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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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^{TM} 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.

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 ºF 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.

Table 1: Input Parameters

	CASE-1		**CASE-2**
	N2 Only	**N2&Water**	**All Runs**
Formation	Sandstone	Sandstone	Sandstone
Geothermal Gradient (ºF/ft)	0.015	0.015	0.015
Surface Temperature (ºF)	60	60	60
Injected Fluid Temperature (ºF)	75	75	75
Return Choke Pressure (psia)	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

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.

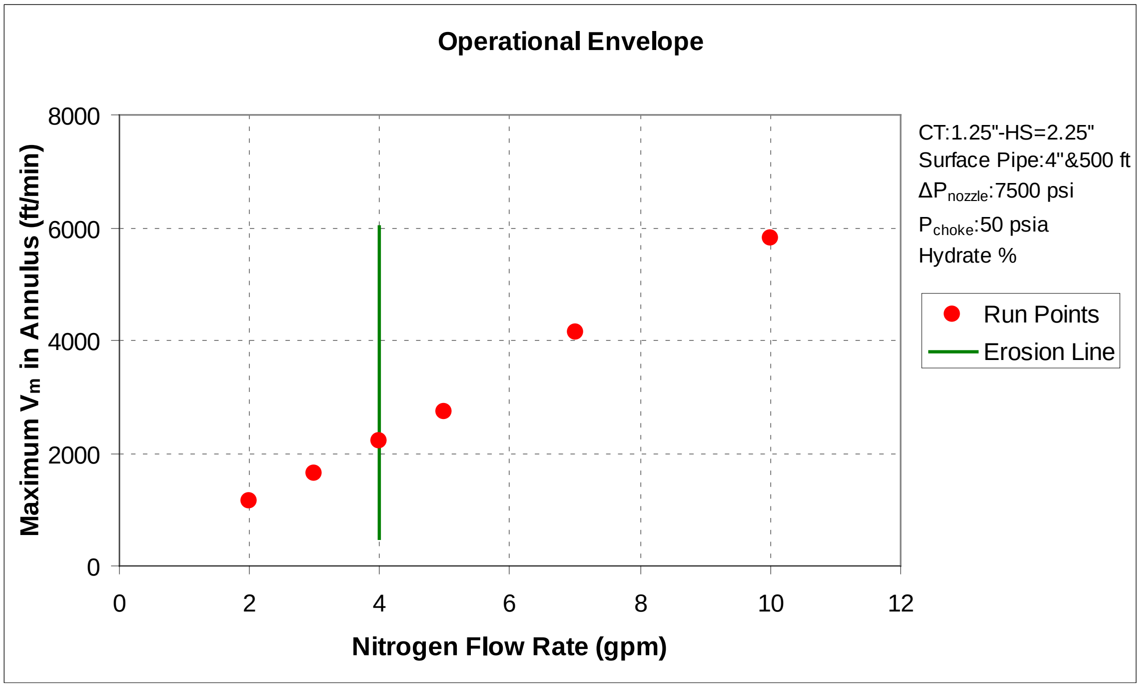

Figure 1: Operational Envelope for N_2 (CT:1.25”-HS:2.25”, N_2 Only)

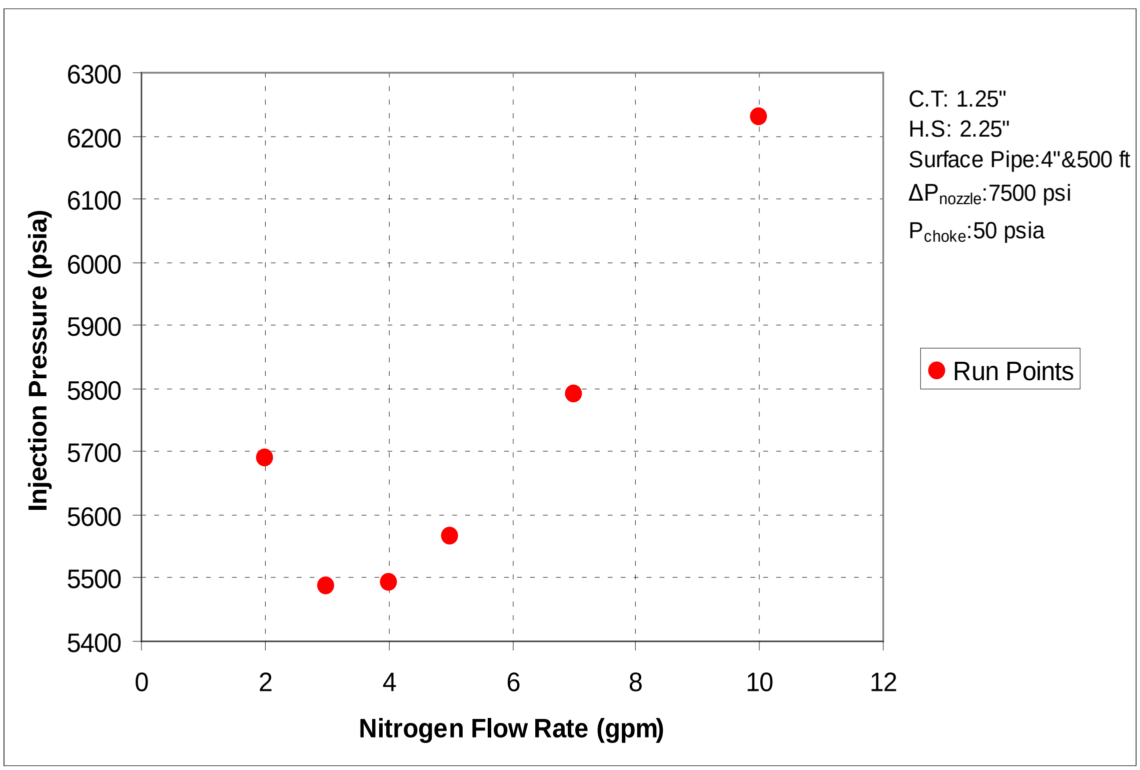

Figure 2: Flow Rate vs. Inj. Pressure (N_2, CT:1.25”-HS:2.25”, N_2 Only)

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.

Table 2: Output Pressure Values (N_2 Only, CT: 1.25’’-HS: 2.25’’, 5 gpm)

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

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.

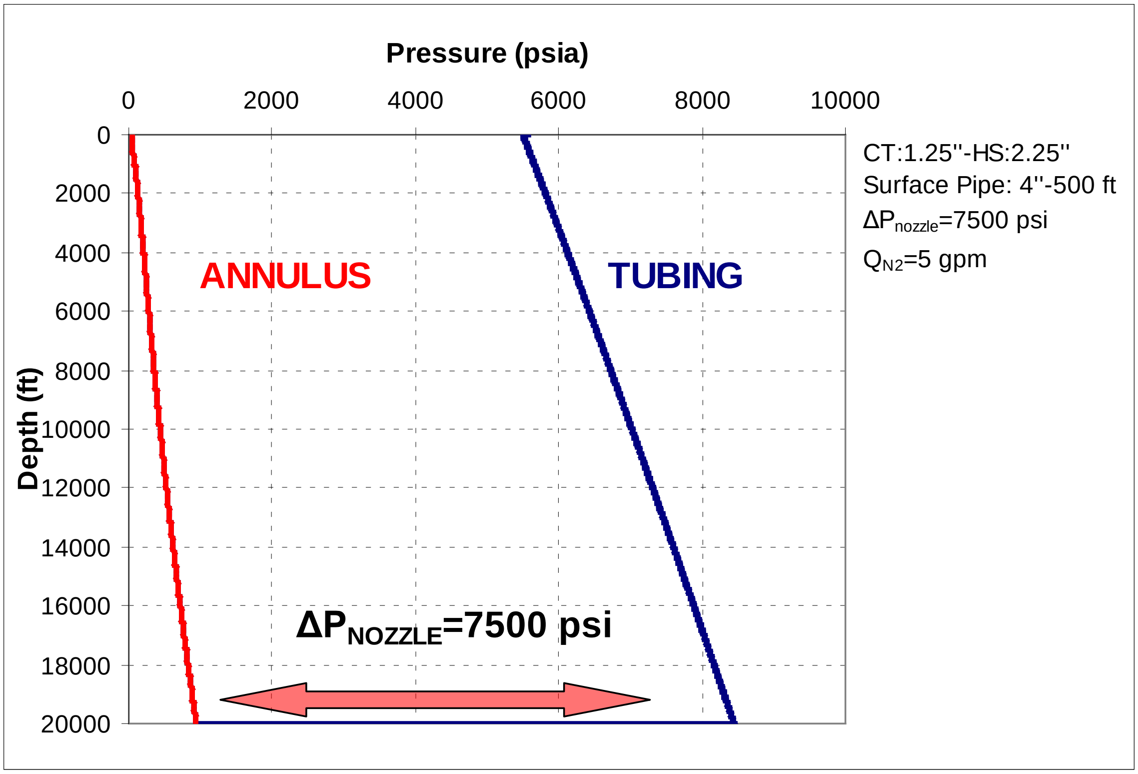

Figure 3: Pressure vs Depth (N_2 Only, CT:1.25”, H.S:2.25”, Q=5 gpm)

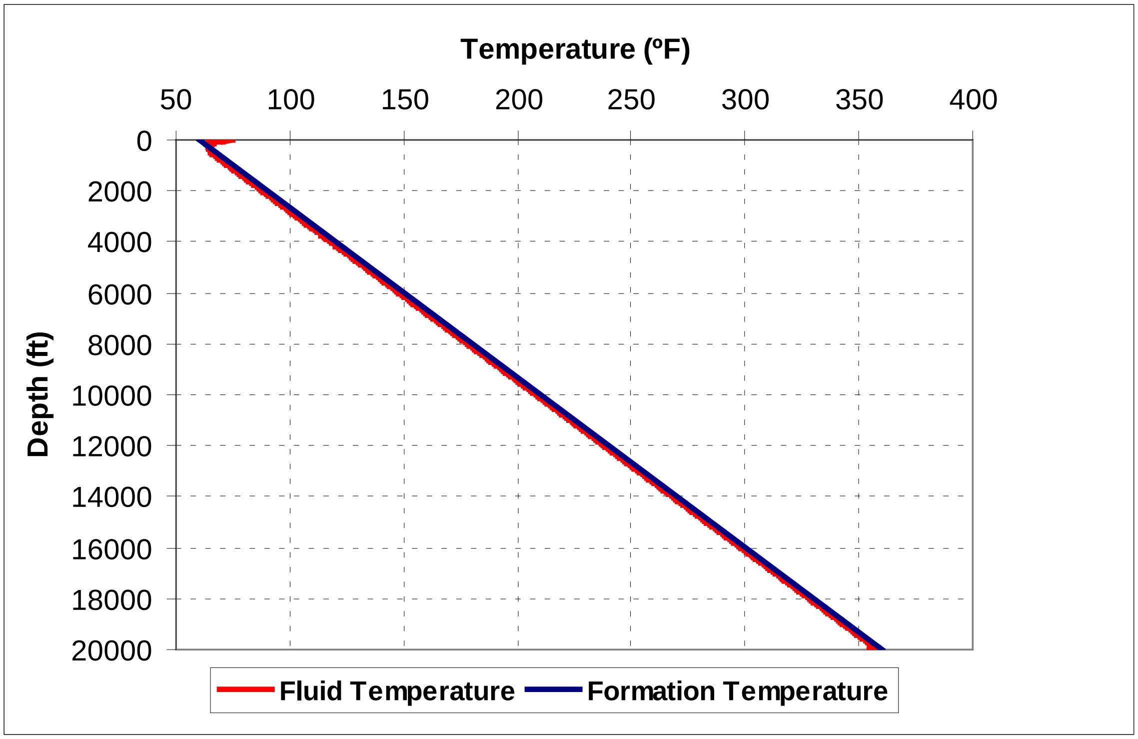

Figure 4: Temperature vs. Depth (N_2 Only, CT:1.25”, H.S:2.25”, Q=5 gpm)

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.

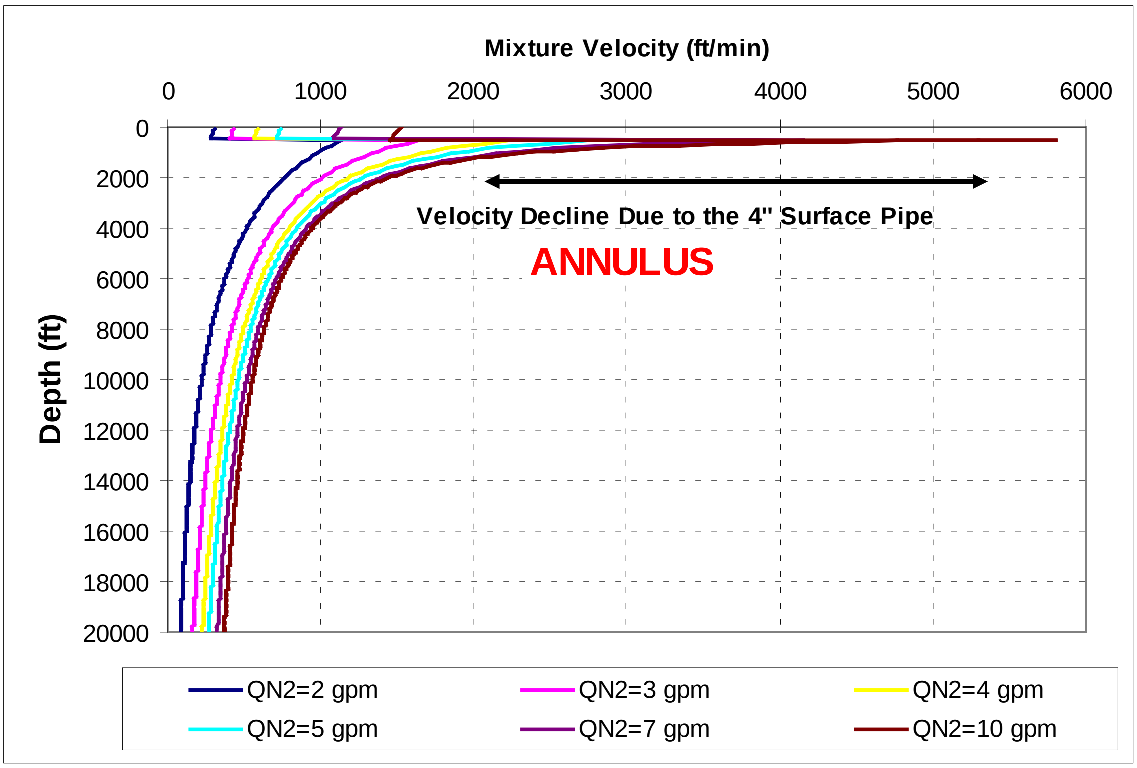

Figure 5: Mixture Velocity Profile for N_2 (CT:1.25”-HS:2.25”, N_2 Only)

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.

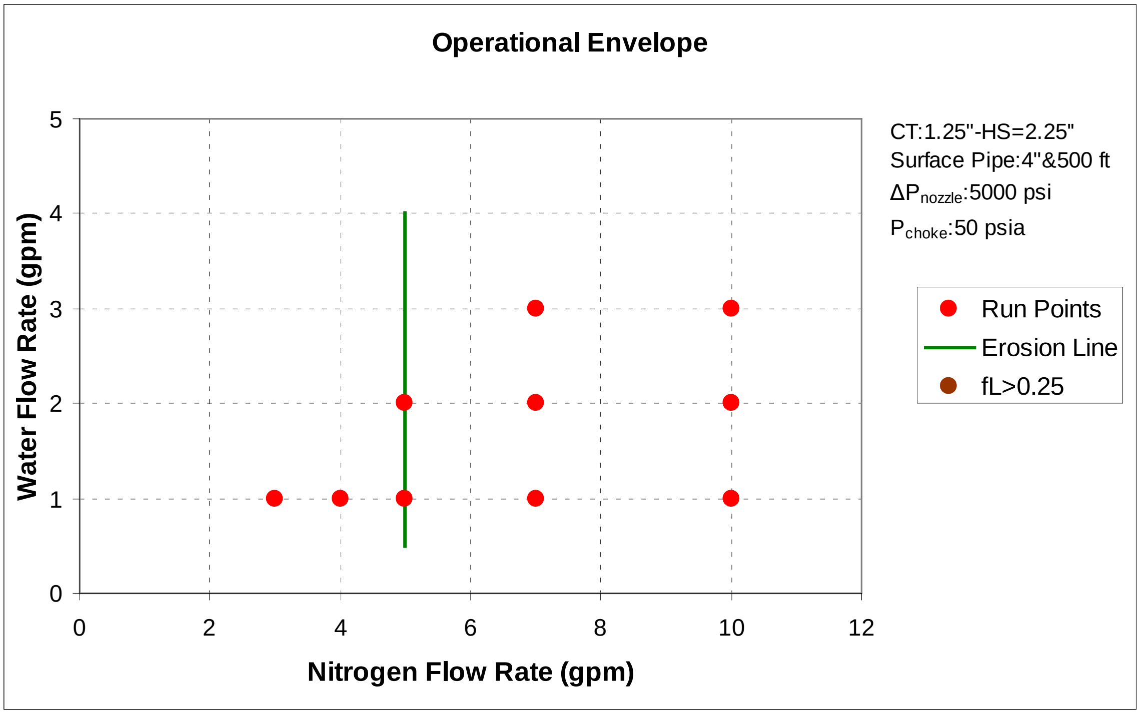

Figure 6: Operational Envelope for N_2 (CT:1.25”-HS:2.25”, With Water Addition)

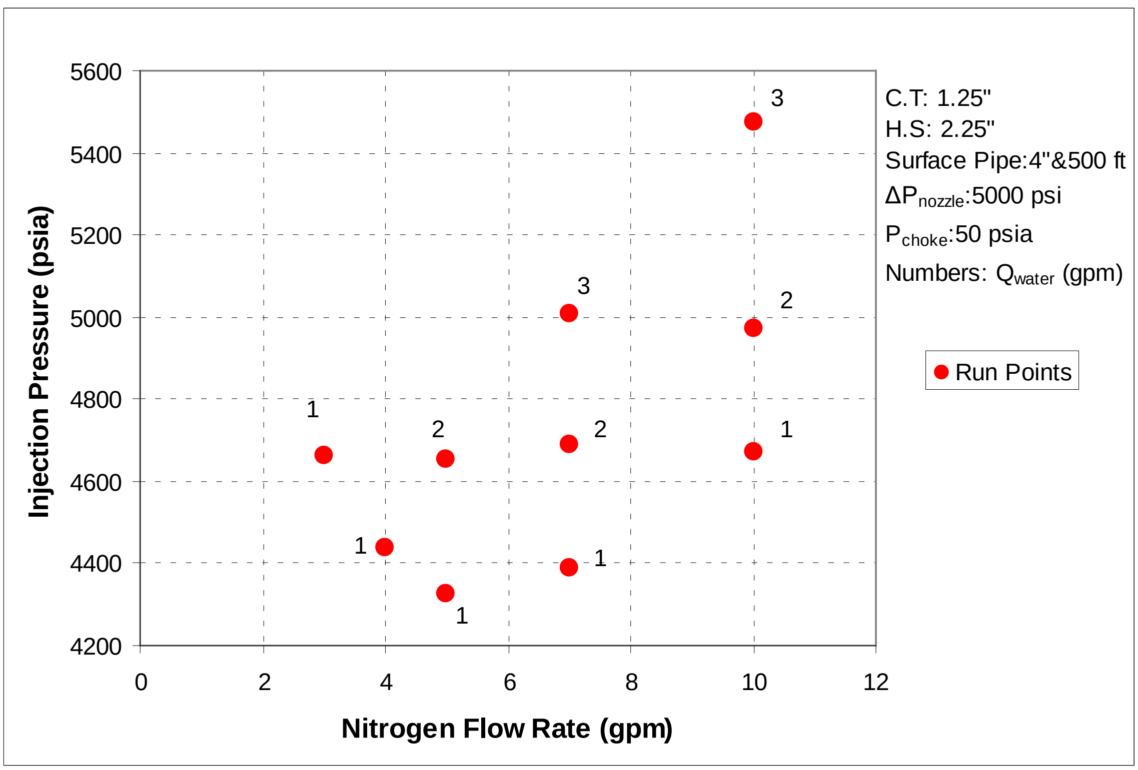

Figure 7: Flow Rate vs. Inj. Pressure for N_2 (CT:1.25”-HS:2.25”,With Water Addition)

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_2 with Water Addition, Q_{N2}=7 gpm, Q_w= 1gpm)

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.

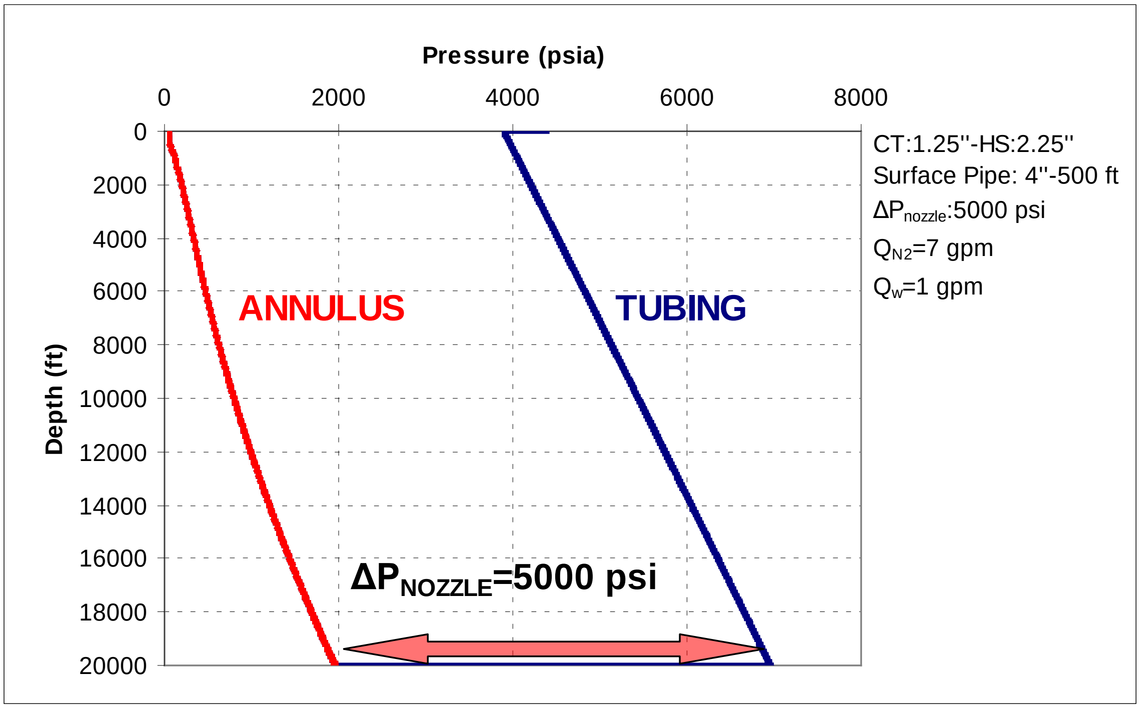

Figure 8: Pressure vs Depth (N_2 with Water, CT:1.25", H.S:2.25")

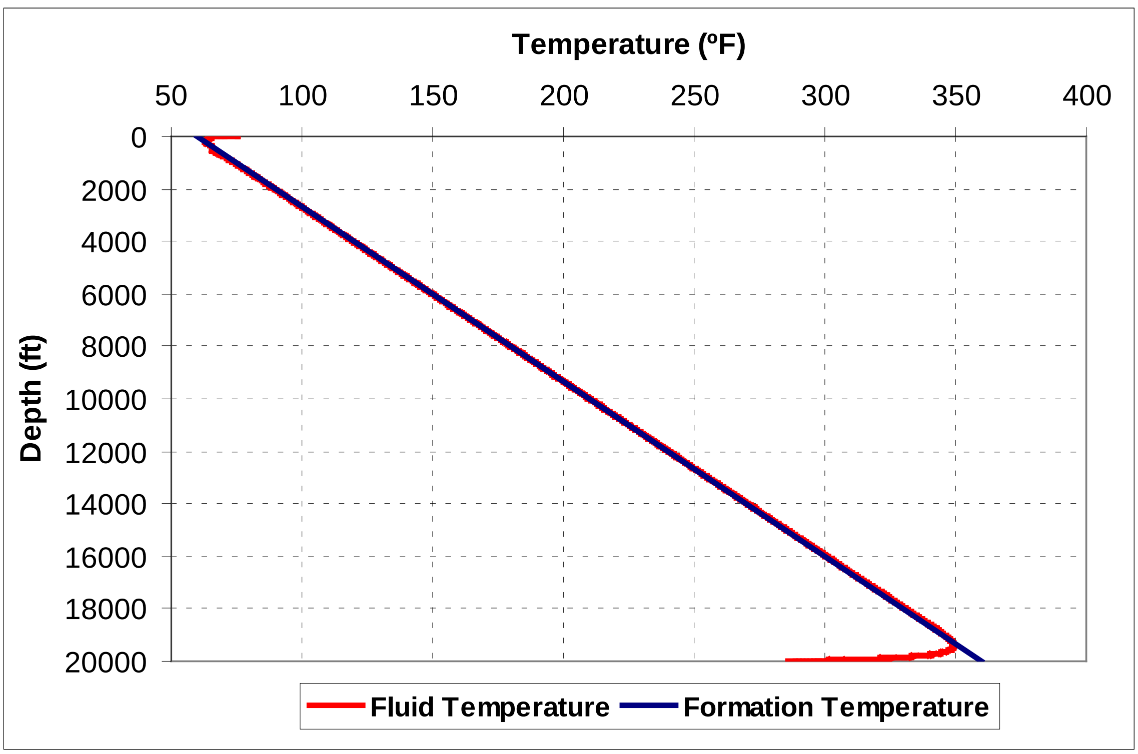

Figure 9: Temperature vs. Depth (N_2 With Water, CT:1.25", H.S:2.25")

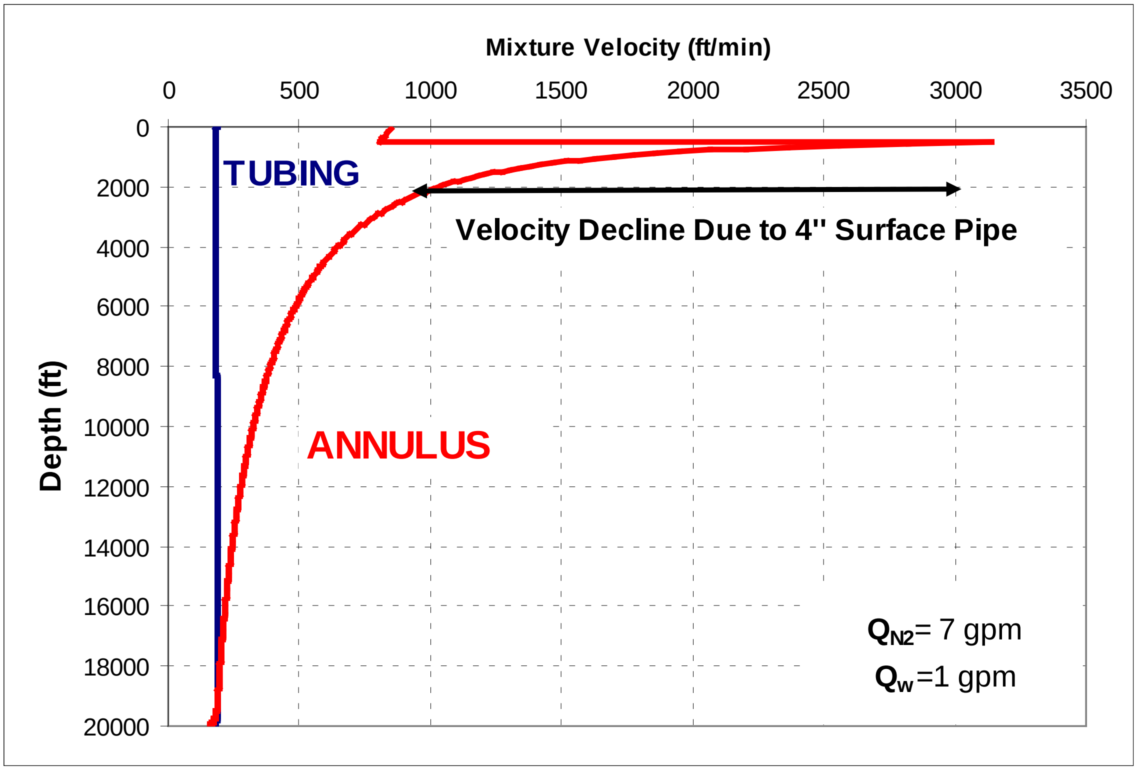

Figure 10: Velocity Profile (N_2 with Water, CT:1.25”, H.S:2.25”)

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.

Table 4: Casing and Cutting Sizes

Casing Sizes (in)	Cutting Sizes (micron)
3	25
4	50
5	75
7	100

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.

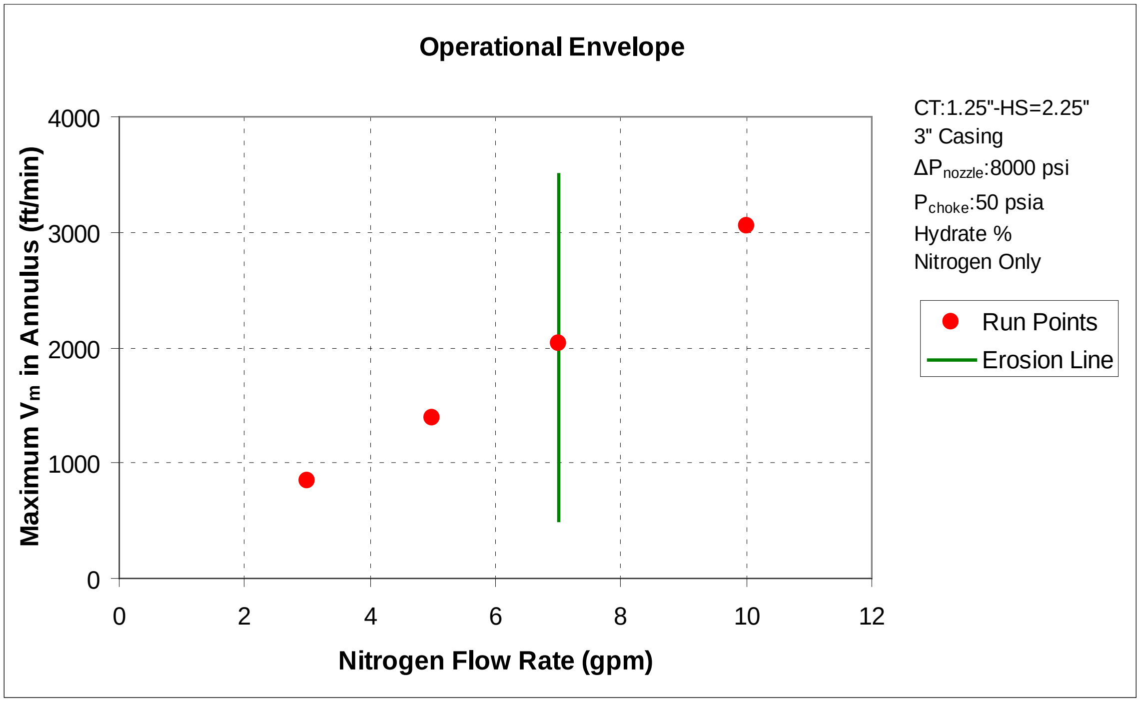

Figure 11: Operational Envelope for N_2 (3" Casing, N_2 Only)

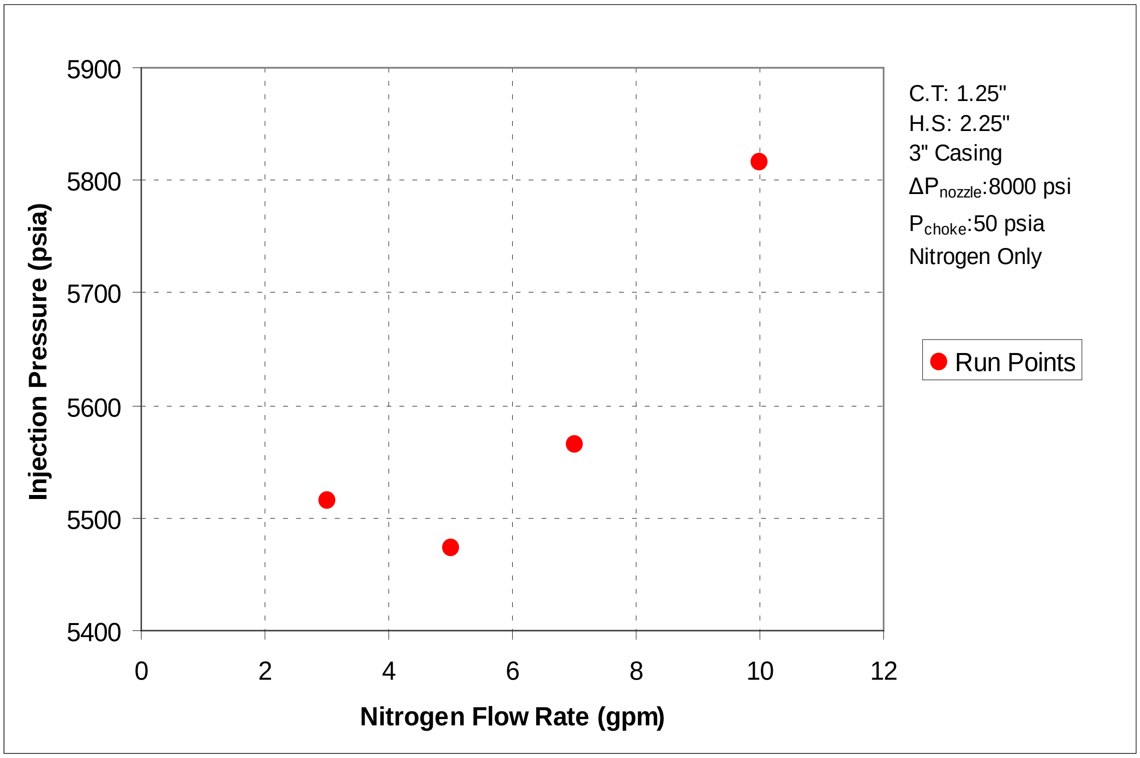

Figure 12: Flow Rate vs. Inj. Pressure for N_2 (3" Casing, N_2 Only)

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_2 Only, 3'' Casing, Q_{N2}=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.

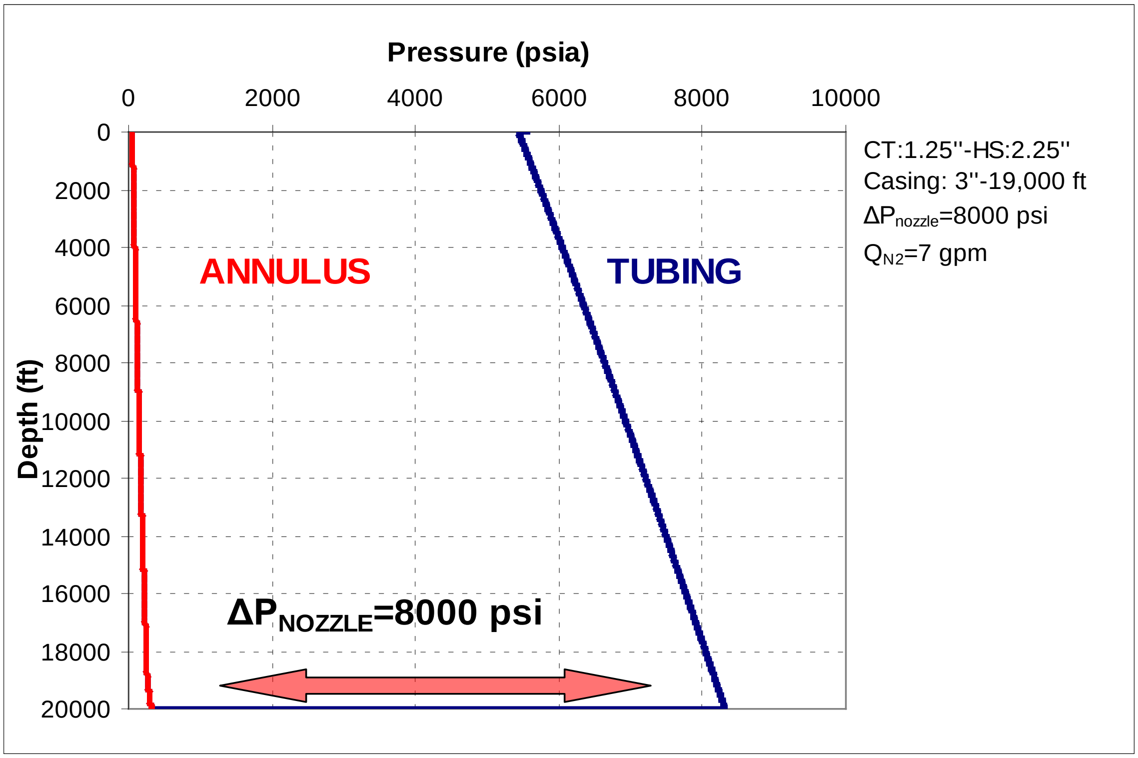

Figure 13: Pressure vs Depth (N_2 Only, 3'' Casing)

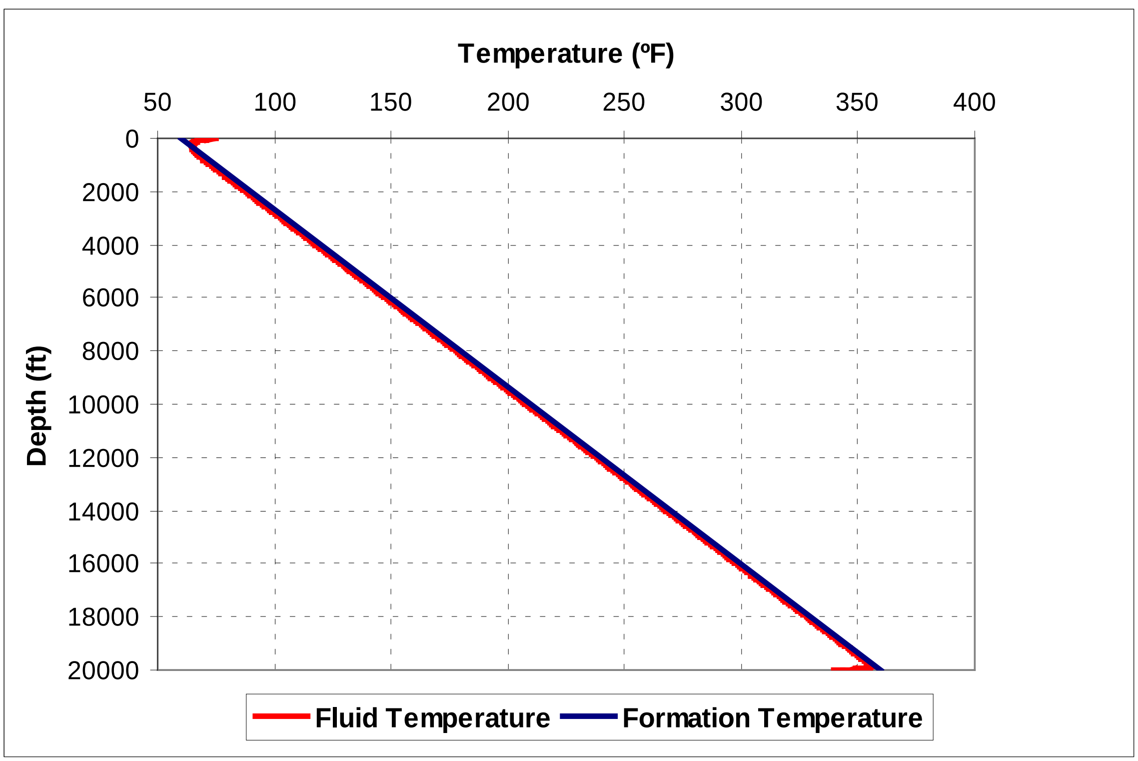

Figure 14: Temperature vs. Depth (N_2 Only, 3'' Casing)

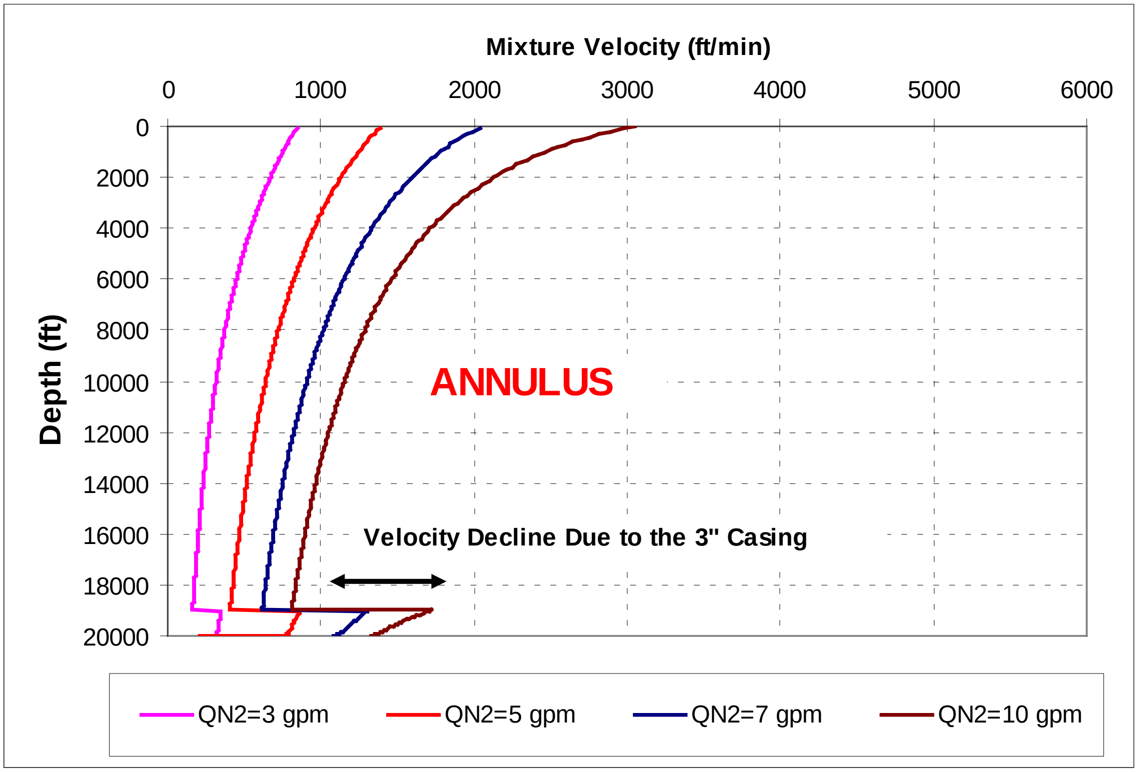

Figure 15: Velocity Profile (N_2 Only, 3'' Casing)

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.

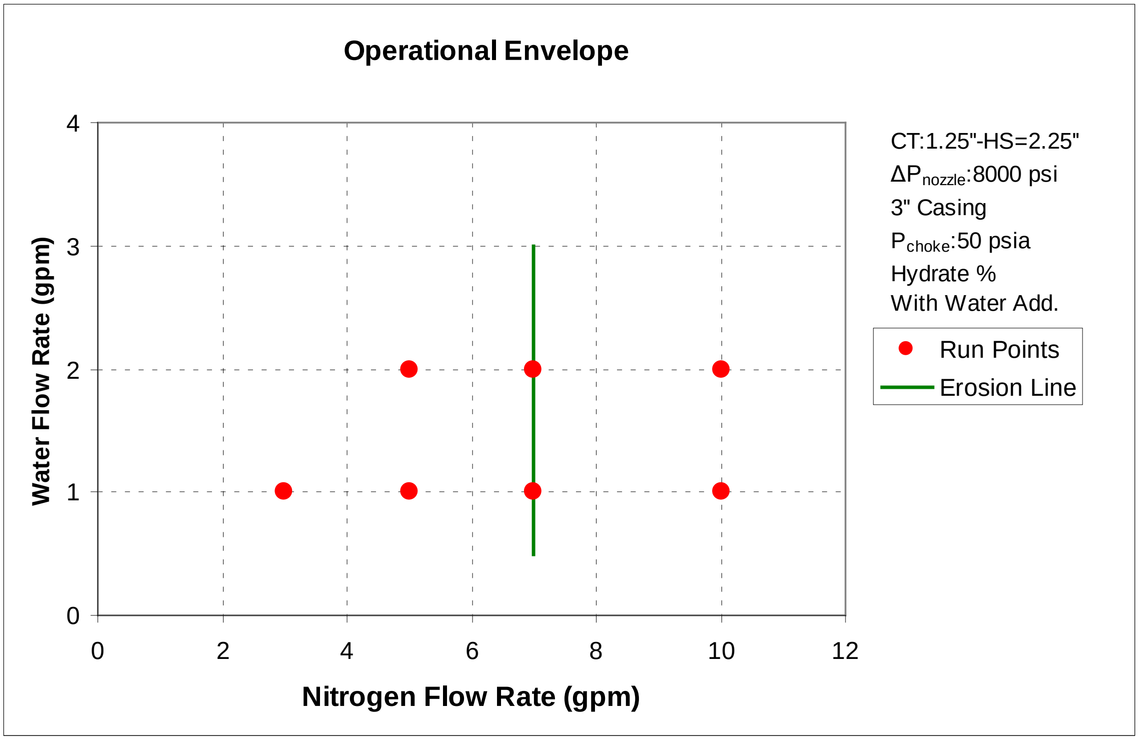

Figure 16: Operational Envelope for N_2 (3” Casing, With Water Addition)

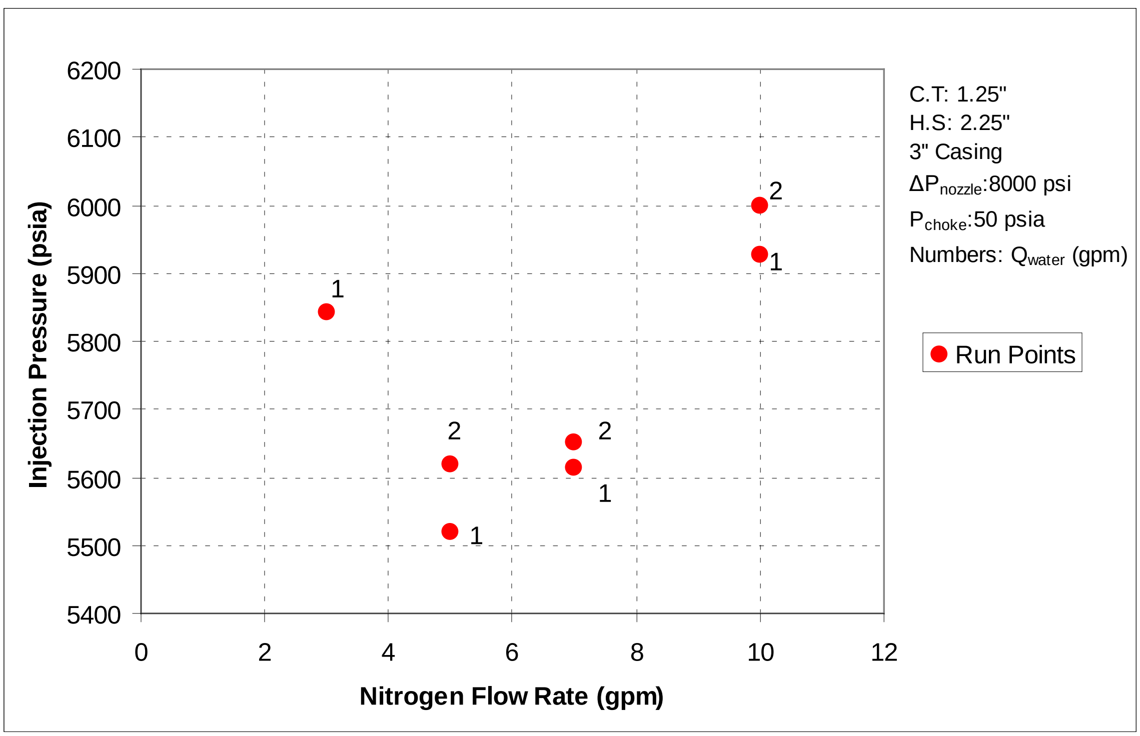

Figure 17: Flow Rate vs. Inj. Pressure for N_2 (3” Casing, With Water Addition)

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_2 With Water Addition, 3'', Q_{N2}=7 gpm, Q_w=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.

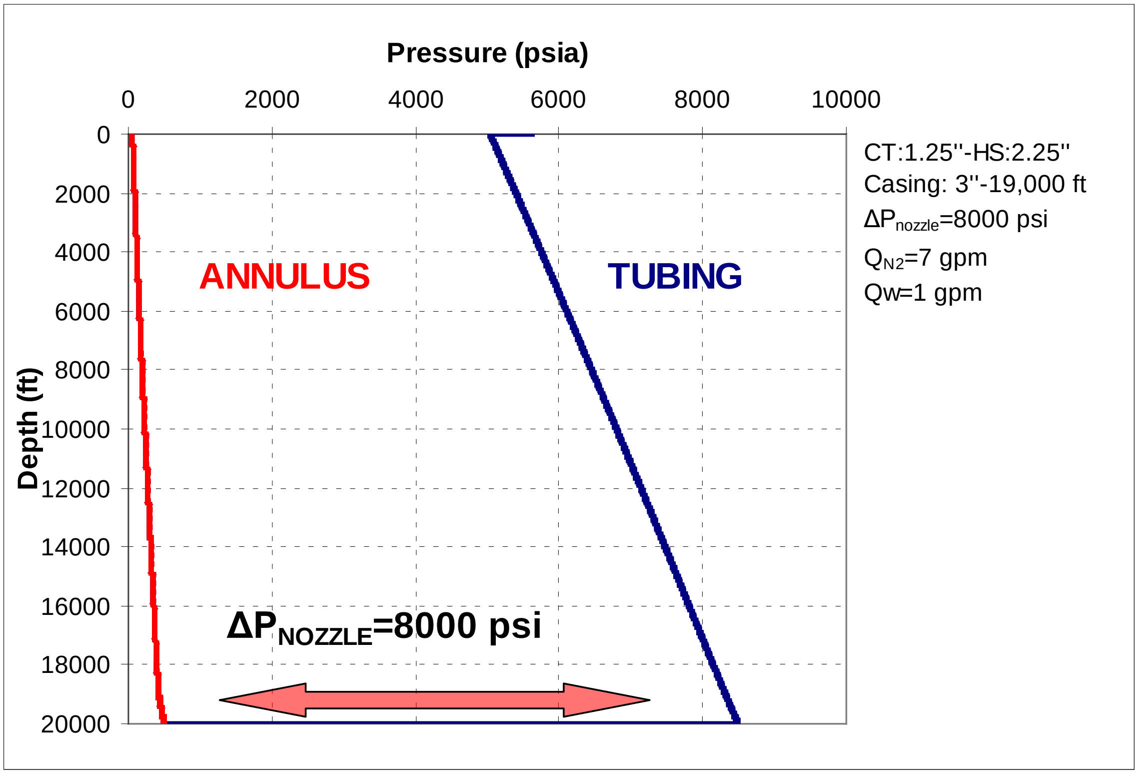

Figure 18: Pressure vs Depth (N_2 with Water Addition, 3'' Casing)

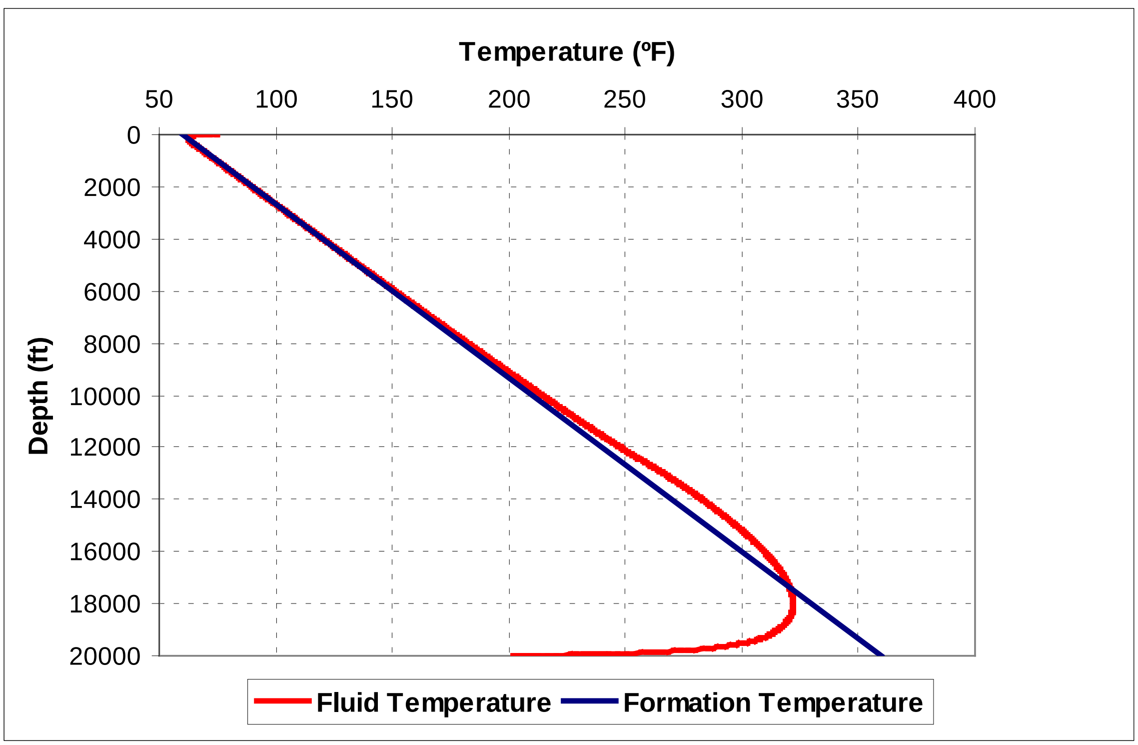

Figure 19: Temperature vs. Depth (N_2 with Water Addition, 3'' Casing)

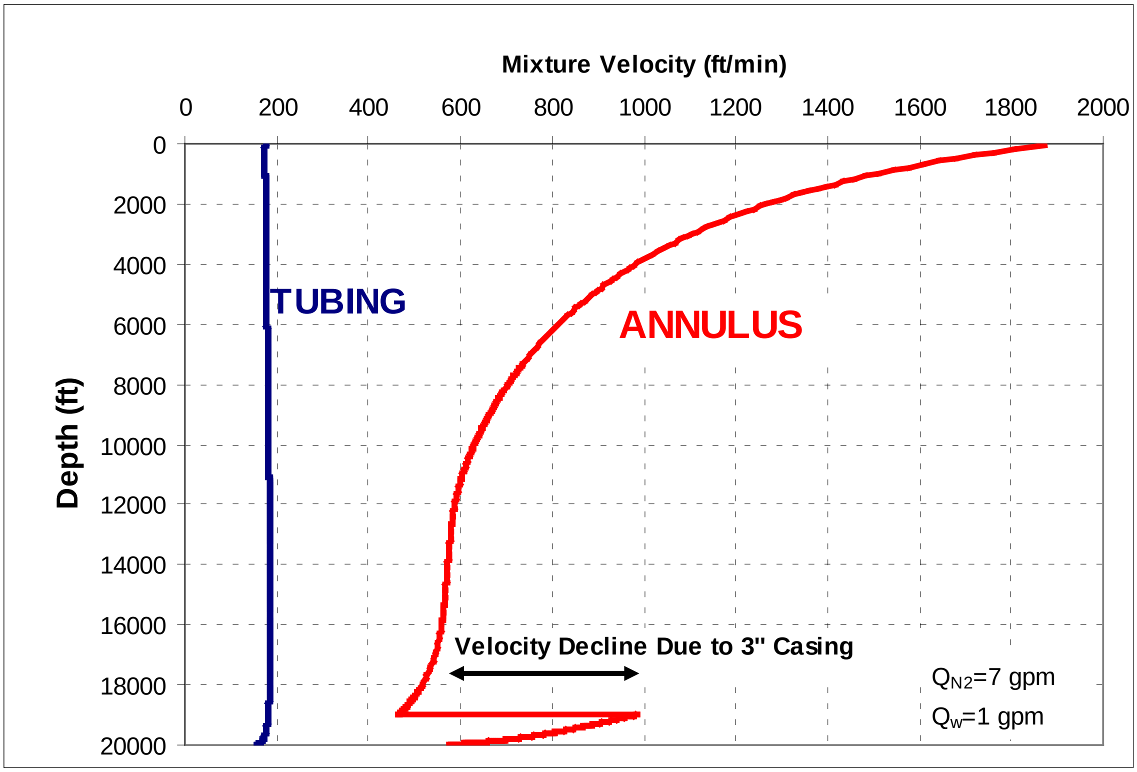

Figure 20: Velocity Profile (N_2 with Water Addition, 3'' Casing)

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.

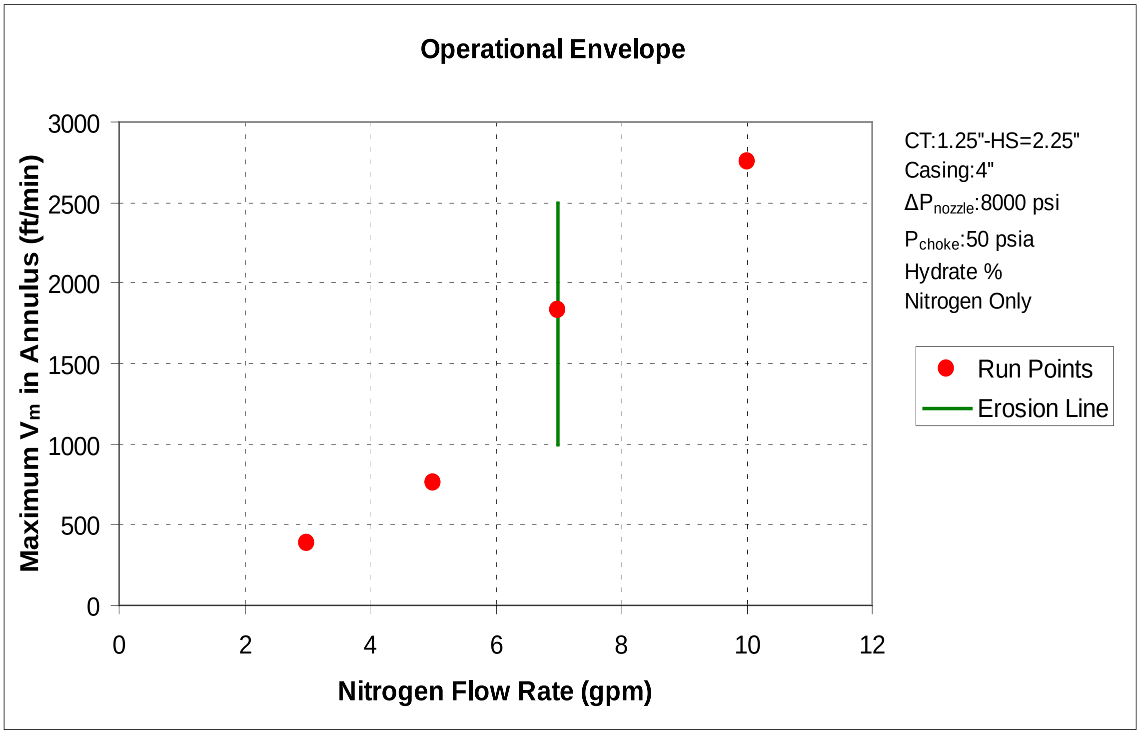

Figure 21: Operational Envelope for N_2 (4" Casing, Nitrogen Only)

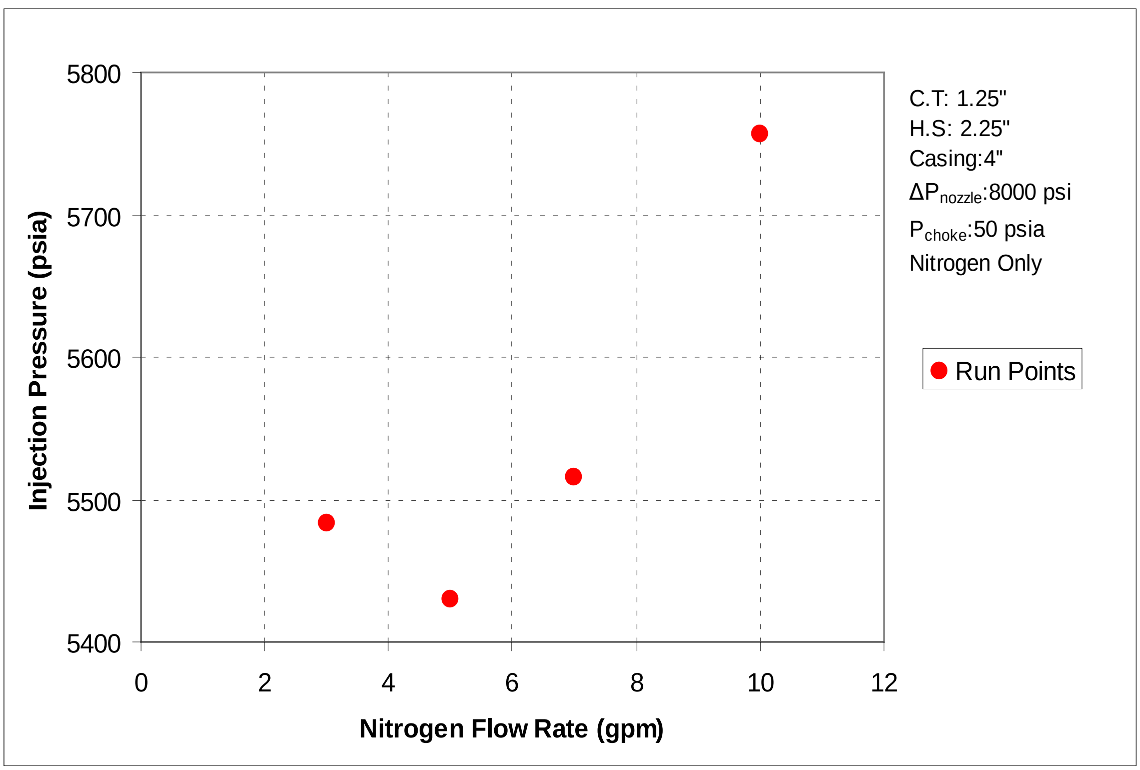

Figure 22: Flow Rate vs. Inj. Pressure for N_2 (4" Casing, Nitrogen Only)

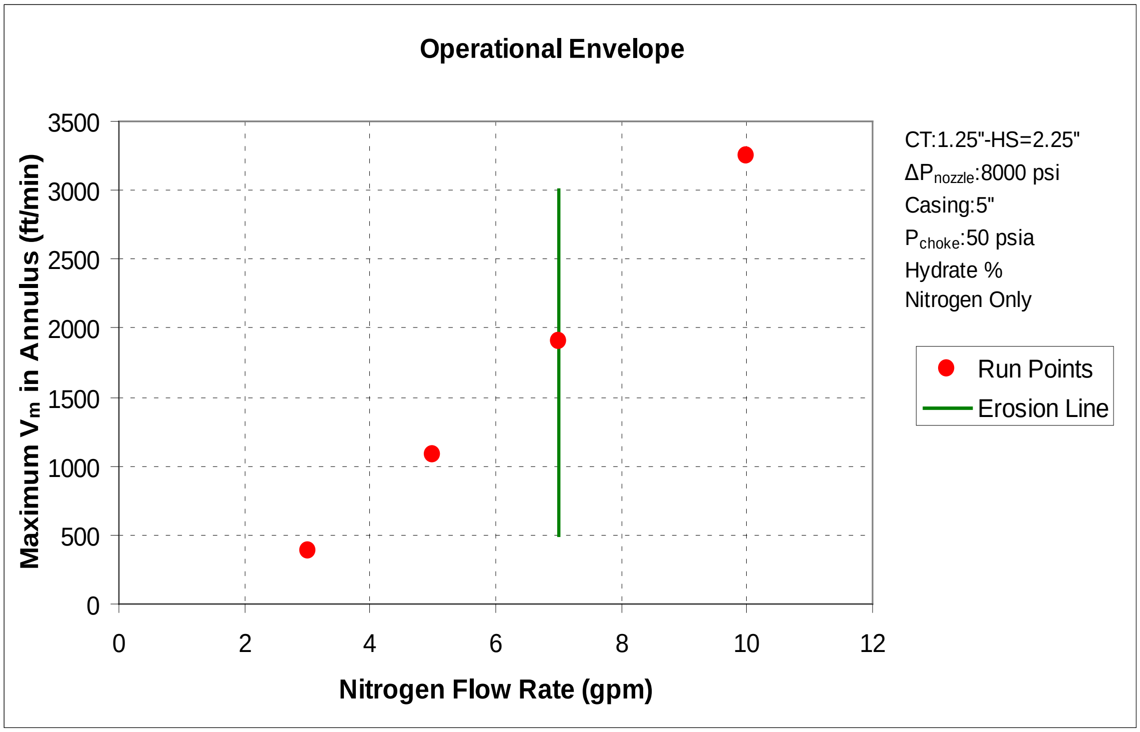

Figure 23: Operational Envelope for N_2 (5" Casing, Nitrogen Only)

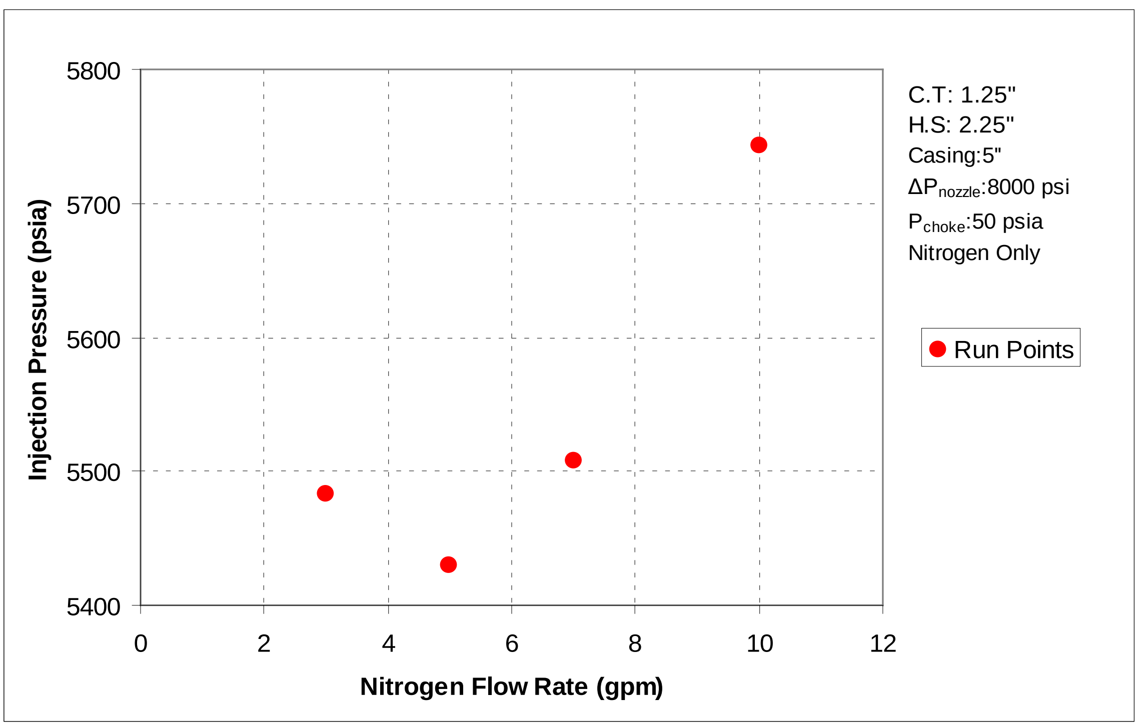

Figure 24: Flow Rate vs. Inj. Pressure for N_2 (5" Casing, Nitrogen Only)

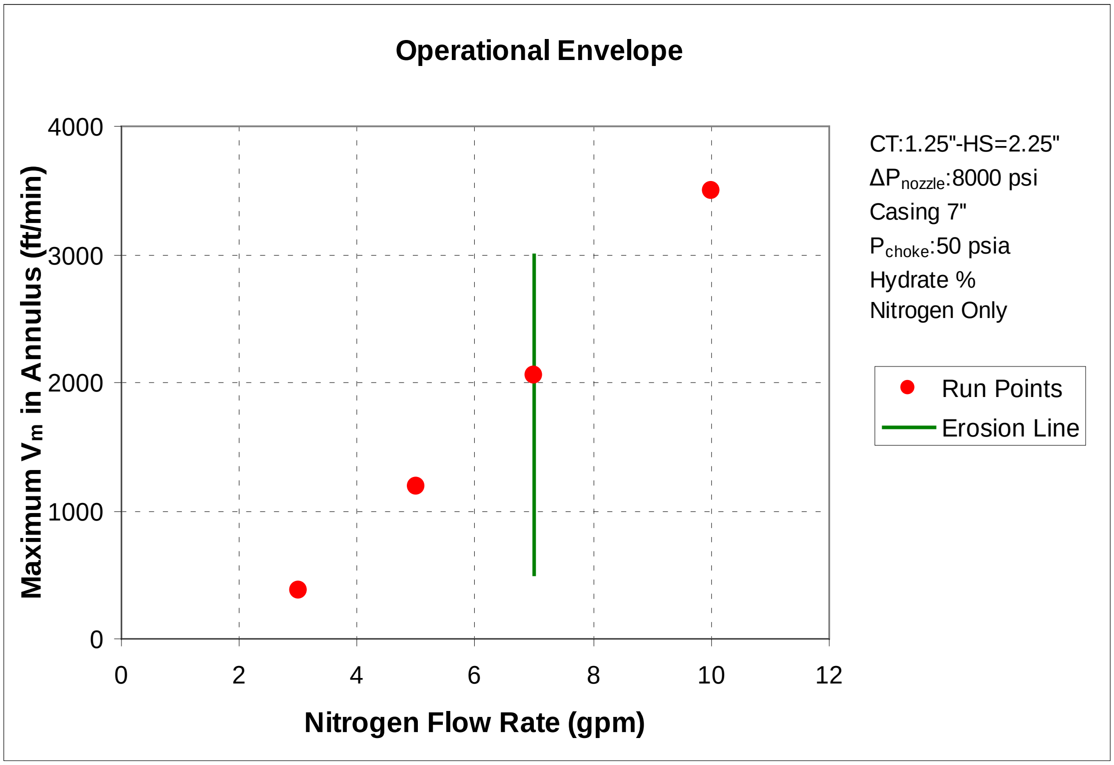

Figure 25: Operational Envelope for N_2 (7” Casing, Nitrogen Only)

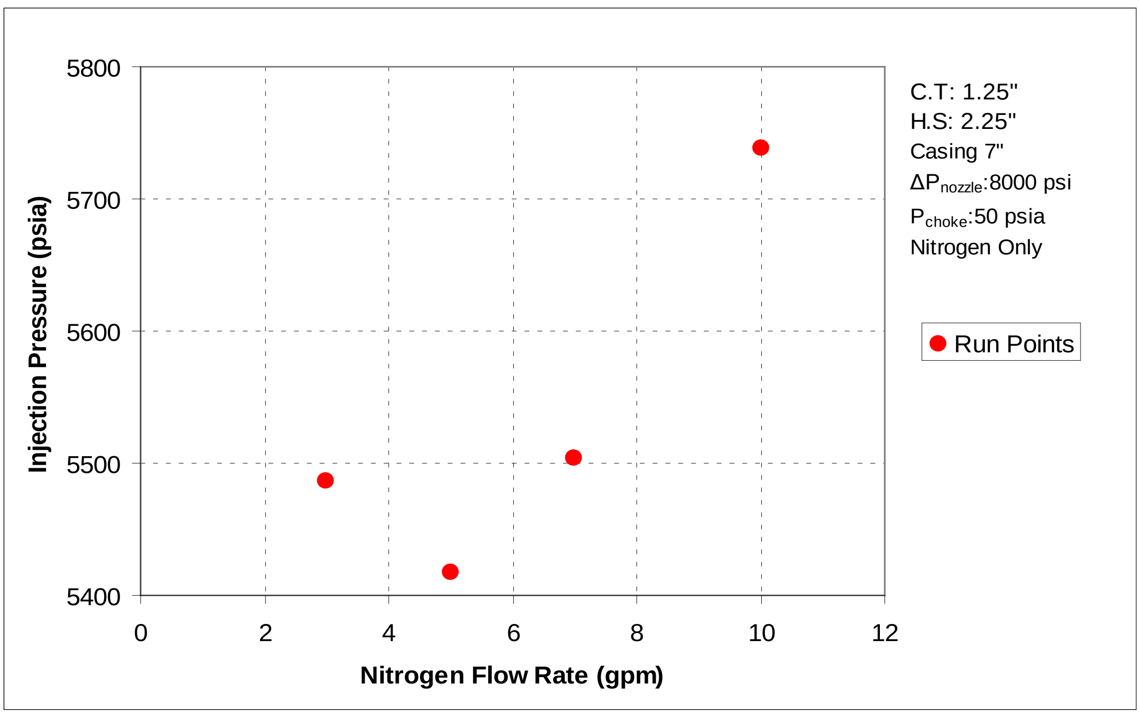

Figure 26: Flow Rate vs. Inj. Pressure for N_2 (7” Casing, Nitrogen Only)

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.

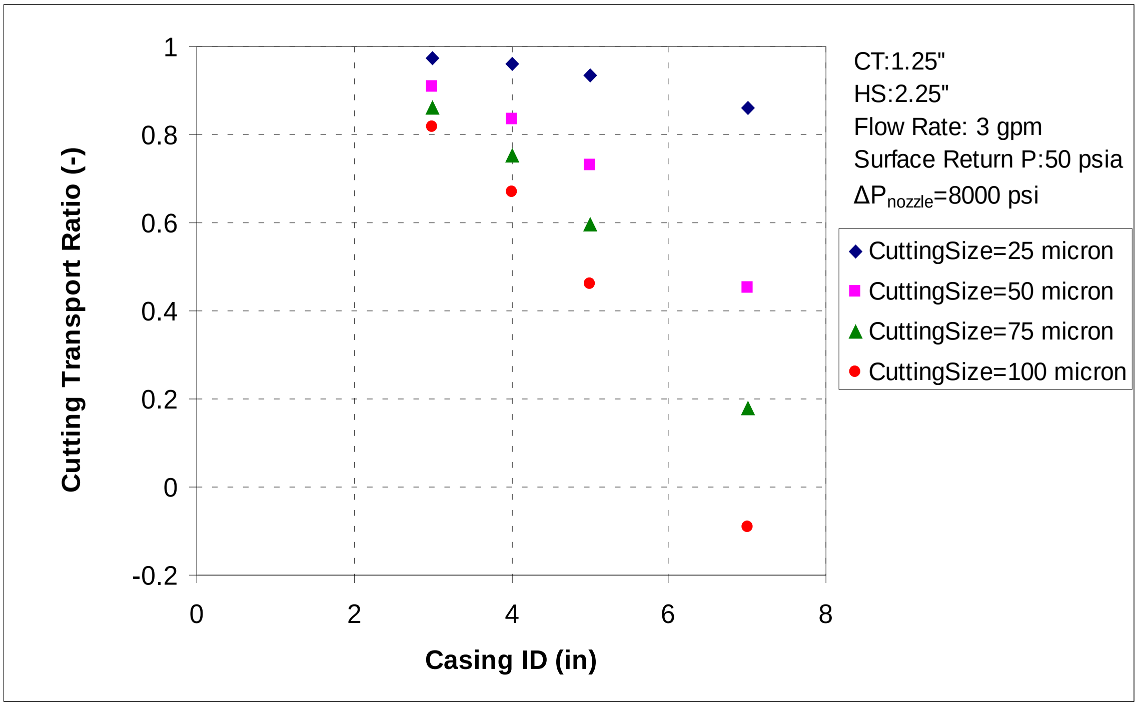

Figure 27: CTR vs. Casing ID (Nitrogen Only, Q_{N2}=3 gpm)

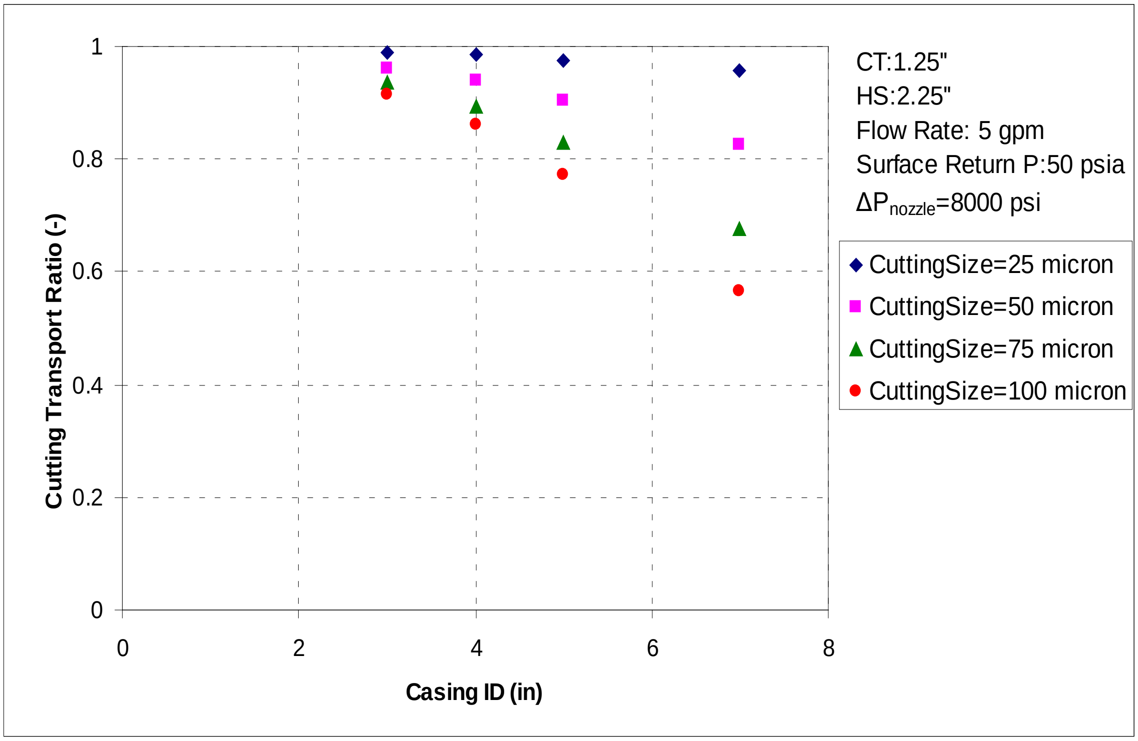

Figure 28: CTR vs. Casing ID (Nitrogen Only, Q_{N2}=5 gpm)

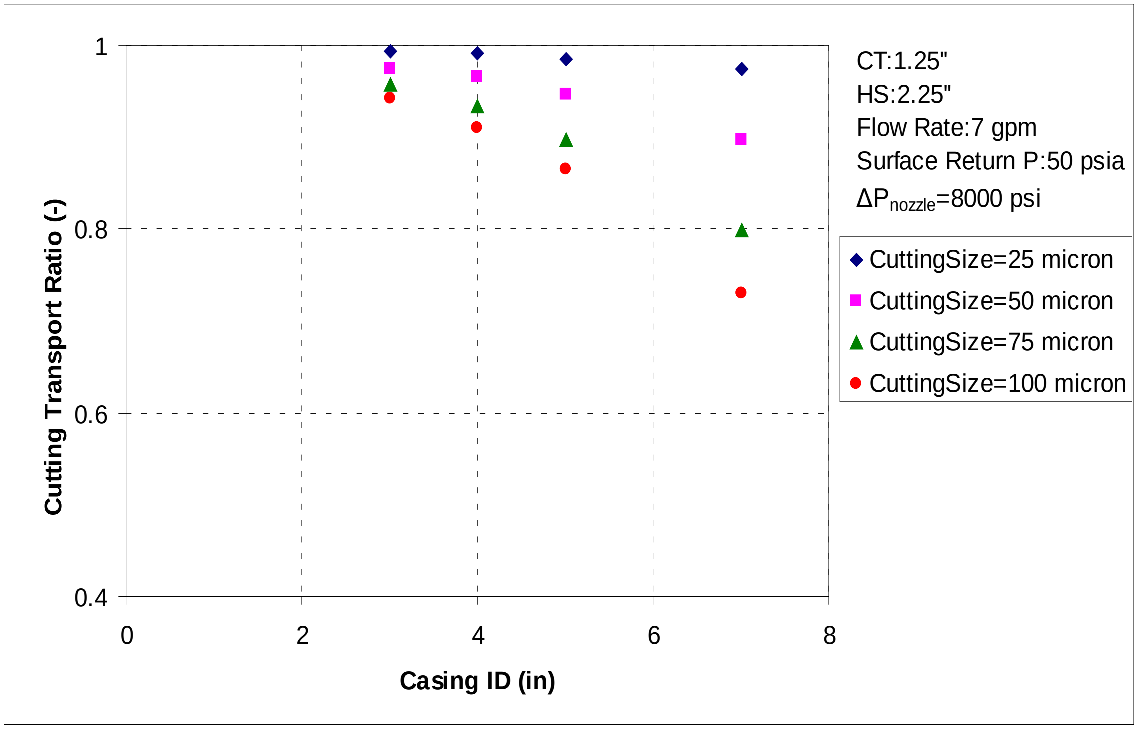

Figure 29: CTR vs. Casing ID (Nitrogen Only, Q_{N2}=7 gpm)

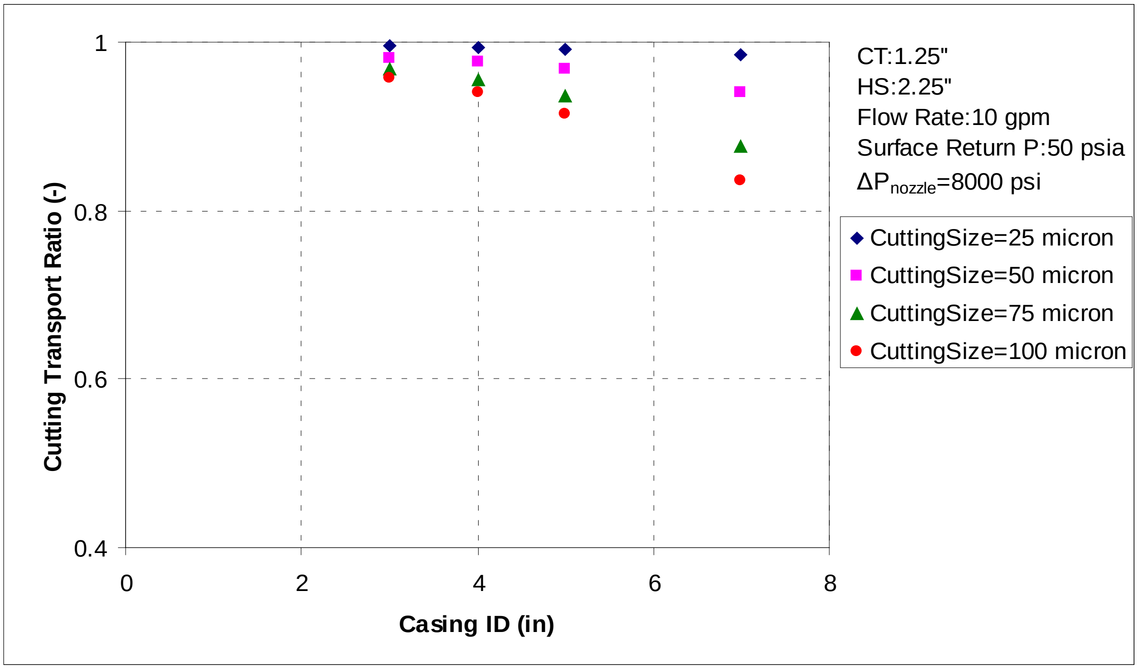

Figure 30: CTR vs. Casing ID (Nitrogen Only, Q_{N2}=10 gpm)

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

In this section, simulations were made for the wells which have 30º 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_2 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.

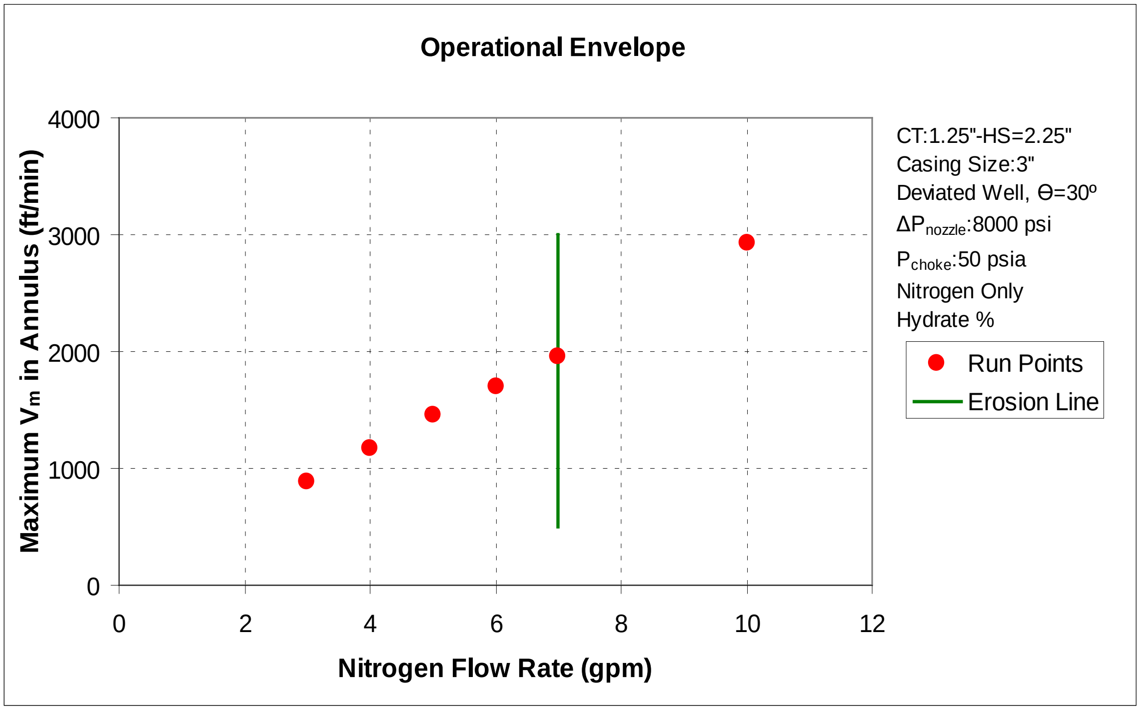

Figure 31: Operational Envelope for N_2 (3” Casing, N_2 Only, Deviated Well)

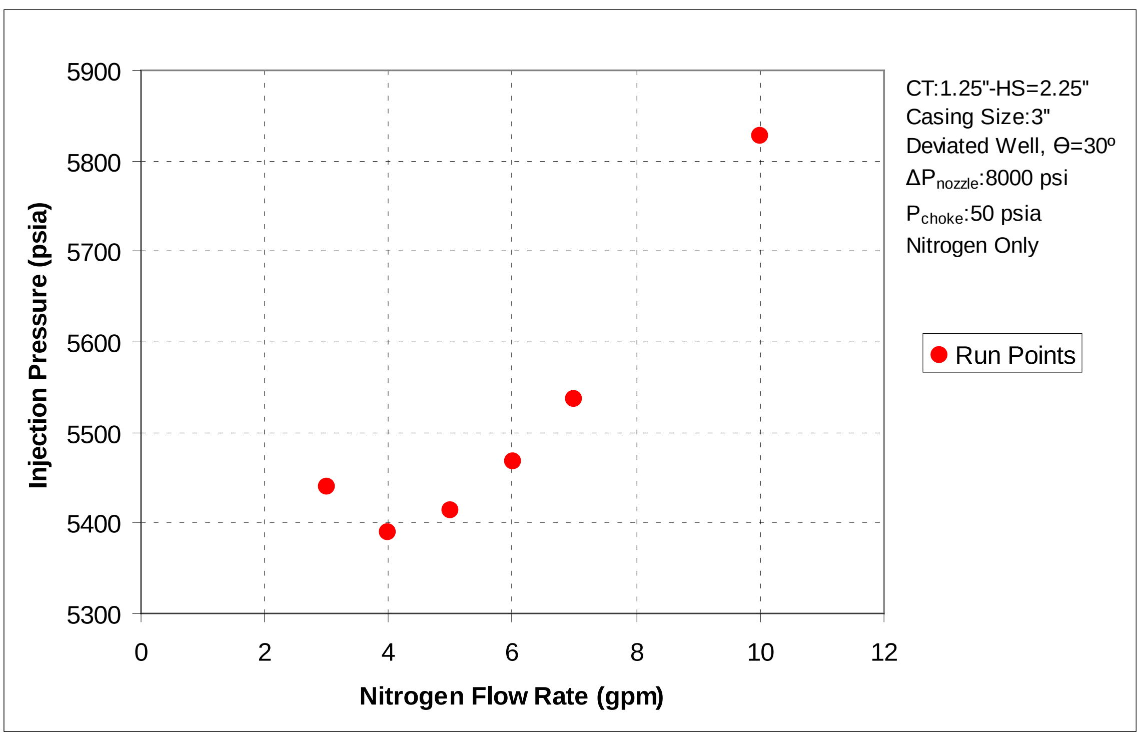

Figure 32: Flow Rate vs. Inj. Pressure for N_2 (3” Casing, N_2 Only, Deviated Well)

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_2 Only, 3'' Casing, Q_{N2}=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.

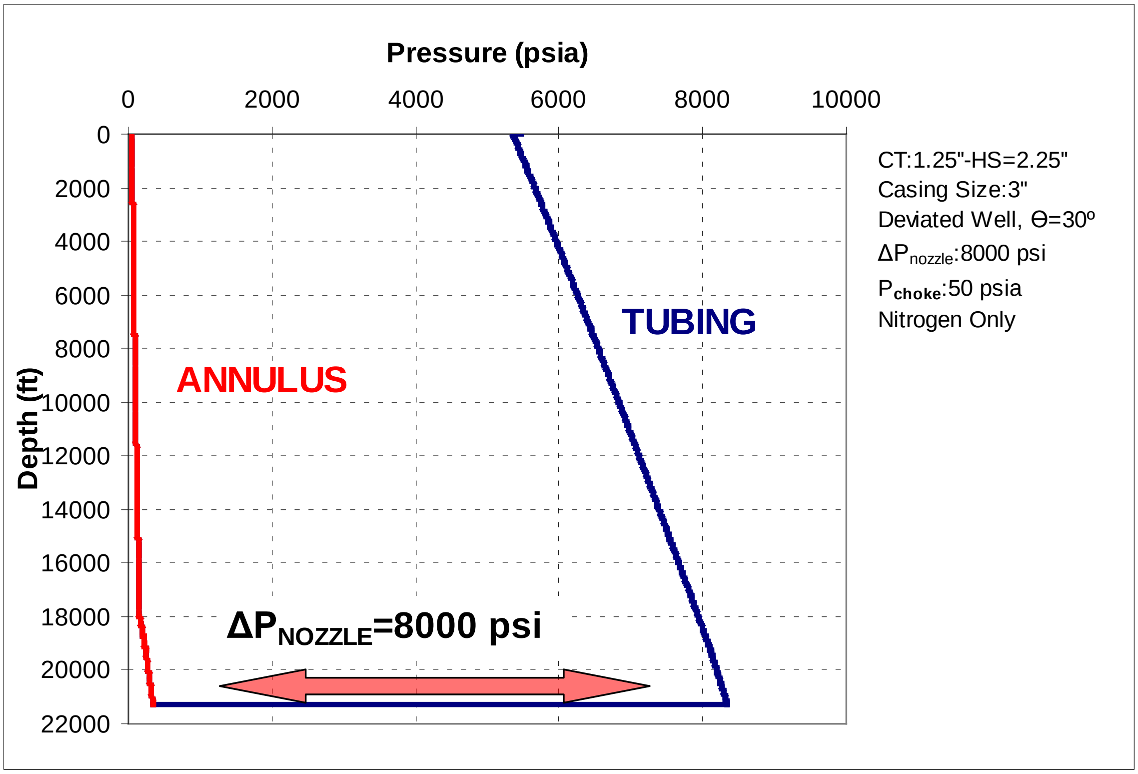

Figure 33: Pressure vs Depth (N_2 Only, 3'' Casing, Deviated Well)

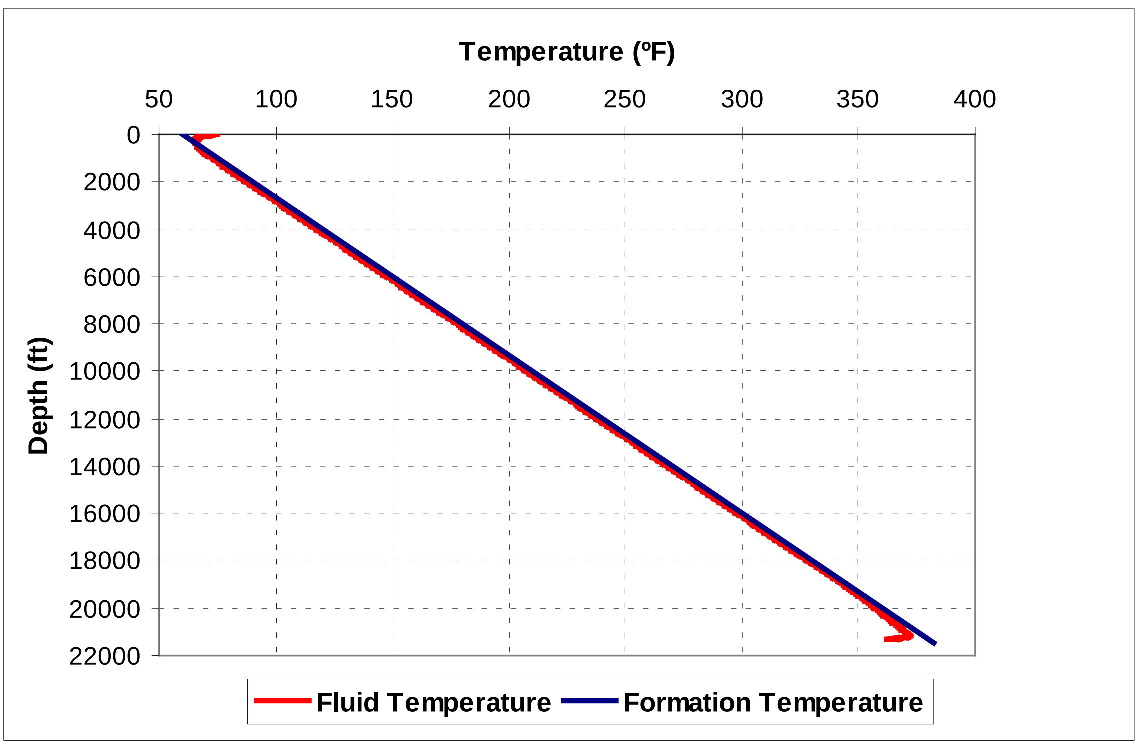

Figure 34: Temperature vs. Depth (N_2 Only, 3'' Casing, Deviated Well)

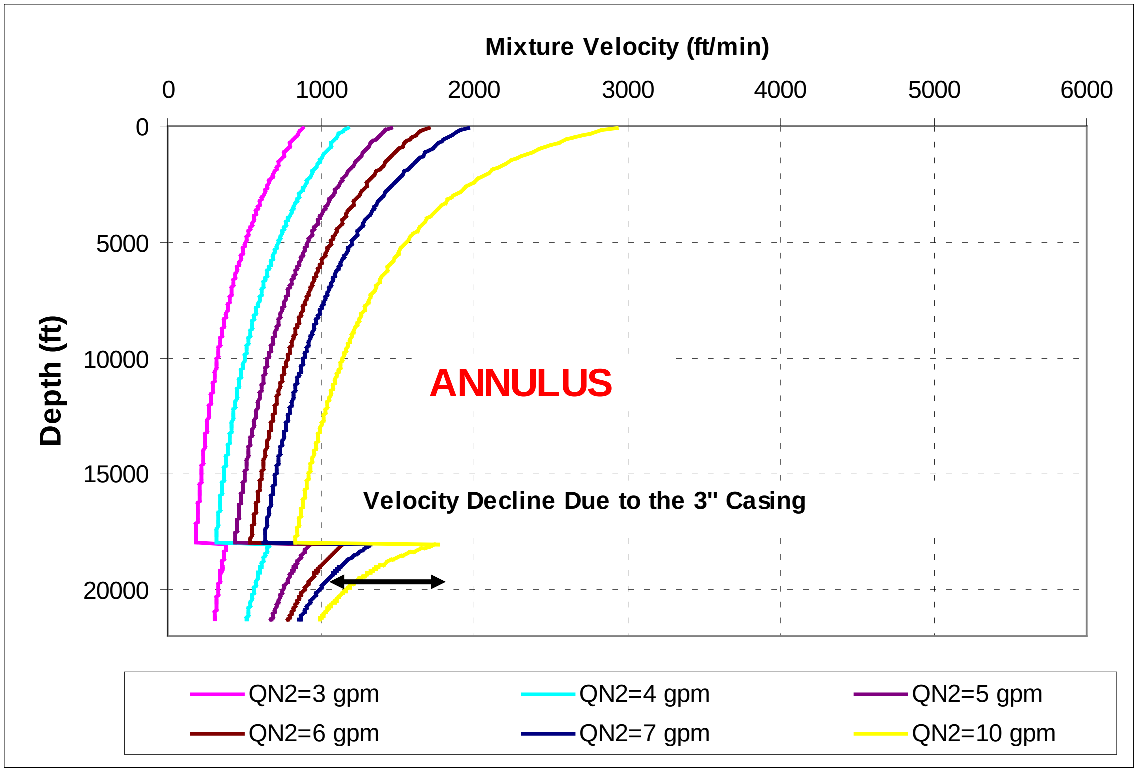

Figure 35: Velocity Profile (N_2 Only, 3'' Casing, Deviated Well)

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.

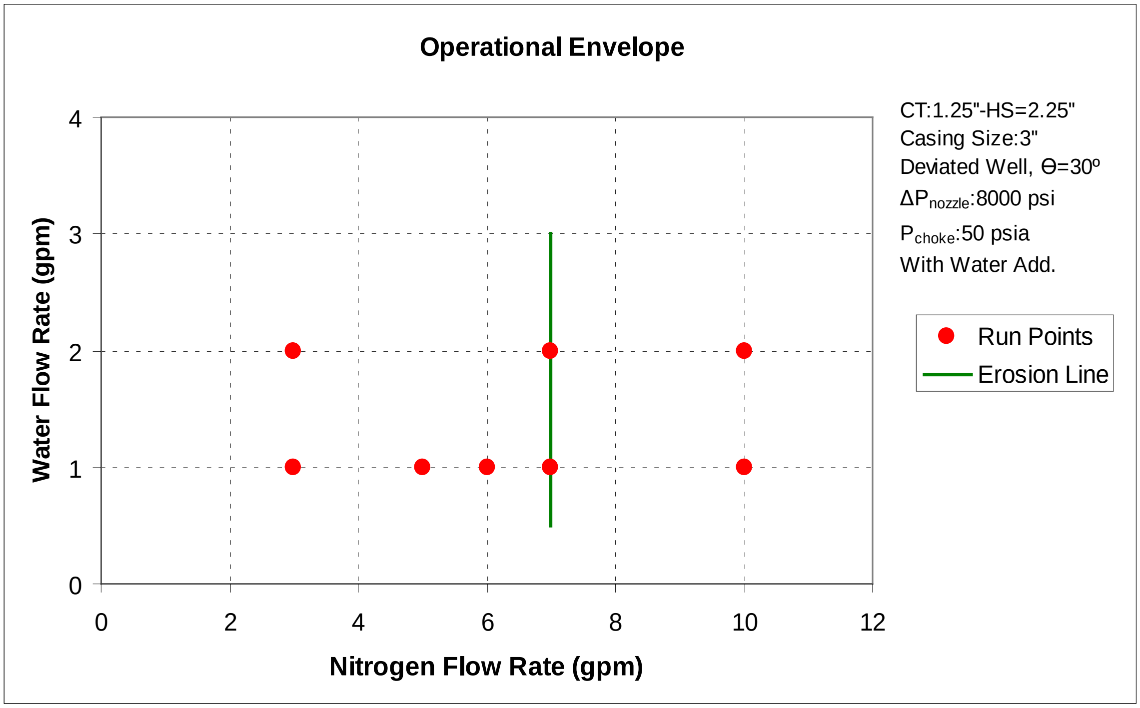

Figure 36: Operational Envelope for N_2 (3” Casing, With Water, Deviated Well)

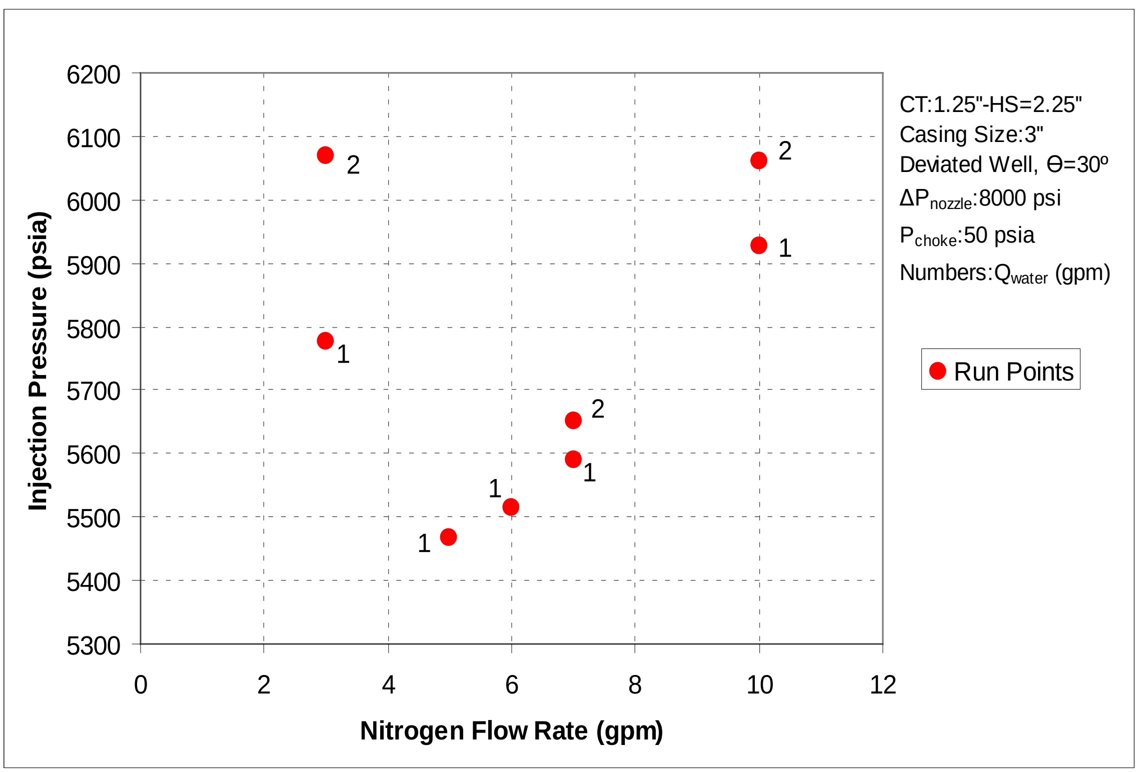

Figure 37: Flow Rate vs. Inj. Pressure for N_2 (3” Casing, With Water, Deviated Well)

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_2 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.

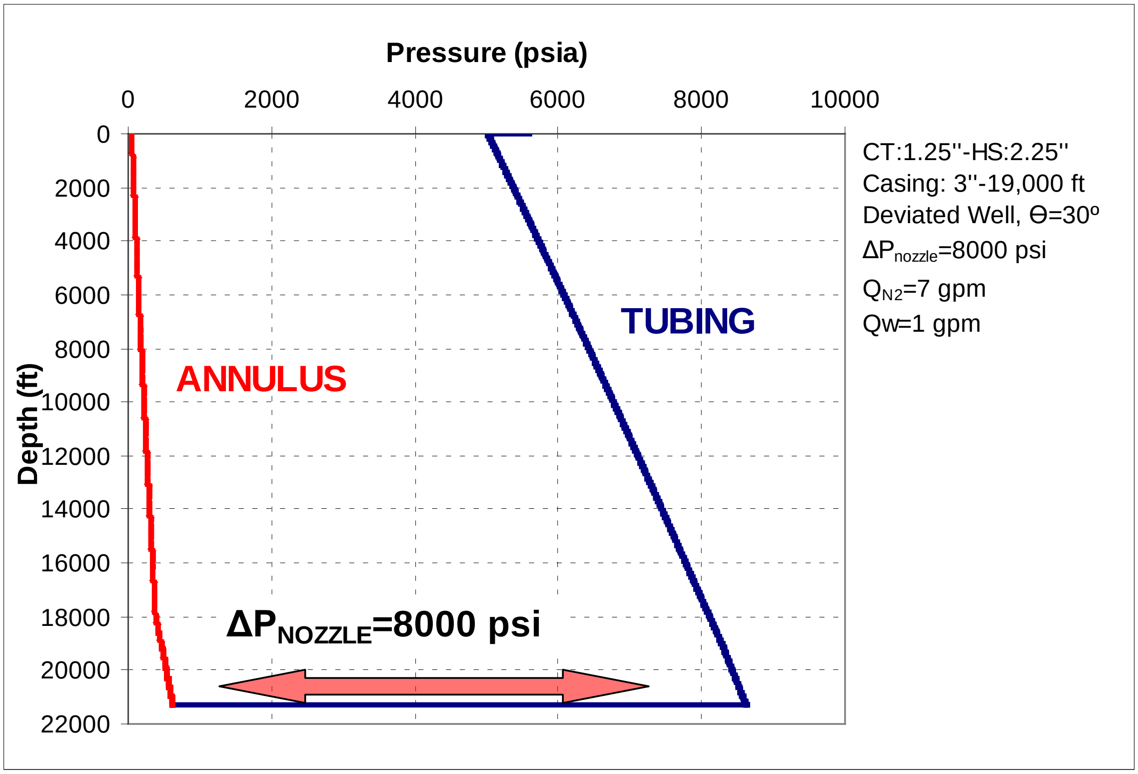

Figure 38: Pressure vs Depth (N_2 with Water, 3'' Casing, Deviated Well)

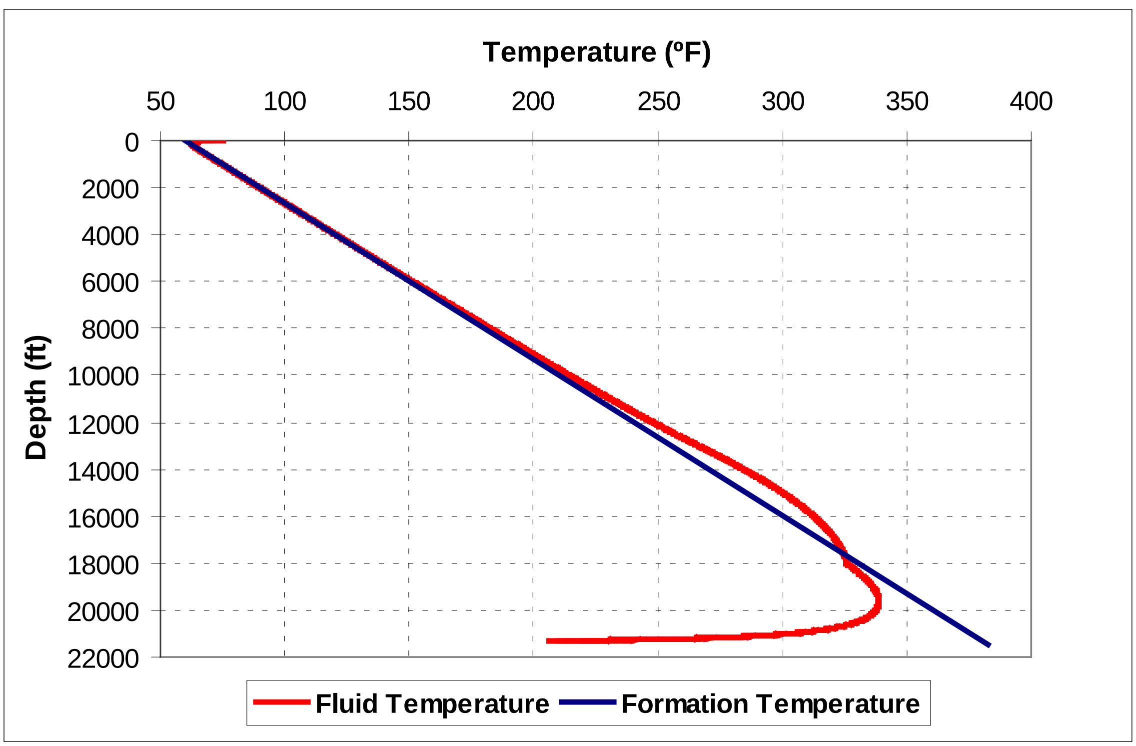

Figure 39: Temperature vs. Depth (N_2 with Water, 3'' Casing, Deviated Well)

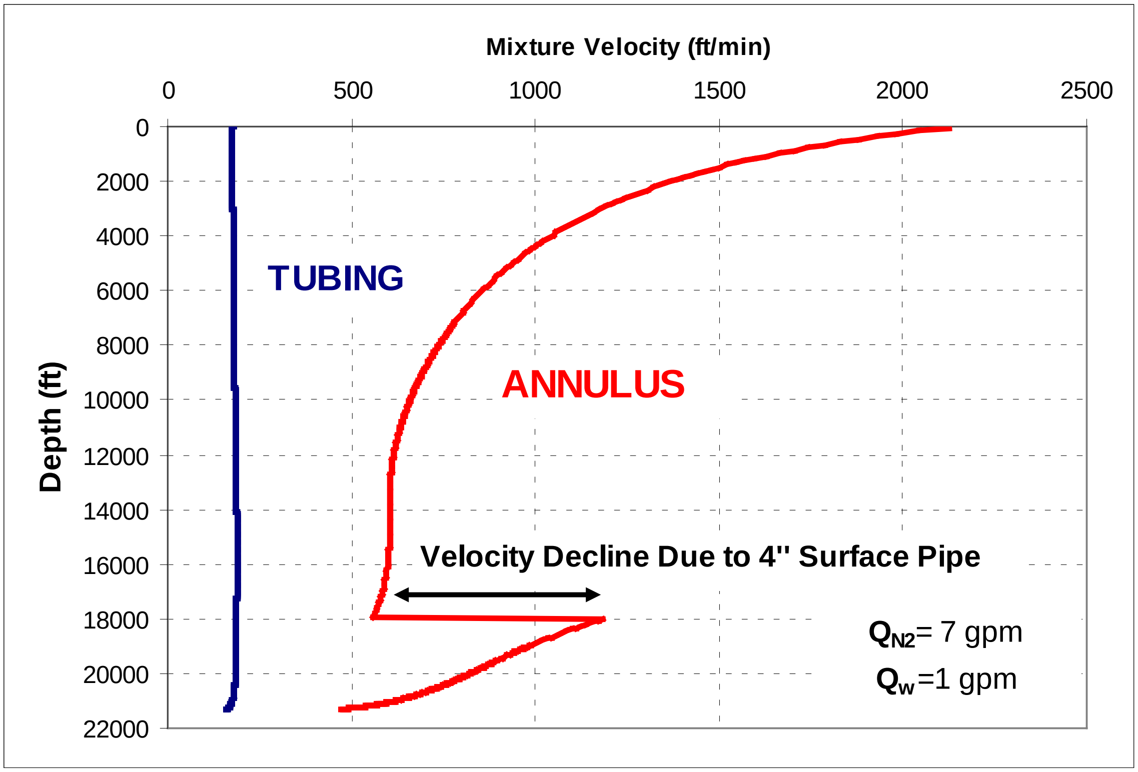

Figure 40: Velocity Profile (N_2 with Water, 3’’ Casing, Deviated Well)

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.

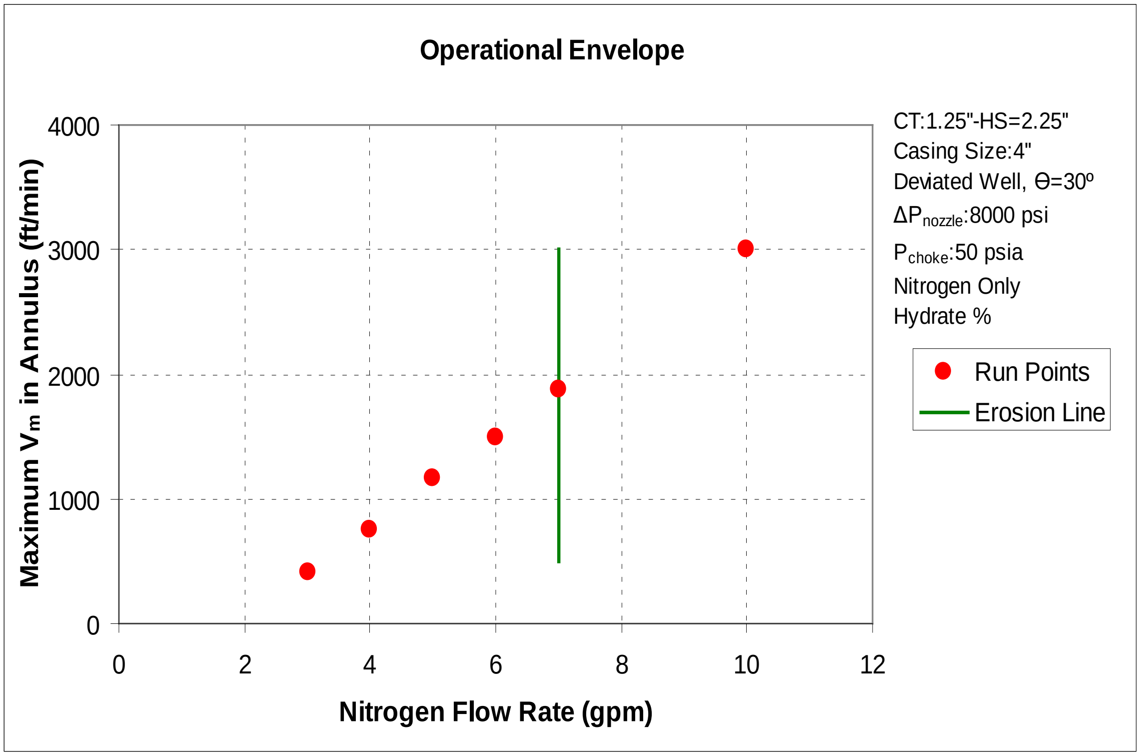

Figure 41: Operational Envelope for N_2 (N_2 Only, 4” Casing, Deviated Well)

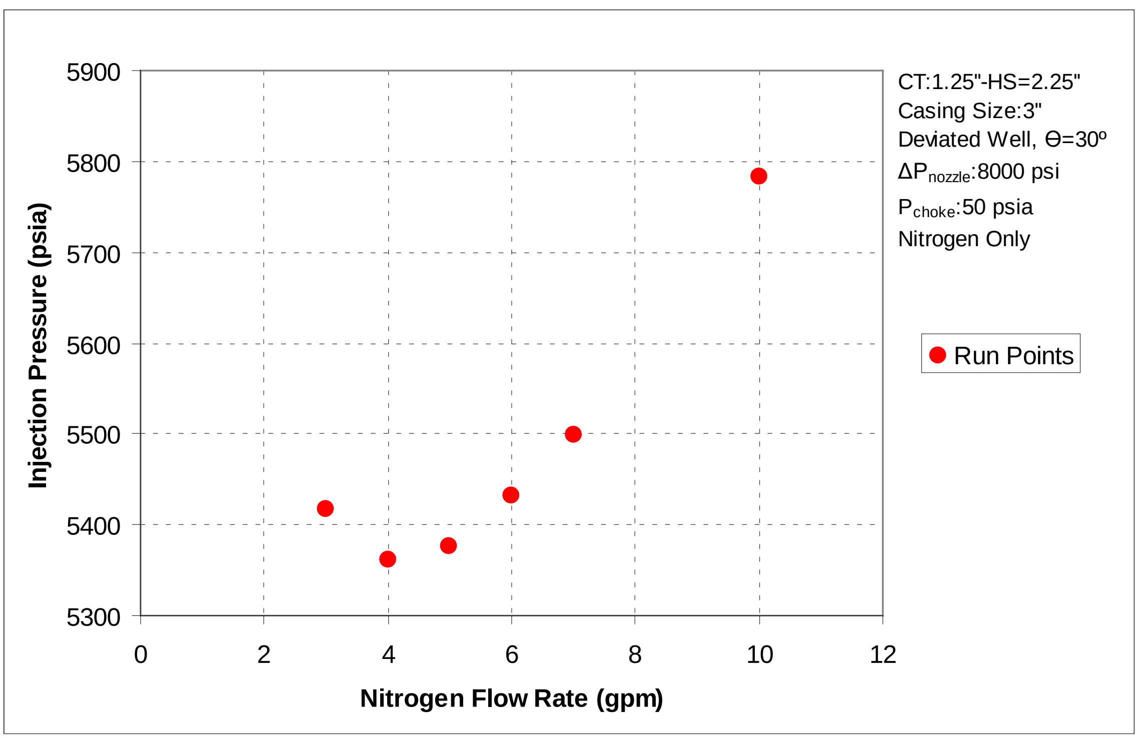

Figure 42: Flow Rate vs. Inj. Pressure for N_2 (N_2 Only, 4’’ Casing, Deviated Well)

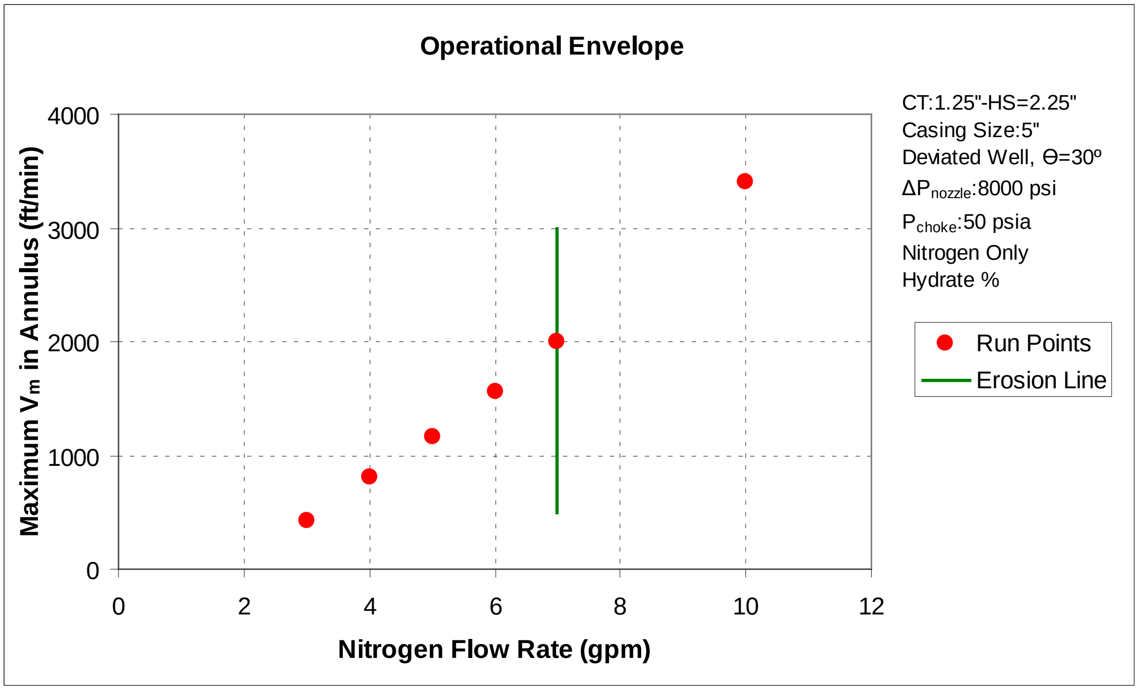

Figure 43: Operational Envelope for N_2 (N_2 Only, 5” Casing, Deviated Well)

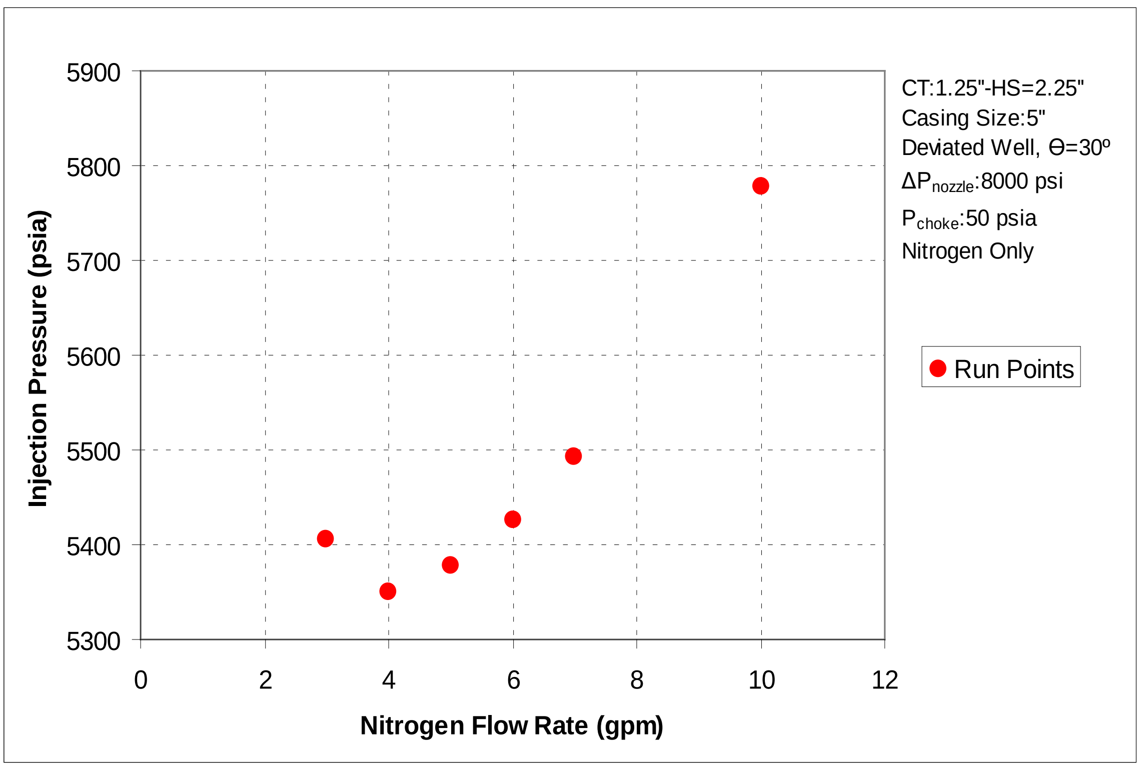

Figure 44: Flow Rate vs. Inj. Pressure for N_2 (N_2 Only, 5” Casing, Deviated Well)

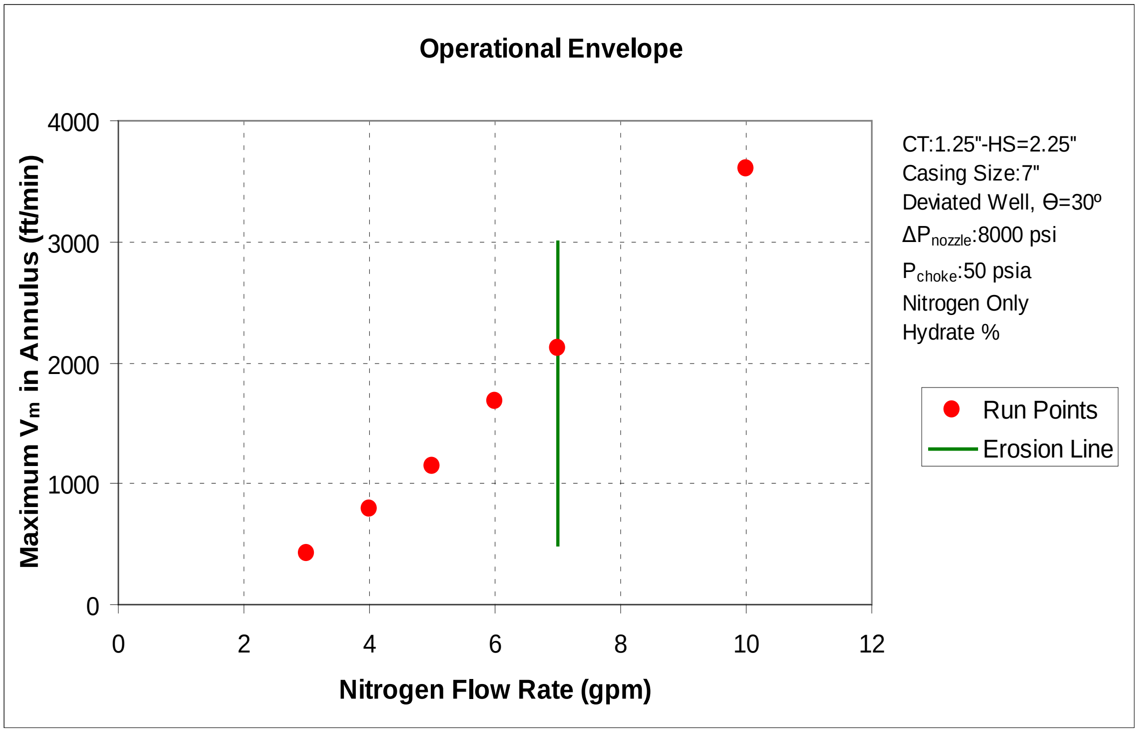

Figure 45: Operational Envelope for N_2 (N_2 Only, 7" Casing, Deviated Well)

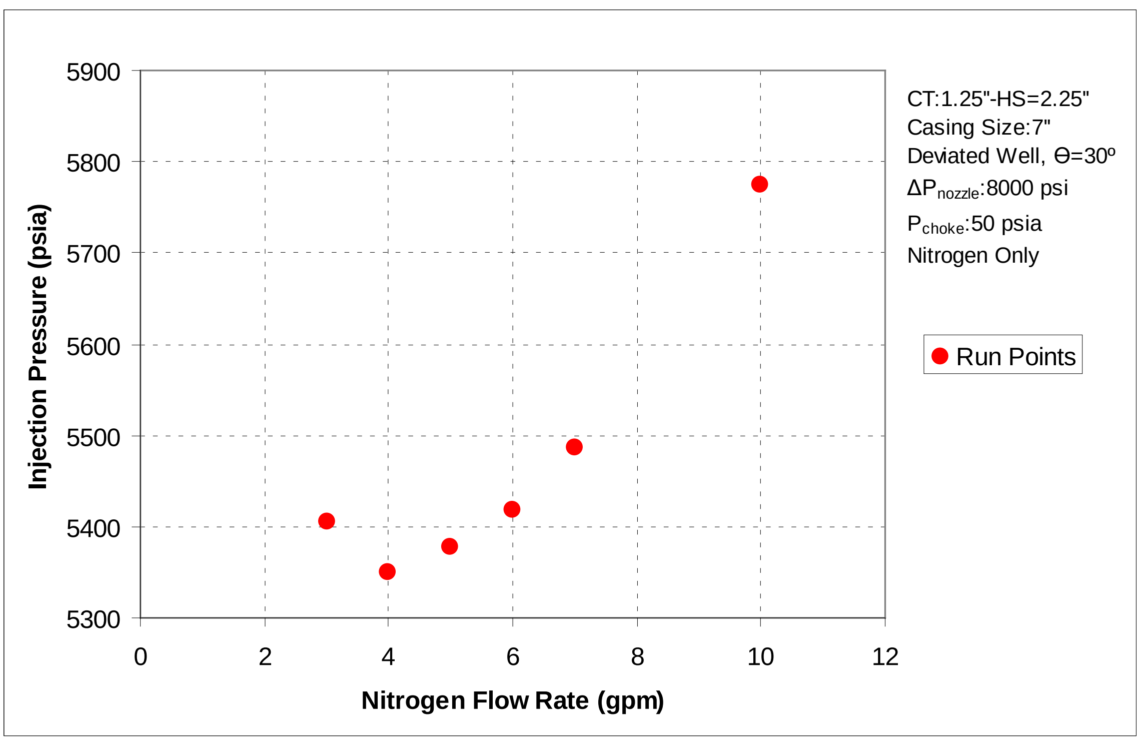

Figure 46: Flow Rate vs. Inj. Pressure for N_2 (N_2 Only, 7" Casing, Deviated Well)

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.

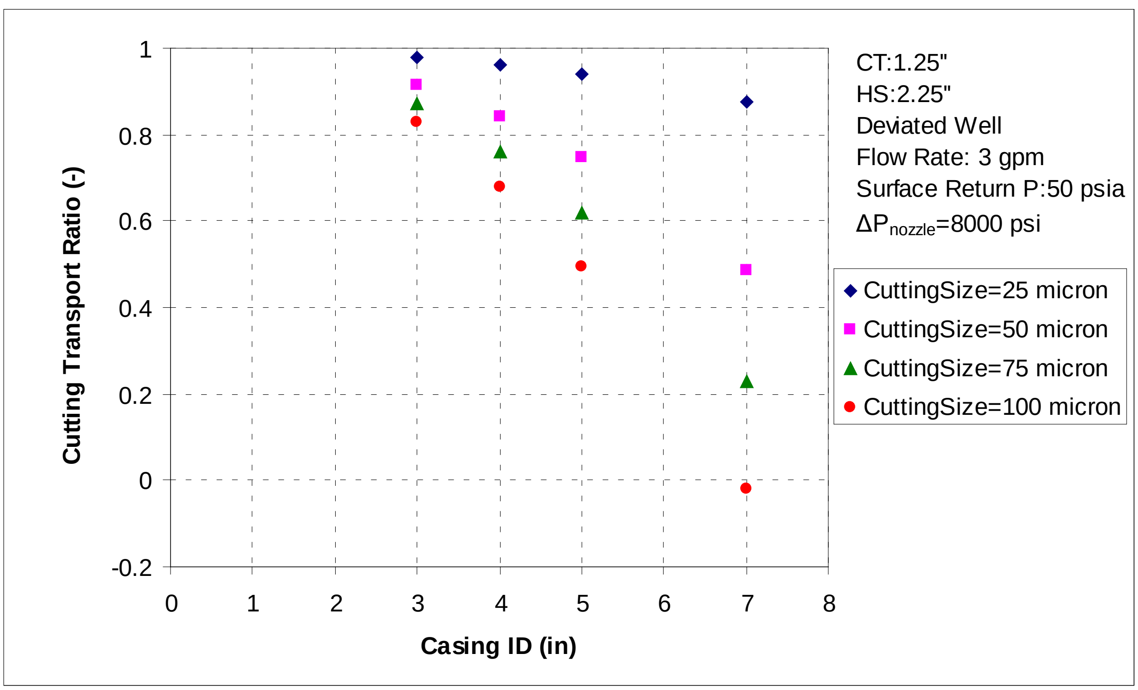

Figure 47: CTR vs. Casing ID (Nitrogen Only, Q_{N2}=3 gpm, Deviated Well)

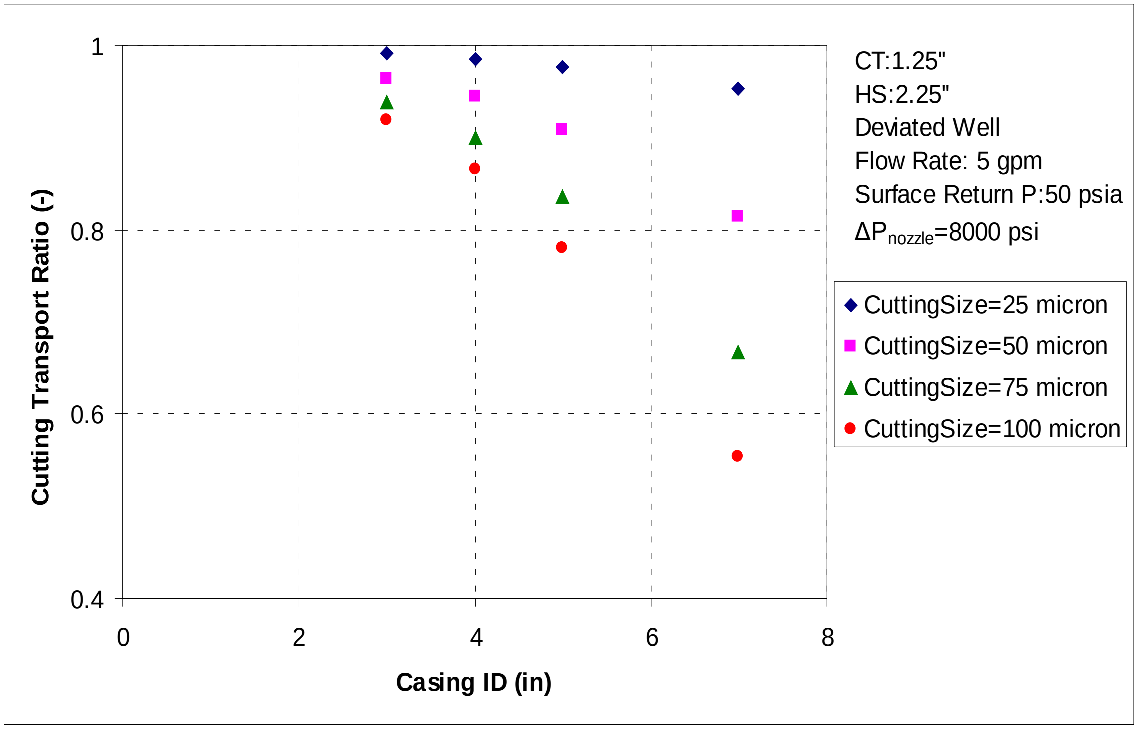

Figure 48: CTR vs. Casing ID (Nitrogen Only, Q_{N2}=5 gpm, Deviated Well)

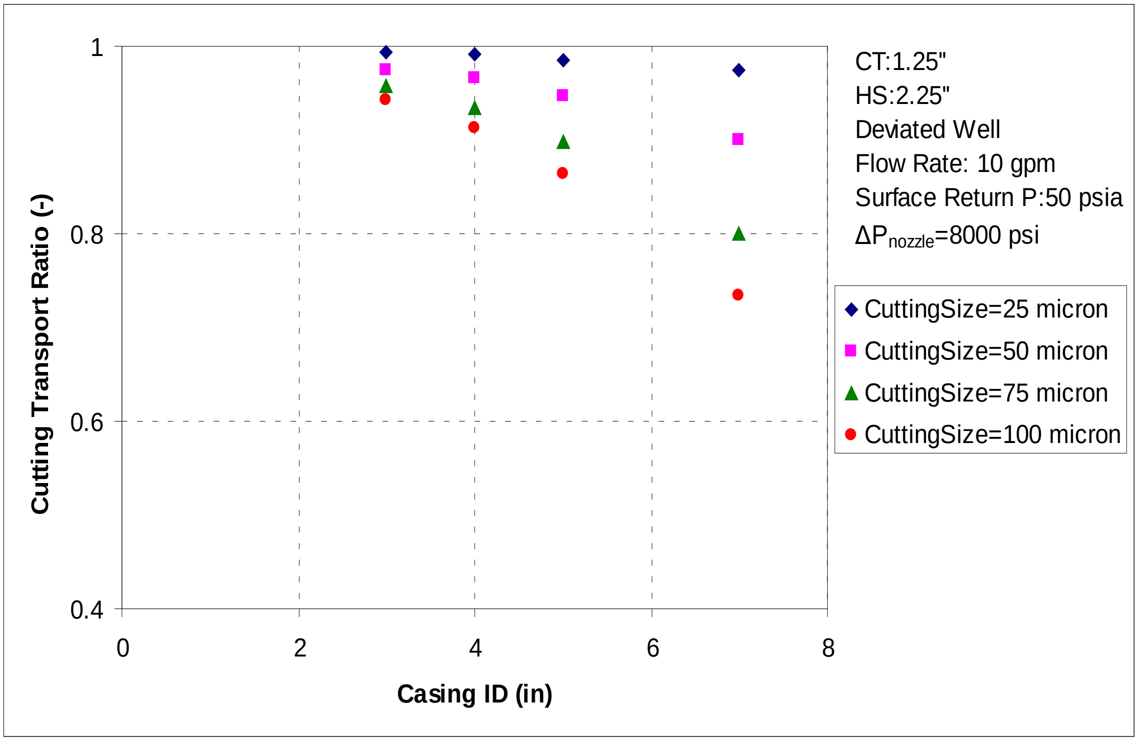

Figure 49: CTR vs. Casing ID (Nitrogen Only, Q_{N2}=7 gpm, Deviated Well)

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 ºF 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 30º 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_c	= Surface Return Choke Pressure (psia)
ROP	= Rate of Penetration (ft/hour)
Q	= Flow Rate, gpm
Q_w	= Water flow Rate (gpm)
Q_{wi}	= Water Influx Flow Rate (gpm)
O.D.	= Outer Diameter (inch)
T	= Temperature (^oF)

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

Coiled Tubing O.D: 1.25 inch –Bore Hole Size: 2.25 inch- Nitrogen Only							
Q N_2 (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 (%)**
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 (ºF)**	**T D.Stream Nozzle (ºF)**	**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
Coiled Tubing O.D: 1.25 inch –Bore Hole Size: 2.25 inch-Nitrogen with Water Addition							
Q N_2 (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	-	-
5	1	2505	114	0.08	143	-	-
5	2	2240	99	0.16	164	-	-
7	1	3139	157	0.07	186	-	-
7	2	3321	144	0.11	212	-	-
7	3	3430	139	0.17	236	-	-
10	1	4942	225	0.13	254	-	-
10	2	5213	211	0.18	282	-	-
10	3	5269	203	0.11	309	-	-
Q N_2 (gpm)	**Q Water (gpm)**	**Injection Pressure (psi)**	**BHP Upstream Nozzle (psi)**	**BHP D.Stream Nozzle (psi)**	**T Upstream Nozzle (ºF)**	**T D.stream Nozzle (ºF)**	**CTR (%)**
3	1	4663	7619	2619	340	336	0.968
4	1	4439	7246	2246	325	318	0.974
5	1	4325	7036	2036	312	303	0.98
5	2	4653	7820	2820	346	344	0.982
7	1	4387	6956	1956	295	286	0.985
7	2	4690	7567	2567	330	325	0.985
7	3	5007	8105	3105	349	348	0.987
10	1	4669	6933	1933	278	268	0.992
10	2	4973	7390	2390	309	303	0.992
10	3	5476	7964	2964	334	331	0.99

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

Casing Size:3'', Nitrogen Only							
Q N_2 (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	-	851	318	0	63.4	-	-
5	-	1392	766	0	106.7	-	-
7	-	2036	1088	0	149	-	-
10	-	3049	1311	0	213	-	-
Q N2 (gpm)	**Q Water (gpm)**	**Injection Pressure (psi)**	**BHP Upstream Nozzle (psi)**	**BHP D. Stream Nozzle (psi)**	**T Upstream Nozzle (ºF)**	**T D.Stream Nozzle (ºF)**	**CTR (%)**
3	-	5516	8463	463	353	347	0.976
5	-	5473	8318	318	349	341	0.99
7	-	5565	8312	312	347	339	0.993
10	-	5816	8372	372	348	340	0.995
Casing Size:3'', Nitrogen With Water Addition							
Q N_2 (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	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	-	-
Q N_2 (gpm)	**Q Water (gpm)**	**Injection Pressure (psi)**	**BHP Upstream Nozzle (psi)**	**BHP D.Stream Nozzle (psi)**	**T Upstream Nozzle (ºF)**	**T D.stream Nozzle (ºF)**	**CTR (%)**
3	1	5841	9237	1237	301	292	0.972
5	1	5519	8566	566	226	214	0.986
5	2	5618	8979	979	284	278	0.984
7	1	5613	8493	493	201	187	0.991
7	2	5651	8701	701	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: Continuation

Casing Size: 4’’							
Q N_2 (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 (ºF)**	**T D.Stream Nozzle (ºF)**	**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_2 (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 N_2 (gpm)	**Q Water (gpm)**	**Injection Pressure (psi)**	**BHP Upstream Nozzle (psi)**	**BHP D.Stream Nozzle (psi)**	**T Upstream Nozzle (ºF)**	**T D.stream Nozzle (ºF)**	**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

Table A-2: Continuation

Casing Size:7''							
Q N_2 (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 (ºF)**	**T D.Stream Nozzle (ºF)**	**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-3: Output for Drilling 20,000 ft (Different Casing Sizes, Deviated Well)

Casing Size:3'', Nitrogen Only							
Q N_2 (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	-	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	-	-
Q N2 (gpm)	**Q Water (gpm)**	**Injection Pressure (psi)**	**BHP Upstream Nozzle (psi)**	**BHP D. Stream Nozzle (psi)**	**T Upstream Nozzle (ºF)**	**T D.Stream Nozzle (ºF)**	**CTR (%)**
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
7	-	5537	8410	410	368	364	0.993
10	-	5828	8520	520	369	366	0.995
Casing Size:3'', Nitrogen with Water Addition							
Q N_2 (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	899	119	0.09	91	-	-
3	2	886	93	0.18	113	-	-
5	1	1486	329	0.06	137	-	-
6	1	1714	408	0.06	157	-	-
7	1	2127	472	0.06	178	-	-
7	2	1988	380	0.07	207	-	-
10	1	3225	627	0.05	244	-	-
10	2	3151	519	0.07	268	-	-
Q N_2 (gpm)	**Q Water (gpm)**	**Injection Pressure (psi)**	**BHP Upstream Nozzle (psi)**	**BHP D.Stream Nozzle (psi)**	**T Upstream Nozzle (ºF)**	**T D.stream Nozzle (ºF)**	**CTR (%)**
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	8902	902	249	239	0.993

Table A-3: Continuation

Casing Size:4''							
Q N_2 (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 (psi)	BHP D. Stream Nozzle (psi)	T Upstream Nozzle (ºF)	T D.Stream Nozzle (ºF)	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 N_2 (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_2 (gpm)	Q Water (gpm)	Injection Pressure (psi)	BHP Upstream Nozzle (psi)	BHP D.Stream Nozzle (psi)	T Upstream Nozzle (ºF)	T D.stream Nozzle (ºF)	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

Table A-3: Continuation

Casing Size:7''							
Q N_2 (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 (ºF)**	**T D.Stream Nozzle (ºF)**	**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

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_2 Only				
Q N2 (gpm)	**Q Water (gpm)**	**Frictional Pres. Loss (psi/ft)**	**Hydrostatic Pres. Loss (psi/ft)**	**Total Pres. Loss (psi/ft)**
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
Coiled Tubing O.D: 1.25 inch –Bore Hole Size: 2.25 inch, N_2 with Water Addition				
Q N2 (gpm)	**Q Water (gpm)**	**Frictional Pres. Loss (psi/ft)**	**Hydrostatic Pres. Loss (psi/ft)**	**Total Pres. Loss (psi/ft)**
3	1	278	662	940
4	1	313	439	752
5	1	345	260	606
5	2	507	428	936
7	1	402	92	494
7	2	604	157	761
7	3	787	199	987
10	1	520	16	536
10	2	752	35	787
10	3	999	51	1050

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

Casing Size:3'', Nitrogen Only				
Q N2 (gpm)	**Q Water (gpm)**	**Frictional Pres. Loss (psi/ft)**	**Hydrostatic Pres. Loss (psi/ft)**	**Total Pres. Loss (psi/ft)**
3	-	25	0.4	25.4
5	-	68.1	0.4	68.5
7	-	130.4	0.4	130.8
10	-	265.4	0.4	265.8
Casing Size:3'', Nitrogen with Water Addition				
Q N2 (gpm)	**Q Water (gpm)**	**Frictional Pres. Loss (psi/ft)**	**Hydrostatic Pres. Loss (psi/ft)**	**Total Pres. Loss (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 N2 (gpm)	**Q Water (gpm)**	**Frictional Pres. Loss (psi/ft)**	**Hydrostatic Pres. Loss (psi/ft)**	**Total Pres. Loss (psi/ft)**
3	-	25.2	0.4	25.6
5	-	68.5	0.4	68.9
7	-	131.2	0.4	131.6
10	-	267.3	0.4	267.7
Casing Size:5''				
Q N2 (gpm)	**Q Water (gpm)**	**Frictional Pres. Loss (psi/ft)**	**Hydrostatic Pres. Loss (psi/ft)**	**Total Pres. Loss (psi/ft)**
3	-	25.2	0.4	25.6
5	-	68.5	0.4	68.9
7	-	131.3	0.4	131.7
10	-	267.7	0.4	268.1
Casing Size:7"				
Q N2 (gpm)	**Q Water (gpm)**	**Frictional Pres. Loss (psi/ft)**	**Hydrostatic Pres. Loss (psi/ft)**	**Total Pres. Loss (psi/ft)**
3	-	25.2	0.4	25.6
5	-	68.6	0.4	69
7	-	131.4	0.4	131.8
10	-	267.8	0.4	268

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

Casing Size:3'', Nitrogen Only				
Q N2 (gpm)	**Q Water (gpm)**	**Frictional Pres. Loss (psi/ft)**	**Hydrostatic Pres. Loss (psi/ft)**	**Total Pres. Loss (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 N2 (gpm)	**Q Water (gpm)**	**Frictional Pres. Loss (psi/ft)**	**Hydrostatic Pres. Loss (psi/ft)**	**Total Pres. Loss (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 N2 (gpm)	**Q Water (gpm)**	**Frictional Pres. Loss (psi/ft)**	**Hydrostatic Pres. Loss (psi/ft)**	**Total Pres. Loss (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 N2 (gpm)	**Q Water (gpm)**	**Frictional Pres. Loss (psi/ft)**	**Hydrostatic Pres. Loss (psi/ft)**	**Total Pres. Loss (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: Continuation

Casing Size:7''				
Q N2 (gpm)	**Q Water (gpm)**	**Frictional Pres. Loss (psi/ft)**	**Hydrostatic Pres. Loss (psi/ft)**	**Total Pres. Loss (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

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.

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

	Water Only	**N_2 & Water**
Depth (ft)	21,000	21,000
Formation	Sandstone	Sandstone
Geothermal Gradient (°F/ft)	0.015	0.015
Surface Temperature (°F)	60	60
Injected Fluid Temperature (°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

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.

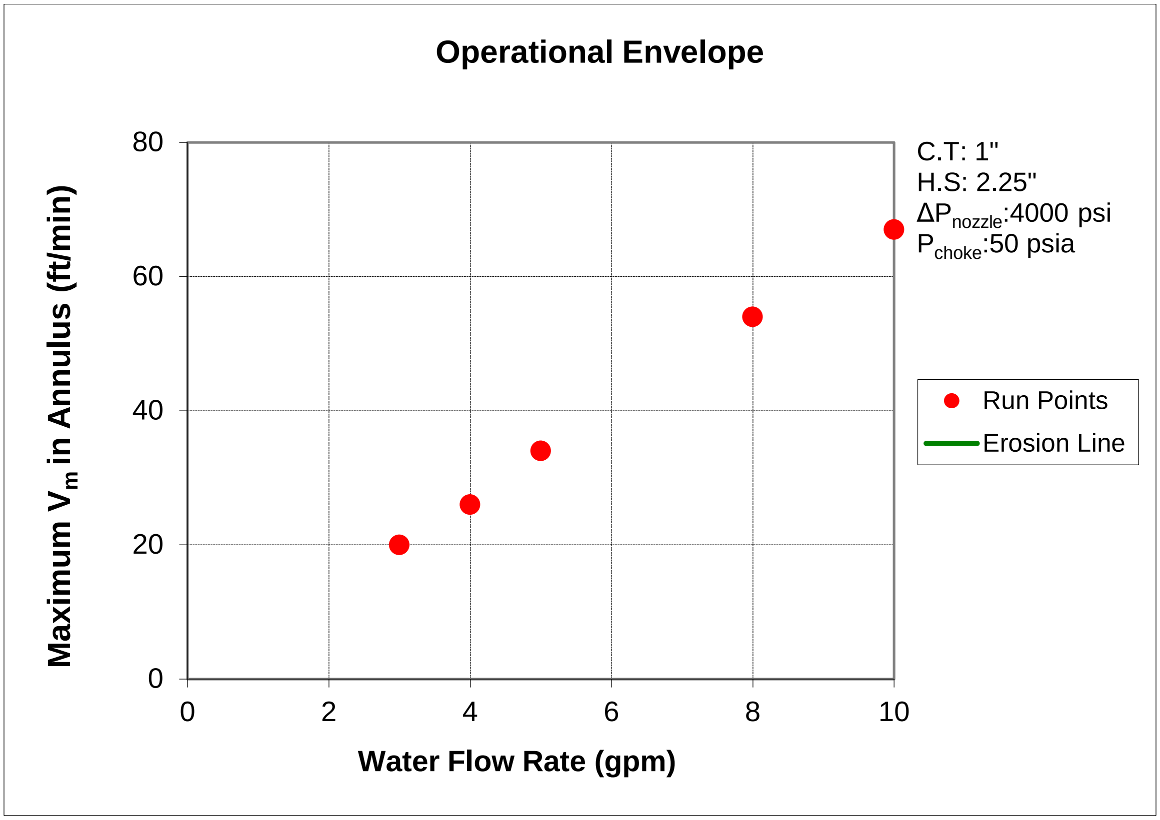

Figure C-1: Operational Envelope for Water Only (CT: 1”-HS:2.25”, 21,000 ft)

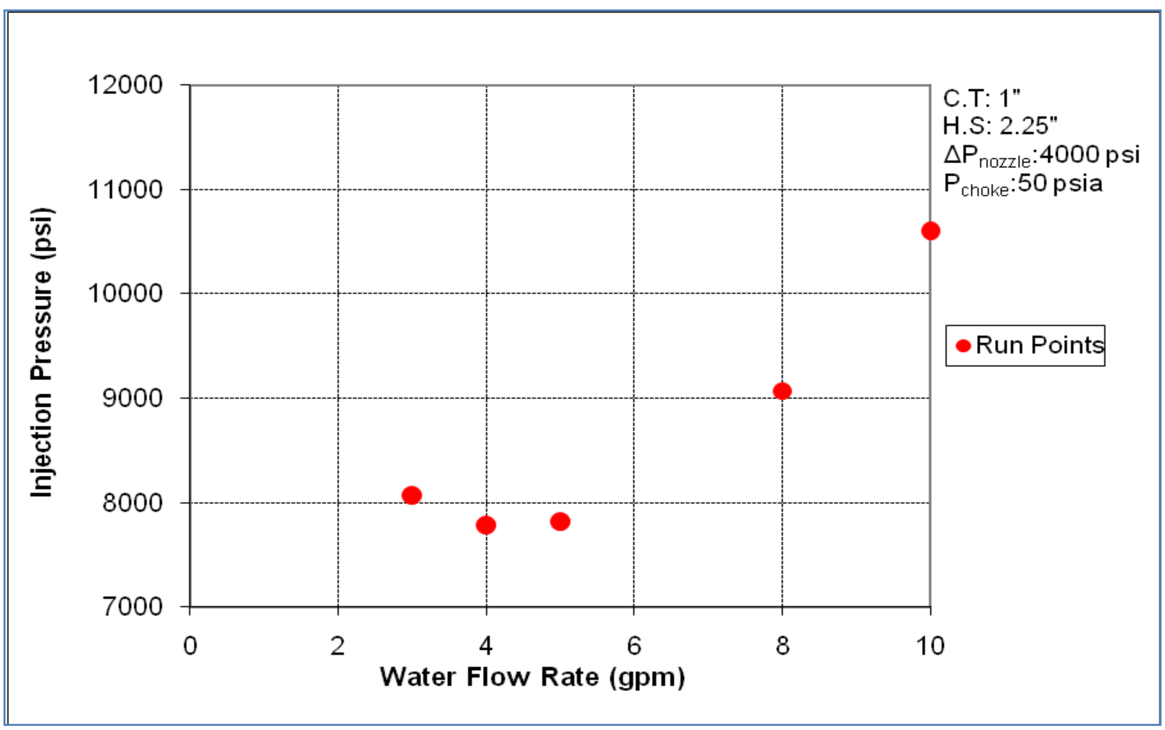

Figure C-2: Flow Rate vs. Inj. Pressure for Water Only (CT: 1”-HS:2.25”, 21,000 ft)

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.

Table C-2: Output Pressure Values (Water only, Q_w=5 gpm, 21,000 ft)

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

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.

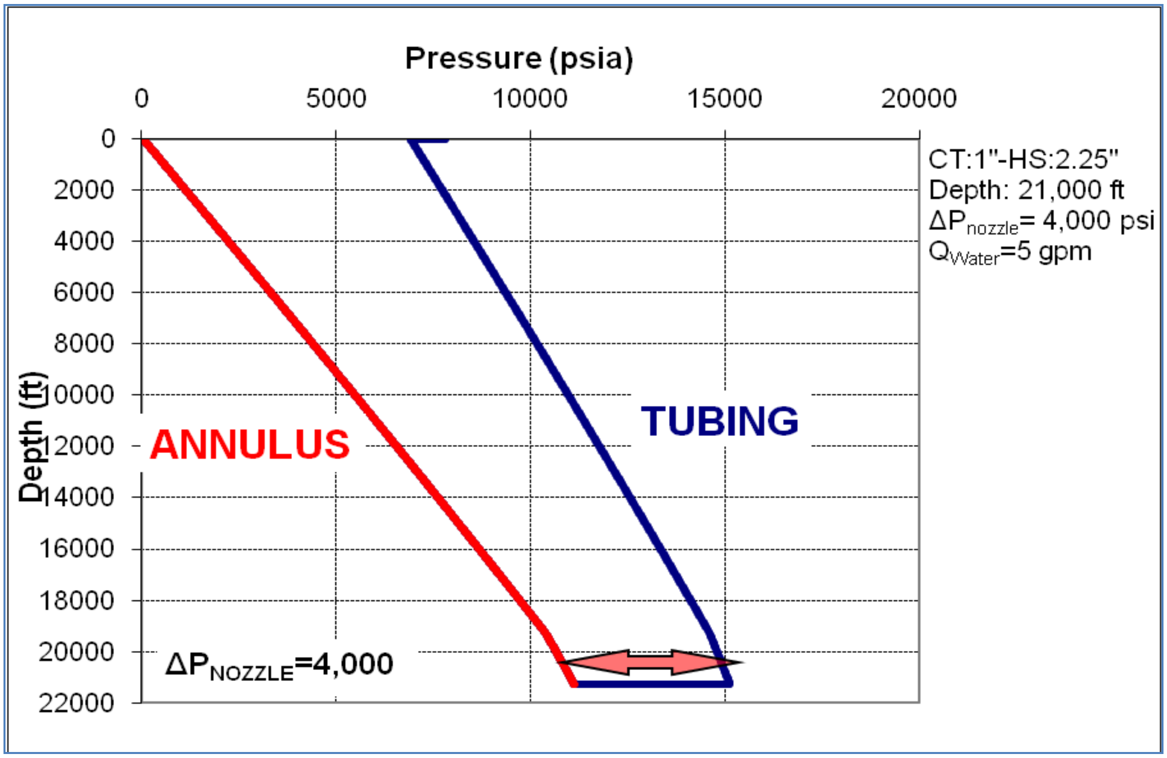

Figure C-3: Pressure vs Depth (CT:1”, H.S:2.25”, Q_w: 1 gpm, 21,000 ft)

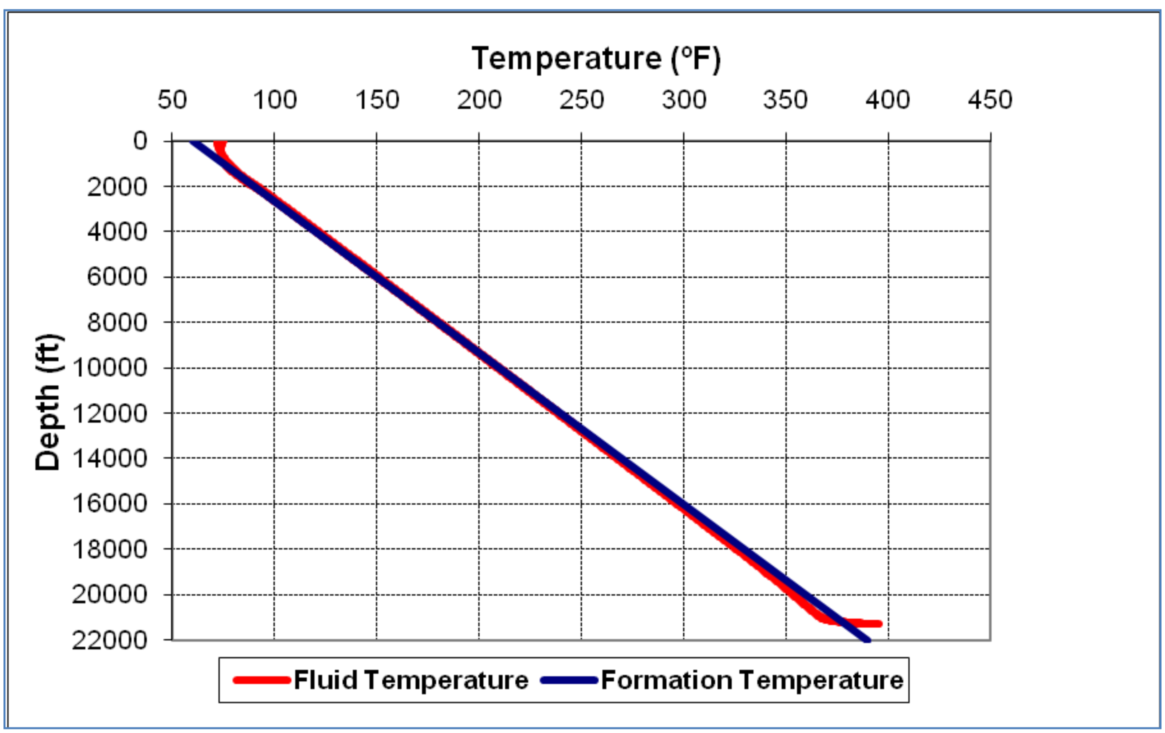

Figure C-4: Temperature vs Depth (CT:1”, H.S:2.25”, Q_w: 1 gpm, 21,000 ft)

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.

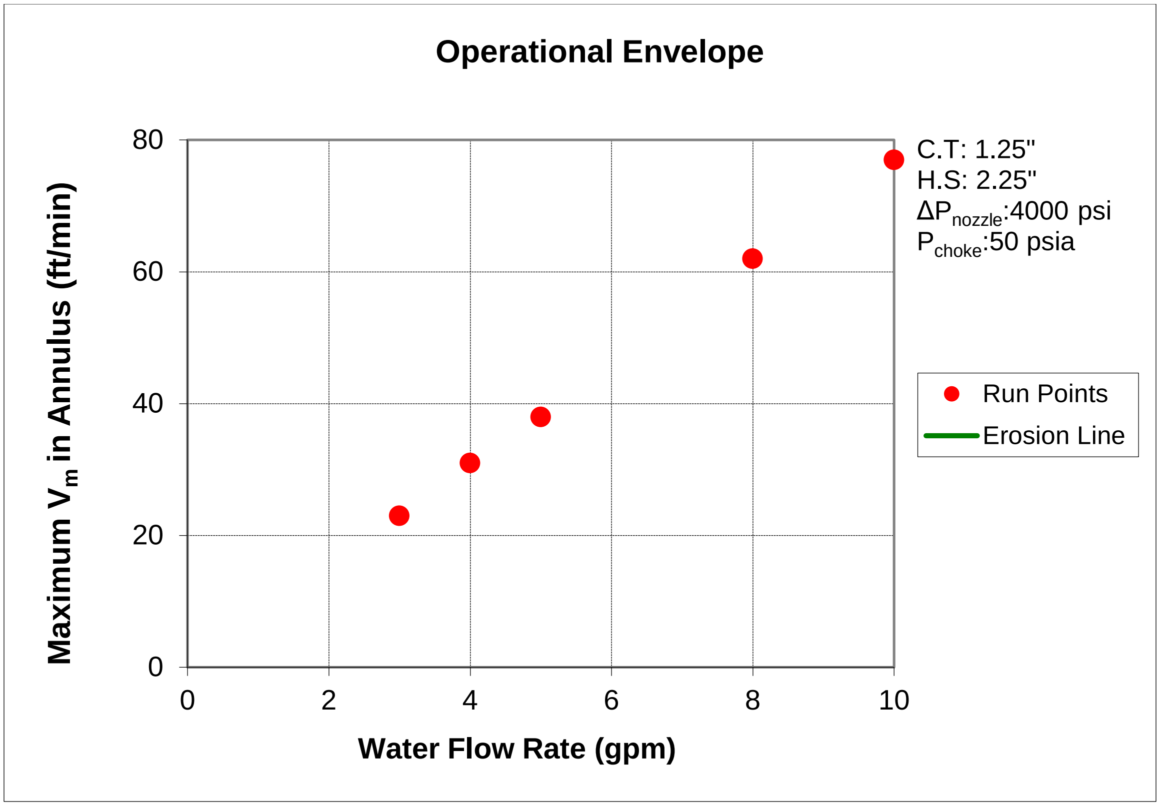

Figure C-5: Operational Envelope for Water Only (CT: 1.25”-HS:2.25”, 21,000 ft)

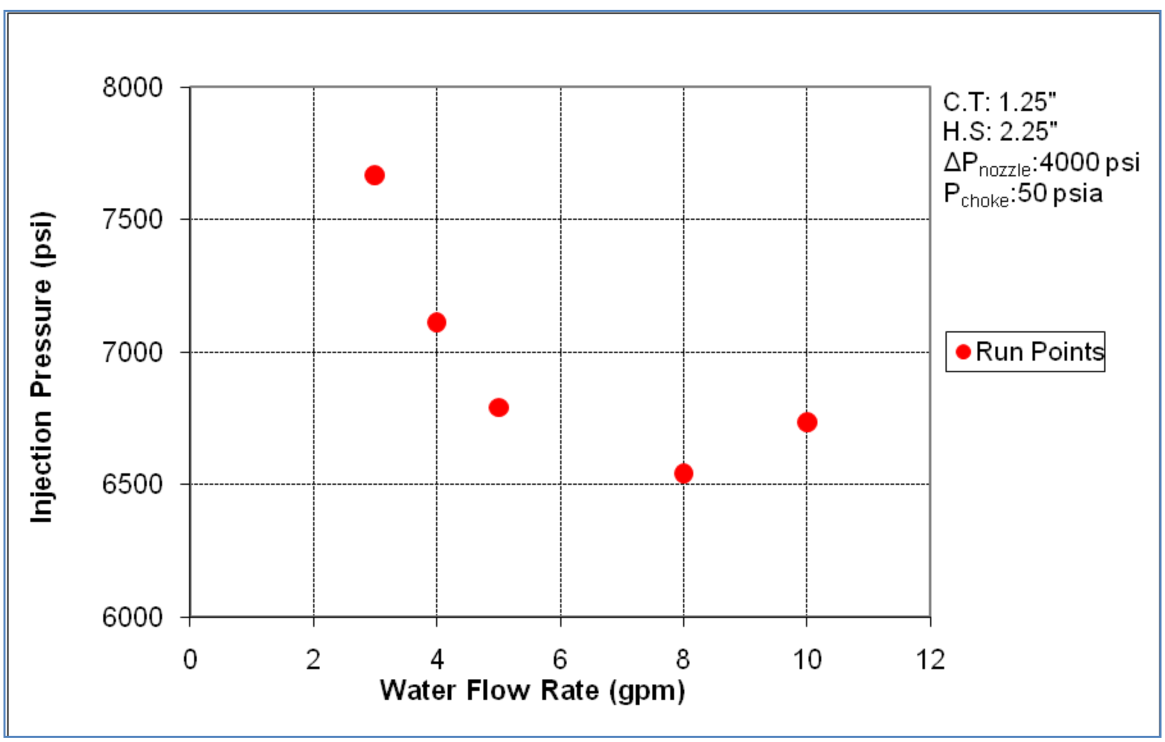

Figure C-6: Flow Rate vs. Inj. Pressure for Water Only (CT: 1.25”-HS:2.25”, 21,000 ft)

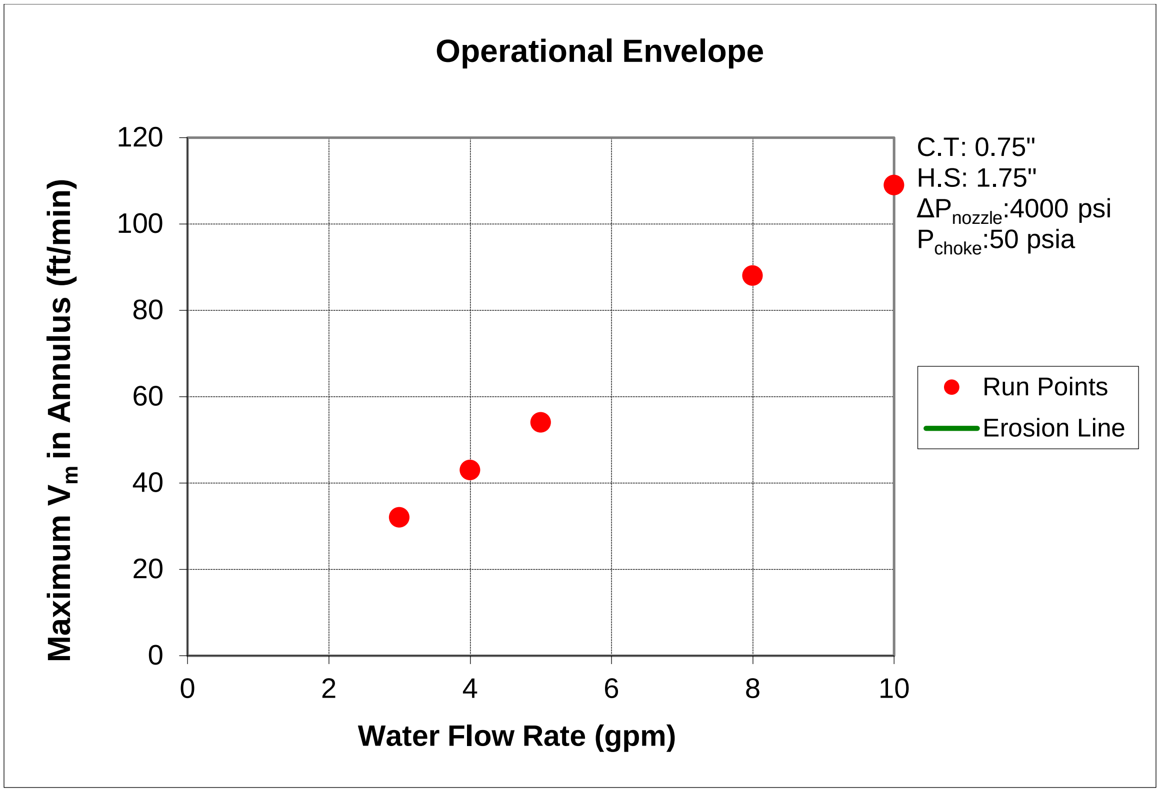

Figure C-7: Operational Envelope for Water Only (CT: 0.75”-HS:1.75”, 21,000 ft)

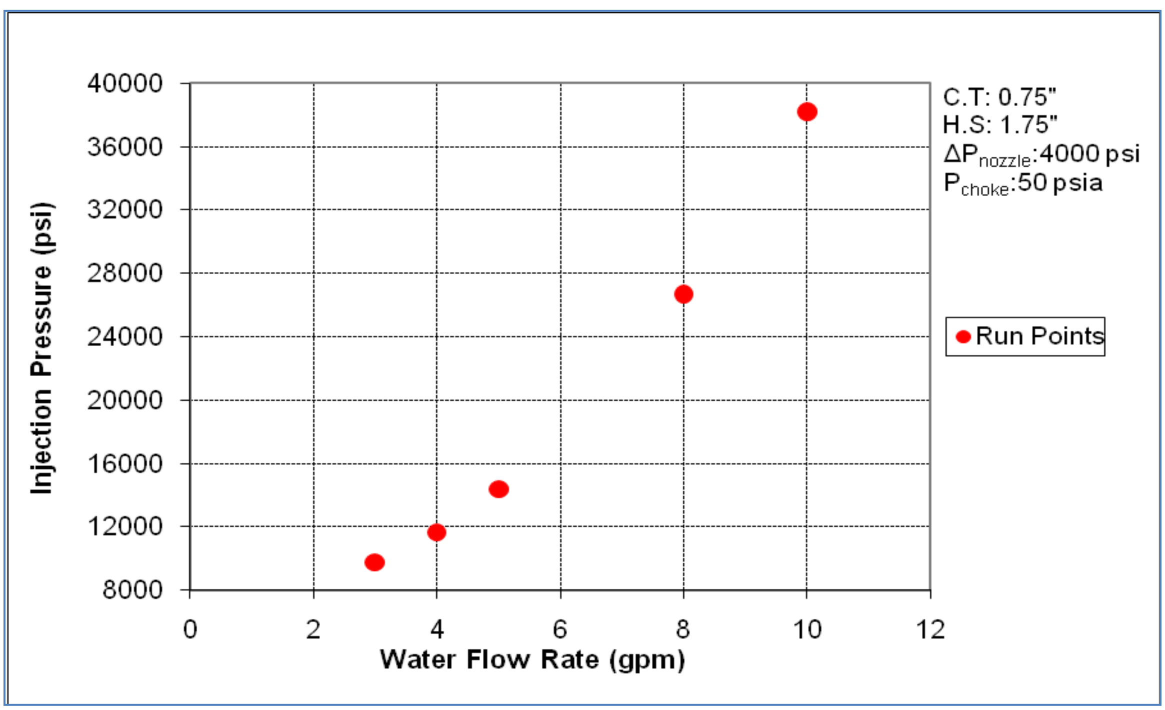

Figure C-8: Flow Rate vs. Inj. Pressure for Water Only (CT: 0.75”-HS:1.75”, 21,000 ft)

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.

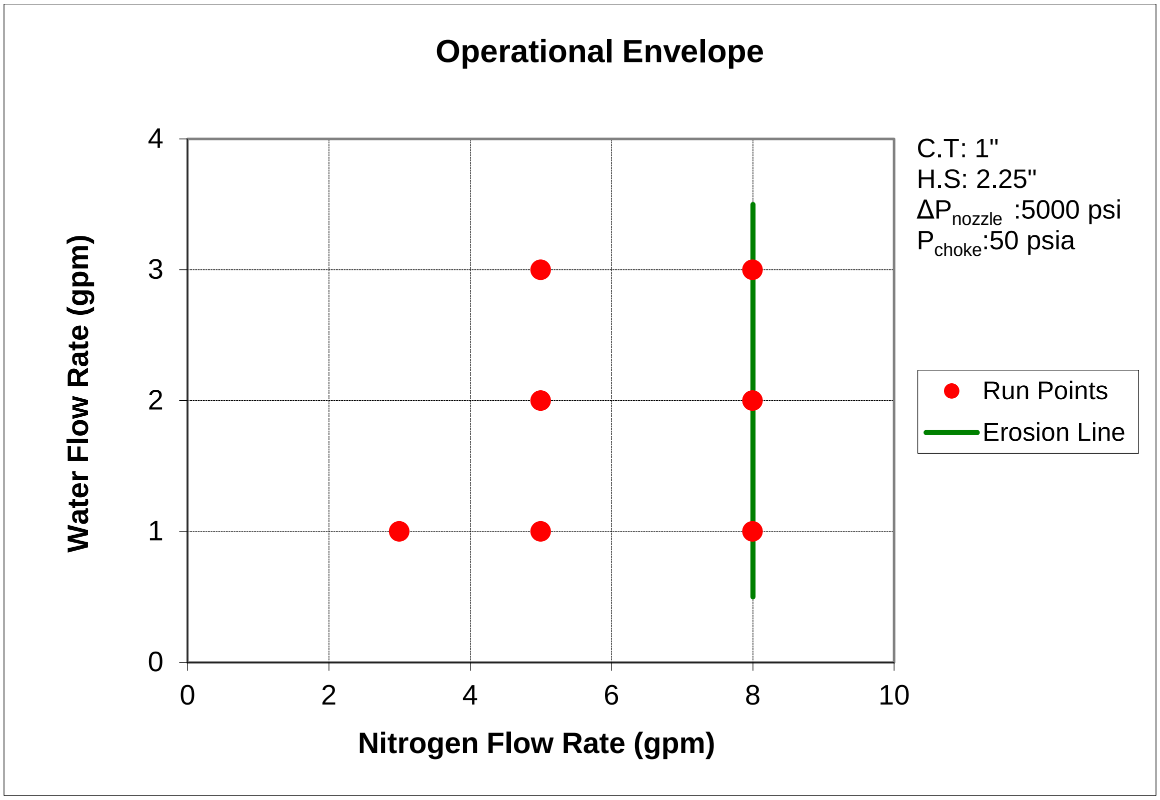

Figure C-9: Operational Envelope for N_2 with Water (CT: 1”-HS:2.25”, 21,000 ft)

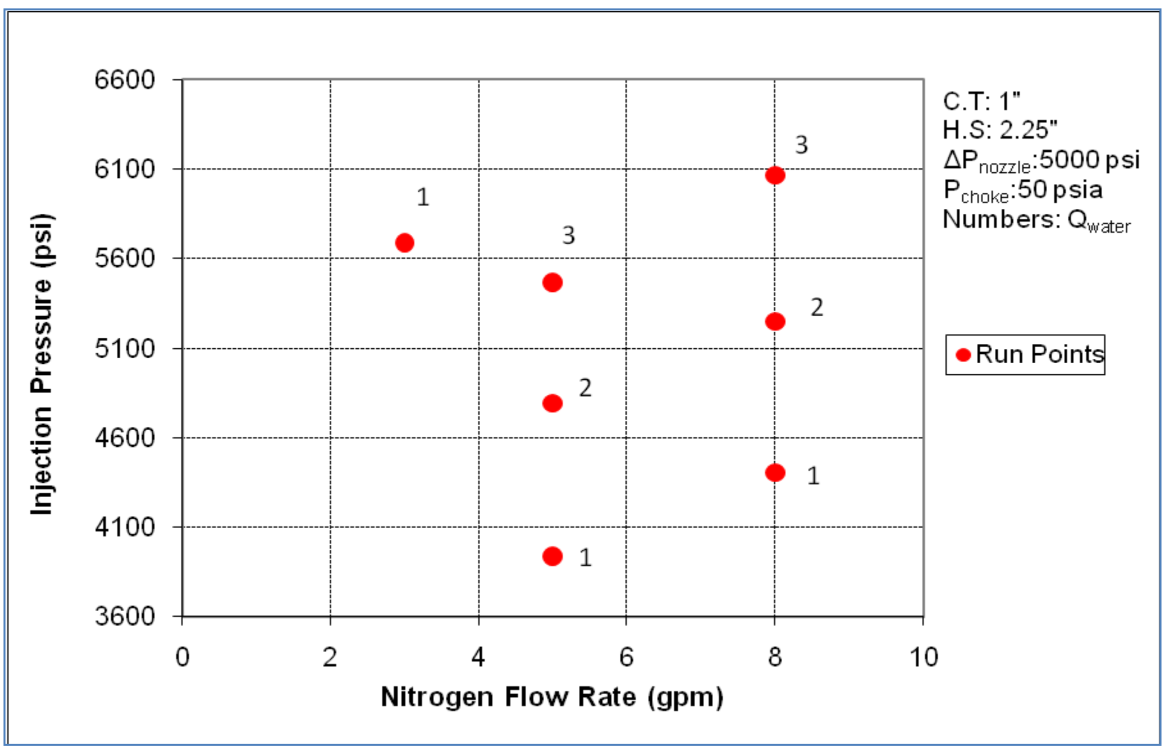

Figure C-10: Flow Rate vs. Inj. Pressure for N_2 with Water (CT: 1”-HS:2.25”, 21,000 ft)

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_{N2}=5 gpm, Q_w=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.

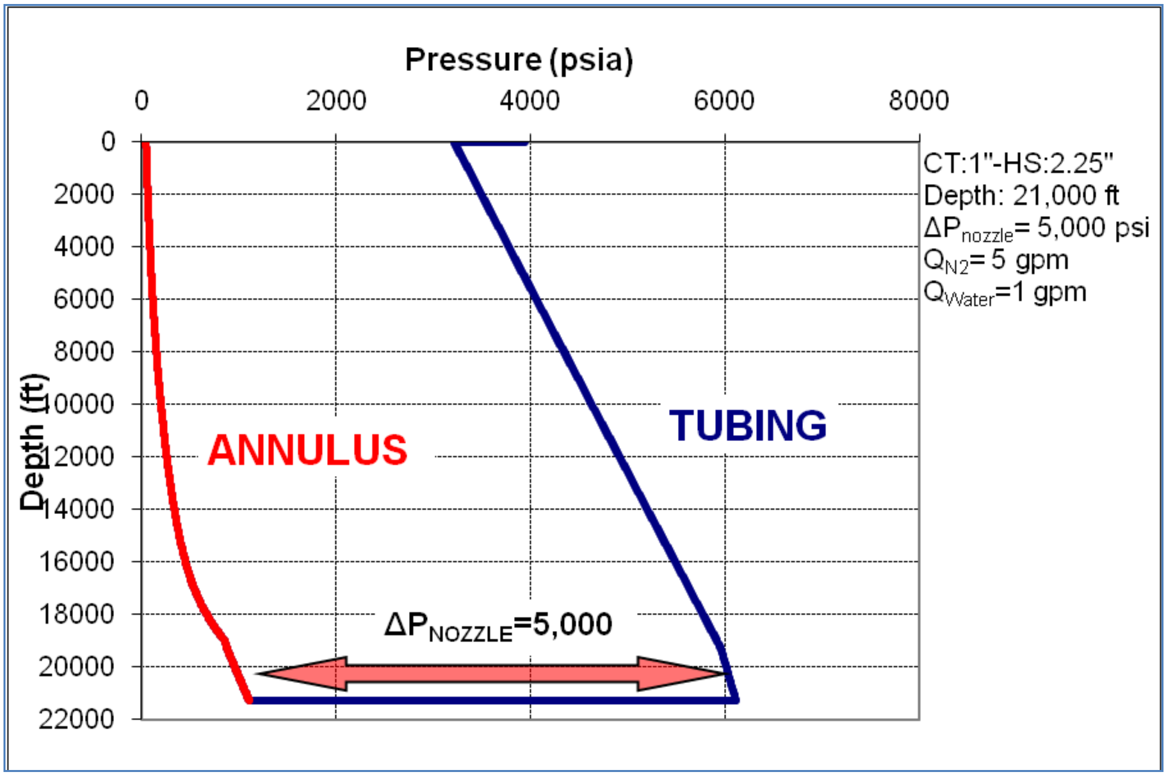

Figure C-11: Pressure vs Depth (CT:1”, H.S:2.25”, Q_{N2} :5 gpm Q_w: 1 gpm, 21,000 ft)

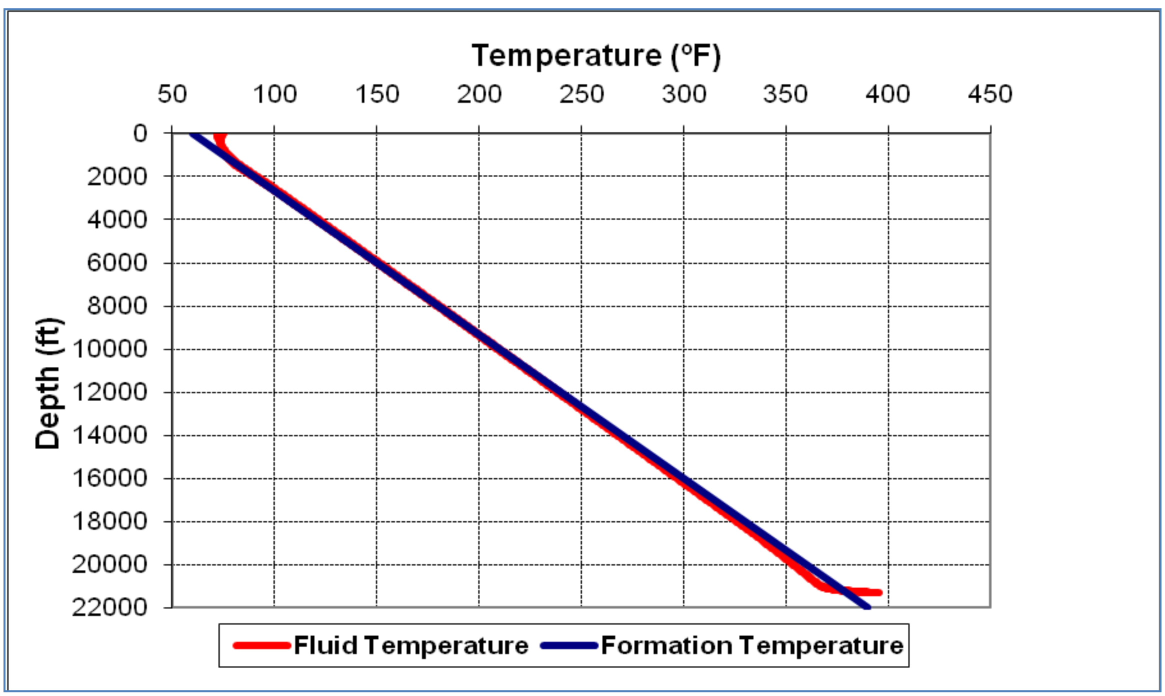

Figure C-12: Temperature vs Depth(CT:1”,H.S:2.25”, Q_{N2}: 5 gpm, Q_w: 1 gpm, 21,000 ft)

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.

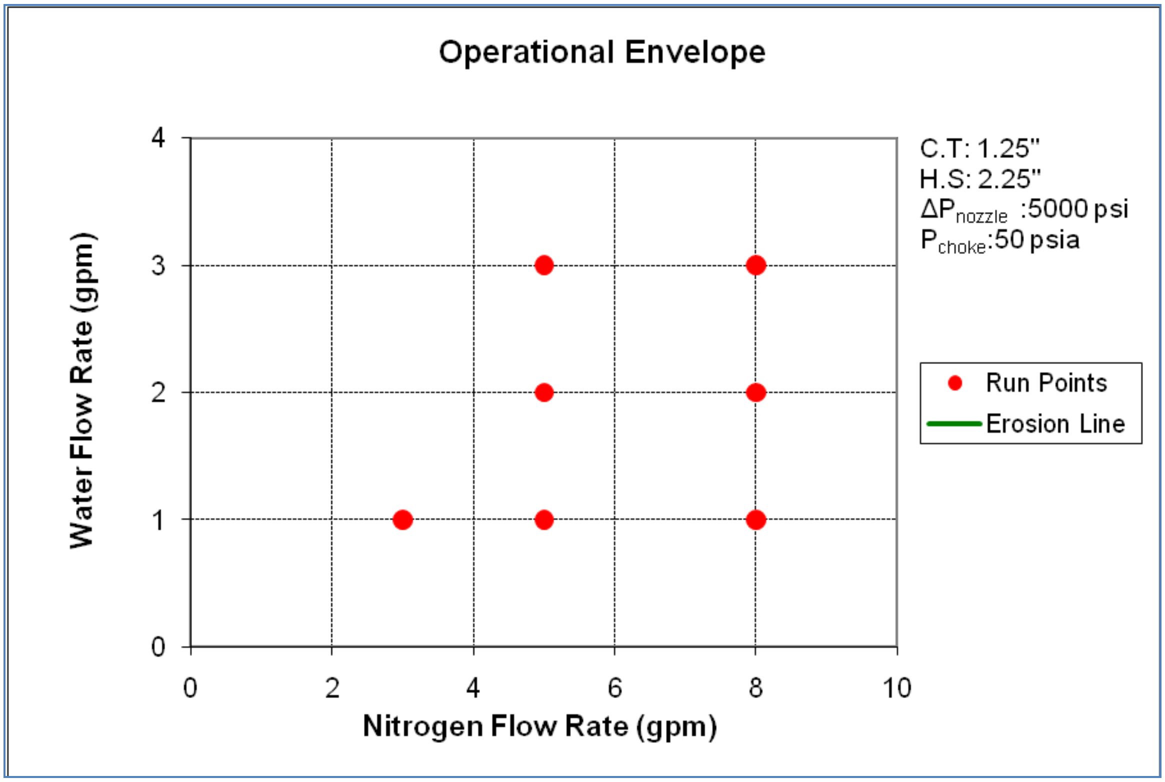

Figure C-13: Operational Envelope for N_2 with Water (CT: 1.25”-HS:2.25”, 21,000 ft)

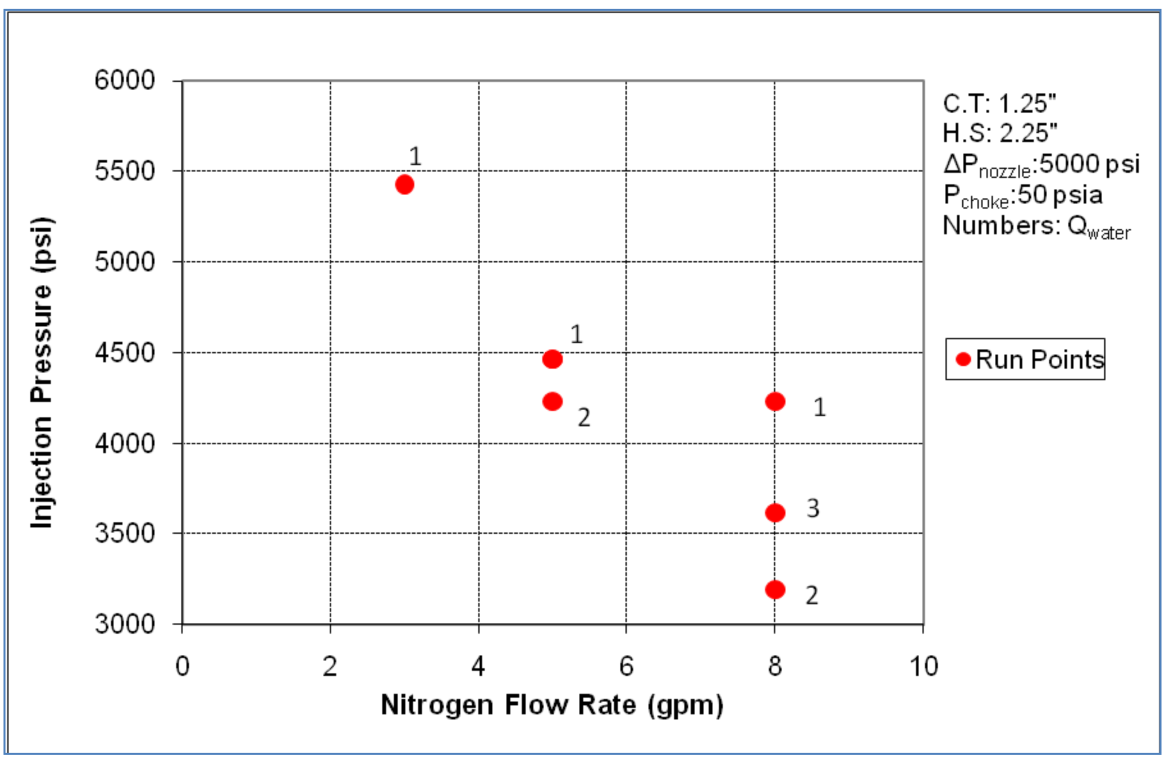

Figure C-14:Flow Rate vs. Inj. Pressure for N_2 with Water (CT:1.25”-HS:2.25”,21,000 ft)

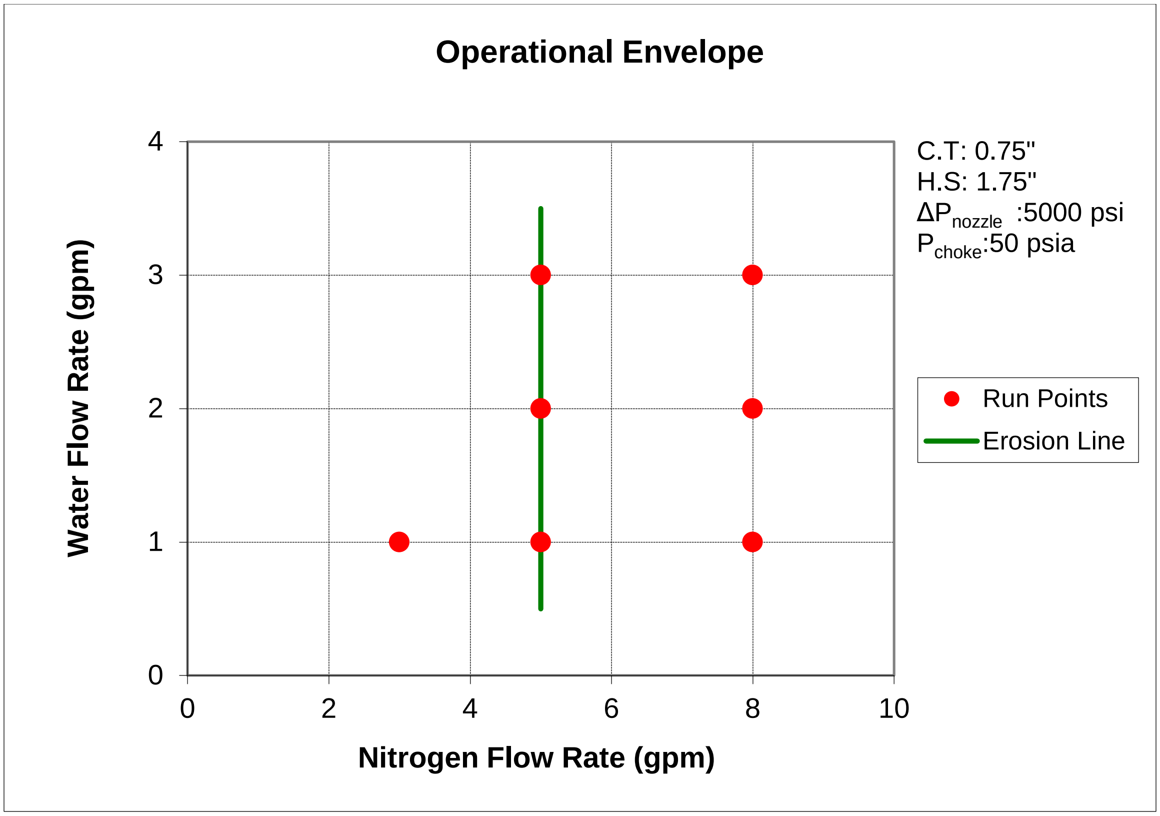

Figure C-15: Operational Envelope for N_2 with Water (CT: 0.75"-HS:1.75", 21,000 ft)

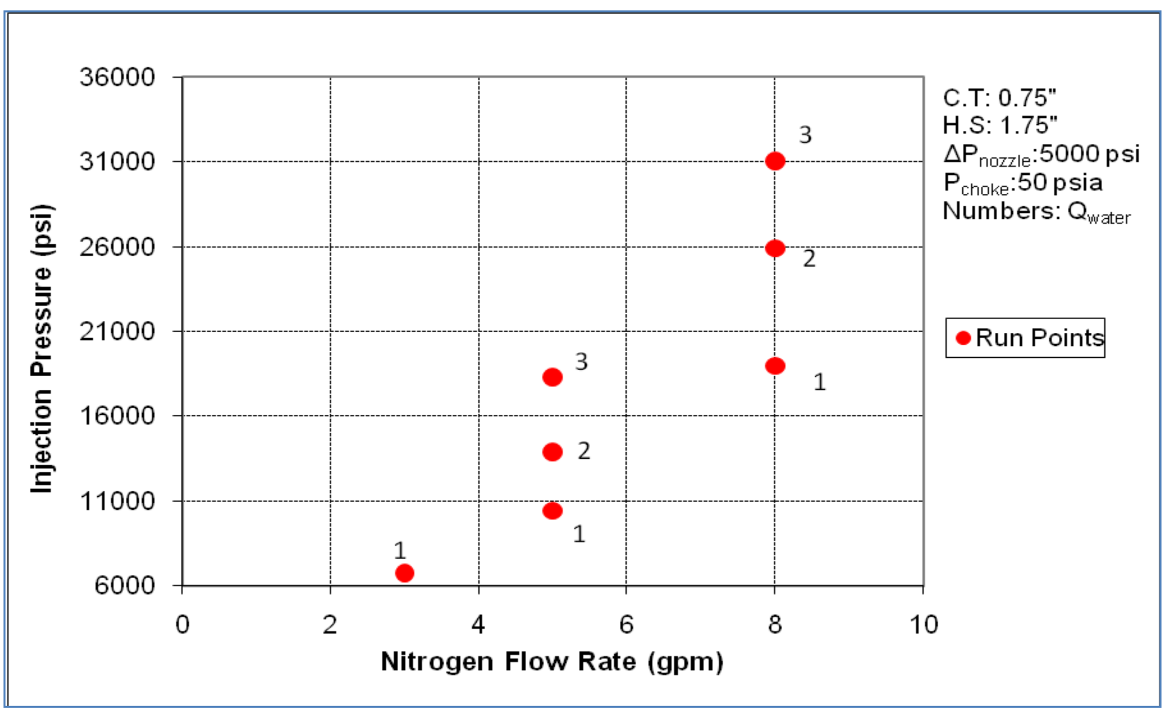

Figure C-16:Flow Rate vs. Inj. Pressure for N_2 with Water (CT:0.75"-HS:1.75",21,000 ft)

3. Conclusions

Water Only:

- ✓ Water Injected with 75°F initial temperature.
- ✓ Three different coiled tubing-hole size combinations were used.
- ✓ 7” casing was used for the first 19,000 ft of the well.
- ✓ 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.
- ✓ Increasing flow rates increased the injection pressures.

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

Coiled Tubing O.D: 1 inch –Bore Hole Size: 2.25 inch							
Q N_2 (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 Tubing O.D: 1.25 inch –Bore Hole Size: 2.25 inch							
Q N_2 (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: Continuation

Coiled Tubing O.D: 0.75 inch –Bore Hole Size: 1.75 inch							
Q N_2 (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 (ºF)**	**T D.Stream Nozzle (ºF)**	
-	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-5: Output for 21,000 ft (Nitrogen with Water Addition)

Coiled Tubing O.D: 1 inch –Bore Hole Size: 2.25 inch							
Q N_2 (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	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		
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	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							
Q N_2 (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	170	0.38	93.8	0.82		
5	1	206	0.32	119	0.916		
8	1	208	0.31	128	0.932		
5	2	238	0.33	174	0.932		
5	3	265	0.36	199	0.921		
8	2	1065	0.1	261	0.957		
8	3	284	0.27	260	0.964		
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	1	5428	8735	3735	362	360	
5	1	4464	7338	2338	340	331	
8	1	4229	7023	2023	332	321	
5	2	4229	7369	2369	351	346	
5	3	4464	7917	2917	365	364	
8	2	3193	5546	546	276	254	
8	3	3616	6563	1563	336	328	

Table C-5: Continuation

Coiled Tubing O.D: 0.75 inch –Bore Hole Size: 1.75 inch							
Q N_2 (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 (ºF)**	**T D.Stream Nozzle (ºF)**	
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	

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.

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

	Water & N_2
Depth (ft)	21,000
Formation	Sandstone
Geothermal Gradient (ºF/ft)	0.015
Surface Temperature (ºF)	60
Injected Fluid Temperature (ºF)	75
Return Choke Pressure (psia)	50
Nozzle Pressure Drop (psi)	5000
Cutting Size (micron)	25
ROP (ft/hour)	400

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.

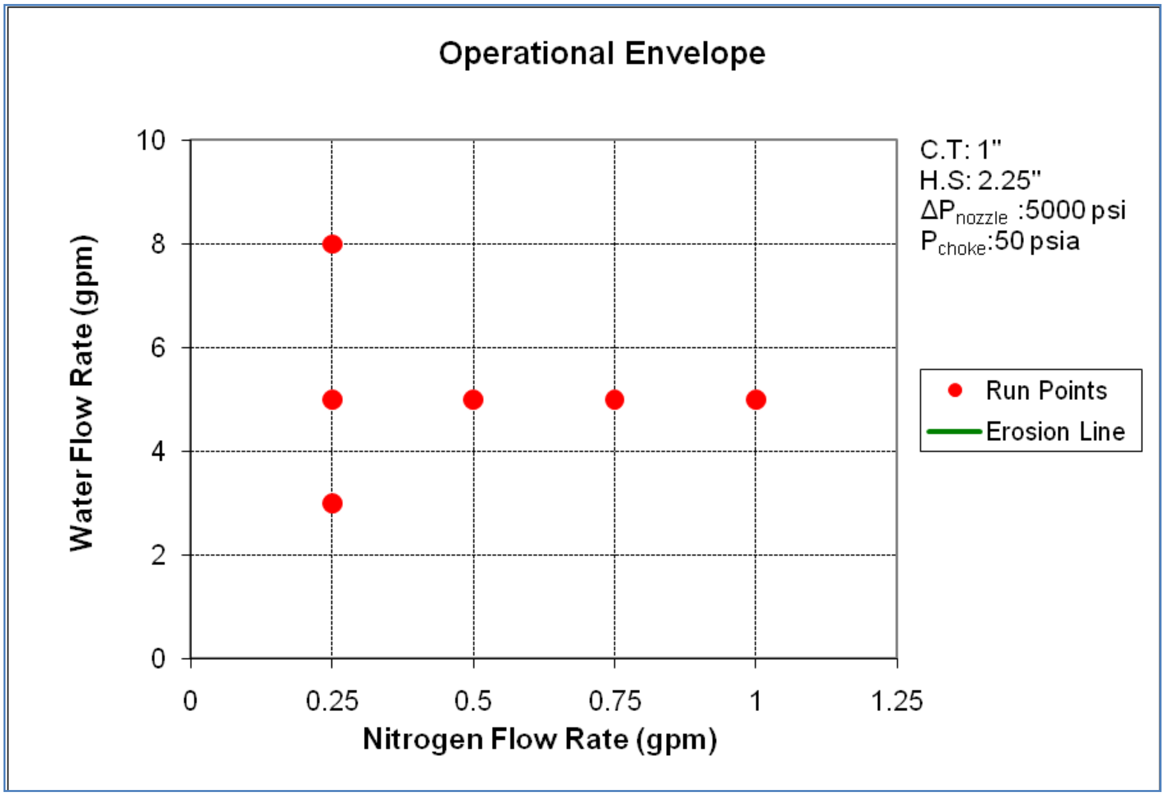

Figure D-1: Operational Envelope for Water with N_2 (CT: 1”-HS:2.25”, 21,000 ft)

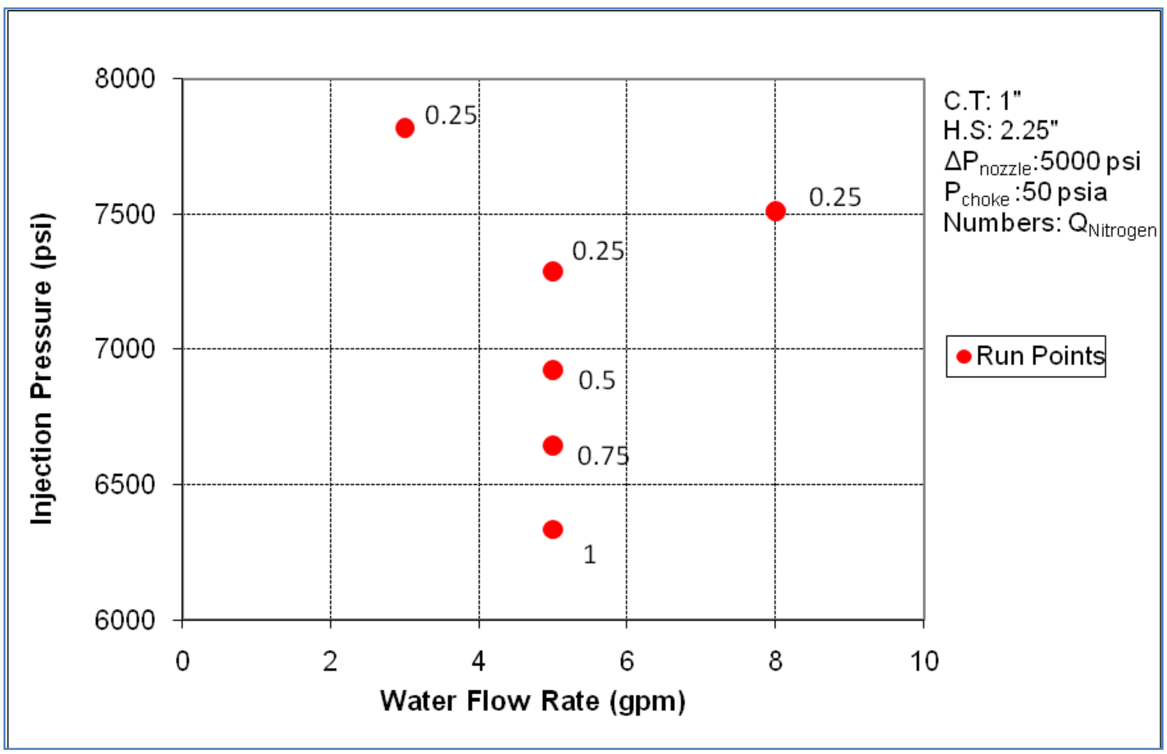

Figure D-2: Flow Rate vs. Inj. Pressure for N_2 with Water (CT: 1”-HS:2.25”, 21,000 ft)

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_w:5 gpm,Q_{N2}: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.

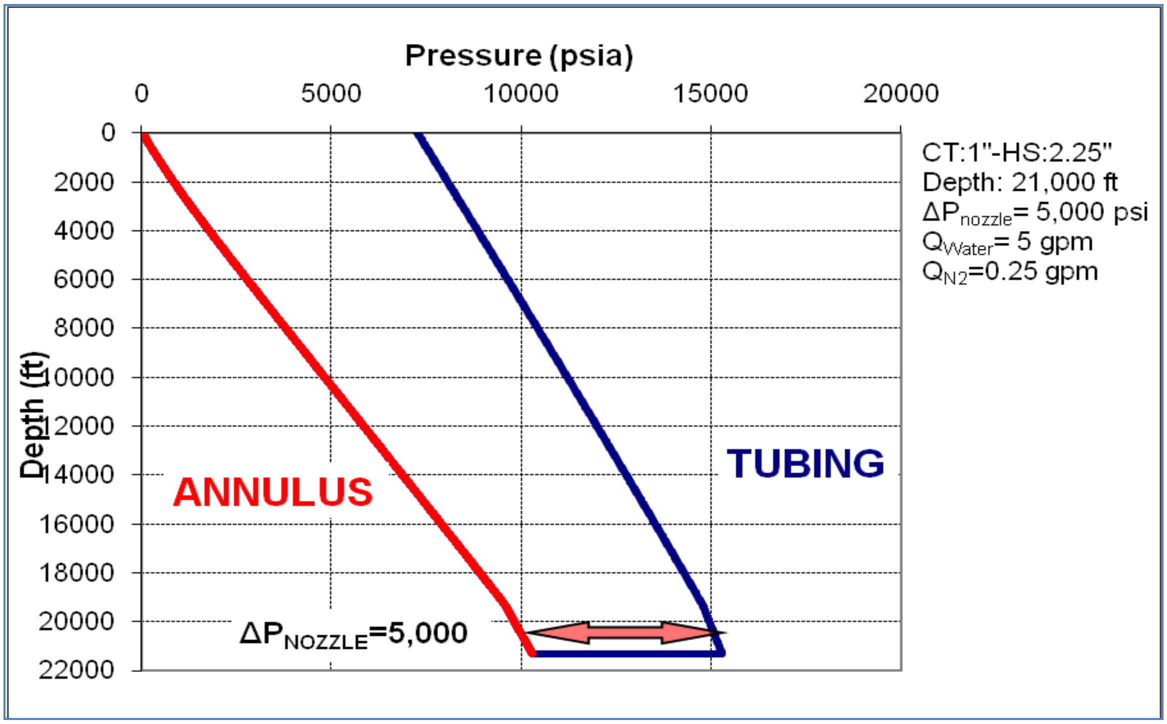

Figure D-3: Pressure vs Depth (CT:1”, H.S:2.25”, Q_w: 5 gpm Q_{N2}: 0.25 gpm, 21,000 ft)

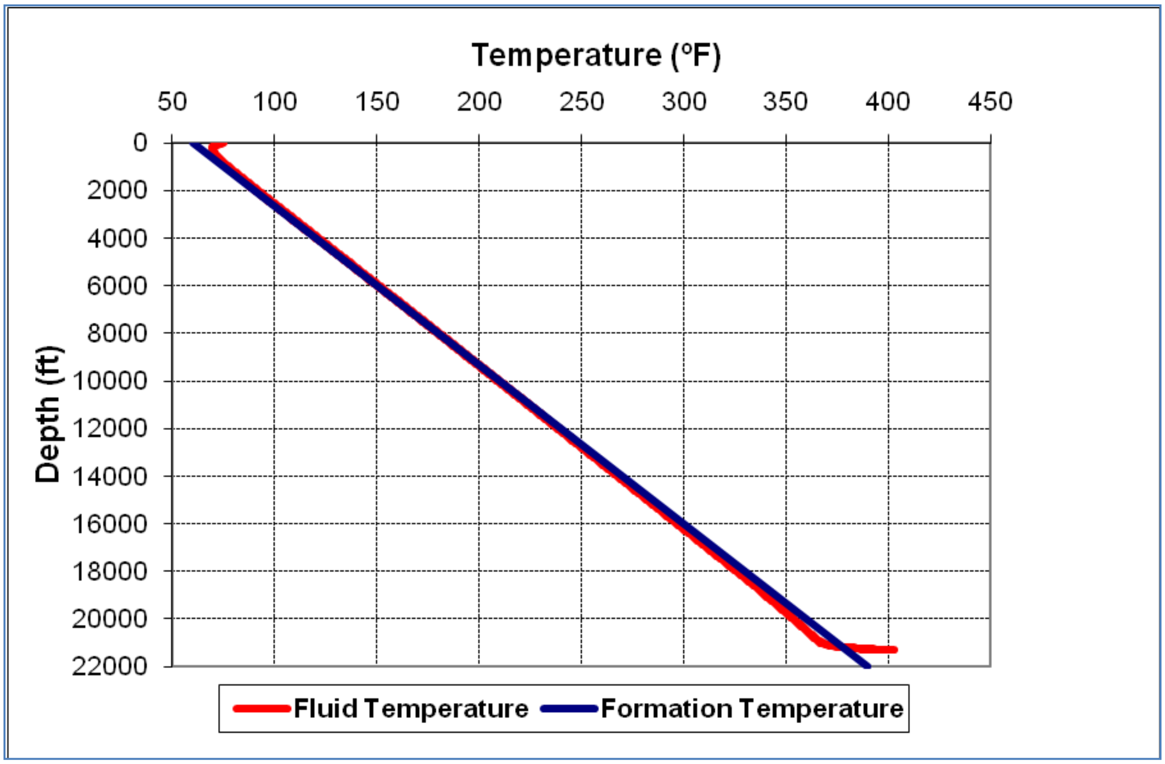

Figure D-4: Temperature vs Depth(CT:1”,H.S:2.25”,Q_w:5 gpm Q_{N2}:0.25 gpm, 21,000 ft)

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.

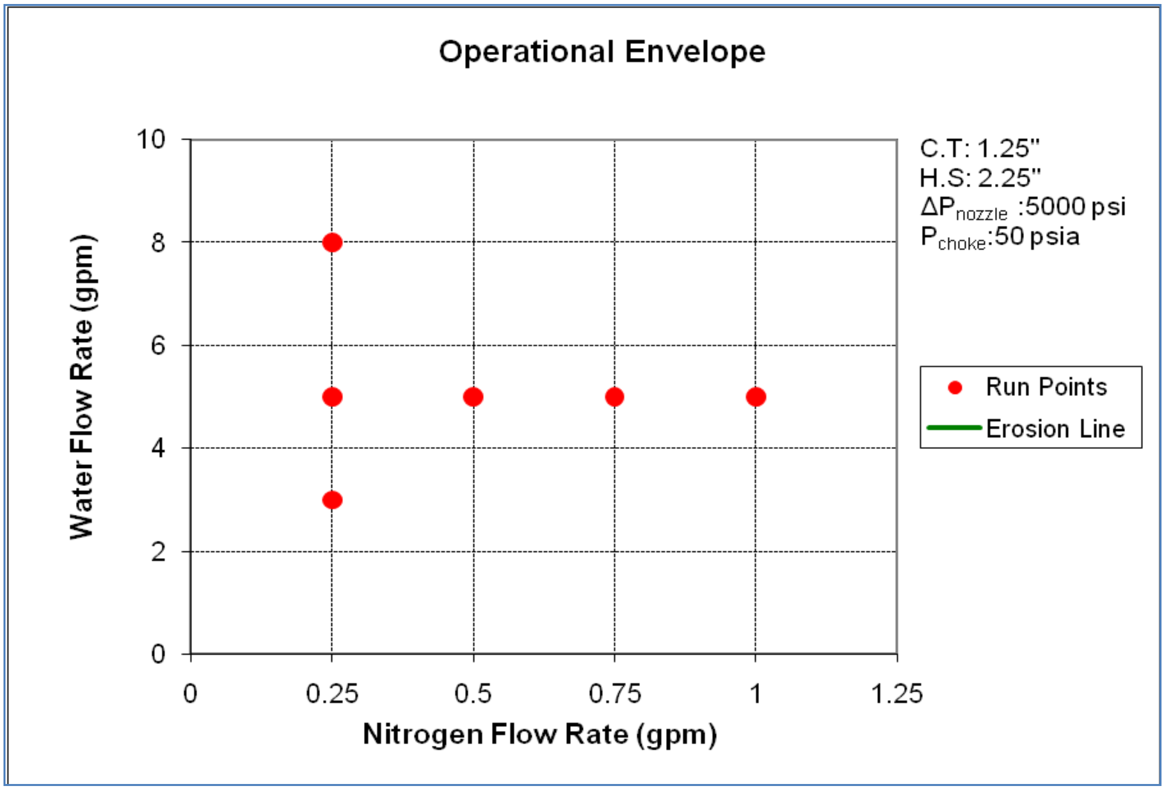

Figure D-5: Operational Envelope for Water with N_2 (CT: 1.25"-HS:2.25", 21,000 ft)

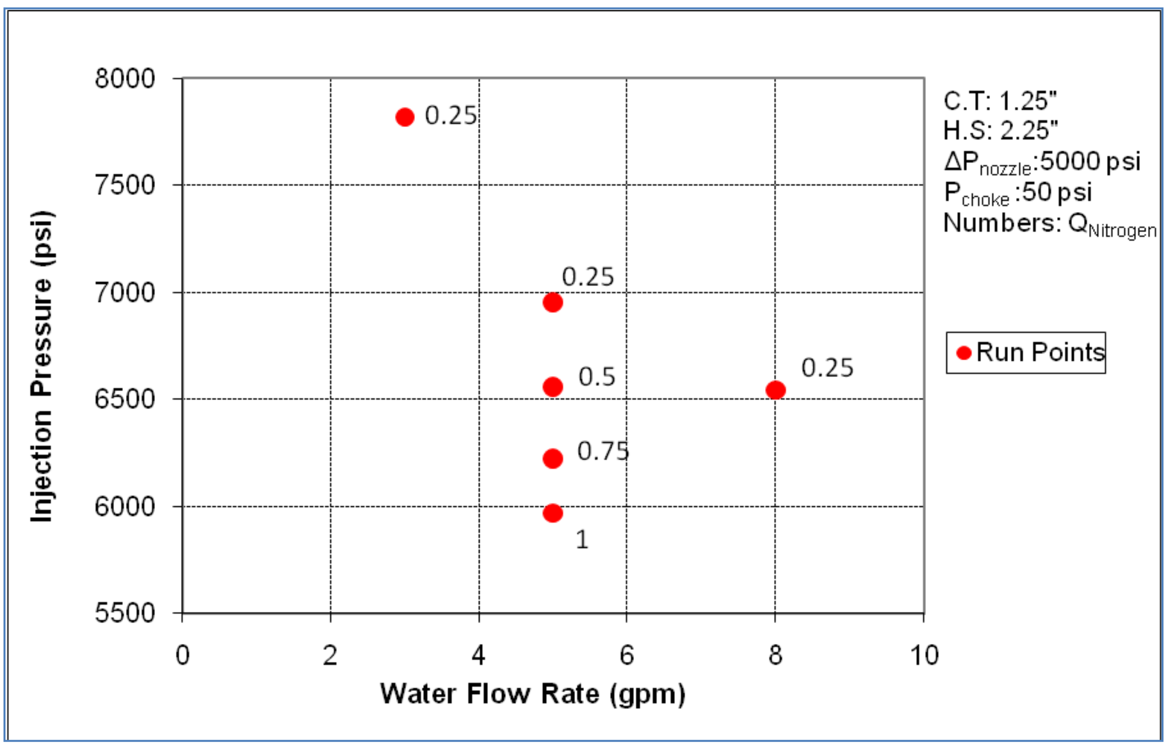

Figure D-6:Flow Rate vs. Inj. Pressure for Water with N_2 (CT: 1.25"-HS:2.25",21,000 ft)

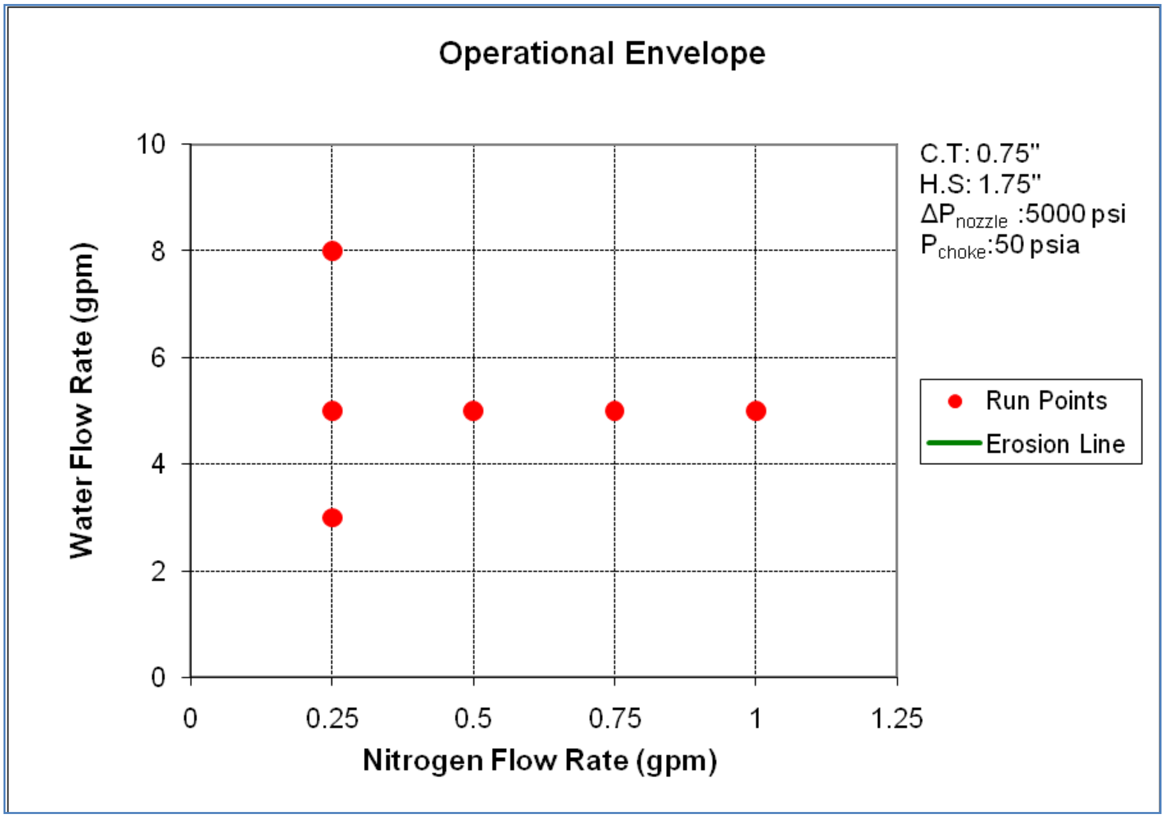

Figure D-7: Operational Envelope for Water with N_2 (CT: 0.75”-HS:1.75”, 21,000 ft)

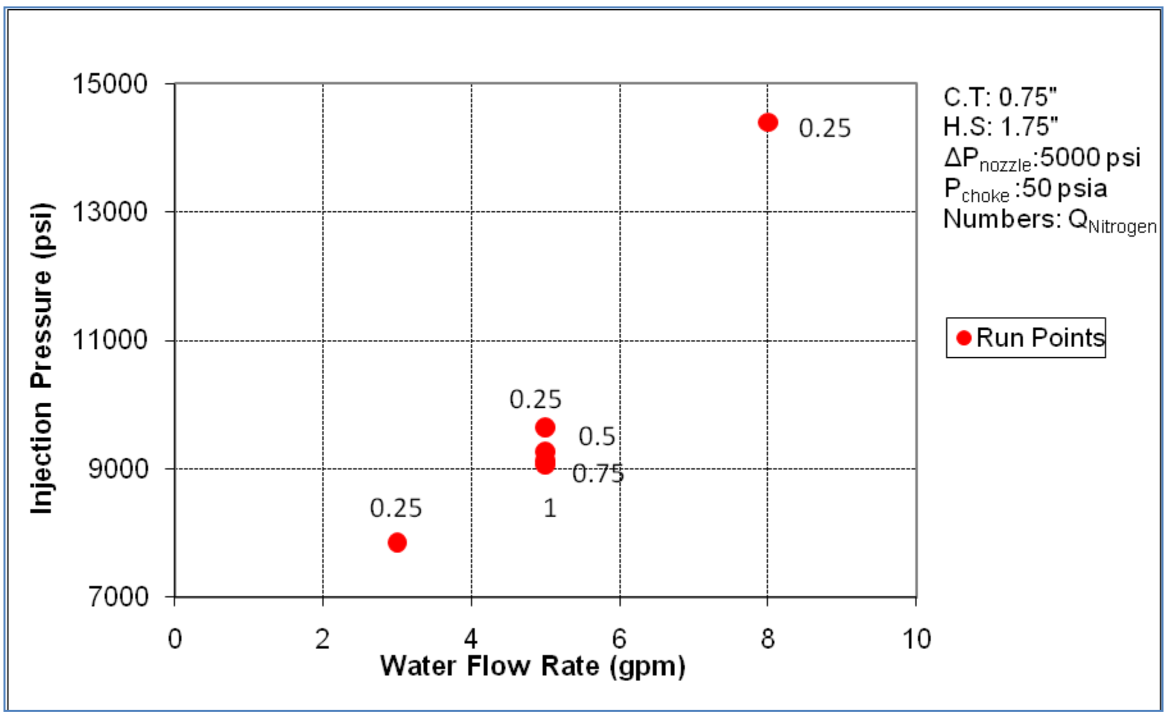

Figure D-8: Flow Rate vs. Inj. Pressure for Water with N_2 (CT:0.75”-HS:1.75”,21,000 ft)

Conclusions

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

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

Coiled Tubing O.D: 1 inch –Bore Hole Size: 2.25 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	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		
Q Water (gpm	**Q N2 (gpm)**	**Injection Pressure (psi)**	**BHP Upstream Nozzle (psi)**	**BHP D. Stream Nozzle (psi)**	**T Upstream Nozzle (ºF)**	**T D.Stream Nozzle (ºF)**	
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							
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	25	1	69	0.836		
5	0.25	41	1	111	0.904		
8	0.25	64	1	175	0.941		
5	0.5	43	1	116	0.899		
5	0.75	46	1	122	0.894		
5	1	56	1	127	0.89		
Q Water (gpm	**Q N2 (gpm)**	**Injection Pressure (psi)**	**BHP Upstream Nozzle (psi)**	**BHP D. Stream Nozzle (psi)**	**T Upstream Nozzle (ºF)**	**T D.Stream Nozzle (ºF)**	
3	0.25	7819	16040	11040	392	402	
5	0.25	6953	15295	10295	394	403	
8	0.25	6543	14833	9833	391	400	
5	0.5	6560	14742	9742	392	402	
5	0.75	6224	14220	9220	391	400	
5	1	5970	13785	8785	391	401	

Table D-3: Continuation

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	