cutting Sizes 3) Simulations with Different Casing and Cutting Sizes (Deviated Wells).

As known, in order to provide proper FLASH ASJ<sup>TM</sup> cutting at the bottom of the well, gas fraction should dominate after the nozzle. In all the cases, 0.25 liquid fraction was taken as a maximum liquid fraction that the operation can tolerate. Also, due to the erosion velocity limit of 1800 ft/min, mixture velocity in the annulus should be less than this erosion limit. In order to decrease effect of the erosion velocity problem, 4" casing was used for the first 500 ft. for the well in case 1 simulations.

WellFlo Version 8.0.13 allows the user to add coiled tubing spooled onto a peel at the surface in order to fully calculate pressure losses of the system. In all of the 20,000 ft. drilling simulations, total coiled length of the system was set to 30,000 ft length on a 7 ft. spool diameter a with horizontal axle orientation. Results of the surface coil tubing losses are given in Appendix B.

Operational envelopes were created based on erosion velocity limit which is 1800 ft/min mixture velocity in the annulus. On the operational envelopes, a vertical erosion line was used to show the maximum injection flow rates for set erosion velocity.

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Therefore, the run points on the left of the vertical erosion line are the points which the maximum mixture velocity at the annulus does not exceed 1800 ft/min.

Fluids were injected into the coiled tubing with a 75 °F initial temperature. Pressure drop across the nozzle was fixed at 8,000 psi, except the case 1 runs. In that condition, 7,500 psi pressure drop across the nozzle was used for nitrogen only injections and 5,000 psi was used for nitrogen injection with water addition. Table 1 gives the input parameters for nitrogen for all conditions.

	CASE-1		CASE-2
	N2 Only	N2&Water	All Runs
Formation	Sandston	Sandstone	Sandstone
	e		
Geothermal Gradient ( <sup>o</sup> F/ft)	0.015	0.015	0.015
Surface Temperature ( <sup>o</sup> F)	60	60	60
Injected Fluid Temperature ( <sup>o</sup> F)	75	75	75
<b>Return Choke Pressure (psia)</b>	50	50	50
Nozzle Pressure Drop (psi)	7500	5000	8000
Cutting Size (micron)	25-100	25-100	25-100
ROP (ft/hour)	400	400	400

Table 1: Input Parameters

#### 2. Simulations with 1.25" Coiled Tubing-2.25" Hole Size

In this schematic, 20,000 ft vertical wells are drilled with 1.25" coiled tubing which has 2.25" hole size. 4" surface pipe was used for the first 500 ft of the well. Runs were started with injecting only nitrogen to the system and then nitrogen was injected into the system with different amounts of water.

#### 2.1. Nitrogen without Water Addition Cases

In this condition only nitrogen was injected with different flow rates. Figure 1 gives the operational envelope for nitrogen without water condition. In the graph, the vertical erosion line shows the maximum injection flow rates for the erosion velocity limit (1800 ft/min). Run points, left of the erosion line are for the conditions where the maximum mixture velocity of fluid in the annulus does not exceed erosion velocity limit. For nitrogen only cases 7,500 psi pressure drop was used at the nozzle and there was no liquid fraction observed after the nozzle which means all the liquid phase changed to gas phase after the pressure drop at the nozzle. Figure 2 shows the change of injection pressure with flow rate. Increasing flow rate of the nitrogen to 10 gpm, increased the injected pressure to 6230 psia.



Figure 1: Operational Envelope for N<sub>2</sub> (CT:1.25"-HS:2.25", N<sub>2</sub> Only)



Figure 2: Flow Rate vs. Inj. Pressure (N2, CT:1.25"-HS:2.25", N2 Only)

Example pressure and temperature profile graphs for nitrogen only case are given for the flow rate of 5 gpm in Figures 3 and 4, respectively. As seen in Figure 3, the pressure drop of 7500 psi occurs at the nozzle. Pressure outputs for 5 gpm are given in Table 2.

Injection Pressure (psia)	5566
BHP Upstream Nozzle (psia)	8443
BHP Downstream Nozzle (psi)	943

Table 2: Output Pressure Values (N<sub>2</sub> Only, CT: 1.25"-HS: 2.25", 5 gpm)

Figure 4 is the temperature profile of the fluid inside the coiled tubing and annulus with the formation temperature profile. The red line shows the temperature profile for fluid in the pipe and annulus and blue line shows the surrounding temperature profile. As can be seen from the figure, fluid temperature followed surrounding temperature in the tubing and the annulus. There was not a significant temperature drop observed at the nozzle for this condition. Selected output results for all other flow rate data are given in Appendix A.



Figure 3: Pressure vs Depth (N<sub>2</sub> Only, CT:1.25", H.S:2.25", Q=5 gpm)



Figure 4: Temperature vs. Depth (N<sub>2</sub> Only, CT:1.25", H.S:2.25", Q=5 gpm)

Figure 5 is the mixture velocity profile in annulus for 1.25" coiled tubing and 2.25" hole size combination for all nitrogen flow rates. As can be seen from the graph, due to the expansion of gas phase nitrogen in the annulus, mixture velocity shows increase while reaching surface. Due to the 4" surface pipe for the first 500 ft, mixture velocity decreases in the larger annulus.



Figure 5: Mixture Velocity Profile for N<sub>2</sub> (CT:1.25"-HS:2.25", N<sub>2</sub> Only)

#### 2.2 Nitrogen with Water Addition Cases

In this part, results are given for nitrogen with water addition cases. Nitrogen was injected with different flow rates of water to create the operational envelope and to analyze the injection pressure profile for nitrogen. For nitrogen with water cases, input pressure drop at the nozzle was fixed to 5000 psi.

Figure 6 gives the operational envelope for nitrogen with water addition using 1.25" coiled tubing and a 2.25" bore hole size.

Run points at the right of the erosion line shows the conditions which maximum mixture velocity in the annulus exceeds the set erosion velocity (1800 ft/min).

Figure 7 is the injection pressure profile of nitrogen with water addition runs. Numbers near the run points indicate injected amount of water flow rate (gpm) at that condition. As can be seen from the graph, increasing nitrogen flow rate increased the needed injection pressure for the operation. Due to the density difference between nitrogen and water, significant amount of hydrostatic pressure losses were calculated at the surface coiled tubing facility. Amount of frictional and hydrostatic pressure losses are given in Appendix B.



Figure 6: Operational Envelope for N<sub>2</sub> (CT:1.25"-HS:2.25", With Water Addition)



Figure 7: Flow Rate vs. Inj. Pressure for N<sub>2</sub> (CT:1.25"-HS:2.25", With Water Addition)

Example pressure and temperature profile graphs for nitrogen with water additions are given for the nitrogen flow rate of 7 gpm and water flow rate of 1 gpm in Figure 8 and 9, respectively. As can be seen in Figure 8, the pressure drop of 5000 psi occurs at the nozzle. Also due to the surface coiled tubing facility, 493 psi total pressure drop occurred at the surface. Pressure outputs are given in Table 3.

Table 3: Output Pressure Values (N<sub>2</sub> with Water Addition,  $Q_{N2}=7$  gpm,  $Q_w=1$ gpm)

Injection Pressure (psia)	4387
BHP Upstream Nozzle (psia)	6956
BHP Downstream Nozzle (psia)	1956

Figure 9 is the temperature profile of the fluid inside the tubing and annulus (red line) with the formation temperature profile (blue line). As can be seen from the figure, temperature dropped occurred at the nozzle for nitrogen with water addition case. Selected output results for all flow rates are given in Appendix A.

Figure 10 shows mixture velocity profile in the tubing and annulus. As seen from the graph, mixture velocity in the annulus increases while reaching surface and due to the 4'' surface pipe, mixture velocity showed a sudden decline at 500 ft depth.



Figure 8: Pressure vs Depth (N<sub>2</sub> with Water, CT:1.25", H.S:2.25")



Figure 9: Temperature vs. Depth (N<sub>2</sub> With Water, CT:1.25", H.S:2.25")



Figure 10: Velocity Profile (N<sub>2</sub> with Water, CT:1.25", H.S:2.25")

#### 3. Simulations with Different Casing and Cutting Sizes

In this part, simulation results are given for wells with different size of casings. Also, different size of cuttings was used to analyze cutting transport ratio in the annulus. For these simulations, well's first 19,000 ft was designed with different size of casings and then last 1,000 ft of the well was drilled with 1.25'' coiled tubing which has 2.25'' hole size. Size of casing and cuttings used for the simulations are shown in Table 4.

Casing Sizes	Cutting Sizes
( <b>in</b> )	(micron)
3	25
4	50
5	75
7	100

Table 4: Casing and Cutting Sizes

In this part, pressure drop at the nozzle was fixed to 8,000 psi for all runs. For 3" casing runs, nitrogen was injected with and without water addition. For the other casing sizes, simulations were made with nitrogen only conditions.

#### 3.1 3" Casing Size

Runs were started with the well designed with 3" casing for the first 19,000 ft. 1.25" coiled tubing was used to drill the well with 2.25" hole size for the last 1,000 ft. Runs started with injecting only nitrogen into the system. Then, for water addition cases, different amount of water was injected into the system with nitrogen.

### 3.1.1 Casing Size: 3" (Nitrogen Only)

Figure 11 shows operational envelope for nitrogen only case runs. Run points at the right of the erosion line shows the conditions which maximum mixture velocity in the annulus exceeds the set erosion velocity (1800 ft/min).

Figure 12 is the injection pressure profile for different nitrogen flow rates. As can be seen from the graph, increasing nitrogen flow rate increased needed injection pressure up to 5816 psia.



Figure 11: Operational Envelope for N2 (3" Casing, N2 Only)



Figure 12: Flow Rate vs. Inj. Pressure for N2 (3" Casing, N2 Only)

Example pressure and temperature profile graphs for 7 gpm nitrogen injection rate are given in Figure 13 and 14, respectively. As can be seen in Figure 13, the pressure drop of 8000 psi occurs at the nozzle. Also due to the surface coiled tubing facility, 130 psi total pressure drop occurs at the surface. Pressure outputs are given in Table 5.

Table 5: Output Pressure Values (N<sub>2</sub> Only, 3'' Casing, Q<sub>N2</sub>=7 gpm)

Injection Pressure (psia)	5565
BHP Upstream Nozzle (psia)	8312
BHP Downstream Nozzle (psia)	312

Figure 14 is the temperature profile of the fluid inside the tubing and annulus (red line) with the formation temperature profile (blue line). Similar to first part's nitrogen only cases, temperature drop at the nozzle is not significant. Selected output results for all flow rates are given in Appendix A.

Figure 15 shows mixture velocity profile in the annulus for all flow rates. As seen from the graph, mixture velocity decreases at 19,000 ft due to the beginning of 3'' casing.



Figure 13: Pressure vs Depth (N<sub>2</sub> Only, 3" Casing)



Figure 14: Temperature vs. Depth (N<sub>2</sub> Only, 3" Casing)



Figure 15: Velocity Profile (N<sub>2</sub> Only, 3" Casing)

#### **3.1.2 Casing Size: 3'' (Nitrogen with Water Addition)**

In this part, results are given for nitrogen with water addition cases for the well with 3" casing for the first 19,000 ft. Figure 16 gives the operational envelope for nitrogen with water addition. Run points at the right of the erosion line shows the conditions which maximum mixture velocity in the annulus exceeds the set erosion velocity (1800 ft/min).

Figure 17 is the injection pressure profile of nitrogen with water addition runs. Numbers near the run points indicate injected amount of water flow rate (gpm) at that condition. As can be seen from the graph, increasing nitrogen flow rate increased the needed injection pressure for the operation.



Figure 16: Operational Envelope for N<sub>2</sub> (3" Casing, With Water Addition)



Figure 17: Flow Rate vs. Inj. Pressure for N<sub>2</sub> (3" Casing, With Water Addition)

Example pressure and temperature profiles are given for 7 gpm nitrogen and 1 gpm water rate in Figure 18 and 19. As can be seen from the Figure 18, pressure drop of 8,000 psi occurs at the nozzle. Also due to the surface coiled tubing facility, 575 psi pressure loss occurred at the surface. Pressure outputs are given in Table 6.

Table 6: Output Pressure Values (N<sub>2</sub> With Water Addition, 3'', Q<sub>N2</sub>=7 gpm, Q<sub>w</sub>=1 gpm)

Injection Pressure (psia)	5613
BHP Upstream Nozzle (psia)	8493
BHP Downstream Nozzle (psia)	493

Figure 19 is the temperature profile of the fluid inside the tubing and annulus (red line ) with the formation temperature profile (blue line). As can be seen from the figure, temperature drop occurred at the nozzle for nitrogen with water addition condition. Selected output results for all flow rates are given in Appendix A.

Figure 20 shows mixture velocity profile in the tubing and annulus. Larger annulus resulted in a sudden decrease of mixture velocity in the annulus at 19,000 ft and then mixture velocity increases while reaching surface.



Figure 18: Pressure vs Depth (N<sub>2</sub> with Water Addition, 3" Casing)



Figure 19: Temperature vs. Depth (N<sub>2</sub> with Water Addition, 3" Casing)



Figure 20: Velocity Profile (N<sub>2</sub> with Water Addition, 3" Casing)

### 3.2 Different Casing Sizes: 4, 5 and 7" (Nitrogen Only)

In this section, the operational envelopes and injection pressure profiles are given for different casing sizes for nitrogen only injection cases. Casing sizes used for these simulations are 4, 5 and 7''.

Increasing casing size decreased the needed injection pressure to ensure the operation. In the next section, effect of casing size on cutting transport efficiency with different casing sizes will be analyzed.



Figure 21: Operational Envelope for N2 (4" Casing, Nitrogen Only)



Figure 22: Flow Rate vs. Inj. Pressure for N<sub>2</sub> (4" Casing, Nitrogen Only)



Figure 23: Operational Envelope for N<sub>2</sub> (5" Casing, Nitrogen Only)



Figure 24: Flow Rate vs. Inj. Pressure for N2 (5" Casing, Nitrogen Only)



Figure 25: Operational Envelope for N<sub>2</sub> (7" Casing, Nitrogen Only)



Figure 26: Flow Rate vs. Inj. Pressure for N2 (7" Casing, Nitrogen Only)

#### **3.3 Cutting Transport Analysis**

In this part, cutting transport analysis is made for different casing sizes used for the first 19,000 ft. Cutting sizes used for these simulations are; 25, 50, 75 and 100 micron.

Figure 27 through 30 shows cutting transport ratios for different casing and cutting sizes for 3, 5, 7 and 10 gpm nitrogen injection rates.

WellFlo notes for drilling applications propose that a fluid can be considered to provide adequate hole cleaning if the minimum value of the CTR is found to be:

- Greater than 0.55 for vertical sections
- Greater than 0.9 for horizontal sections

It needs to be noted, for gas drilling applications; further attention needs to be paid for cutting transport ratio analysis.

In Figure 27, nitrogen injection rate is 3 gpm. As can be seen from the graph, increasing casing size to 7" and cutting size to 100 micron made cutting transport ratio less than zero.

As expected, increasing nitrogen flow rates increased cutting transport ratio which are shown from Figure 28 to 30.



Figure 27: CTR vs. Casing ID (Nitrogen Only, Q<sub>N2</sub>=3 gpm)



Figure 28: CTR vs. Casing ID (Nitrogen Only, Q<sub>N2</sub>=5 gpm)


Figure 29: CTR vs. Casing ID (Nitrogen Only, Q<sub>N2</sub>=7 gpm)



Figure 30: CTR vs. Casing ID (Nitrogen Only, Q<sub>N2</sub>=10 gpm)

#### 4. Simulations with Different Casing and Cutting Sizes (Deviated Wells)

In this section, simulations were made for the wells which have 30° deviations from vertical path after 19,000 ft (kick of point) of the well. Different sizes of casings used for the first 18,000 ft (vertical section). Then, in deviated section, 2,000 ft were drilled with 1.25'' coiled tubing which has 2.25'' hole size. Also, similar to vertical drilling with different size of casings, four different cutting sizes were used for the simulations to analyze cutting transport ratios in the annulus.

In this part, pressure drop at the nozzle was fixed to 8,000 psi for all runs. For 3" casing runs, nitrogen was injected into the system with and without water addition conditions. For the other casing sizes, simulations were made with nitrogen only conditions.

#### 4.1 3" Casing Size (Deviated Well)

Runs were started with simulating deviated wells designed with 3" casing as explained above. For the first case, only nitrogen was injected to the well and for the second case different amount of water was injected to the well with nitrogen.

## 4.1.1 Casing Size: 3" (N<sub>2</sub> Only, Deviated Well)

Figure 31 shows operational envelope for nitrogen only case runs. Run points at the right of the erosion line shows the conditions which maximum mixture velocity in the annulus exceeds the set erosion velocity (1800 ft/min).

Figure 32 is the injection pressure profile for different nitrogen flow rates. As can be seen from the graph, increasing nitrogen flow rate increased needed injection pressure up to 5823 psia.



Figure 31: Operational Envelope for N<sub>2</sub> (3" Casing, N<sub>2</sub> Only, Deviated Well)



Figure 32: Flow Rate vs. Inj. Pressure for  $N_2$  (3" Casing,  $N_2$  Only, Deviated Well)

Example pressure and temperature profile graphs for 7 gpm nitrogen injection rate are given in Figure 31 and 32, respectively. As can be seen in Figure 31, the pressure drop of 8000 psi occurs at the nozzle. Also due to the surface coiled tubing facility, 132 psi total pressure drop occurred at the surface. Pressure outputs are given in Table 7.

Table 7: Output Pressure Values (N<sub>2</sub> Only, 3" Casing, Q<sub>N2</sub>=7 gpm, Deviated Well)

Injection Pressure (psia)	5487
BHP Upstream Nozzle (psia)	8342
BHP Downstream Nozzle (psia)	342

Figure 32 is the temperature profile of the fluid inside the tubing and annulus (red line) with the formation temperature profile (blue line). Selected output results for all flow rates are given in Appendix A.

Figure 33 shows mixture velocity profile in the annulus for all nitrogen flow rates. As seen from the graph, mixture velocities in the annulus decreased at 18,000 ft due to

the beginning of 3" casing and then started to increase while reaching surface.



Figure 33: Pressure vs Depth (N<sub>2</sub> Only, 3" Casing, Deviated Well)



Figure 34: Temperature vs. Depth (N<sub>2</sub> Only, 3" Casing, Deviated Well)



Figure 35: Velocity Profile (N<sub>2</sub> Only, 3" Casing, Deviated Well)

#### 4.1.2 Casing Size: 3" (Nitrogen with Water Addition, Deviated Well)

In this part, results are given for nitrogen with water addition cases for the deviated wells with 3" casing at the first 18,000 ft. Figure 34 gives the operational envelope for nitrogen with water addition case. Run points at the right of the erosion line shows the conditions which maximum mixture velocity in the annulus exceeds the set erosion velocity (1800 ft/min).

Figure 35 is the injection pressure profile of nitrogen with water addition runs. Numbers near the run points indicate injected amount of water flow rate (gpm) at that condition. As can be seen from the graph, increasing nitrogen flow rate increased the needed injection pressure for the operation.



Figure 36: Operational Envelope for N<sub>2</sub> (3" Casing, With Water, Deviated Well)



Figure 37: Flow Rate vs. Inj. Pressure for N2 (3" Casing, With Water, Deviated Well)

Example pressure and temperature profiles are given for 7 gpm nitrogen and 1 gpm water rate in Figures 36 and 37. As can be seen from the Figure 36, the pressure drop of 8,000 psi occurs at the nozzle. Also due to the surface coiled tubing facility, 575 psi pressure loss occurred at the surface. Pressure outputs are given in Table 8.

Table 8: Output Pressure Values (N<sub>2</sub> with Water Add., 3" Casing,  $Q_{N2}=7$  gpm,  $Q_w=1$  gpm, Deviated Well)

Injection Pressure (psia)	5589
BHP Upstream Nozzle (psia)	8622
BHP Downstream Nozzle (psia)	622

Figure 37 is the temperature profile of the fluid inside the tubing and annulus (red line ) with the formation temperature profile (blue line). As can be seen from the figure, temperature drop occurred at the nozzle for nitrogen with water addition condition. Selected output results for all flow rates are given in Appendix A.

Figure 38 shows mixture velocity profile in the tubing and annulus. Larger annulus resulted in a sudden decrease of mixture velocity in the annulus at 18,000 ft and then mixture velocity increases while reaching surface.



Figure 38: Pressure vs Depth (N<sub>2</sub> with Water, 3" Casing, Deviated Well)



Figure 39: Temperature vs. Depth (N<sub>2</sub> with Water, 3" Casing, Deviated Well)



Figure 40: Velocity Profile (N<sub>2</sub> with Water, 3" Casing, Deviated Well)

## 4.2 Different Cases Sizes: 4", 5" and 7" (Deviated Well)

In this section, the operational envelopes and injection pressure profiles are given for different casing sizes for nitrogen only injection cases. Casing sizes used for these simulations are 4, 5 and 7''.

Increasing casing size decreased the needed injection pressure to ensure the operation. In the next section, effect of casing size on cutting transport efficiency will be analyzed.



Figure 41: Operational Envelope for N<sub>2</sub> (N<sub>2</sub> Only, 4" Casing, Deviated Well)



Figure 42: Flow Rate vs. Inj. Pressure for N<sub>2</sub> (N<sub>2</sub> Only, 4" Casing, Deviated Well)



Figure 43: Operational Envelope for N2 (N2 Only, 5" Casing, Deviated Well)



Figure 44: Flow Rate vs. Inj. Pressure for N<sub>2</sub> (N<sub>2</sub> Only, 5" Casing, Deviated Well)



Figure 45: Operational Envelope for N2 (N2 Only, 7" Casing, Deviated Well)



Figure 46: Flow Rate vs. Inj. Pressure for N2 (N2 Only, 7" Casing, Deviated Well)

## **4.3 Cutting Transport Analysis (Deviated Well)**

In this part, cutting transport ratios are compared for different casing and cutting sizes. Cutting sizes used for these simulations are; 25, 50, 75 and 100 micron.

Figure 45 through 47 shows cutting transport ratios for different casing and cutting sizes for 3, 5 and 7 gpm nitrogen injection rates.

In Figure 45, nitrogen injection rate is 3 gpm. As can be seen from the graph, increasing casing size to 7" and cutting size to 100 micron made cutting transport ratio less than zero.

As expected increasing nitrogen flow rates increased cutting transport ratio which are shown from Figure 28 to 30.



Figure 47: CTR vs. Casing ID (Nitrogen Only, Q<sub>N2</sub>=3 gpm, Deviated Well)



Figure 48: CTR vs. Casing ID (Nitrogen Only, Q<sub>N2</sub>=5 gpm, Deviated Well)



Figure 49: CTR vs. Casing ID (Nitrogen Only, Q<sub>N2</sub>=7 gpm, Deviated Well)

#### 5. CONCLUSIONS

Simulations of drilling operation with supercritical fluid;  $N_2$  has been carried out utilizing WellFlo Version 8.0.13 for 20,000 ft. wells. The following specific outcomes have been accomplished in this report for the topic studied. Important output results for the software runs are given in Appendix A and B.

#### Simulations with 1.25" Coiled Tubing-2.25" Hole Size

In these simulations, 4" surface pipe for the first 500 ft to drill 20,000 ft wells. Supercritical nitrogen was injected into the system for two different cases: 1) Nitrogen Only 2) Nitrogen with Water Addition

- 1. Nitrogen without Water Addition Cases:
  - Only Nitrogen was injected into the system with 75 °F initial temperature and 7,500 psi pressure drop set as an input to keep the nitrogen in supercritical liquid state in the tubing.
  - Nitrogen phase in the tubing was liquid in the tubing and all the liquid phase changed to gas phase in the annulus.
  - Operational envelope, temperature and pressure profiles were created.
  - Operational envelopes were created based on erosion velocity which is set at 1800 ft/min maximum mixture velocity (anywhere in the annulus).
  - Needed injection pressure increased with increasing flow rate.
  - There was not significant temperature drop occurred around the nozzle.

- 4" surface pipe for the first 500 ft in the well decreased the mixture velocity in the annulus while the fluid reaching surface.
- 2. Nitrogen with Water Addition Cases:
  - Different amounts of water were injected with nitrogen.
  - Pressure drop at the nozzle fixed to 5,000 psi for nitrogen with water addition runs.
  - Operational envelope, temperature and pressure profiles were created.
  - Increasing injection flow rates increased the injection pressures.
  - Temperature drop across the nozzle is more than that of nitrogen only conditions.

#### **Simulations with Different Casing and Cutting Sizes**

In these simulations, different sizes of casings were used for the first 18,000 ft of the wells. Also four different cutting sizes (25-50-75 and 100 micron) were used to analyze cutting transport efficiencies in the annulus.

- Operational envelopes and pressure profiles were created for the casing sizes: 3", 4", 5 and 7".
- For 3" casing size, simulations were made both for nitrogen only and nitrogen with water conditions. For other casing sizes, simulations were made for nitrogen only conditions.
- Pressure drop at the nozzle for the simulations are 8,000 psi.
- Increasing casing sizes decreased the needed injection pressures.

- For 3" casing size; temperature drop around the nozzle is higher than that of nitrogen only condition.
- Increasing cutting and cutting sizes negatively affected the cutting transport ratio.

## Simulations with Different Casing and Cutting Sizes (Deviated Wells)

Simulations were made for the wells which have 30° deviations from vertical path after 19,000 ft (kick of point) of the well. Same procedure also followed for deviated wells (using different casing and cutting sizes).

- Operational envelopes and pressure profiles were created for all casing sizes.
- 8,000 psi pressure drop was used at the nozzle.
- For 3" casing size, simulations were made both for nitrogen only and nitrogen with water conditions. For other casing sizes, simulations were made for nitrogen only conditions.
- Increasing casing and cutting sizes decreased the cutting transport ratio.

## Nomenclature

BHP	= Bottom Hole Pressure (psi)
$CO_2$	= Carbon dioxide
C.T	= Coiled Tubing
CTR	= Cutting Transport Ratio (CTR)
D. Stream	= Downstream
f.L.	= Liquid fraction (-)
$N_2$	= Nitrogen
I.D.	= Inner Diameter (inch)
Inj.	= Injection
P <sub>c</sub>	= Surface Return Choke Pressure (psia)
ROP	= Rate of Penetration (ft/hour)
Q	= Flow Rate, gpm
$Q_{\rm w}$	= Water flow Rate (gpm)
$\mathbf{Q}_{\mathrm{wi}}$	= Water Influx Flow Rate (gpm)
O.D.	= Outer Diameter (inch)
Т	= Temperature ( <sup>o</sup> F)

	Coiled Tubing O.D: 1.25 inch –Bore Hole Size: 2.25 inch- Nitrogen Only							
Q N <sub>2</sub> (gpm)	Q Water (gpm	Maximum Mixture Velocity Annulus	Mixture Velocity Annulus (ft/m)	Liquid Fraction After Nozzle	Liquid Velocity Tubing (ft/m)	Total Hydrate (%)	Solid Phase (%)	
		(ft/m)	20,000 ft	(20,000 ft)	(IUIII)			
2	-	1138	83	0	41	-	-	
3	-	1634	164	0	63	-	-	
4	-	2225	224	0	85	-	-	
5	-	2745	267	0	105	-	-	
7	-	4153	324	0	147	-	-	
10	-	5808	372	0	206	-	-	
Q N2 (gpm)	Q Water (gpm)	Injection Pressure (psi)	BHP Upstream Nozzle (psi)	BHP D. Stream Nozzle (psi)	T Upstream Nozzle (°F)	T D.Stream Nozzle (°F)	CTR (%)	
2	-	5691	8725	1225	359	361	0.956	
3	-	5486	8421	921	356	354	0.977	
4	-	5494	8394	894	355	353	0.983	
5	-	5566	8443	943	356	354	0.986	
7	-	5791	8615	1115	358	359	0.988	
10	-	6231	8931	1431	362	367	0.99	
Coi	led Tubing	g O.D: 1.25 inch	n –Bore Hole Si	ize: 2.25 inch-N	litrogen with	Water Addi	tion	
Q N2 (gpm)	Q Water (gpm	Maximum Mixture Velocity Annulus (ft/m)	Mixture Velocity Annulus (ft/m) 20 000 ft	Liquid Fraction After Nozzle (20 000 ft)	Liquid Velocity Tubing (ft/m)	Total Hydrate (%)	Solid Phase (%)	
3	1	1497	63	0.12	97	-	-	
4	1	1797	87.36	0.09	119	-	-	
4	1	1797 2505	87.36 114	0.09 0.08	119 143	-	-	
4 5 5	1 1 2	1797 2505 2240	87.36 114 99	0.09 0.08 0.16	119 143 164	- - -	- - -	
4 5 5 7	1 1 2 1	1797 2505 2240 3139	87.36 114 99 157	0.09 0.08 0.16 0.07	119 143 164 186	- - - -	- - - -	
4 5 5 7 7	1 1 2 1 2	1797 2505 2240 3139 3321	87.36 114 99 157 144	0.09 0.08 0.16 0.07 0.11	119 143 164 186 212	- - - - -	- - - -	
4 5 5 7 7 7 7	1 2 1 2 3	1797 2505 2240 3139 3321 3430	87.36 114 99 157 144 139	0.09 0.08 0.16 0.07 0.11 0.17	119 143 164 186 212 236	- - - - -	- - - - -	
4 5 7 7 7 7 10	1 2 1 2 3 1	1797 2505 2240 3139 3321 3430 4942	87.36 114 99 157 144 139 225	0.09 0.08 0.16 0.07 0.11 0.17 0.13	119 143 164 186 212 236 254	- - - - - - -	- - - - - - -	
4 5 7 7 7 7 10 10	1 2 1 2 3 1 2 2	1797 2505 2240 3139 3321 3430 4942 5213	87.36 114 99 157 144 139 225 211	0.09 0.08 0.16 0.07 0.11 0.17 0.13 0.18	119 143 164 186 212 236 254 282	- - - - - - - - -	- - - - - - - -	
4 5 7 7 7 10 10 10	1 2 1 2 3 1 2 3 3	1797 2505 2240 3139 3321 3430 4942 5213 5269	87.36 114 99 157 144 139 225 211 203	0.09 0.08 0.16 0.07 0.11 0.17 0.13 0.18 0.11	119 143 164 186 212 236 254 282 309	- - - - - - - - - - - -	- - - - - - - - - - - -	
$ \begin{array}{r}     4 \\     5 \\     5 \\     7 \\     7 \\     7 \\     10 \\     10 \\     10 \\     0 \\     0 \\     N_2 \\     (gnm) \\   \end{array} $	1 2 1 2 3 1 2 3 4 2 3 2 3 4 2 3 4 2 3 4 2 3 4 2 3 4 2 4 3 4 2 4 3 4 5 4 5 4 5 4 5 4 5 4 5 5 5 5 5 5 5	1797 2505 2240 3139 3321 3430 4942 5213 5269 Injection Pressure (nsi)	87.36 114 99 157 144 139 225 211 203 BHP Upstream Nozzle	0.09 0.08 0.16 0.07 0.11 0.17 0.13 0.13 0.18 0.11 BHP D.Stream Nozzle	119 143 164 186 212 236 254 282 309 T Upstream Nozzle	- - - - - - - T D.stream Nozzle	- - - - - - - - - - - - - - - - - - -	
4 5 7 7 7 10 10 10 10 0 <b>Q</b> N <sub>2</sub> (gpm)	1 1 2 1 2 3 1 2 3 Q Water (gpm)	1797 2505 2240 3139 3321 3430 4942 5213 5269 Injection Pressure (psi)	87.36 114 99 157 144 139 225 211 203 BHP Upstream Nozzle (psi)	0.09 0.08 0.16 0.07 0.11 0.17 0.13 0.18 0.11 BHP D.Stream Nozzle (psi)	119 143 164 186 212 236 254 282 309 T Upstream Nozzle ( <sup>0</sup> F)	- - - - - - - T D.stream Nozzle (°F)	- - - - - - - - - - - - - - - - - - -	
4 5 7 7 7 10 10 10 10 10 0 0 N <sub>2</sub> (gpm) 3	1 1 2 1 2 3 1 2 3 Vater (gpm)	1797 2505 2240 3139 3321 3430 4942 5213 5269 Injection Pressure (psi) 4663	87.36 114 99 157 144 139 225 211 203 BHP Upstream Nozzle (psi) 7619	0.09 0.08 0.16 0.07 0.11 0.17 0.13 0.18 0.11 BHP D.Stream Nozzle (psi) 2619	119 143 164 186 212 236 254 282 309 T Upstream Nozzle (°F) 340	- - - - - - - T D.stream Nozzle (°F) 336	- - - - - - - - CTR (%) 0.968	
$ \begin{array}{r}     4 \\     5 \\     7 \\     7 \\     7 \\     7 \\     7 \\     10 \\     10 \\     10 \\     10 \\     0 \\     0 \\     N_2 \\     (gpm) \\     3 \\     4 \\     5 \end{array} $	1 1 2 3 1 2 3 Vater (gpm) 1 1	1797 2505 2240 3139 3321 3430 4942 5213 5269 Injection Pressure (psi) 4663 4439	87.36 114 99 157 144 139 225 211 203 BHP Upstream Nozzle (psi) 7619 7246	0.09 0.08 0.16 0.07 0.11 0.17 0.13 0.18 0.11 BHP D.Stream Nozzle (psi) 2619 2246	119 143 164 186 212 236 254 282 309 T Upstream Nozzle (°F) 340 325	- - - - - - - T D.stream Nozzle (°F) 336 318	- - - - - - - - - - - - - - - - - - -	
$ \begin{array}{r}     4 \\     5 \\     7 \\     7 \\     7 \\     7 \\     10 \\     10 \\     10 \\     10 \\     0 \\     0 \\     0 \\     0 \\     0 \\     0 \\     10 \\     10 \\     10 \\     10 \\     3 \\     4 \\     5 $	1 1 2 3 1 2 3 Vater (gpm) 1 1 1	1797 2505 2240 3139 3321 3430 4942 5213 5269 <b>Injection</b> <b>Pressure</b> ( <b>psi</b> ) 4663 4439 4325	87.36 114 99 157 144 139 225 211 203 BHP Upstream Nozzle (psi) 7619 7246 7036	0.09 0.08 0.16 0.07 0.11 0.17 0.13 0.13 0.18 0.11 BHP D.Stream Nozzle (psi) 2619 2246 2036	119 143 164 186 212 236 254 282 309 T Upstream Nozzle (°F) 340 325 312	- - - - - - - - - - - - - - - - - - -	- - - - - - - - - - - - - - - - - - -	
$ \begin{array}{r}     4 \\     5 \\     5 \\     7 \\     7 \\     7 \\     10 \\     10 \\     10 \\     10 \\     0 \\     0 \\     0 \\     0 \\     0 \\     0 \\     10 \\     10 \\     10 \\     10 \\     10 \\     10 \\     10 \\     10 \\     10 \\     10 \\     10 \\     5 \\$	1 1 2 3 1 2 3 Vater (gpm) 1 1 1 2	1797 2505 2240 3139 3321 3430 4942 5213 5269 <b>Injection</b> <b>Pressure</b> (psi) 4663 4439 4325 4653	87.36 114 99 157 144 139 225 211 203 BHP Upstream Nozzle (psi) 7619 7246 7036 7820	0.09 0.08 0.16 0.07 0.11 0.17 0.13 0.18 0.11 BHP D.Stream Nozzle (psi) 2619 2246 2036 2820	119 143 164 186 212 236 254 282 309 T Upstream Nozzle (°F) 340 325 312 346	- - - - - - - - - - - - - - - - - - -	- - - - - - - - - - - - - - - - - - -	
$ \begin{array}{r}     4 \\     5 \\     5 \\     7 $	1 1 2 1 2 3 1 2 3 Q Water (gpm) 1 1 1 2 1 2 3 0 0 1 1 1 2 3 0 0 0 1 1 1 2 3 0 1 1 2 3 0 0 1 1 2 3 0 0 1 1 2 3 0 0 1 1 2 3 0 1 1 2 3 0 1 1 2 3 0 1 1 2 1 1 2 3 0 1 1 2 1 1 2 1 1 1 2 1 1 1 2 1 1 1 2 1 1 1 2 1 1 1 2 1 1 1 2 1 1 1 2 1 1 1 2 1 1 1 2 1 1 1 1 2 1 1 1 1 1 1 1 1 1 1 1 1 1	1797 2505 2240 3139 3321 3430 4942 5213 5269 Injection Pressure (psi) 4663 4439 4325 4653 4387	87.36 114 99 157 144 139 225 211 203 BHP Upstream Nozzle (psi) 7619 7246 7036 7820 6956	0.09 0.08 0.16 0.07 0.11 0.17 0.13 0.18 0.11 BHP D.Stream Nozzle (psi) 2619 2246 2036 2820 1956	119 143 164 186 212 236 254 282 309 T Upstream Nozzle (°F) 340 325 312 346 295	- - - - - - - - - - - - - - - - - - -	- - - - - - - - - - - - - - - - - - -	
$ \begin{array}{r}     4 \\     5 \\     5 \\     7 \\     7 \\     7 \\     7 \\     7 \\     7 \\     7 \\     7 \\     7 \\     7 \\     0 \\     10 \\     10 \\     10 \\     10 \\     10 \\     10 \\     10 \\     10 \\     10 \\     10 \\     3 \\     4 \\     5 \\     5 \\     7 \\     $	1 1 2 1 2 3 1 2 3 Q Water (gpm) 1 1 1 2 1 2 1 2 2 5	1797 2505 2240 3139 3321 3430 4942 5213 5269 Injection Pressure (psi) 4663 4439 4325 4653 4387 4690	87.36 114 99 157 144 139 225 211 203 BHP Upstream Nozzle (psi) 7619 7246 7036 7820 6956 7820	0.09 0.08 0.16 0.07 0.11 0.17 0.13 0.18 0.11 BHP D.Stream Nozzle (psi) 2619 2246 2036 2820 1956 2567	119 143 164 186 212 236 254 282 309 T Upstream Nozzle (°F) 340 325 312 340 325 312 346 295 330	- - - - - - - - T D.stream Nozzle (°F) 336 318 303 344 286 325	- - - - - - - - - - - - - - - - - - -	
$ \begin{array}{r}     4 \\     5 \\     7 $	1 1 2 1 2 3 1 2 3 <b>Q</b> <b>Water</b> (gpm) 1 1 1 2 1 2 3 <b>V</b> <b>V</b> <b>V</b> <b>V</b> <b>V</b> <b>V</b> <b>V</b> <b>V</b>	1797 2505 2240 3139 3321 3430 4942 5213 5269 Injection Pressure (psi) 4663 4439 4325 4653 4387 4690 5007	87.36 114 99 157 144 139 225 211 203 BHP Upstream Nozzle (psi) 7619 7246 7036 7820 6956 7820 6956 7567 8105	0.09 0.08 0.16 0.07 0.11 0.17 0.13 0.18 0.11 BHP D.Stream Nozzle (psi) 2619 2246 2036 2820 1956 2567 3105	119 143 164 186 212 236 254 282 309 T Upstream Nozzle (°F) 340 325 312 340 325 312 346 295 330 349	- - - - - - - - - T D.stream Nozzle (°F) 336 318 303 344 286 325 348	- - - - - - - - - - - - - - - - - - -	
$ \begin{array}{r}     4 \\     5 \\     7 \\     7 \\     7 \\     7 \\     7 \\     7 \\     7 \\     7 \\     10 \\     10 \\     10 \\     10 \\     10 \\     10 \\     10 \\     10 \\     10 \\     10 \\     10 \\     10 \\     10 \\     3 \\     4 \\     5 \\     5 \\     7 \\     7 \\     7 \\     7 \\     7 \\     7 \\     7 \\     10 $	1 1 2 3 1 2 3 Vater (gpm) 1 1 2 1 1 2 3 1 1 2 3 1 1 2 3 1 1 2 3 1 1 2 3 1 1 2 3 1 1 2 3 1 1 1 2 3 1 1 2 3 1 1 2 3 1 1 2 3 1 1 1 2 3 1 1 2 3 1 1 2 3 1 1 2 3 1 1 2 3 1 1 2 3 1 1 2 3 1 1 2 3 1 1 2 3 1 1 2 3 1 2 3 1 2 3 1 2 3 1 2 3 3 1 2 3 3 1 2 3 3 1 2 3 3 1 2 3 3 1 2 3 3 1 2 3 3 1 2 3 3 1 2 3 3 1 2 3 3 1 2 3 3 1 2 3 3 1 2 3 3 1 2 3 1 2 3 3 1 2 3 3 1 2 3 3 1 2 2 3 1 2 2 3 1 2 3 1 2 2 2 3 1 2 3 1 2 2 3 1 2 2 2 3 1 2 2 3 1 2 2 2 3 1 2 2 3 1 2 3 1 2 2 2 3 1 2 2 2 2 3 1 2 2 2 2 2 2 2 2 2 2 2 2 2	1797 2505 2240 3139 3321 3430 4942 5213 5269 <b>Injection</b> <b>Pressure</b> ( <b>psi</b> ) 4663 4439 4325 4653 4387 4690 5007 4669 4072	87.36 114 99 157 144 139 225 211 203 BHP Upstream Nozzle (psi) 7619 7246 7036 7820 6956 7567 8105 6933 7200	0.09 0.08 0.16 0.07 0.11 0.17 0.13 0.18 0.11 BHP D.Stream Nozzle (psi) 2619 2246 2036 2820 1956 2820 1956 2567 3105	119 143 164 186 212 236 254 282 309 T Upstream Nozzle ( <sup>0</sup> F) 340 325 312 346 295 330 349 278	- - - - - - - - - - - - - - - - - - -	- - - - - - - - - - - - - - - - - - -	
$ \begin{array}{r} 4 \\ 5 \\ 7 \\ 7 \\ 7 \\ 10 \\ 10 \\ 10 \\ 0 \\ 0 \\ 10 \\ 0 \\ 10 \\ 0 \\ 10 \\ 1$	1 1 2 3 1 2 3 1 2 3 Vater (gpm) 1 1 1 2 3 1 1 2 3 1 1 2 3 1 1 2 3 1 1 2 3 1 1 2 3 1 1 2 3 1 1 2 3 1 1 2 3 1 1 2 3 1 1 2 3 1 1 2 3 1 1 2 3 1 1 2 3 1 2 3 1 2 3 1 2 3 1 2 3 1 2 3 1 2 3 1 2 3 1 2 3 1 2 3 1 2 3 1 2 3 1 2 3 1 2 3 1 2 3 1 2 3 1 2 3 1 2 3 1 2 3 2 2 3 1 2 3 1 2 2 3 1 2 2 3 1 2 2 3 1 2 2 3 1 2 2 3 1 2 2 3 1 2 2 3 1 2 2 3 1 2 2 3 2 2 2 3 1 2 2 3 2 2 2 3 2 2 3 2 2 3 2 2 2 3 2 2 3 2 2 2 3 2 2 2 3 2 2 2 3 2 2 2 2 2 3 2 2 2 2 2 2 2 2 2 2 2 2 2	1797 2505 2240 3139 3321 3430 4942 5213 5269 Injection Pressure (psi) 4663 4439 4325 4653 4387 4690 5007 4669 4973 5472	87.36 114 99 157 144 139 225 211 203 BHP Upstream Nozzle (psi) 7619 7246 7036 7820 6956 7567 8105 6933 7390	0.09 0.08 0.16 0.07 0.11 0.17 0.13 0.13 0.18 0.11 <b>BHP</b> <b>D.Stream</b> <b>Nozzle</b> ( <b>psi</b> ) 2619 2246 2036 2820 1956 2820 1956 2567 3105 1933 2390	119 143 164 186 212 236 254 282 309 T Upstream Nozzle (°F) 340 325 312 346 295 330 349 278 309	- - - - - - - - - - - - - - - - - - -	- - - - - - - - - - - - - - - - - - -	

**Appendix A:** Table A-1: Output for Drilling with CT:1.25''-HS:2.25'' (Case-1)

Casing Size:3'', Nitrogen Only							
Q N <sub>2</sub> (gpm)	Q Water (gpm	Maximum Mixture Velocity Annulus	Mixture Velocity Annulus (ft/m)	Liquid Fraction After Nozzle	Liquid Velocity Tubing (ft/m)	Total Hydrate (%)	Solid Phase (%)
2		(II/M) 951	20,000 IL	(20,000 It)	62.4		
5	-	1202	766	0	106.7	-	-
7	_	2036	1088	0	1/0		_
10		3049	1311	0	213		
10		3043	1011	0	210		
Q N2	Q Water	Injection Pressure	BHP Upstream	BHP D. Stream	T Upstream	T D.Stream	CTR
(gpm)	(gpm)	(psi)	Nozzle	Nozzle	Nozzle	Nozzle	(%)
		GF	(psi)	(psi)	(°F)	(ºF)	0.070
3	-	5516	8463	463	353	347	0.976
5	-	5473	8318	318	349	341	0.99
1	-	5565	8312	312	347	339	0.993
10	-	5816	8372	312	348	340	0.995
		Coging S	izo. 2? Nitrog	n With Watan	Addition		
		Casilig 5	Mixturo	Liquid	Addition		
Q N.	Q Water	Mixture	Velocity	Fraction	Liquid Velocity	Total Hydrate	Solid Phase
(gpm)	(gpm	Annulus (ft/m)	(ft/m) 20.000 ft	Nozzle (20.000 ft)	Tubing (ft/m)	(%)	(%)
3	1	899	128	0.08	90.4	-	-
5	1	1410	379	0.01	136	-	-
5	2	1438	259.53	0.186	161	-	-
7	1	1872	574	0.08	178	-	-
7	2	1960	462	0.11	207	-	-
10	1	3134	772	0.07	244	-	-
10	2	2936	680	0.09	270	-	-
0	0	Injection	BHP	BHP	Т	Т	
	V Water	Pressure	Upstream	D.Stream	Upstream	D.stream	CTR
(gnm)	(gpm)	(nsi)	Nozzle	Nozzle	Nozzle	Nozzle	(%)
(81)	(81)	(PS2)	(psi)	(psi)	(°F)	(°F)	
3		5841	9237	1237	301	292	0.972
5	1	5519	8566	566	226	214	0.986
5	2	5618	8979	979	284	2/8	0.984
/	1	5613	8493	493	201	187	0.991
/	2	5651	8701	/01	246	238	0.995
10	1	5926	8521	521	185	169	0.993
10	2	5999	8651	651	222	213	0.992

Table A-2: Output for Simulations with Different Casing and Cutting Sizes

|--|

	Casing Size: 4"							
Q N <sub>2</sub> (gpm)	Q Water (gpm	Maximum Mixture Velocity Annulus (ft/m)	Mixture Velocity Annulus (ft/m) 20,000 ft	Liquid Fraction After Nozzle (20,000 ft)	Liquid Velocity Tubing (ft/m)	Total Hydrate (%)	Solid Phase (%)	
3	-	383	351	0	63.71	-	-	
5	-	760.18	935.86	0	107.33	-	-	
7	-	1827	1377	0	149	-	-	
10	-	2752	1714	0	215	-	-	
Q N2 (gpm)	Q Water (gpm)	Injection Pressure (psi)	BHP Upstream Nozzle (psi)	BHP D. Stream Nozzle (psi)	T Upstream Nozzle (°F)	T D.Stream Nozzle (°F)	CTR (%)	
3	-	5483	8420	420	352	346	0.959	
5	-	5430	8259	259	348	339	0.985	
7	-	5516	8246	246	347	337	0.991	
10	-	5756	8287	287	345	336	0.994	
			Casing	Size:5"				
Q N <sub>2</sub> (gpm)	Q Water (gpm	Maximum Mixture Velocity Annulus (ft/m)	Mixture Velocity Annulus (ft/m) 20,000 ft	Liquid Fraction After Nozzle (20,000 ft)	Liquid Velocity Tubing (ft/m)	Total Hydrate (%)	Solid Phase (%)	
3	-	382	350	0	63.73	-	-	
5	-	1088	936	0	107	-	-	
7	-	1911	1443	0	150	-	-	
10	-	3247	1825	0	215	-	-	
Q N2 (gpm)	Q Water (gpm)	Injection Pressure (psi)	BHP Upstream Nozzle (psi)	BHP D.Stream Nozzle (psi)	T Upstream Nozzle (°F)	T D.stream Nozzle (°F)	CTR (%)	
3	-	5483	8420	420	352	346	0.933	
5	-	5430	8260	260	350	341	0.976	
7	-	5508	8235	235	347	337	0.986	
10	-	5743	8269	269	345	335	0.992	

	Casing Size:7"								
Q N <sub>2</sub> (gpm)	Q Water (gpm	Maximum Mixture Velocity Annulus (ft/m)	Mixture Velocity Annulus (ft/m) 20,000 ft	Liquid Fraction After Nozzle (20,000 ft)	Liquid Velocity Tubing (ft/m)	Total Hydrate (%)	Solid Phase (%)		
3	-	378	347	0	63	-	-		
5	-	1185	1003	0	107	-	-		
7	-	2058	1471	0	150	-	-		
10	-	3498	1870	0	215	-	-		
Q N2 (gpm)	Q Water (gpm)	Injection Pressure (psi)	BHP Upstream Nozzle (psi)	BHP D. Stream Nozzle (psi)	T Upstream Nozzle (°F)	T D.Stream Nozzle (°F)	CTR (%)		
3	-	5486	8425	425	353	346	0.863		
5	-	5417	8242	242	350	341	0.956		
7	-	5504	8230	230	346	336	0.974		
10	-	5738	8263	263	345	335	0.985		

Table A-2: Continuation

Casing Size:3'', Nitrogen Only							
		Maximum	Mixture	Liquid	Liquid	Total	
Q	Q	Mixture	Velocity	Fraction	Liquia Valeeiter	10tai Uruduoto	Solid
$N_2$	Water	Velocity	Annulus	After	v elocity	Hydrate	Phase
(gpm)	(gpm	Annulus	(ft/m)	Nozzle	I ubing	(%)	(%)
		(ft/m)	20,000 ft	(20,000 ft)	(11/m)		
3	-	883	303	0	64	-	-
4	-	1174	511	0	86	-	-
5	-	1455	673	0	108	-	-
6	-	1700	781	0	128	-	-
7	-	1959	856	0	149	-	-
10	-	2933	990	0	213	-	-
0	0	Injection	BHP	BHP	T	T	
N2	Water	Pressure	Upstream	D. Stream	Upstream	D.Stream	CTR
(gpm)	(gnm)	(nsi)	Nozzle	Nozzle	Nozzle	Nozzle	(%)
(SPIII)	(SPIII)	(PSI)	(psi)	(psi)	( <b>°</b> F)	( <b>°</b> F)	
3	-	5439	8501	501	371	368	0.978
4	-	5390	8393	393	369	365	0.987
5	-	5413	8372	372	368	363	0.991
6	-	5467	8365	385	368	363	0.992
1	-	5537	8410	410	368	364	0.993
10	-	5828	8520	520	369	366	0.995
		Casing S	Size:3", Nitrog	en with Water	Addition		
•	0	Maximum	Mixture	Liquid	Liquid	Total	G 11 1
Q	Q	Mixture	velocity	Fraction	Velocity	Hvdrate	Solid
N <sub>2</sub>	Water	Velocity	Annulus	After	Tubing	(%)	Phase
(gpm)	(gpm	Annulus	(ft/m)	Nozzle	(ft/m)		(%)
2	1	(II/M) 800	20,000 It	(20,000 It)	01		
3	1	099	119	0.09	91	-	-
5	2 1	000	93	0.16	113	-	-
5	1	1400	329	0.06	157	-	-
7	1	2127	400	0.00	178	-	-
7	2	1088	380	0.00	207		-
10	1	3225	627	0.07	207		
10	2	3151	519	0.03	268		_
10	~	0101	010	0.07	200		
	<u> </u>		BHP	BHP	Т	Т	
Q	Q	Injection	Upstream	D.Stream	Upstream	D.stream	CTR
$N_2$	Water	Pressure	Nozzle	Nozzle	Nozzle	Nozzle	(%)
(gpm)	(gpm)	(psi)	(psi)	(psi)	(°F)	(°F)	(70)
3	1	5776	9359	1359	311	302	0.974
3	1	6069	10243	2243	363	362	0.968
5	1	5466	8672	672	241	229	0.987
6	2	5514	8629	629	228	215	0.99
7	1	5589	8622	622	220	206	0.992
7	2	5652	8891	891	266	257	0.99
10	3	5927	8668	668	205	190	0.994
10	1	6062	8002	902	249	239	0 993
		0002	0302	502	245	200	0.000
		0002	0302	502	243	200	0.000

Table A-3: Output for Drilling 20,000 ft (Different Casing Sizes, Deviated Well)

Table A-3:	Continuation
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Casing Size:4"							
Q N <sub>2</sub> (gpm)	Q Water (gpm	Maximum Mixture Velocity Annulus (ft/m)	Mixture Velocity Annulus (ft/m) 20,000 ft	Liquid Fraction After Nozzle (20,000 ft)	Liquid Velocity Tubing (ft/m)	Total Hydrate (%)	Solid Phase (%)
3	-	407	321	0	64	-	-
4	-	755	566	0	86	-	-
5	-	1163	774	0	108	-	-
6	-	1491	893	0	129	-	-
7	-	1875	985	0	150	-	-
10	-	2998	1124	0	214	-	-
Q N2 (gpm)	Q Water (gpm)	Injection Pressure (psi)	BHP Upstream Nozzle (nsi)	BHP D. Stream Nozzle (nsi)	T Upstream Nozzle (°F)	T D.Stream Nozzle (°F)	CTR (%)
3	-	5417	8471	471	371	368	0.96
4	-	5362	8354	354	368	364	0.978
5	-	5376	8323	323	368	362	0.986
6	-	5431	8336	336	367	362	0.989
7	-	5498	8356	356	367	362	0.991
10	-	5783	8455	455	368	364	0.994
			Casing	Size:5"	•	•	•
Q N2 (gpm)	Q Water (gpm	Maximum Mixture Velocity Annulus (ft/m)	Mixture Velocity Annulus (ft/m) 20,000 ft	Liquid Fraction After Nozzle (20,000 ft)	Liquid Velocity Tubing (ft/m)	Total Hydrate (%)	Solid Phase (%)
3	-	423	333	0	64	-	-
4	-	802	592	0	86.5	-	-
5	-	1158	772	0	108	-	-
6	-	1562	911	0	129	-	-
7	-	1995	1005	0	150	-	-
10	-	3403	1144	0	214	-	-
Q N <sub>2</sub> (gpm)	Q Water (gpm)	Injection Pressure (psi)	BHP Upstream Nozzle (nsi)	BHP D.Stream Nozzle (nsi)	T Upstream Nozzle (°F)	T D.stream Nozzle (°F)	CTR (%)
3	-	5405	8454	454	371	367	0.938
4	-	5350	8338	338	369	364	0.967
5	-	5377	8324	324	368	362	0.977
6	-	5426	8329	329	367	362	0.983
7	-	5493	8349	349	367	362	0.986
10	-	5777	8446	446	367	364	0.992

Casing Size:7"								
Q N <sub>2</sub> (gpm)	Q Water (gpm	Maximum Mixture Velocity Annulus (ft/m)	Mixture Velocity Annulus (ft/m) 10,000 ft	Liquid Fraction After Nozzle (10,000 ft)	Liquid Velocity Tubing (ft/m)	Total Hydrate (%)	Solid Phase (%)	
3	-	421	332	0	64	-	-	
4	-	796	589	0	86	-	-	
5	-	1148	768	0	108	-	-	
6	-	1684	937	0	129	-	-	
7	-	2123	1023	0	150	-	-	
10	-	3609	1152	0	214	-	-	
Q N2 (gpm)	Q Water (gpm)	Injection Pressure (psi)	BHP Upstream Nozzle (psi)	BHP D. Stream Nozzle (psi)	T Upstream Nozzle (°F)	T D.Stream Nozzle (°F)	CTR (%)	
3	-	5405	8456	456	371	367	0.875	
4	-	5350	8340	340	369	363	0.933	
5	-	5377	8325	325	368	363	0.953	
6	-	5418	8319	319	367	361	0.968	
7	-	5487	8342	342	367	361	0.974	
10	-	5774	8443	443	367	363	0.985	

Table A-3: Continuation

# Appendix B

Table B-1: Total Pressure Losses at Surface Coiled Tubing Unit (CT:1.25-HS:2.25'')

Coiled Tubing O.D: 1.25 inch –Bore Hole Size: 2.25 inch, N <sub>2</sub> Only							
Q	Q	Frictional	Hydrostatic	Total Drag Loga			
N2	Water	Pres. Loss	Pres. Loss	10tal Pres. Loss			
(gpm)	(gpm)	(psi/ft)	(psi/ft)	(psi/it)			
2	-	11.3	0.4	11.8			
3	-	25.2	0.5	25.7			
4	-	44	0.4	44.4			
5	-	67.3	0.5	67.8			
7	-	131	0.4	131.4			
10	-	261.7	0.5	262.2			
Coi	Coiled Tubing O.D: 1.25 inch –Bore Hole Size: 2.25 inch,						
	$N_2$ with Water Addition						
Q	Q	Frictional	Hydrostatic	Total Drog Loga			
Q N2	Q Water	Frictional Pres. Loss	Hydrostatic Pres. Loss	Total Pres. Loss			
Q N2 (gpm)	Q Water (gpm)	Frictional Pres. Loss (psi/ft)	Hydrostatic Pres. Loss (psi/ft)	Total Pres. Loss (psi/ft)			
Q N2 (gpm) 3	Q Water (gpm) 1	Frictional Pres. Loss (psi/ft) 278	Hydrostatic Pres. Loss (psi/ft) 662	Total Pres. Loss (psi/ft) 940			
Q N2 (gpm) 3 4	Q Water (gpm) 1 1	Frictional Pres. Loss (psi/ft) 278 313	Hydrostatic Pres. Loss (psi/ft) 662 439	Total Pres. Loss (psi/ft) 940 752			
Q N2 (gpm) 3 4 5	Q Water (gpm) 1 1 1	Frictional Pres. Loss (psi/ft) 278 313 345	Hydrostatic Pres. Loss (psi/ft) 662 439 260	<b>Total Pres. Loss</b> (psi/ft) 940 752 606			
Q (gpm) 3 4 5 5	Q Water (gpm) 1 1 1 2	Frictional Pres. Loss (psi/ft) 278 313 345 507	Hydrostatic Pres. Loss (psi/ft) 662 439 260 428	Total Pres. Loss (psi/ft) 940 752 606 936			
Q (gpm) 3 4 5 5 7	Q Water (gpm) 1 1 1 2 1	Frictional Pres. Loss (psi/ft) 278 313 345 507 402	Hydrostatic Pres. Loss (psi/ft) 662 439 260 428 92	Total Pres. Loss (psi/ft) 940 752 606 936 494			
Q (gpm) 3 4 5 5 7 7 7	Q Water (gpm) 1 1 2 1 2 2	Frictional Pres. Loss (psi/ft) 278 313 345 507 402 604	Hydrostatic Pres. Loss (psi/ft) 662 439 260 428 92 157	Total Pres. Loss (psi/ft) 940 752 606 936 494 761			
Q (gpm) 3 4 5 5 7 7 7 7	Q Water (gpm) 1 1 1 2 1 2 3	Frictional Pres. Loss (psi/ft) 278 313 345 507 402 604 787	Hydrostatic Pres. Loss (psi/ft) 662 439 260 428 92 157 199	<b>Total Pres. Loss</b> (psi/ft) 940 752 606 936 494 761 987			
Q N2 (gpm) 3 4 5 5 7 7 7 7 7 10	Q Water (gpm) 1 1 2 1 2 3 3 1	Frictional Pres. Loss (psi/ft) 278 313 345 507 402 604 787 520	Hydrostatic Pres. Loss (psi/ft) 662 439 260 428 92 157 199 16	<b>Total Pres. Loss</b> (psi/ft) 940 752 606 936 494 761 987 536			
Q N2 (gpm) 3 4 5 5 7 7 7 7 7 7 10 10	Q Water (gpm) 1 1 2 1 2 3 3 1 2	Frictional Pres. Loss (psi/ft) 278 313 345 507 402 604 787 520 752	Hydrostatic Pres. Loss (psi/ft) 662 439 260 428 92 157 199 16 35	Total Pres. Loss (psi/ft) 940 752 606 936 494 761 987 536 787			
Q N2 (gpm) 3 4 5 5 7 7 7 7 7 7 10 10 10	Q Water (gpm) 1 1 2 1 2 3 3 1 2 3 3	Frictional Pres. Loss (psi/ft) 278 313 345 507 402 604 787 520 752 999	Hydrostatic Pres. Loss (psi/ft) 662 439 260 428 92 157 199 16 35 51	Total Pres. Loss (psi/ft) 940 752 606 936 936 494 761 987 536 787 1050			

Casing Size:3", Nitrogen Only						
Q	Q	Frictional	Hydrostatic	Total Pres.		
N2	Water	Pres. Loss	Pres. Loss	Loss		
(gpm)	(gpm)	(psi/ft)	(psi/ft)	(psi/ft)		
3	-	25	0.4	25.4		
5	-	68.1	0.4	68.5		
7	-	130.4	0.4	130.8		
10	265.8					
Casing Size:3", Nitrogen with Water Addition						
Q	Q	Frictional	Hydrostatic	Total Pres.		
N2	Water	Pres. Loss	Pres. Loss	Loss		
(gpm)	(gpm)	(psi/ft)	(psi/ft)	(psi/ft)		
3	1	256.3	644	900.4		
5	1	343.7	318	661.6		
5	2	499.5	464.5	964		
7	1	428.2	147.6	575.8		
7	2	623.1	217.2	840.4		
10	1	575.2	32.8	608.1		
10	2	797.4	62.3	859.8		
Casing Size:4"						
Q	Q	Frictional	Hydrostatic	Total Pres.		
N2	Water	Proc Loss	Pres Loss	Loss		
1 1 4	water	11C5. L055	1103. 2035	1000		
(gpm)	(gpm)	(psi/ft)	(psi/ft)	(psi/ft)		
(gpm) 3	(gpm)	(psi/ft) 25.2	(psi/ft) 0.4	(psi/ft) 25.6		
(gpm) 3 5	(gpm) -	(psi/ft) 25.2 68.5	(psi/ft) 0.4 0.4	(psi/ft) 25.6 68.9		
(gpm) 3 5 7	(gpm) - - -	(psi/ft) 25.2 68.5 131.2	(psi/ft) 0.4 0.4 0.4	(psi/ft) 25.6 68.9 131.6		
(gpm) 3 5 7 10	(gpm) - - - -	(psi/ft) 25.2 68.5 131.2 267.3	(psi/ft) 0.4 0.4 0.4 0.4 0.4	(psi/ft) 25.6 68.9 131.6 267.7		
(gpm) 3 5 7 10	(gpm) - - - -	(psi/ft) 25.2 68.5 131.2 267.3 Casing S	(psi/ft) 0.4 0.4 0.4 0.4 0.4 ize:5''	(psi/ft) 25.6 68.9 131.6 267.7		
(gpm) 3 5 7 10 Q	(gpm) - - - - Q	(psi/ft) 25.2 68.5 131.2 267.3 Casing S Frictional	(psi/ft) 0.4 0.4 0.4 0.4 0.4 ize:5" Hydrostatic	(psi/ft) 25.6 68.9 131.6 267.7 Total Pres.		
(gpm) 3 5 7 10 Q N2	(gpm) - - - - - - - Water	(psi/ft) 25.2 68.5 131.2 267.3 Casing S Frictional Pres. Loss	(psi/ft) 0.4 0.4 0.4 0.4 0.4 ize:5" Hydrostatic Pres. Loss	(psi/ft) 25.6 68.9 131.6 267.7 Total Pres. Loss		
(gpm) 3 5 7 10 Q N2 (gpm)	(gpm) - - - - - - - - - - - - - - - - - - -	(psi/ft) 25.2 68.5 131.2 267.3 Casing S Frictional Pres. Loss (psi/ft)	(psi/ft) 0.4 0.4 0.4 0.4 ize:5'' Hydrostatic Pres. Loss (psi/ft)	(psi/ft) 25.6 68.9 131.6 267.7 Total Pres. Loss (psi/ft)		
(gpm) 3 5 7 10 Q N2 (gpm) 3	(gpm) - - - - - - - - - - - - - - - - - - -	Trest Loss           (psi/ft)           25.2           68.5           131.2           267.3           Casing S           Frictional           Pres. Loss           (psi/ft)           25.2	(psi/ft) 0.4 0.4 0.4 0.4 0.4 ize:5'' Hydrostatic Pres. Loss (psi/ft) 0.4	(psi/ft) 25.6 68.9 131.6 267.7 Total Pres. Loss (psi/ft) 25.6		
(gpm) 3 5 7 10 Q N2 (gpm) 3 5	(gpm) - - - - - - - - - - - - - - - - - - -	Trest Loss           (psi/ft)           25.2           68.5           131.2           267.3           Casing S           Frictional           Pres. Loss           (psi/ft)           25.2           68.5	(psi/ft) 0.4 0.4 0.4 0.4 0.4 ize:5'' Hydrostatic Pres. Loss (psi/ft) 0.4 0.4 0.4	(psi/ft) 25.6 68.9 131.6 267.7 Total Pres. Loss (psi/ft) 25.6 68.9		
(gpm) 3 5 7 10 Q N2 (gpm) 3 5 7 7	(gpm) - - - - - - - - - - - - - - - -	(psi/ft)         25.2         68.5         131.2         267.3         Casing S         Frictional         Pres. Loss         (psi/ft)         25.2         68.5         131.3	(psi/ft) 0.4 0.4 0.4 0.4 0.4 ize:5'' Hydrostatic Pres. Loss (psi/ft) 0.4 0.4 0.4 0.4 0.4 0.4 0.4	(psi/ft) 25.6 68.9 131.6 267.7 Total Pres. Loss (psi/ft) 25.6 68.9 131.7		
(gpm) 3 5 7 10 Q N2 (gpm) 3 5 7 10	(gpm) - - - - - - - - - - - - - - - - -	(psi/ft)         25.2         68.5         131.2         267.3         Casing S         Frictional         Pres. Loss         (psi/ft)         25.2         68.5         131.3         267.7	(psi/ft) 0.4 0.4 0.4 0.4 ize:5" Hydrostatic Pres. Loss (psi/ft) 0.4 0.4 0.4 0.4 0.4 0.4 0.4 0.4	(psi/ft) 25.6 68.9 131.6 267.7 Total Pres. Loss (psi/ft) 25.6 68.9 131.7 268.1		
(gpm) 3 5 7 10 Q N2 (gpm) 3 5 7 10 10	(gpm) - - - - - - - - - - - - - - - - - - -	(psi/ft)         25.2         68.5         131.2         267.3         Casing S         Frictional         Pres. Loss         (psi/ft)         25.2         68.5         131.3         267.7         Casing S	(psi/ft)         0.4	(psi/ft) 25.6 68.9 131.6 267.7 Total Pres. Loss (psi/ft) 25.6 68.9 131.7 268.1		
(gpm) 3 5 7 10 Q N2 (gpm) 3 5 7 10 Q Q Q	(gpm) - - - - - - - - - - - - -	(psi/ft)         25.2         68.5         131.2         267.3         Casing S         Frictional         Pres. Loss         (psi/ft)         25.2         68.5         131.3         267.7         Casing S         Frictional	(psi/ft) 0.4 0.4 0.4 0.4 0.4 ize:5'' Hydrostatic Pres. Loss (psi/ft) 0.4 0.4 0.4 0.4 0.4 0.4 0.4 0.4	(psi/ft) 25.6 68.9 131.6 267.7 Total Pres. Loss (psi/ft) 25.6 68.9 131.7 268.1 Total Pres.		
(gpm) 3 5 7 10 Q N2 (gpm) 3 5 7 10 Q N2 (gpm) 3 5 7 10 2 (gpm) 3 5 7 10 2 (gpm) 3 5 7 10 2 (gpm) 3 5 7 10 2 (gpm) 3 5 7 10 2 (gpm) 3 5 7 10 2 (gpm) 3 5 7 10 2 (gpm) 3 5 7 10 2 (gpm) 3 5 7 10 2 (gpm) 3 5 7 10 2 (gpm) 3 5 7 10 2 (gpm) 3 5 7 10 2 (gpm) 3 5 7 10 2 2 (gpm) 3 5 7 10 2 2 2 2 2 2 2 2 2 2 2 2 2	vvater (gpm) - - - - - - - - - - - - - - - - - - -	(psi/ft)         25.2         68.5         131.2         267.3         Casing S         Frictional         Pres. Loss         (psi/ft)         25.2         68.5         131.3         267.7         Casing S         Frictional         Pres. Loss         (psi/ft)         25.2         68.5         131.3         267.7         Casing S         Frictional         Pres. Loss	(psi/ft) 0.4 0.4 0.4 0.4 0.4 ize:5" Hydrostatic Pres. Loss (psi/ft) 0.4 0.4 0.4 0.4 0.4 0.4 0.4 0.4	(psi/ft) 25.6 68.9 131.6 267.7 Total Pres. Loss (psi/ft) 25.6 68.9 131.7 268.1 Total Pres. Loss		
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(gpm) 3 5 7 10 Q N2 (gpm) 3 5 7 10 Q N2 (gpm) 3 5 7 10 3 5 7 10 3 5 7 10 8 9 9 9 10 10 10 10 10 10 10 10 10 10	Vater (gpm) - - - - - - - - - - - - - - - - - - -	(psi/ft)         25.2         68.5         131.2         267.3         Casing S         Frictional         Pres. Loss         (psi/ft)         25.2         68.5         131.3         267.7         Casing S         Frictional         Pres. Loss         (psi/ft)         25.2         68.5         131.3         267.7         Casing S         Frictional         Pres. Loss         (psi/ft)         25.2         68.6	(psi/ft) 0.4 0.4 0.4 0.4 0.4 ize:5" Hydrostatic Pres. Loss (psi/ft) 0.4 0.4 0.4 0.4 0.4 0.4 0.4 0.4	(psi/ft) 25.6 68.9 131.6 267.7 Total Pres. Loss (psi/ft) 25.6 68.9 131.7 268.1 Total Pres. Loss (psi/ft) 25.6 68.9 131.7 268.1		
(gpm) 3 5 7 10 Q N2 (gpm) 3 5 7 10 Q N2 (gpm) 3 5 7 10 7 10 7 10 7 10 7 7 10 7 7 10 7 7 10 7 7 10 7 7 10 7 7 10 7 7 10 7 7 10 7 7 10 7 7 10 7 7 10 7 7 10 7 7 10 7 7 10 7 7 10 7 7 10 7 7 7 10 7 7 7 7 7 7 7 7 7 7 7 7 7	vvater (gpm) - - - - - - - - - - - - - - - - - - -	(psi/ft)         25.2         68.5         131.2         267.3         Casing S         Frictional         Pres. Loss         (psi/ft)         25.2         68.5         131.3         267.7         Casing S         Frictional         Pres. Loss         (psi/ft)         25.2         68.5         131.3         267.7         Casing S         Frictional         Pres. Loss         (psi/ft)         25.2         68.6         131.4	(psi/ft)         0.4	(psi/ft) 25.6 68.9 131.6 267.7 Total Pres. Loss (psi/ft) 25.6 68.9 131.7 268.1 Total Pres. Loss (psi/ft) 25.6 68.9 131.7 268.1		

Table B-2: Total Pressure Losses at Surface Coiled Tubing Unit (Different Casing Sizes)

Casing Size:3", Nitrogen Only							
Q	Q	Frictional	Hydrostatic	Total Pres.			
N2	Water	Pres. Loss	Pres. Loss	Loss			
(gpm)	(gpm)	(psi/ft)	(psi/ft)	(psi/ft)			
3	-	25.4	0.4	25.8			
4	-	44.6	0.4	45			
5	-	68.6	0.4	69			
6	-	97.4	0.4	97.8			
7	-	130.9	0.4	140.3			
10	-	265	0.4	265.9			
	Casing Size:3". Nitrogen with Water Addition						
Q	Q	Frictional	Hydrostatic	Total Pres.			
N2	Water	Pres. Loss	Pres. Loss	Loss			
(gpm)	(gpm)	(psi/ft)	(psi/ft)	(psi/ft)			
3	1	258.1	642.4	900			
3	2	371	848	1220			
5	1	345.2	314.3	659.5			
6	1	387	216	603			
7	1	429	146	575			
7	2	623	217	840			
10	1	575	32.9	608			
10	2	796	65	861			
Casing Size:4"							
Q	Q	Frictional	Hydrostatic	Total Pres.			
N2	Water	Pres. Loss	Pres. Loss	Loss			
(gpm)	(gpm)	(psi/ft)	(psi/ft)	(psi/ft)			
3	-	25.5	0.4	25.9			
4	-	45	0.4	45.4			
5	-	69	0.4	69.4			
6	-	98	0.4	98.4			
7	-	131.5	0.4	132			
10	-	266.4	0.4	266.8			
Casing Size:5"							
Q	Q	Frictional	Hydrostatic	Total Pres.			
N2	Water	Pres. Loss	Pres. Loss	Loss			
(gpm)	(gpm)	(psi/ft)	(psi/ft)	(psi/ft)			
3	-	25.5	0.4	25.9			
4	-	45	0.4	45.9			
5	-	69	0.4	69.4			
6	-	98	0.4	98.4			
7	-	131.6	0.4	132			
10	-	266.6	0.4	267			

 Table B-3: Total Pressure Losses at Surface Coiled Tubing Unit (Deviated Wells)

Casing Size:7"				
Q	Q	Frictional	Hydrostatic	Total Pres.
N2	Water	Pres. Loss	Pres. Loss	Loss
(gpm)	(gpm)	(psi/ft)	(psi/ft)	(psi/ft)
3	-	25.5	0.4	25.9
4	-	44.8	0.4	45.2
5	-	69	0.4	69.4
6	-	98	0.4	98.4
7	-	131.7	0.4	132.1
10	-	266.7	0.4	267.2

Table D-3. Commu	Table B-3:	ontinuation
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#### Appendix C

#### Additional Runs to Fill the Gaps

In this part, WellFlo simulation results are given for drilling 21,000 ft wells with two different cases to fill the gaps from previous runs: 1) Injecting only water 2) Injecting nitrogen with water addition. Three different coiled tubing-hole size combinations were used for simulations. These combinations are: 1) CT:1"-HS:2.25", 2) CT:1.25"-HS:2.25" and 3) CT:0.75"-HS:1.75" In these simulations, well has 7 inch casing for the first 19,000 ft (kick of point). After 19,000 ft well is inclined 45° and additional 2,000 ft was drilled with given coiled tubing sizes. Table C-1 gives input parameters for the runs.

	Water	N <sub>2</sub> &
	Only	Water
Depth (ft)	21,000	21,000
Formation	Sandstone	Sandstone
Geothermal Gradient ( <sup>o</sup> F/ft)	0.015	0.015
Surface Temperature ( <sup>o</sup> F)	60	60
Injected Fluid Temperature ( <sup>o</sup> F)	75	75
Return Choke Pressure (psia)	50	50
Nozzle Pressure Drop (psi)	4000	5000
Cutting Size (micron)	25	25
ROP (ft/hour)	400	400

Table C-1: Input Parameters (21,000 ft)

#### 1. Water Only (21,000 ft )

Water was injected into the system with 75° F initial temperature. Figure C-1 is the operational envelope for CT: 1"-HS: 2.25" combination. As can be seen from the graph, five different injection rates were used for the runs. Water stayed in liquid phase in both tubing and the annulus. Figure C-2 is injection pressure profile for the runs. Increasing water flow rate, increased the injection pressure in the system.



Figure C-1: Operational Envelope for Water Only (CT: 1"-HS:2.25", 21,000 ft)



Figure C-2: Flow Rate vs. Inj. Pressure for Water Only (CT: 1"-HS:2.25", 21,000 ft)

Example pressure and temperature profile graphs for water only case are given for 5 gpm water flow rate in Figures C-3 and C-4, respectively. As seen in Figure C-3, the pressure drop of 4,000 psi occurs at the nozzle. Pressure outputs are given in Table C-2.

Injection Pressure (psia)	7823
BHP Upstream Nozzle (psia)	15131
BHP Downstream Nozzle (psi)	11131

Table C-2: Output Pressure Values (Water only, Q<sub>w</sub>=5 gpm, 21,000 ft)

Figure C-4 is the temperature profile of the fluid inside the coiled tubing and annulus with the formation temperature profile. The red line shows the temperature profile for fluid in the pipe and annulus and blue line shows the surrounding temperature profile. Selected output results for all other flow rate data are given after conclusions.



Figure C-3: Pressure vs Depth ( CT:1", H.S:2.25", Q<sub>w</sub>: 1 gpm, 21,000 ft)



Figure C-4: Temperature vs Depth ( CT:1", H.S:2.25", Q<sub>w</sub>: 1 gpm, 21,000 ft)

Figures C-5 through C-8 are operational envelopes and injection pressure profiles for CT: 1.25"-HS:2.25" and CT:0.75"-HS:1.75" combinations. As can be seen from the injection pressure profile graphs, due to the higher frictional pressure loss in smaller size coiled tubing, injection pressures are higher for 0.75" coiled tubing size.



Figure C-5: Operational Envelope for Water Only (CT: 1.25"-HS:2.25", 21,000 ft)



Figure C-6: Flow Rate vs. Inj. Pressure for Water Only (CT: 1.25"-HS:2.25", 21,000 ft)


Figure C-7: Operational Envelope for Water Only (CT: 0.75"-HS:1.75", 21,000 ft)



Figure C-8: Flow Rate vs. Inj. Pressure for Water Only (CT: 0.75"-HS:1.75", 21,000 ft)

#### 2. Nitrogen with Water Addition (21,000 ft)

In this part, WellFlo simulation results are given for drilling 21,000 ft wells with injecting nitrogen with water addition. Well configuration and coiled tubing-hole size combinations are same with water only runs in previous section. Pressure drop at the nozzle was fixed to 5000 psi for nitrogen with water addition runs. In some of the runs, liquid fraction after the nozzle at the bottom of the well is higher than 0.25. Liquid fractions for all the runs are given in Appendix A.

Figure C-9 is the operational envelope for CT: 1"-HS: 2.25" combination. Nitrogen was injected into the system with different amounts of water. For all the run points, maximum velocity in the annulus was less than 1,800 ft/min. Figure C-10 is injection pressure profile for the runs.



Figure C-9: Operational Envelope for N<sub>2</sub> with Water (CT: 1"-HS:2.25", 21,000 ft)



Figure C-10: Flow Rate vs. Inj. Pressure for N<sub>2</sub> with Water (CT: 1"-HS:2.25", 21,000 ft)

Example pressure and temperature profile graph for nitrogen with water addition case are given for 5 gpm nitrogen and 1 gpm water flow rate in Figures C-11 and C-12, respectively. As seen in Figure C-11, the pressure drop of 5,000 psi occurs at the nozzle. Pressure outputs are given in Table C-3.

Table C-3: Output Press. Values (Nitrogen with Water, Q<sub>N2</sub>=5 gpm, Q<sub>w</sub>=1 gpm 21,000 ft)

Injection Pressure (psia)	3939
BHP Upstream Nozzle (psia)	6114
BHP Downstream Nozzle (psi)	1114

Figure C-12 is the temperature profile of the fluid inside the coiled tubing and annulus with the formation temperature profile. The red line shows the temperature profile for fluid in the pipe and annulus and blue line shows the surrounding temperature profile. Selected output results for all other flow rate data are given after conclusions.



Figure C-11: Pressure vs Depth ( CT:1", H.S:2.25", Q<sub>N2</sub>:5 gpm Q<sub>w</sub>: 1 gpm, 21,000 ft)



Figure C-12: Temperature vs Depth( CT:1",H.S:2.25", Q<sub>N2</sub>: 5 gpm, Q<sub>w</sub>: 1 gpm, 21,000 ft)

Figures C-13 through C-16 are operational envelopes and injection pressure profiles for CT: 1.25"-HS:2.25" and CT:0.75"-HS:1.75" combinations. As can be seen from the injection pressure profile graphs, due to the higher frictional pressure loss in smaller size coiled tubing, injection pressures are higher for 0.75" coiled tubing size.



Figure C-13: Operational Envelope for N<sub>2</sub> with Water (CT: 1.25"-HS:2.25", 21,000 ft)



Figure C-14:Flow Rate vs. Inj. Pressure for N<sub>2</sub> with Water (CT:1.25"-HS:2.25",21,000 ft)



Figure C-15: Operational Envelope for N<sub>2</sub> with Water (CT: 0.75"-HS:1.75", 21,000 ft)



Figure C-16:Flow Rate vs. Inj. Pressure for N<sub>2</sub> with Water (CT:0.75"-HS:1.75",21,000 ft)

### 3. Conclusions

## Water Only:

- ✓ Water Injected with  $75^{\circ}$ F initial temperature.
- $\checkmark$  Three different coiled tubing-hole size combinations were used.
- $\checkmark$  7" casing was used for the first 19,000 ft of the well.
- $\checkmark$  Phase of the water is liquid both in the tubing and annulus.
- ✓ Increasing water flow rate increased injection pressures.

## Nitrogen with water addition:

- ✓ Nitrogen is injected with different amount of water into the system.
- ✓ Liquid fraction after the nozzle at the bottom of the well is higher than 0.25 in few of the runs.
- $\checkmark$  Increasing flow rates increased the injection pressures.

		Coiled Tubi	ng O.D: 1 inch	-Bore Hole Siz	ze: 2.25 inch		
Q N <sub>2</sub> (gpm)	Q Water (gpm	Maximum Mixture Velocity Annulus (ft/m)	Liquid Fraction After Nozzle (21,000 ft)	Liquid Velocity Tubing (ft/m)	CTR (25 Micron)	CTR (100 Micron)	
-	3	20	1	107	0.891		
-	4	26	1	143	0.882		
-	5	34	1	178	0.906		
-	8	54	1	286	0.941		
-	10	67	1	357	0.952		
Q N2 (gpm)	Q Water (gpm)	Injection Pressure (psi)	BHP Upstream Nozzle (psi)	BHP D. Stream Nozzle (psi)	T Upstream Nozzle (°F)	T D.Stream Nozzle (°F)	
-	3	8070	16259	12259	390	398	
-	4	7789	15585	11585	389	397	
-	5	7823	15131	11131	387	395	
-	8	9067	14346	10346	387	395	
-	10	10603	14059	10059	387	394	
		Coiled Tubin	g O.D: 1.25 inc	h –Bore Hole S	Size: 2.25 incl	h	
Q N <sub>2</sub> (gpm)	Q Water (gpm	Maximum Mixture Velocity Annulus (ft/m)	Liquid Fraction After Nozzle (21,000 ft)	Liquid Velocity Tubing (ft/m)	CTR (25 Micron)	CTR (100 Micron)	
-	3	23	1	63.24	0.846		
-	4	31	1	84	0.883		
-	5	38	1	105	0.906		
-	8	62	1	168	0.941		
-	10	77	1	211	0.952		
Q N2 (gpm)	Q Water (gpm)	Injection Pressure (psi)	BHP Upstream Nozzle (psi)	BHP D. Stream Nozzle (psi)	T Upstream Nozzle (°F)	T D.Stream Nozzle (°F)	
-	3	7667	16255	12255	391	399	
-	4	7112	15588	11588	391	398	
-	5	6791	15135	11135	390	398	
-	8	6543	14350	10350	391	398	
-	10	6737	14069	10069	386	393	

Table C-4: Output for 21,000 ft (Water Only)

Coiled Tubing O.D: 0.75 inch –Bore Hole Size: 1.75 inch							
Q N <sub>2</sub> (gpm)	Q Water (gpm	Maximum Mixture Velocity Annulus (ft/m)	Liquid Fraction After Nozzle (21,000 ft)	Liquid Velocity Tubing (ft/m)	CTR (25 Micron)	CTR (100 Micron)	
-	3	32	1	220	0.839		
-	4	43	1	294	0.878		
-	5	54	1	367	0.902		
-	8	88	1	585	0.938		
-	10	109	1	730	0.951		
Q N2 (gpm)	Q Water (gpm)	Injection Pressure (psi)	BHP Upstream Nozzle (psi)	BHP D. Stream Nozzle (psi)	T Upstream Nozzle (°F)	T D.Stream Nozzle ( <sup>o</sup> F)	
-	3	9755	15148	11148	390	398	
-	4	11657	14636	10636	394	402	
-	5	14370	14307	10307	392	399	
-	8	26704	13764	9764	404	411	
-	10	38192	13583	9583	392	399	

Table C-4: Continuation

		Coiled Tubi	ng O.D: 1 inch	-Bore Hole Siz	ze: 2.25 inch		
		Maximum	Liquid	Liquid			
Q	Q	Mixture	Fraction	Liquia Valesiter	CTR	CTR	
$N_2$	Water	Velocity	After	velocity Thim a	(25	(100	
(gpm)	(gpm	Annulus	Nozzle	I ubing	Micron)	Micron)	
		( <b>ft/m</b> )	(21,000 ft)	(It/m)			
3	1	158	1	155	0.806		
5	1	234	0.28	251	0.949		
8	1	2467	0.07	389	0.978		
5	2	243	0.33	296	0.969		
5	3	269	0.35	350	0.942		
8	2	2180	0.07	469	0.978		
8	3	1941	0.08	518	0.979		
0	0	Injection	BHP	BHP	Т	Т	
	Q Watar	Drossuro	Upstream	D. Stream	Upstream	D.Stream	
$(\mathbf{q}\mathbf{n}\mathbf{m})$	(gnm)	(psi)	Nozzle	Nozzle	Nozzle	Nozzle	
(gpm)	(gpm)	(psi)	(psi)	(psi)	( <b>°</b> F)	( <b>°</b> F)	
3	1	5687	8895	3895	363	361	
5	1	3939	6114	1114	292	276	
8	1	4405	5303	303	166	148	
5	2	4793	7053	2053	342	335	
5	3	5469	7352	2352	347	344	
8	2	5249	5367	367	192	180	
8	3	6064	5442	442	216	207	
Coiled Tubing O.D: 1.25 inch –Bore Hole Size: 2.25 inch							
		Coiled Tubin	g O.D: 1.25 inc	h –Bore Hole S	Size: 2.25 incl	1	
		Coiled Tubin Maximum	g O.D: 1.25 inc Liquid	h –Bore Hole S Liquid	Size: 2.25 incl	1	
Q	Q	Coiled Tubin Maximum Mixture	g O.D: 1.25 inc Liquid Fraction	h –Bore Hole S Liquid Velocity	Size: 2.25 incl CTR	ı CTR	
Q N <sub>2</sub>	Q Water	Coiled Tubin Maximum Mixture Velocity	g O.D: 1.25 inc Liquid Fraction After	h –Bore Hole S Liquid Velocity Tubing	Size: 2.25 incl CTR (25	n CTR (100	
Q N <sub>2</sub> (gpm)	Q Water (gpm	Coiled Tubin Maximum Mixture Velocity Annulus	g O.D: 1.25 ind Liquid Fraction After Nozzle	h –Bore Hole S Liquid Velocity Tubing (ft/m)	Size: 2.25 incl CTR (25 Micron)	n CTR (100 Micron)	
Q N2 (gpm)	Q Water (gpm	Coiled Tubin Maximum Mixture Velocity Annulus (ft/m)	g O.D: 1.25 ind Liquid Fraction After Nozzle (21,000 ft)	h –Bore Hole S Liquid Velocity Tubing (ft/m)	CTR (25 Micron)	CTR (100 Micron)	
Q N <sub>2</sub> (gpm) 3	Q Water (gpm	Coiled Tubin Maximum Mixture Velocity Annulus (ft/m) 170	g O.D: 1.25 ind Liquid Fraction After Nozzle (21,000 ft) 0.38	h –Bore Hole S Liquid Velocity Tubing (ft/m) 93.8	CTR (25 Micron)	n CTR (100 Micron)	
Q (gpm) 3 5	Q Water (gpm 1	Coiled Tubin Maximum Mixture Velocity Annulus (ft/m) 170 206	g O.D: 1.25 inc Liquid Fraction After Nozzle (21,000 ft) 0.38 0.32	h –Bore Hole S Liquid Velocity Tubing (ft/m) 93.8 119	Size: 2.25 incl CTR (25 Micron) 0.82 0.916	n CTR (100 Micron)	
Q (gpm) 3 5 8	Q Water (gpm 1 1 1	Coiled Tubin Maximum Mixture Velocity Annulus (ft/m) 170 206 208	g O.D: 1.25 inc Liquid Fraction After Nozzle (21,000 ft) 0.38 0.32 0.31	h –Bore Hole S Liquid Velocity Tubing (ft/m) 93.8 119 128	Size: 2.25 incl CTR (25 Micron) 0.82 0.916 0.932	n CTR (100 Micron)	
Q (gpm) 3 5 8 5	Q Water (gpm 1 1 1 2	Coiled Tubin Maximum Mixture Velocity Annulus (ft/m) 170 206 208 238	g O.D: 1.25 inc Liquid Fraction After Nozzle (21,000 ft) 0.38 0.32 0.31 0.33	h –Bore Hole S Liquid Velocity Tubing (ft/m) 93.8 119 128 174	CTR (25 Micron) 0.82 0.916 0.932 0.932	n CTR (100 Micron)	
Q N <sub>2</sub> (gpm) 3 5 8 5 5 5	Q Water (gpm 1 1 1 2 3	Coiled Tubin Maximum Mixture Velocity Annulus (ft/m) 170 206 208 208 238 265	g O.D: 1.25 inc Liquid Fraction After Nozzle (21,000 ft) 0.38 0.32 0.31 0.33 0.36	h –Bore Hole S Liquid Velocity Tubing (ft/m) 93.8 119 128 174 199	CTR (25 Micron) 0.82 0.916 0.932 0.932 0.921	n CTR (100 Micron)	
Q N <sub>2</sub> (gpm) 3 5 8 5 5 8	Q Water (gpm 1 1 1 2 3 2	Coiled Tubin Maximum Mixture Velocity Annulus (ft/m) 170 206 208 208 238 265 1065	g O.D: 1.25 inc Liquid Fraction After Nozzle (21,000 ft) 0.38 0.32 0.31 0.33 0.36 0.1	h –Bore Hole S Liquid Velocity Tubing (ft/m) 93.8 119 128 174 199 261	CTR (25 Micron) 0.82 0.916 0.932 0.932 0.921 0.957	n CTR (100 Micron)	
Q (gpm) 3 5 8 5 5 8 8 8 8	Q Water (gpm 1 1 1 2 3 2 3	Coiled Tubin Maximum Mixture Velocity Annulus (ft/m) 170 206 208 208 238 265 1065 284	g O.D: 1.25 inc Liquid Fraction After Nozzle (21,000 ft) 0.38 0.32 0.31 0.33 0.36 0.1 0.27	h –Bore Hole S Liquid Velocity Tubing (ft/m) 93.8 119 128 174 199 261 260	CTR (25 Micron) 0.82 0.916 0.932 0.932 0.921 0.957 0.964	n CTR (100 Micron)	
Q (gpm) 3 5 8 5 5 8 8 8 8 0	Q Water (gpm 1 1 1 2 3 2 3 0	Coiled Tubin Maximum Mixture Velocity Annulus (ft/m) 170 206 208 208 238 265 1065 284 Injection	g O.D: 1.25 inc Liquid Fraction After Nozzle (21,000 ft) 0.38 0.32 0.31 0.33 0.36 0.1 0.27 BHP	h –Bore Hole S Liquid Velocity Tubing (ft/m) 93.8 119 128 174 199 261 260 BHP	CTR (25 Micron) 0.82 0.916 0.932 0.932 0.921 0.957 0.964 T	r CTR (100 Micron)	
Q (gpm) 3 5 8 5 5 5 8 8 8 2 0 N2	Q Water (gpm 1 1 1 2 3 2 3 2 3 2 3 Water	Coiled Tubin Maximum Mixture Velocity Annulus (ft/m) 170 206 208 208 238 265 1065 284 Injection Pressure	g O.D: 1.25 inc Liquid Fraction After Nozzle (21,000 ft) 0.38 0.32 0.31 0.33 0.36 0.1 0.27 BHP Upstream	h –Bore Hole S Liquid Velocity Tubing (ft/m) 93.8 119 128 174 199 261 260 BHP D. Stream	CTR (25 Micron) 0.82 0.916 0.932 0.932 0.932 0.921 0.957 0.964 T Upstream	n CTR (100 Micron)	
Q (gpm) 3 5 8 5 5 8 8 8 2 9 N2 (gnm)	Q Water (gpm) 1 1 1 2 3 2 3 2 3 Q Water (gnm)	Coiled Tubin Maximum Mixture Velocity Annulus (ft/m) 170 206 208 238 238 265 1065 284 Injection Pressure (nsi)	g O.D: 1.25 inc Liquid Fraction After Nozzle (21,000 ft) 0.38 0.32 0.31 0.33 0.36 0.1 0.27 BHP Upstream Nozzle	h –Bore Hole S Liquid Velocity Tubing (ft/m) 93.8 119 128 174 199 261 260 BHP D. Stream Nozzle	CTR (25 Micron) 0.82 0.916 0.932 0.932 0.921 0.957 0.964 T Upstream Nozzle	n CTR (100 Micron)	
Q N2 (gpm) 3 5 8 5 5 8 8 8 8 0 N2 (gpm)	Q Water (gpm 1 1 1 2 3 2 3 2 3 Q Water (gpm)	Coiled Tubin Maximum Mixture Velocity Annulus (ft/m) 170 206 208 238 265 1065 284 Injection Pressure (psi)	g O.D: 1.25 inc Liquid Fraction After Nozzle (21,000 ft) 0.38 0.32 0.31 0.33 0.36 0.1 0.27 BHP Upstream Nozzle (psi)	h –Bore Hole S Liquid Velocity Tubing (ft/m) 93.8 119 128 174 199 261 260 BHP D. Stream Nozzle (psi)	CTR (25 Micron) 0.82 0.916 0.932 0.932 0.932 0.921 0.957 0.964 T Upstream Nozzle (°F)	n CTR (100 Micron) T D.Stream Nozzle (°F)	
Q N2 (gpm) 3 5 8 5 5 8 8 8 8 8 2 (gpm) 3 3	Q Water (gpm 1 1 1 2 3 2 3 2 3 2 3 2 3 2 3 2 3 2 3 2	Coiled Tubin Maximum Mixture Velocity Annulus (ft/m) 170 206 208 238 265 1065 284 Injection Pressure (psi) 5428	g O.D: 1.25 inc Liquid Fraction After Nozzle (21,000 ft) 0.38 0.32 0.31 0.33 0.36 0.1 0.27 BHP Upstream Nozzle (psi) 8735	h –Bore Hole S Liquid Velocity Tubing (ft/m) 93.8 119 128 174 199 261 260 BHP D. Stream Nozzle (psi) 3735	CTR (25 Micron) 0.82 0.916 0.932 0.932 0.921 0.957 0.964 T Upstream Nozzle (°F) 362	n CTR (100 Micron) T D.Stream Nozzle (°F) 360	
Q N <sub>2</sub> (gpm) 3 5 8 5 5 8 8 8 8 8 0 2 (gpm) 3 5 5	Q Water (gpm 1 1 1 2 3 2 3 2 3 2 3 2 3 2 3 2 3 2 3 2	Coiled Tubin Maximum Mixture Velocity Annulus (ft/m) 170 206 208 238 265 1065 284 Injection Pressure (psi) 5428 4464	g O.D: 1.25 inc Liquid Fraction After Nozzle (21,000 ft) 0.38 0.32 0.31 0.33 0.36 0.1 0.27 BHP Upstream Nozzle (psi) 8735 7338	h –Bore Hole S Liquid Velocity Tubing (ft/m) 93.8 119 128 174 199 261 260 BHP D. Stream Nozzle (psi) 3735 2338	CTR (25 Micron) 0.82 0.916 0.932 0.932 0.921 0.957 0.964 T Upstream Nozzle (°F) 362 340	n CTR (100 Micron) T D.Stream Nozzle (°F) 360 331	
Q N <sub>2</sub> (gpm) 3 5 8 5 5 8 8 8 2 (gpm) 3 5 5 8 8	Q Water (gpm 1 1 1 2 3 2 3 2 3 2 3 2 3 2 3 2 3 2 3 2	Coiled Tubin Maximum Mixture Velocity Annulus (ft/m) 170 206 208 238 265 1065 284 Injection Pressure (psi) 5428 4464 4229	g O.D: 1.25 inc Liquid Fraction After Nozzle (21,000 ft) 0.38 0.32 0.31 0.33 0.36 0.1 0.27 BHP Upstream Nozzle (psi) 8735 7338 7023	h –Bore Hole S Liquid Velocity Tubing (ft/m) 93.8 119 128 174 199 261 260 BHP D. Stream Nozzle (psi) 3735 2338 2023	CTR (25 Micron) 0.82 0.916 0.932 0.932 0.932 0.932 0.921 0.957 0.964 T Upstream Nozzle (°F) 362 340 332	n CTR (100 Micron) T D.Stream Nozzle (°F) 360 331 321	
Q N <sub>2</sub> (gpm) 3 5 8 5 5 8 8 8 2 (gpm) 3 5 8 8 5 5	Q Water (gpm) 1 1 1 2 3 2 3 2 3 2 3 2 3 2 3 2 3 2 3 2	Coiled Tubin Maximum Mixture Velocity Annulus (ft/m) 170 206 208 238 238 265 1065 284 1065 284 Injection Pressure (psi) 5428 4464 4229 4229	g O.D: 1.25 inc Liquid Fraction After Nozzle (21,000 ft) 0.38 0.32 0.31 0.33 0.36 0.1 0.27 BHP Upstream Nozzle (psi) 8735 7338 7023 7369	h –Bore Hole S Liquid Velocity Tubing (ft/m) 93.8 119 128 174 199 261 260 BHP D. Stream Nozzle (psi) 3735 2338 2023 2369	Size: 2.25 incl CTR (25 Micron) 0.82 0.916 0.932 0.932 0.932 0.932 0.932 0.932 0.94 T Upstream Nozzle (°F) 362 340 332 351	n CTR (100 Micron) T D.Stream Nozzle (°F) 360 331 321 346	
Q N <sub>2</sub> (gpm) 3 5 8 5 5 8 8 8 2 (gpm) 3 5 8 5 5 5 5	Q Water (gpm) 1 1 2 3 2 3 2 3 2 3 2 3 2 3 2 3 2 3 1 1 1 1	Coiled Tubin     Maximum     Mixture     Velocity     Annulus     (ft/m)     170     206     208     238     265     1065     284     Injection     Pressure     (psi)     5428     4464     4229     4464	g O.D: 1.25 inc Liquid Fraction After Nozzle (21,000 ft) 0.38 0.32 0.31 0.33 0.36 0.1 0.27 BHP Upstream Nozzle (psi) 8735 7338 7023 7369 7917	h -Bore Hole S Liquid Velocity Tubing (ft/m) 93.8 119 128 174 199 261 260 BHP D. Stream Nozzle (psi) 3735 2338 2023 2369 2917	Size: 2.25 incl CTR (25 Micron) 0.82 0.916 0.932 0.932 0.932 0.921 0.957 0.964 T Upstream Nozzle (°F) 362 340 332 351 365	n CTR (100 Micron) T D.Stream Nozzle (°F) 360 331 321 346 364	
Q N <sub>2</sub> (gpm) 3 5 8 5 5 8 8 8 0 V2 (gpm) 3 5 5 8 5 5 8 8 5 5 8	Q Water (gpm) 1 1 2 3 2 3 2 3 2 3 2 3 2 3 2 3 2 1 1 1 2 3 2 2	Coiled Tubin     Maximum     Mixture     Velocity     Annulus     (ft/m)     170     206     208     238     265     1065     284     Injection     Pressure     (psi)     5428     4464     4229     4464     3193	g O.D: 1.25 inc Liquid Fraction After Nozzle (21,000 ft) 0.38 0.32 0.31 0.33 0.36 0.1 0.27 BHP Upstream Nozzle (psi) 8735 7338 7023 7369 7917 5546	h –Bore Hole S Liquid Velocity Tubing (ft/m) 93.8 119 128 174 199 261 260 BHP D. Stream Nozzle (psi) 3735 2338 2023 2369 2917 546	Size: 2.25 incl   CTR   (25   Micron)   0.82   0.916   0.932   0.957   0.964   T   Upstream   Nozzle   (°F)   362   340   332   351   365   276	n CTR (100 Micron) T D.Stream Nozzle (°F) 360 331 321 346 364 254	

Table C-5: Output for 21,000 ft (Nitrogen with Water Addition)

Coiled Tubing O.D: 0.75 inch –Bore Hole Size: 1.75 inch								
Q N <sub>2</sub> (gpm)	Q Water (gpm	Maximum Mixture Velocity Annulus (ft/m)	Liquid Fraction After Nozzle (21,000 ft)	Liquid Velocity Tubing (ft/m)	CTR (25 Micron)	CTR (100 Micron)		
3	1	171	0.3	355	0.938			
5	1	4909	0.05	547	0.982			
8	1	8888	0.03	700	0.991			
5	2	3877	0.07	597	0.979			
5	3	2942	0.08	648	0.976			
8	2	8743	0.05	772	0.991			
8	3	6523	0.07	815	0.989			
Q N2 (gpm)	Q Water (gpm)	Injection Pressure (psi)	BHP Upstream Nozzle (psi)	BHP D. Stream Nozzle (psi)	T Upstream Nozzle ( <sup>o</sup> F)	T D.Stream Nozzle ( <sup>o</sup> F)		
3	1	6745	6940	1940	319	311		
5	1	10426	5430	430	183	167		
8	1	18979	5663	663	184	165		
5	2	13900	5545	545	224	213		
5	3	18294	5637	637	263	250		
8	2	25897	5793	793	222	208		
8	3	31056	5858	858	238	228		

Table C-5: Continuation

#### APPENDIX D

#### Additional Runs to Fill the Gaps

#### (500 ft Coiled Tubing at Surface Facility)

In this part, WellFlo simulation results are given for drilling 21,000 wells with water with small amounts of nitrogen. In these simulations, in order to decrease pressure loss at surface coiled tubing facility, 500 ft coiled tubing used at the spool. Pressure drop at the nozzle was fixed to 5,000 psi. Well configuration and coiled tubing-hole size combinations are same with previous section. Phase of the water remained in liquid both in the tubing and the annulus.

	Water & N <sub>2</sub>
Depth (ft)	21,000
Formation	Sandstone
Geothermal Gradient ( <sup>o</sup> F/ft)	0.015
Surface Temperature ( <sup>o</sup> F)	60
<b>Injected Fluid Temperature (</b> <sup>o</sup> <b>F</b> )	75
<b>Return Choke Pressure (psia)</b>	50
Nozzle Pressure Drop (psi)	5000
Cutting Size (micron)	25
ROP (ft/hour)	400

Table D-1: Input Parameters (21,000 with 500 ft CT at Surface)

Figure D-1 is the operational envelope for CT: 1''-HS: 2.25'' combination. Water was injected into the system with small amount of nitrogen. For all the run points, maximum velocity in the annulus was less than 1,800 ft/min. Figure D-2 is injection pressure profile for the runs. Number near the run points are amount of nitrogen flow rate injected with water.



Figure D-1: Operational Envelope for Water with N<sub>2</sub> (CT: 1"-HS:2.25", 21,000 ft)



Figure D-2: Flow Rate vs. Inj. Pressure for N<sub>2</sub> with Water (CT: 1"-HS:2.25", 21,000 ft)

Example pressure and temperature profile graph for water with nitrogen addition case are given for 5 gpm water and 0.25 gpm nitrogen flow rate in Figures D-3 and D-4, respectively. As seen in Figure D-3, the pressure drop of 5,000 psi occurs at the nozzle. Pressure outputs are given in Table D-2.

Table D-2: Output Press. Values(Water with Nitrogen,Q<sub>w</sub>:5 gpm,Q<sub>N2</sub>:0.25 gpm,21,000 ft)

Injection Pressure (psia)	7,289
BHP Upstream Nozzle (psia)	15,288
BHP Downstream Nozzle (psi)	10,288

Figure D-4 is the temperature profile of the fluid inside the coiled tubing and annulus with the formation temperature profile. The red line shows the temperature profile for fluid in the pipe and annulus and blue line shows the surrounding temperature profile. Selected output results for all other flow rate data are given after conclusions.



Figure D-3: Pressure vs Depth ( CT:1", H.S:2.25", Q<sub>w</sub>: 5 gpm Q<sub>N2</sub>: 0.25 gpm, 21,000 ft)



Figure D-4: Temperature vs Depth( CT:1",H.S:2.25",Q<sub>w</sub>:5 gpm Q<sub>N2</sub>:0.25 gpm, 21,000 ft)

Figures D-5 through D-8 are operational envelopes and injection pressure profiles for CT: 1.25"-HS:2.25" and CT:0.75"-HS:1.75" combinations. As can be seen from the injection pressure profile graphs, due to the higher frictional pressure loss in smaller size coiled tubing, injection pressures are higher for 0.75" coiled tubing size.



Figure D-5: Operational Envelope for Water with N<sub>2</sub> (CT: 1.25"-HS:2.25", 21,000 ft)



Figure D-6:Flow Rate vs. Inj. Pressure for Water with N<sub>2</sub> (CT: 1.25"-HS:2.25",21,000 ft)



Figure D-7: Operational Envelope for Water with N<sub>2</sub> (CT: 0.75"-HS:1.75", 21,000 ft)



Figure D-8: Flow Rate vs. Inj. Pressure for Water with N<sub>2</sub> (CT:0.75"-HS:1.75",21,000 ft)

# Conclusions

- ✓ 21,000 ft wells were drilled with water and small amount of nitrogen addition..
- $\checkmark$  Three different coiled tubing-hole size combinations were used.
- $\checkmark$  7" casing was used for the first 19,000 ft of the well.
- $\checkmark$  Phase of the water is liquid both in the tubing and annulus.
- $\checkmark$  Increasing water flow rate increased injection pressures.

Coiled Tubing O.D: 1 inch –Bore Hole Size: 2.25 inch								
		Maximum	Liquid	Liquid				
Q	Q	Mixture	Fraction	Liquia Valesiter	CTR	CTR		
Water	N2	Velocity	After	velocity Thim a	(25	(100		
(gpm	(gpm)	Annulus	Nozzle	f ubing	Micron)	Micron)		
		( <b>ft/m</b> )	(21,000 ft)	(II/M)				
3	0.25	22	1	22	0.834			
5	0.25	35	1	189	0.902			
8	0.25	55	1	189	0.902			
5	0.5	37	1	198	0.897			
5	0.75	48	1	206	0.893			
5	1	65	1	216	0.888			
0	0	Injection	BHP	BHP	Т	Т		
X Water	N2	Pressure	Upstream	D. Stream	Upstream	D.Stream		
(gnm	(gnm)	(nsi)	Nozzle	Nozzle	Nozzle	Nozzle		
(spm	(Shiii)	(p31)	(psi)	(psi)	( <b>°</b> F)	( <b>°</b> F)		
3	0.25	7819	16035	11035	393	403		
5	0.25	7289	15288	10288	393	402		
8	0.25	7512	14767	9767	392	400		
5	0.5	6924	14691	9691	394	403		
5	0.75	6643	14208	9208	392	401		
5	1	6334	13650	8650	393	402		
Coiled Tubing O.D: 1.25 inch –Bore Hole Size: 2.25 inch								
		Coiled Tubin	g O.D: 1.25 inc	h –Bore Hole S	Size: 2.25 incl	n		
		Coiled Tubin Maximum	g O.D: 1.25 inc Liquid	h –Bore Hole S Liquid	Size: 2.25 incl	n		
Q	Q	Coiled Tubin Maximum Mixture	g O.D: 1.25 inc Liquid Fraction	h –Bore Hole S Liquid Velocity	Size: 2.25 incl	n CTR		
Q Water	Q N2	Coiled Tubin Maximum Mixture Velocity	g O.D: 1.25 inc Liquid Fraction After	h –Bore Hole S Liquid Velocity Tubing	Size: 2.25 incl CTR (25	n CTR (100		
Q Water (gpm	Q N2 (gpm)	Coiled Tubin Maximum Mixture Velocity Annulus	g O.D: 1.25 inc Liquid Fraction After Nozzle	<u>h –Bore Hole S</u> Liquid Velocity Tubing (ft/m)	Size: 2.25 incl CTR (25 Micron)	n CTR (100 Micron)		
Q Water (gpm	Q N2 (gpm)	Coiled Tubin Maximum Mixture Velocity Annulus (ft/m)	g O.D: 1.25 inc Liquid Fraction After Nozzle (21,000 ft)	h –Bore Hole S Liquid Velocity Tubing (ft/m)	CTR (25 Micron)	n CTR (100 Micron)		
Q Water (gpm	Q N2 (gpm) 0.25	Coiled Tubin Maximum Mixture Velocity Annulus (ft/m) 25	g O.D: 1.25 inc Liquid Fraction After Nozzle (21,000 ft)	h –Bore Hole S Liquid Velocity Tubing (ft/m) 69	Size: 2.25 incl CTR (25 Micron) 0.836	n CTR (100 Micron)		
Q Water (gpm 3 5	Q N2 (gpm) 0.25 0.25	Coiled Tubin Maximum Mixture Velocity Annulus (ft/m) 25 41	g O.D: 1.25 inc Liquid Fraction After Nozzle (21,000 ft) 1 1	h –Bore Hole S Liquid Velocity Tubing (ft/m) 69 111	Size: 2.25 incl CTR (25 Micron) 0.836 0.904	n CTR (100 Micron)		
Q Water (gpm 3 5 8	Q N2 (gpm) 0.25 0.25 0.25	Coiled Tubin Maximum Mixture Velocity Annulus (ft/m) 25 41 64	g O.D: 1.25 inc Liquid Fraction After Nozzle (21,000 ft) 1 1 1	h –Bore Hole S Liquid Velocity Tubing (ft/m) 69 111 175	CTR (25 Micron) 0.836 0.904 0.941	n CTR (100 Micron)		
Q Water (gpm 3 5 8 5	Q N2 (gpm) 0.25 0.25 0.25 0.5	Coiled Tubin Maximum Mixture Velocity Annulus (ft/m) 25 41 64 43	g O.D: 1.25 inc Liquid Fraction After Nozzle (21,000 ft) 1 1 1 1	h –Bore Hole S Liquid Velocity Tubing (ft/m) 69 111 175 116	CTR (25 Micron) 0.836 0.904 0.941 0.899	n CTR (100 Micron)		
Q Water (gpm 3 5 8 5 5 5	Q N2 (gpm) 0.25 0.25 0.25 0.25 0.5 0.75	Coiled Tubin Maximum Mixture Velocity Annulus (ft/m) 25 41 64 43 46	g O.D: 1.25 inc Liquid Fraction After Nozzle (21,000 ft) 1 1 1 1 1 1	h –Bore Hole S Liquid Velocity Tubing (ft/m) 69 111 175 116 122	Size: 2.25 incl CTR (25 Micron) 0.836 0.904 0.941 0.899 0.894	n CTR (100 Micron)		
Q Water (gpm 3 5 8 5 5 5 5 5	Q N2 (gpm) 0.25 0.25 0.25 0.25 0.75 1	Coiled Tubin Maximum Mixture Velocity Annulus (ft/m) 25 41 64 43 46 56	g O.D: 1.25 inc Liquid Fraction After Nozzle (21,000 ft) 1 1 1 1 1 1 1 1 1	h –Bore Hole S Liquid Velocity Tubing (ft/m) 69 111 175 116 122 127	Size: 2.25 incl CTR (25 Micron) 0.836 0.904 0.941 0.899 0.894 0.89	n CTR (100 Micron)		
Q Water (gpm 3 5 8 5 5 5 5	Q N2 (gpm) 0.25 0.25 0.25 0.5 0.75 1	Coiled Tubin Maximum Mixture Velocity Annulus (ft/m) 25 41 64 43 46 56	g O.D: 1.25 inc Liquid Fraction After Nozzle (21,000 ft) 1 1 1 1 1 1 1 1	h –Bore Hole S Liquid Velocity Tubing (ft/m) 69 111 175 116 122 127	Size: 2.25 incl CTR (25 Micron) 0.836 0.904 0.941 0.899 0.894 0.89	n CTR (100 Micron)		
Q Water (gpm 3 5 5 8 5 5 5 5 0	Q N2 (gpm) 0.25 0.25 0.25 0.5 0.75 1 0.75	Coiled Tubin Maximum Mixture Velocity Annulus (ft/m) 25 41 64 43 46 56 56 Injection	g O.D: 1.25 inc Liquid Fraction After Nozzle (21,000 ft) 1 1 1 1 1 1 1 1 1 1 1	h –Bore Hole S Liquid Velocity Tubing (ft/m) 69 111 175 116 122 127 BHP	Size: 2.25 incl CTR (25 Micron) 0.836 0.904 0.941 0.899 0.894 0.89 T	n CTR (100 Micron)		
Q Water (gpm 3 5 8 5 5 5 5 5 4 V Water	Q N2 (gpm) 0.25 0.25 0.25 0.5 0.75 1 Q N2	Coiled Tubin Maximum Mixture Velocity Annulus (ft/m) 25 41 64 43 46 56 56 Injection Pressure	g O.D: 1.25 inc Liquid Fraction After Nozzle (21,000 ft) 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1	h –Bore Hole S Liquid Velocity Tubing (ft/m) 69 111 175 116 122 127 BHP D. Stream	Size: 2.25 incl CTR (25 Micron) 0.836 0.904 0.941 0.899 0.894 0.89 T Upstream	n CTR (100 Micron)		
Q Water (gpm 3 5 5 5 5 5 7 9 Water (gpm	Q N2 (gpm) 0.25 0.25 0.25 0.25 0.75 1 Q N2 (gpm)	Coiled Tubin Maximum Mixture Velocity Annulus (ft/m) 25 41 64 43 46 56 Injection Pressure (psi)	g O.D: 1.25 inc Liquid Fraction After Nozzle (21,000 ft) 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1	h –Bore Hole S Liquid Velocity Tubing (ft/m) 69 111 175 116 122 127 BHP D. Stream Nozzle	Size: 2.25 incl CTR (25 Micron) 0.836 0.904 0.941 0.899 0.894 0.89 Upstream Nozzle (05)	n CTR (100 Micron) T D.Stream Nozzle		
Q Water (gpm 3 5 5 5 5 5 V Water (gpm	Q N2 (gpm) 0.25 0.25 0.25 0.25 0.75 1 Q N2 (gpm) 0.25	Coiled Tubin Maximum Mixture Velocity Annulus (ft/m) 25 41 64 43 46 56 Injection Pressure (psi) 7840	g O.D: 1.25 inc Liquid Fraction After Nozzle (21,000 ft) 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1	h –Bore Hole S Liquid Velocity Tubing (ft/m) 69 111 175 116 122 127 BHP D. Stream Nozzle (psi)	Size: 2.25 incl CTR (25 Micron) 0.836 0.904 0.941 0.899 0.894 0.89 0.894 0.89 T Upstream Nozzle (°F) 2002	n CTR (100 Micron) T D.Stream Nozzle (°F)		
Q Water (gpm 3 5 5 5 5 5 5 V Water (gpm 3 5	Q N2 (gpm) 0.25 0.25 0.25 0.75 1 Q N2 (gpm) 0.25 0.25	Coiled Tubin Maximum Mixture Velocity Annulus (ft/m) 25 41 64 43 46 56 56 Injection Pressure (psi) 7819	g O.D: 1.25 inc Liquid Fraction After Nozzle (21,000 ft) 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1	h –Bore Hole S Liquid Velocity Tubing (ft/m) 69 111 175 116 122 127 BHP D. Stream Nozzle (psi) 11040	Size: 2.25 incl CTR (25 Micron) 0.836 0.904 0.941 0.899 0.894 0.89 0.894 0.89 T Upstream Nozzle (°F) 392	n CTR (100 Micron) T D.Stream Nozzle (°F) 402		
Q Water (gpm) 3 5 5 5 5 5 5 V Water (gpm) 3 5 5	Q N2 (gpm) 0.25 0.25 0.25 0.75 1 Q N2 (gpm) 0.25 0.25 0.25	Coiled Tubin Maximum Mixture Velocity Annulus (ft/m) 25 41 64 43 46 56 56 Injection Pressure (psi) 7819 6953 0542	g O.D: 1.25 inc Liquid Fraction After Nozzle (21,000 ft) 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1	h –Bore Hole S Liquid Velocity Tubing (ft/m) 69 111 175 116 122 127 BHP D. Stream Nozzle (psi) 11040 10295	Size: 2.25 incl CTR (25 Micron) 0.836 0.904 0.941 0.899 0.894 0.89 0.894 0.89 T Upstream Nozzle (°F) 392 394	n CTR (100 Micron) T D.Stream Nozzle (°F) 402 403		
Q Water (gpm) 3 5 5 5 5 5 5 7 8 8 5 7 8 8 7 5 8 8 5 5 5 8 5 5 5 5	Q N2 (gpm) 0.25 0.25 0.25 0.5 0.75 1 Q N2 (gpm) 0.25 0.25 0.25	Coiled Tubin Maximum Mixture Velocity Annulus (ft/m) 25 41 64 43 46 56 Injection Pressure (psi) 7819 6953 6543	g O.D: 1.25 inc Liquid Fraction After Nozzle (21,000 ft) 1 1 1 1 1 1 1 BHP Upstream Nozzle (psi) 16040 15295 14833 44740	h –Bore Hole S Liquid Velocity Tubing (ft/m) 69 111 175 116 122 127 BHP D. Stream Nozzle (psi) 11040 10295 9833	Size: 2.25 incl CTR (25 Micron) 0.836 0.904 0.941 0.899 0.894 0.89 0.89 T Upstream Nozzle (°F) 392 394 391 200	n CTR (100 Micron) T D.Stream Nozzle (°F) 402 403 400		
Q Water (gpm 3 5 5 5 5 5 5 7 9 Water (gpm 3 5 8 5 5 5	Q N2 (gpm) 0.25 0.25 0.25 0.5 0.75 1 Q N2 (gpm) 0.25 0.25 0.25 0.25 0.25	Coiled Tubin Maximum Mixture Velocity Annulus (ft/m) 25 41 64 43 46 56 Injection Pressure (psi) 7819 6953 6543 6560	g O.D: 1.25 inc Liquid Fraction After Nozzle (21,000 ft) 1 1 1 1 1 1 1 BHP Upstream Nozzle (psi) 16040 15295 14833 14742 44000	h –Bore Hole S Liquid Velocity Tubing (ft/m) 69 111 175 116 122 127 BHP D. Stream Nozzle (psi) 11040 10295 9833 9742	Size: 2.25 incl CTR (25 Micron) 0.836 0.904 0.904 0.941 0.899 0.894 0.89 T Upstream Nozzle (°F) 392 394 391 392 201	n CTR (100 Micron) T D.Stream Nozzle (°F) 402 403 400 402		
Q Water (gpm) 3 5 8 5 5 5 5 7 9 Water (gpm) 3 5 8 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5	Q N2 (gpm) 0.25 0.25 0.25 0.25 0.75 1 Q N2 (gpm) 0.25 0.25 0.25 0.25 0.25 0.25	Coiled Tubin Maximum Mixture Velocity Annulus (ft/m) 25 41 64 43 46 56 Injection Pressure (psi) 7819 6953 6543 6550 6224	g O.D: 1.25 inc Liquid Fraction After Nozzle (21,000 ft) 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1	h –Bore Hole S Liquid Velocity Tubing (ft/m) 69 111 175 116 122 127 BHP D. Stream Nozzle (psi) 11040 10295 9833 9742 9220	Size: 2.25 incl CTR (25 Micron) 0.836 0.904 0.941 0.899 0.894 0.89 T Upstream Nozzle (°F) 392 394 391 392 391	n CTR (100 Micron) T D.Stream Nozzle ( <sup>0</sup> F) 402 403 400 402		
Q Water (gpm) 3 5 5 5 5 5 7 9 Water (gpm) 3 5 5 8 5 5 5 5 5 5 5 5 5	Q N2 (gpm) 0.25 0.25 0.25 0.25 0.75 1 Q N2 (gpm) 0.25 0.25 0.25 0.25 0.25 0.25 0.75 1	Coiled Tubin Maximum Mixture Velocity Annulus (ft/m) 25 41 64 43 46 56 56 Injection Pressure (psi) 7819 6953 6543 6550 6224 5970	g O.D: 1.25 inc Liquid Fraction After Nozzle (21,000 ft) 1 1 1 1 1 1 1 1 1 1 1 1 BHP Upstream Nozzle (psi) 16040 15295 14833 14742 14220 13785	h –Bore Hole S Liquid Velocity Tubing (ft/m) 69 111 175 116 122 127 BHP D. Stream Nozzle (psi) 11040 10295 9833 9742 9220 8785	Size: 2.25 incl CTR (25 Micron) 0.836 0.904 0.941 0.899 0.894 0.89 0.89 T Upstream Nozzle (°F) 392 394 391 391	n CTR (100 Micron) T D.Stream Nozzle (°F) 402 402 403 400 402 400 401		

Table D-3: Output for Water with  $N_2$  Addition (21,000 ft)

Coiled Tubing O.D: 0.75 inch –Bore Hole Size: 1.75 inch								
Q Water (gpm	Q N2 (gpm)	Maximum Mixture Velocity Annulus (ft/m)	Liquid Fraction After Nozzle (21,000 ft)	Liquid Velocity Tubing (ft/m)	CTR (25 Micron)	CTR (100 Micron)		
3	0.25	36	1	240	0.829			
5	0.25	58	1	389	0.899			
8	0.25	91	1	608	0.938			
5	0.5	62	1	407	0.892			
5	0.75	66	1	425	0.886			
5	1	71	1	442	0.881			
Q Water (gpm	Q N2 (gpm)	Injection Pressure (psi)	BHP Upstream Nozzle (psi)	BHP D. Stream Nozzle (psi)	T Upstream Nozzle (°F)	T D.Stream Nozzle (°F)		
3	0.25	7858	14884	9884	392	402		
5	0.25	9641	14342	9342	394	403		
8	0.25	14399	14072	9072	394	403		
5	0.5	9273	13678	8678	394	403		
5	0.75	9131	13028	8028	392	401		
5	1	9067	12474	7474	391	399		

Table D-3: Continuation