

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

WELLFLO SIMULATIONS REPORT

STEP 6: DRILLING 30,000 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 30,000 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 30,000 wells. In the second cases, 1.25'' coiled tubing was used to drill 30,000 wells which have casing for the first 29,000 ft. For the third cases, well deviated 30° from its vertical path after 29,000 ft depth of the well and has different size of casings for the first 29.000 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 30,000 ft simulations. Higher temperature drop occurred at the nozzle for nitrogen with water addition cases.

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 30,000 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 ASJTM 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 reel at the surface in order to fully calculate pressure losses of the system. In all of the 30,000 ft. drilling simulations, total coiled length of the system was set to 40,000 ft length on a 7 ft. spool diameter 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 °F initial temperature. Pressure drop across the nozzle was fixed at 9,500 psi, except the case 1 runs. In that condition, 8,200 psi pressure drop across the nozzle was used for nitrogen only injections and 5,000 psi was used for nitrogen injection with water addition. Nitrogen changed its phase at the bottom of the well in the tubing for some of the case 1 and case 2 runs. Table 1 gives the input parameters for nitrogen for all conditions.

Table 1: Input Parameters

	CASE-1		CASE-2	CASE-3
	N₂ Only	N₂ & Water	All Runs	All Runs
Depth (ft)	30,000	30,000	30,000	31,300
Formation	Sandstone	Sandstone	Sandstone	Sandstone
Geothermal Gradient (°F/ft)	0.015	0.015	0.015	0.015
Surface Temperature (°F)	60	60	60	60
Injected Fluid Temperature (°F)	75	75	75	75
Return Choke Pressure (psia)	50	50	50	50
Nozzle Pressure Drop (psi)	8,200	5,000	9,500	9,500
Cutting Size (micron)	25-100	25-100	25-100	25-100
ROP (ft/hour)	400	400	400	400

2. Simulations with 1.25'' Coiled Tubing-2.25'' Hole Size

In this schematic, 30,000 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 8,200 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 6,462 psia.

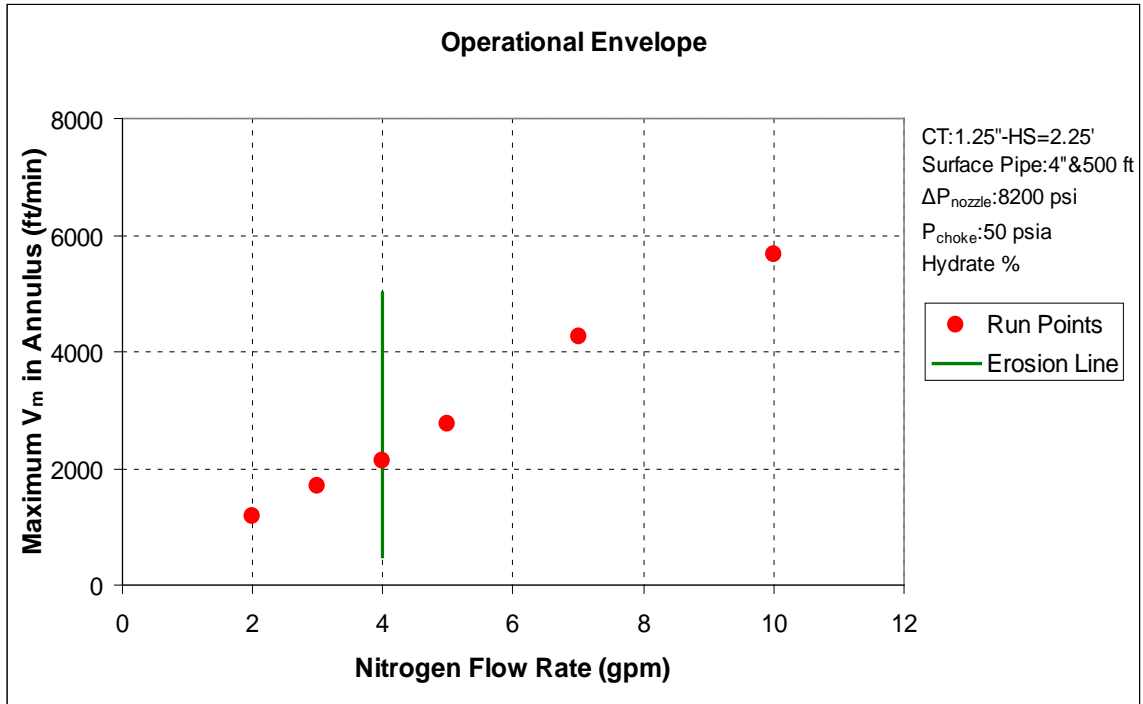


Figure 1: Operational Envelope for N_2 (CT:1.25"-HS:2.25", N_2 Only)

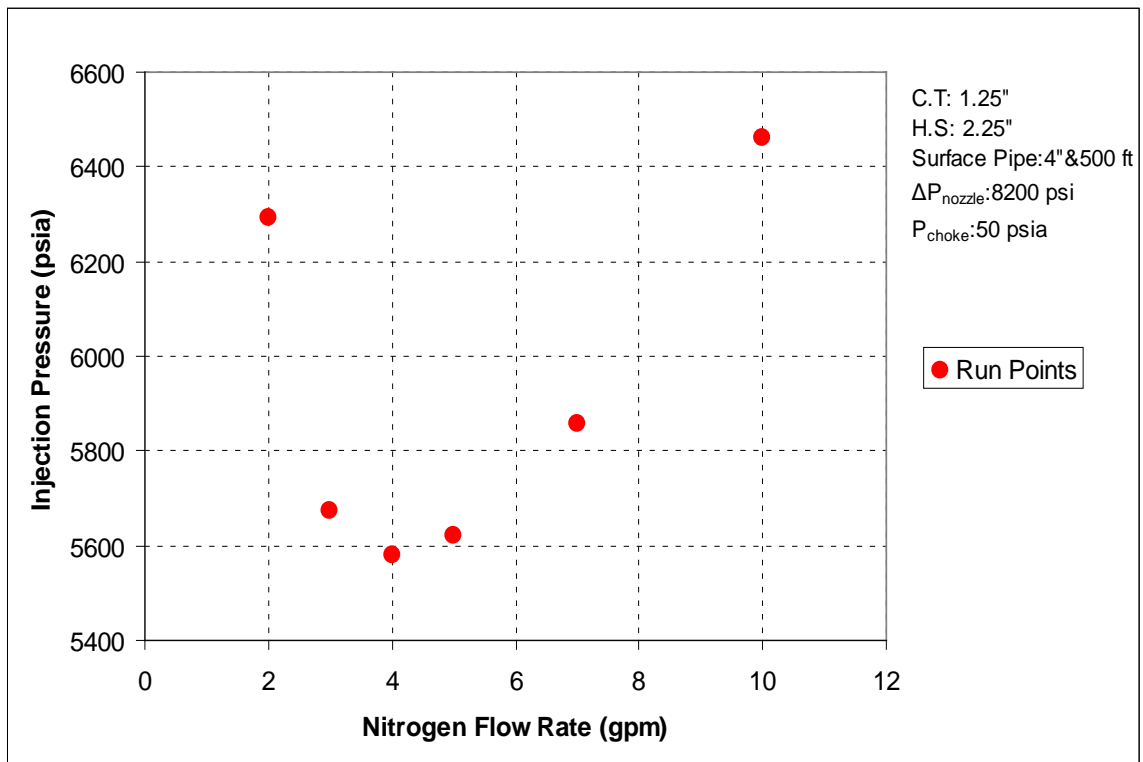


Figure 2: Flow Rate vs. Inj. Pressure (N_2 , CT:1.25"-HS:2.25", N_2 Only)

Example pressure and temperature profile graphs for nitrogen only case are given for the flow rate of 7 gpm in Figures 3 and 4, respectively. As seen in Figure 3, the pressure drop of 8,200 psi occurs at the nozzle. Pressure outputs for 7 gpm are given in Table 2.

Table 2: Output Pressure Values (N₂ Only, CT: 1.25''-HS: 2.25'', 5 gpm)

Injection Pressure (psia)	5,856
BHP Upstream Nozzle (psia)	10,008
BHP Downstream Nozzle (psi)	1,808

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. A small amount of temperature increase was observed at the nozzle for this condition. Selected output results for all other flow rate data are given in Appendix A.

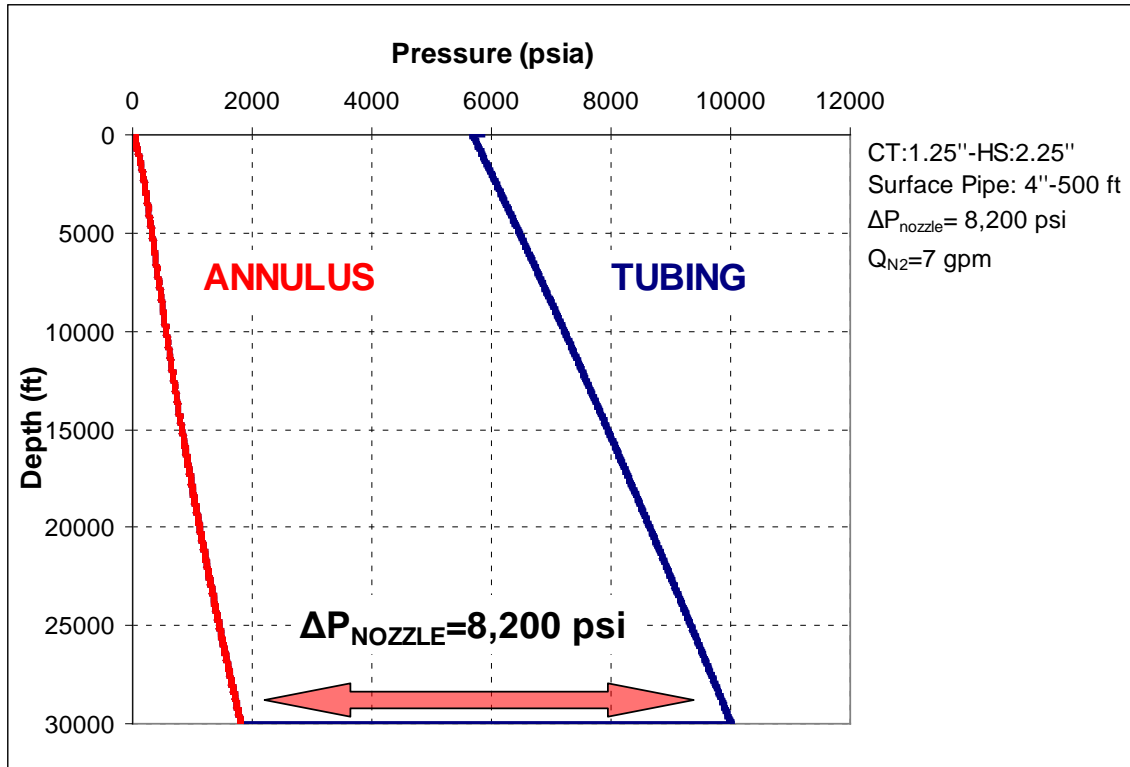


Figure 3: Pressure vs Depth (N₂ Only, CT:1.25", H.S:2.25", Q=7 gpm)

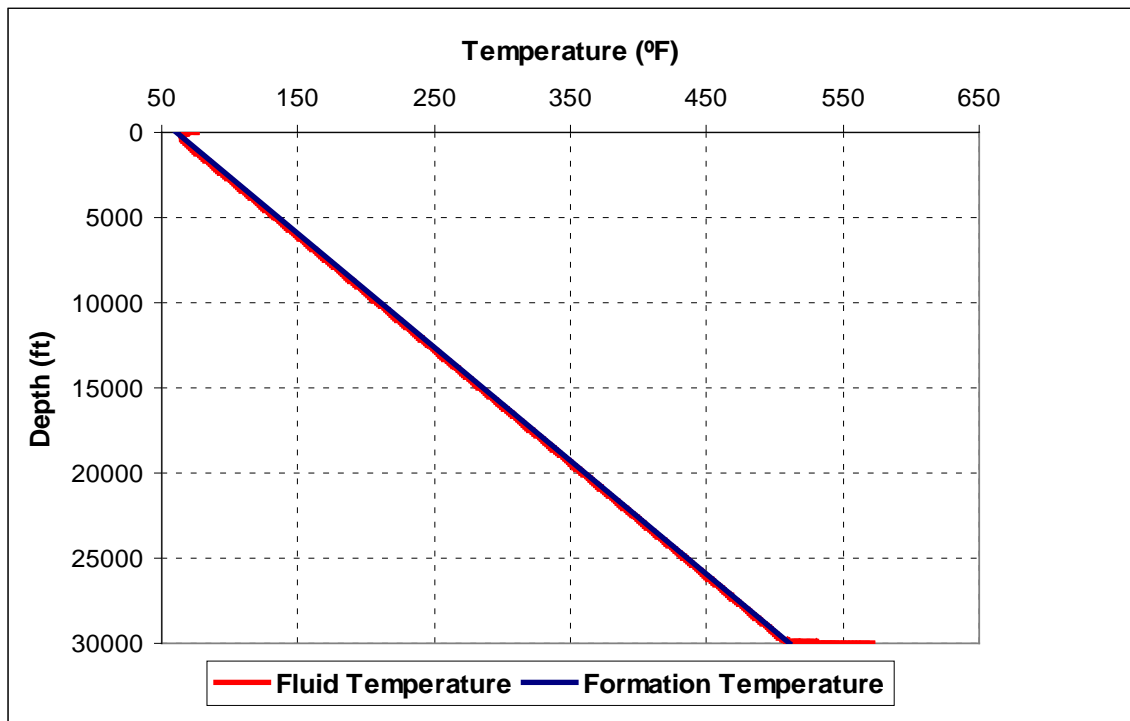


Figure 4: Temperature vs. Depth (N₂ Only, CT:1.25", H.S:2.25", Q=7 gpm)

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.

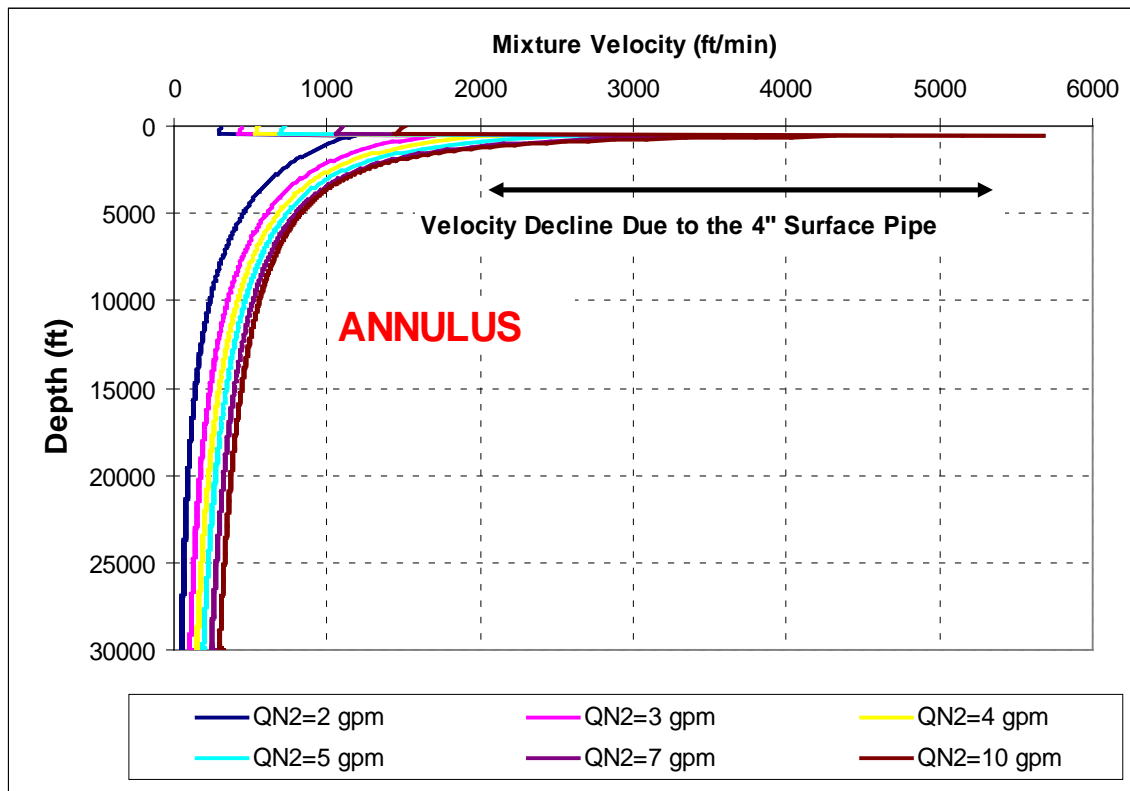


Figure 5: Mixture Velocity Profile for N₂ (CT:1.25"-HS:2.25", N₂ Only)

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). Brown color was used the run points which has liquid fraction more than 0.25 after the nozzle in the annulus.

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.

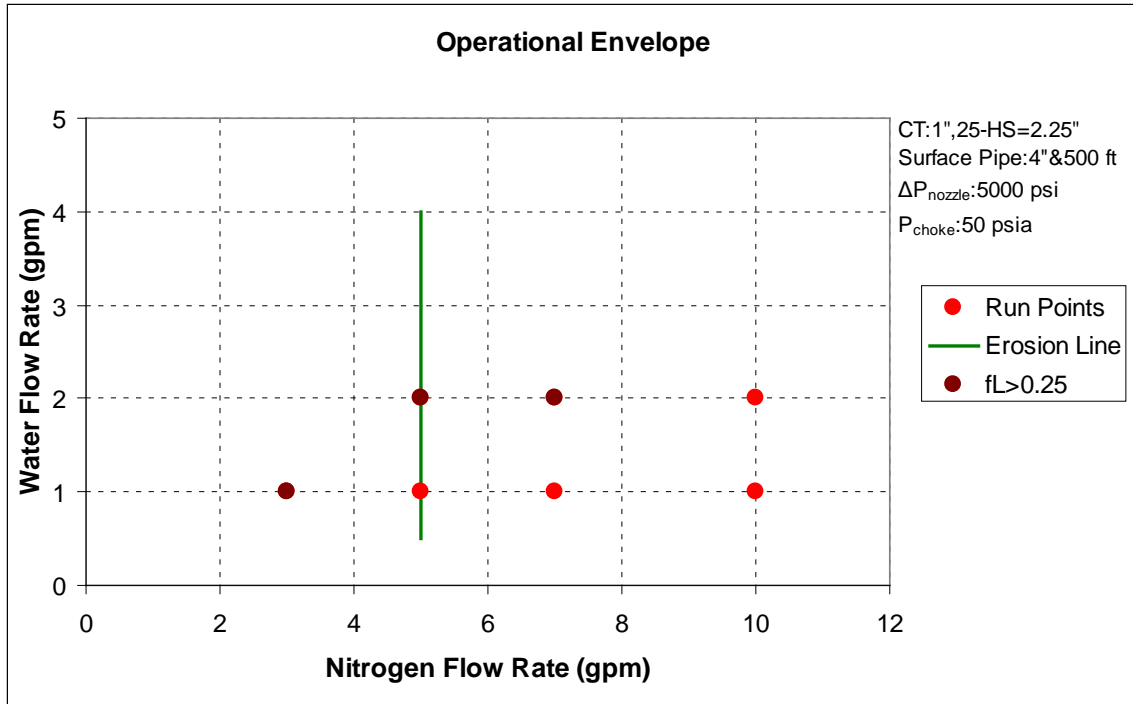


Figure 6: Operational Envelope for N₂ (CT:1.25"-HS:2.25", With Water Addition)

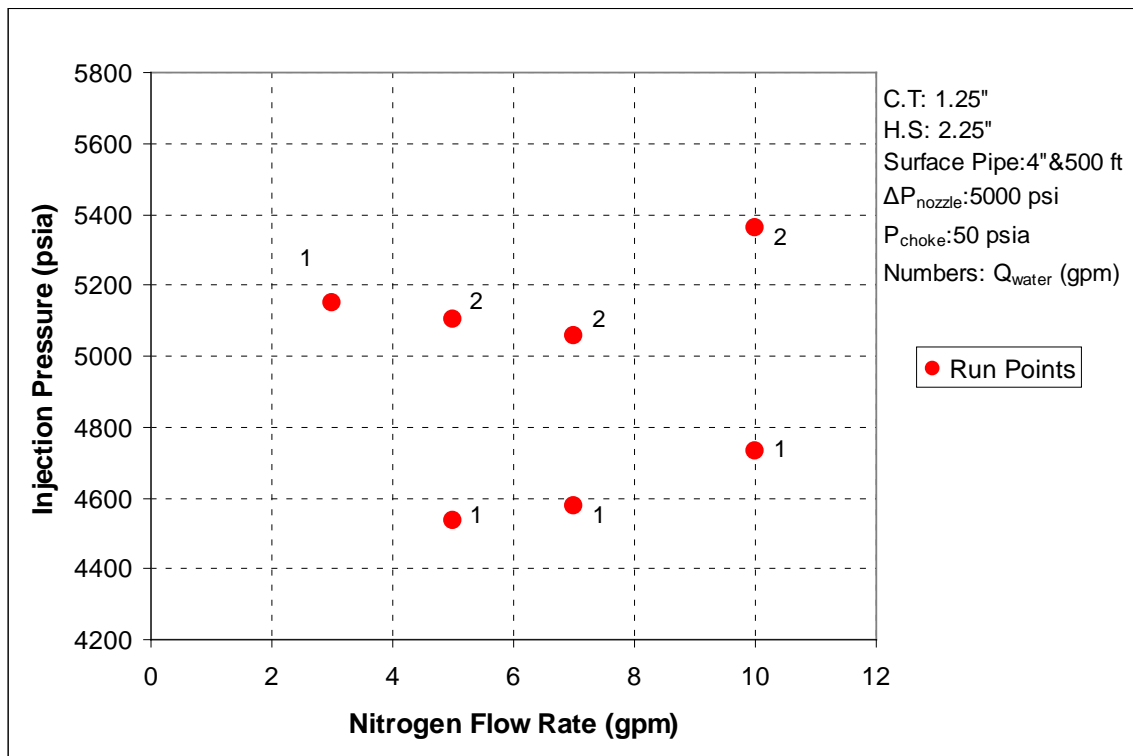


Figure 7: Flow Rate vs. Inj. Pressure for N₂ (CT:1.25"-HS:2.25", With Water Addition)

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 5,000 psi occurs at the nozzle. Also due to the surface coiled tubing facility, 677 psi total pressure drop occurred at the surface. Pressure outputs are given in Table 3.

Table 3: Output Pressure Values (N₂ with Water Addition, Q_{N₂}=7 gpm, Q_w= 1gpm)

Injection Pressure (psia)	4578
BHP Upstream Nozzle (psia)	8420
BHP Downstream Nozzle (psia)	3420

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.

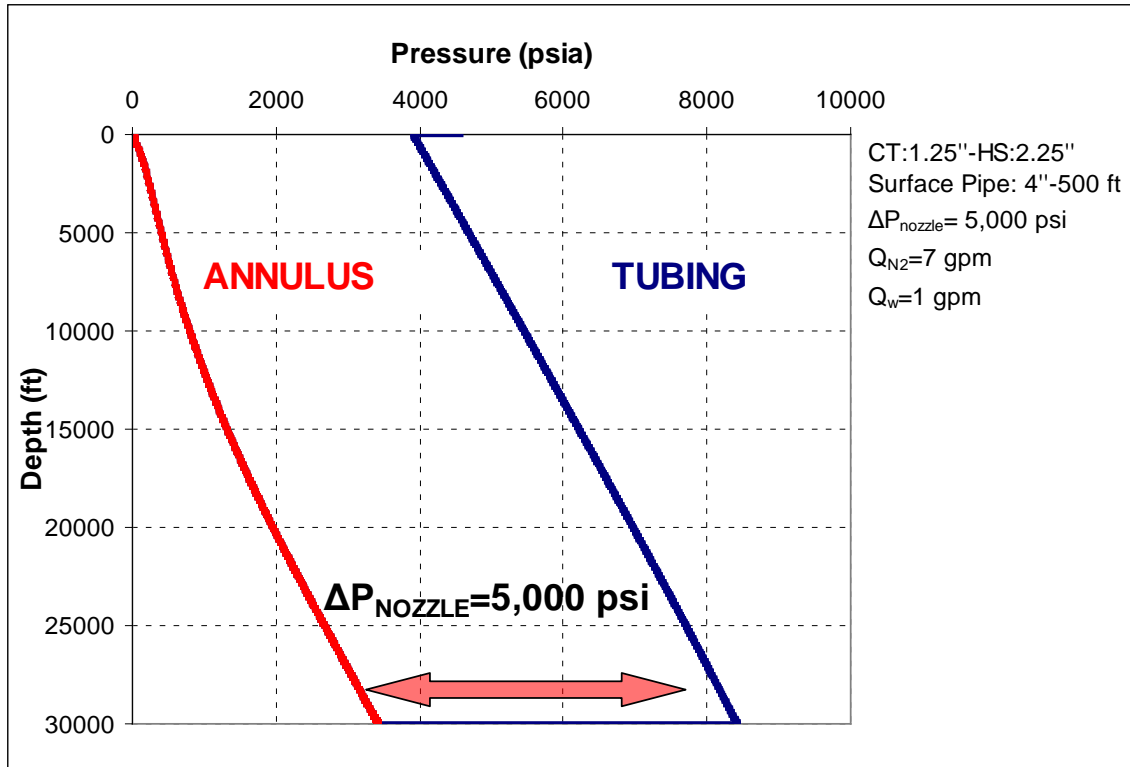


Figure 8: Pressure vs Depth (N₂ with Water, CT:1.25", H.S.:2.25")

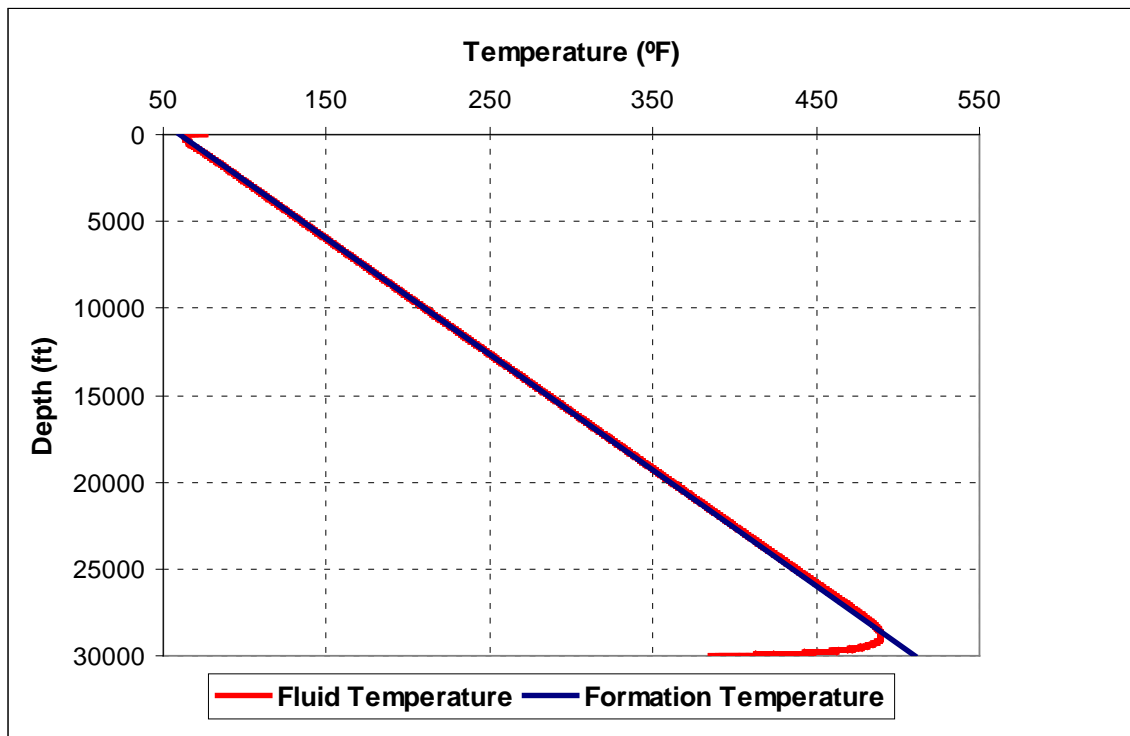


Figure 9: Temperature vs. Depth (N₂ With Water, CT:1.25", H.S.:2.25")

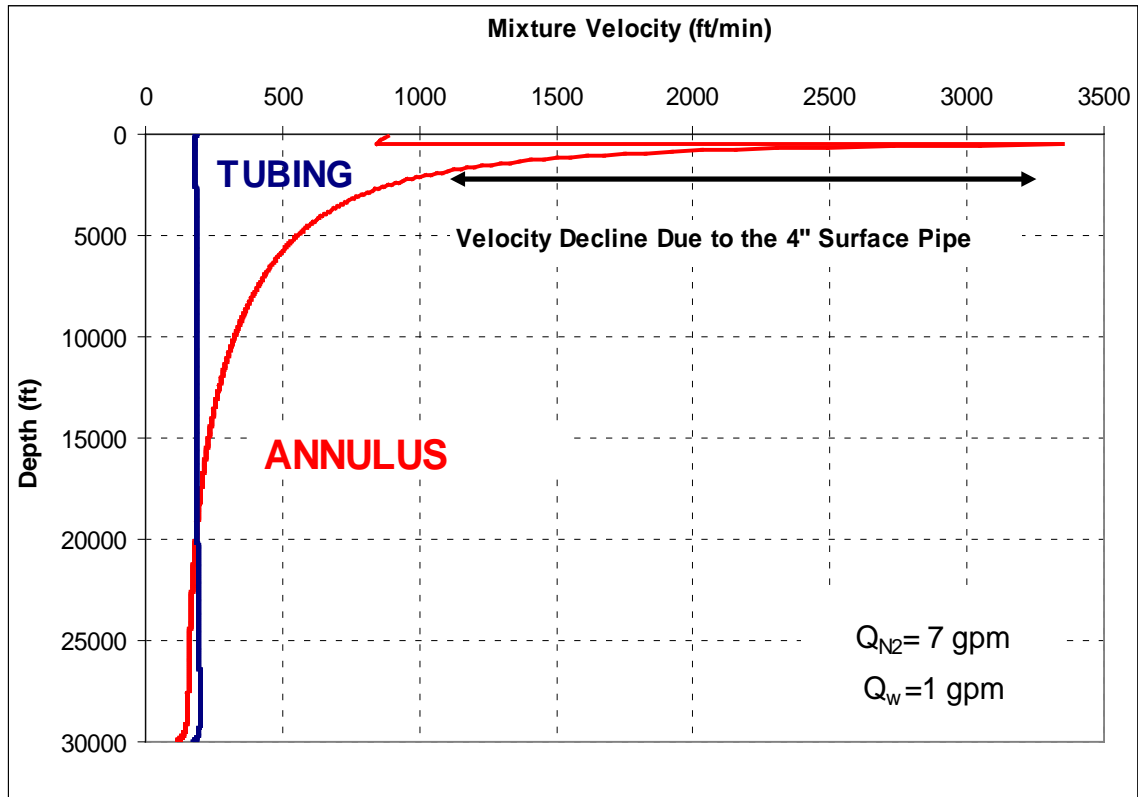


Figure 10: Velocity Profile (N_2 with Water, CT:1.25", H.S:2.25")

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 29,000 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 9,500 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 29,000 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). In these runs, nitrogen changed its phase to gas at the bottom of the well in the annulus for all the runs except 3 gpm injection rate.

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 6154 psia.

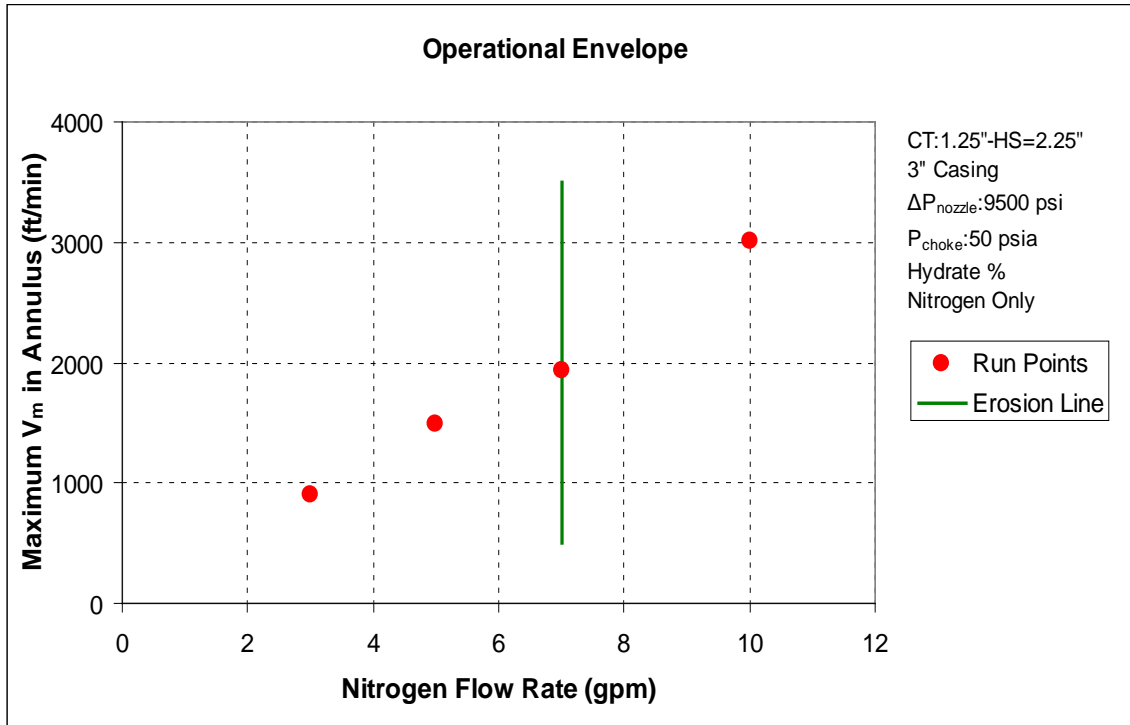


Figure 11: Operational Envelope for N₂ (3" Casing, N₂ Only)

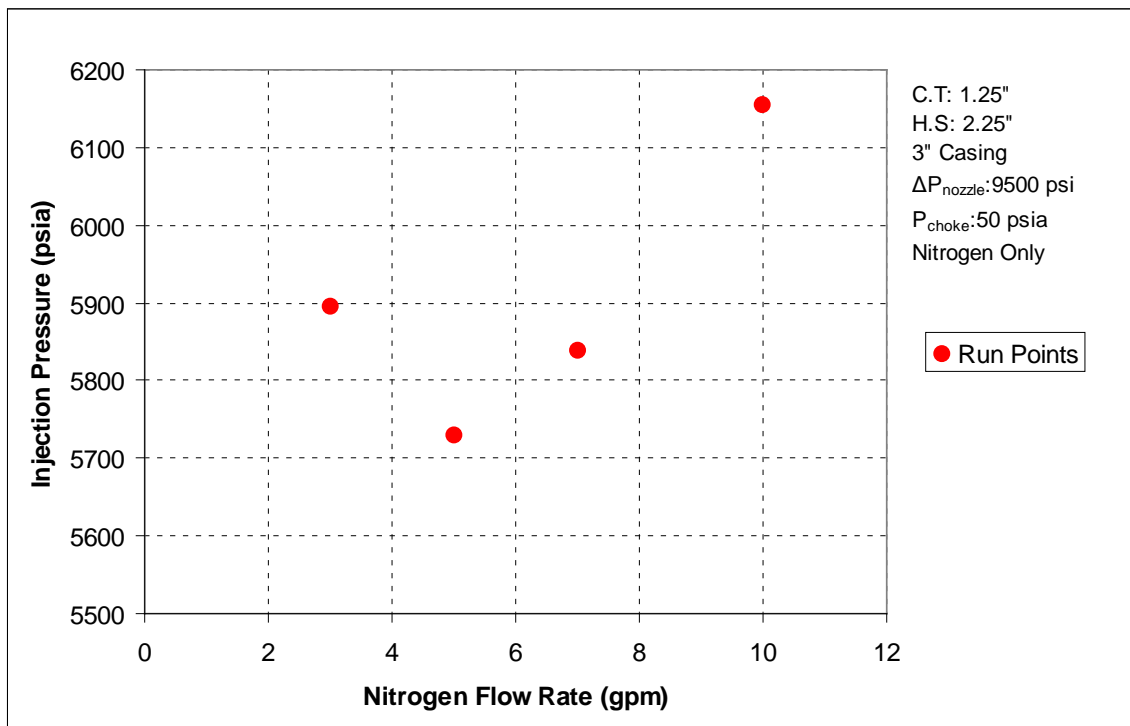


Figure 12: Flow Rate vs. Inj. Pressure for N₂ (3" Casing, N₂ Only)

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 9,500 psi occurs at the nozzle. Also due to the surface coiled tubing facility, 174 psi total pressure drop occurs at the surface. Pressure outputs are given in Table 5.

Table 5: Output Pressure Values (N₂ Only, 3'' Casing, Q_{N₂}=7 gpm)

Injection Pressure (psia)	5839
BHP Upstream Nozzle (psia)	9985
BHP Downstream Nozzle (psia)	485

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, a small amount of temperature increase was observed around the nozzle. 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 29,000 ft due to the beginning of 3'' casing.

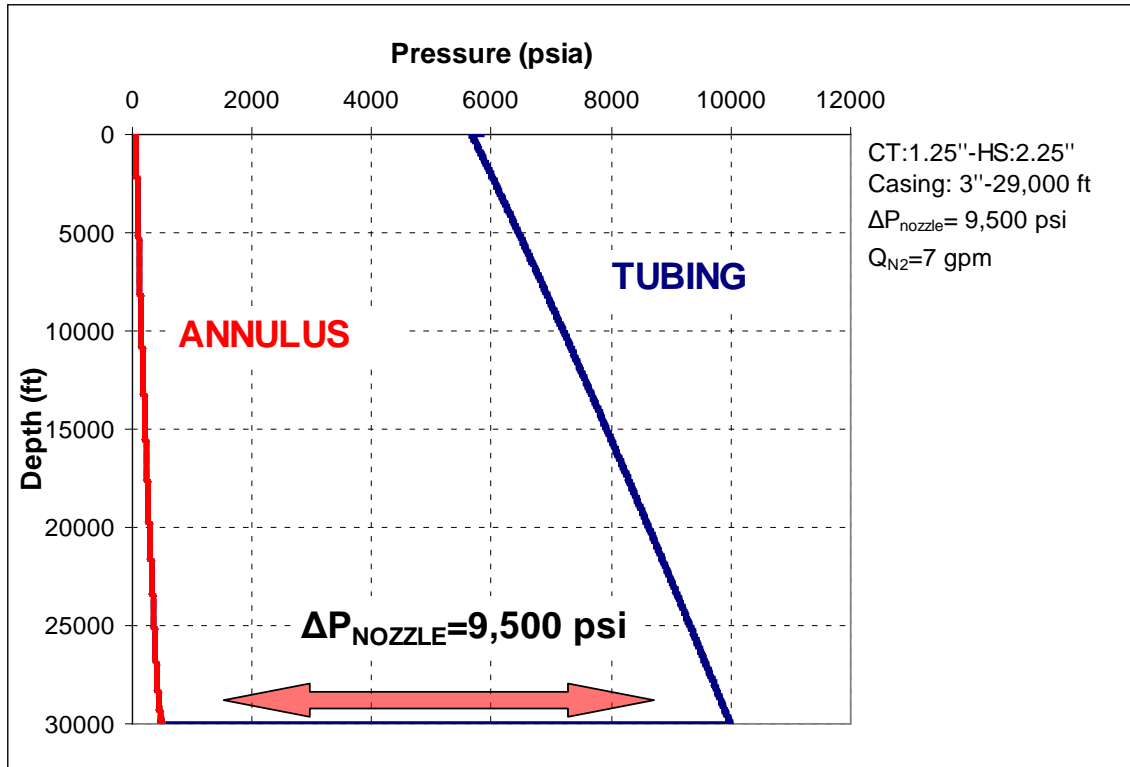


Figure 13: Pressure vs Depth (N₂ Only, 3'' Casing)

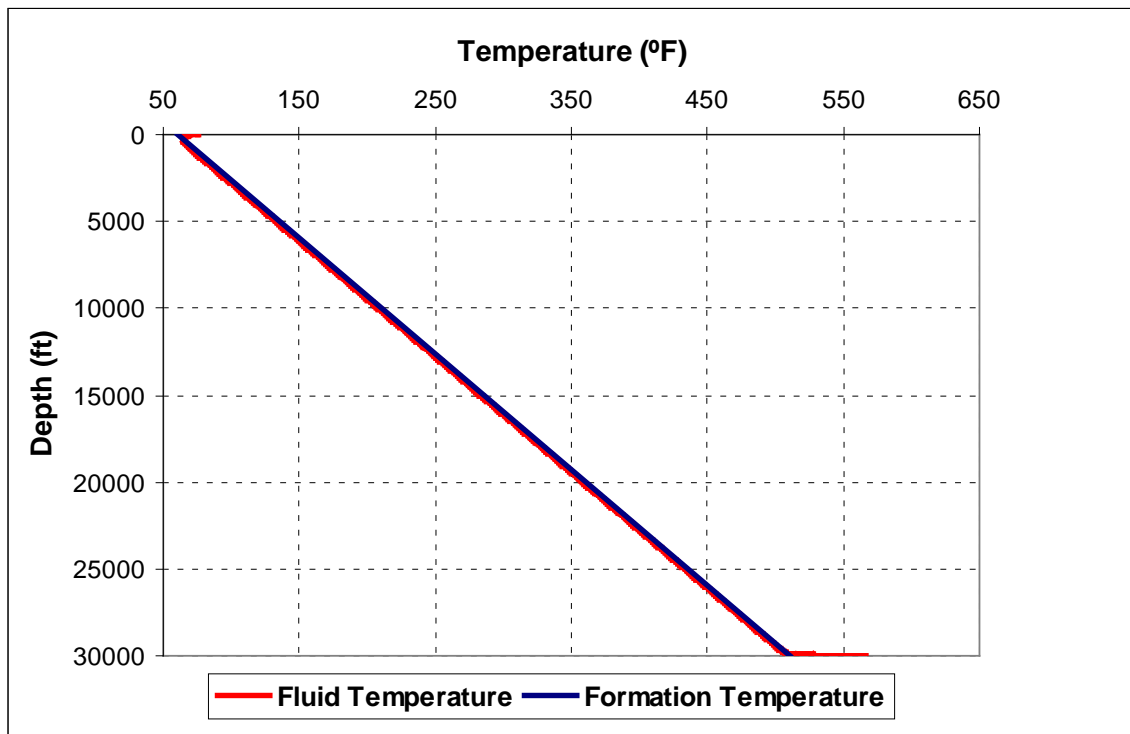


Figure 14: Temperature vs. Depth (N₂ Only, 3'' Casing)

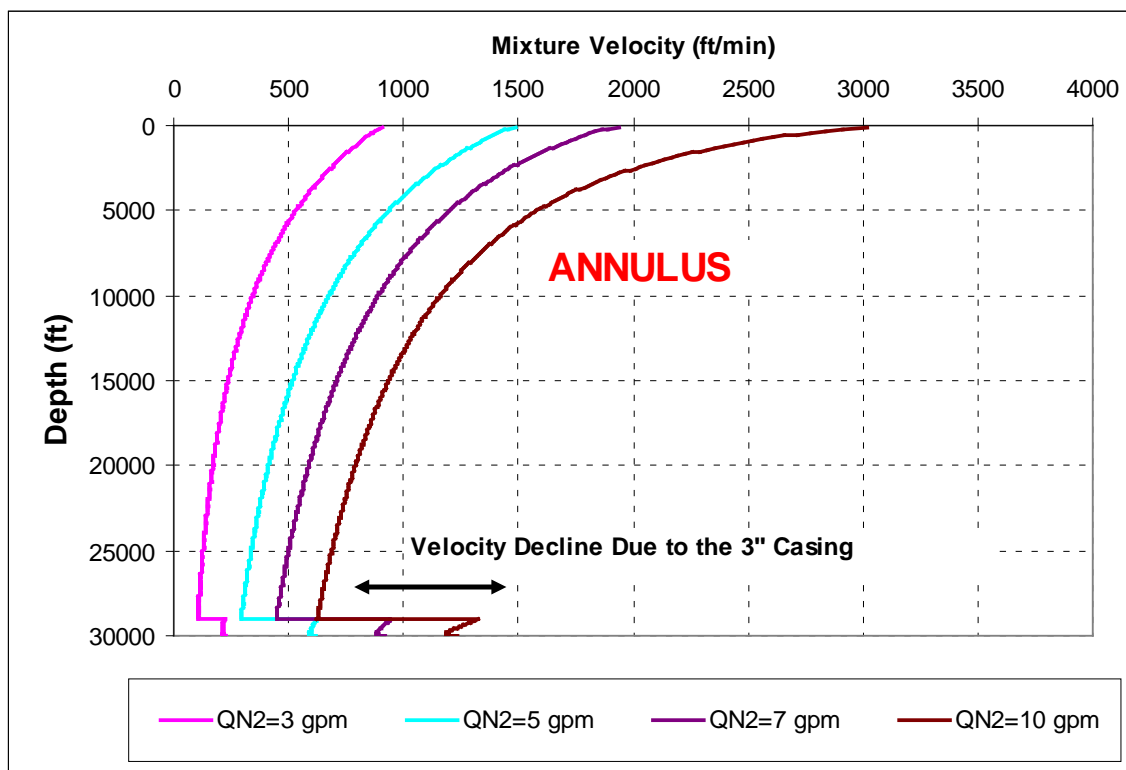


Figure 15: Velocity Profile (N₂ Only, 3'' Casing)

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 29,000 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.

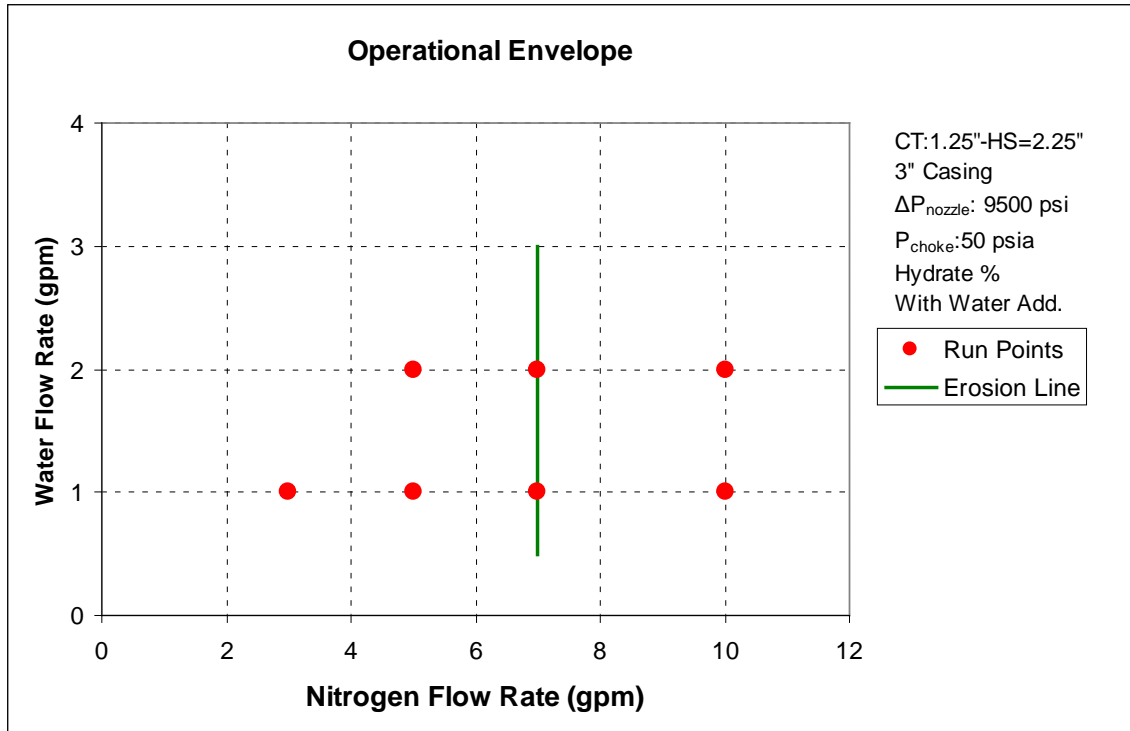


Figure 16: Operational Envelope for N₂ (3" Casing, With Water Addition)

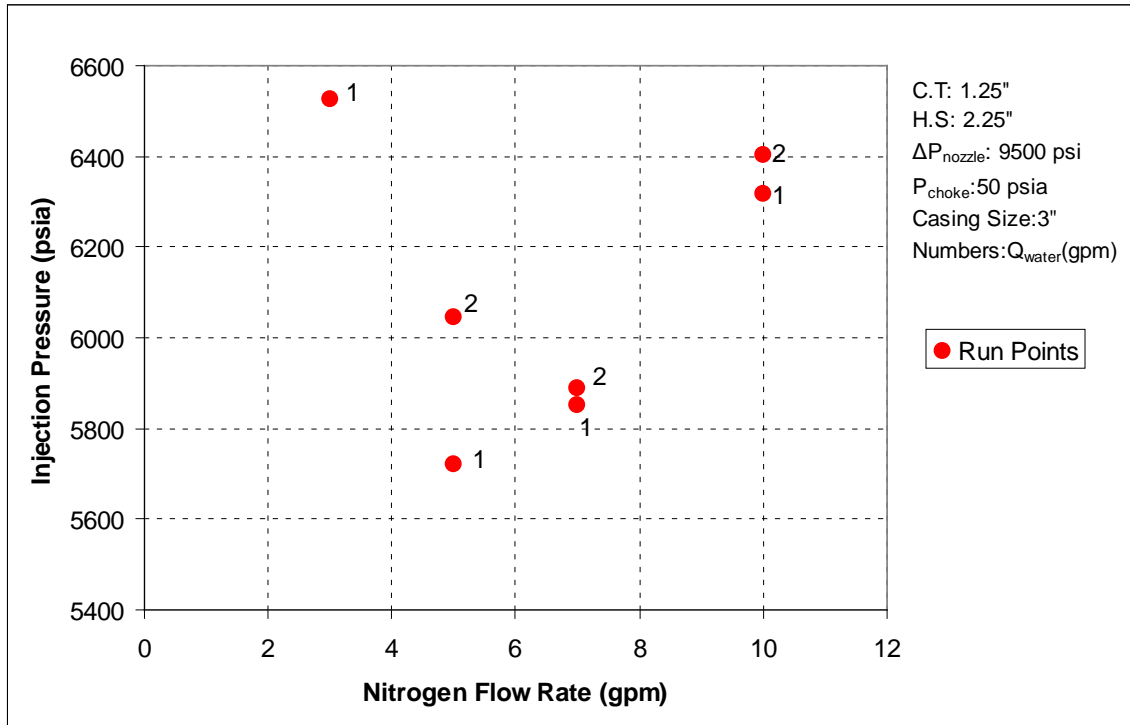


Figure 17: Flow Rate vs. Inj. Pressure for N₂ (3" Casing, With Water Addition)

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 9,500 psi occurs at the nozzle. Also due to the surface coiled tubing facility, 771 psi pressure loss occurred at the surface. Pressure outputs are given in Table 6.

Table 6: Output Pressure Values (N₂ With Water Addition, 3'', Q_{N₂}=7 gpm, Q_w=1 gpm)

Injection Pressure (psia)	5851
BHP Upstream Nozzle (psia)	10145
BHP Downstream Nozzle (psia)	645

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 29,000 ft and then mixture velocity increases while reaching surface.

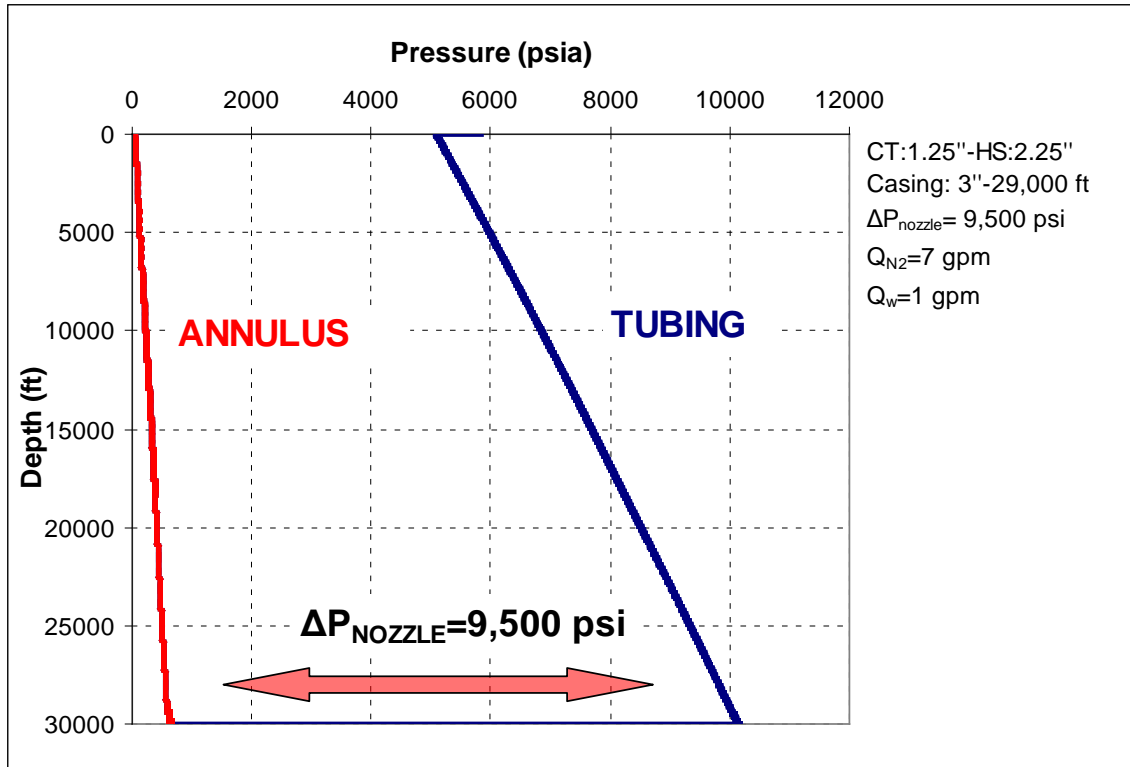


Figure 18: Pressure vs Depth (N₂ with Water Addition, 3'' Casing)

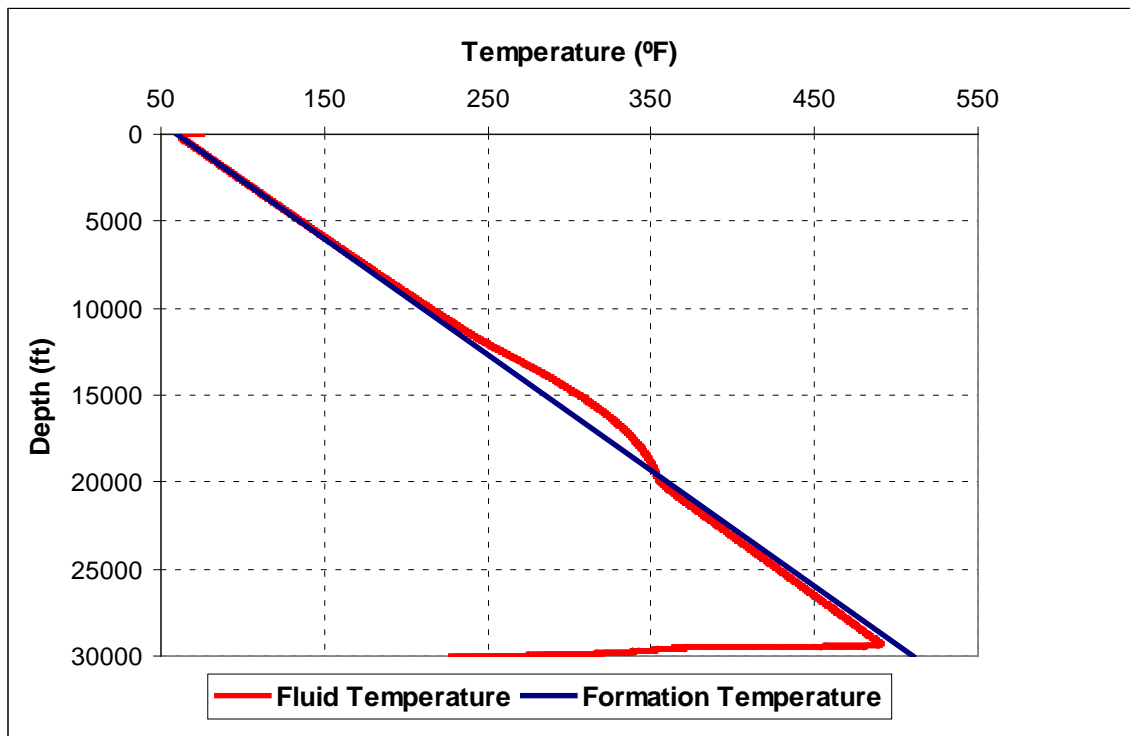


Figure 19: Temperature vs. Depth (N₂ with Water Addition, 3'' Casing)

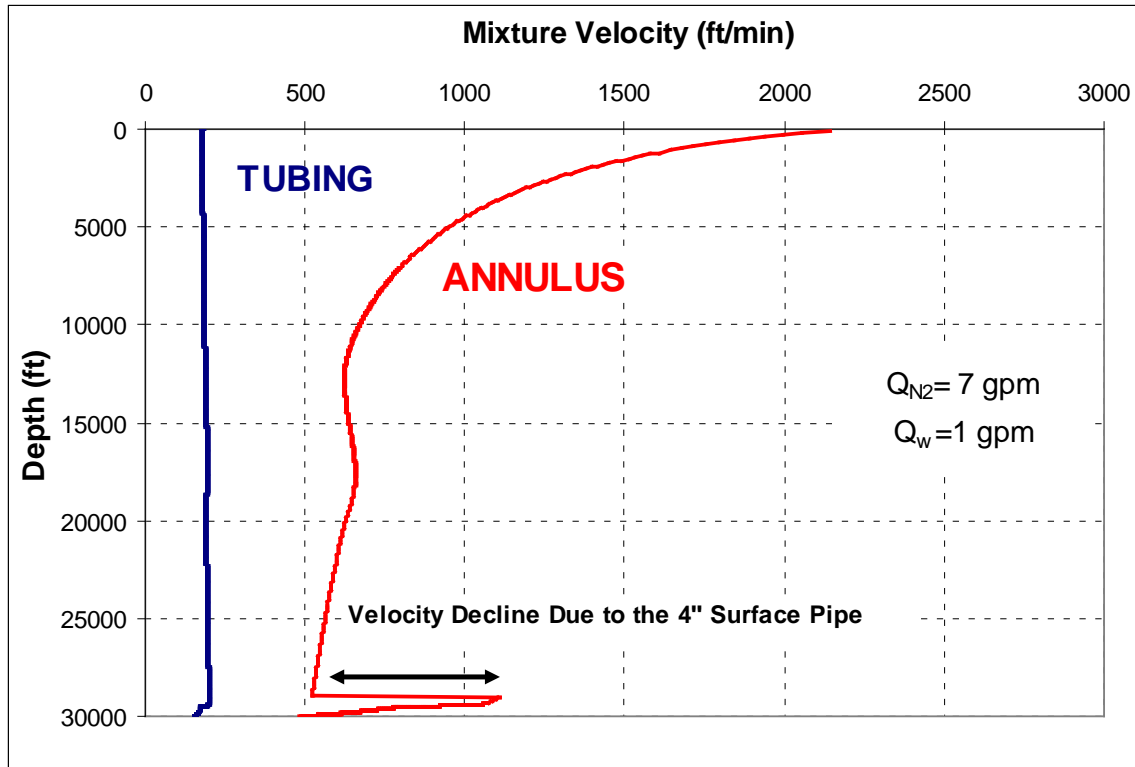


Figure 20: Velocity Profile (N₂ with Water Addition, 3'' Casing)

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''. Similar to 3'' casing runs, nitrogen changed its phase to gas around the bottom of the well in the tubing except 3 gpm runs.

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.

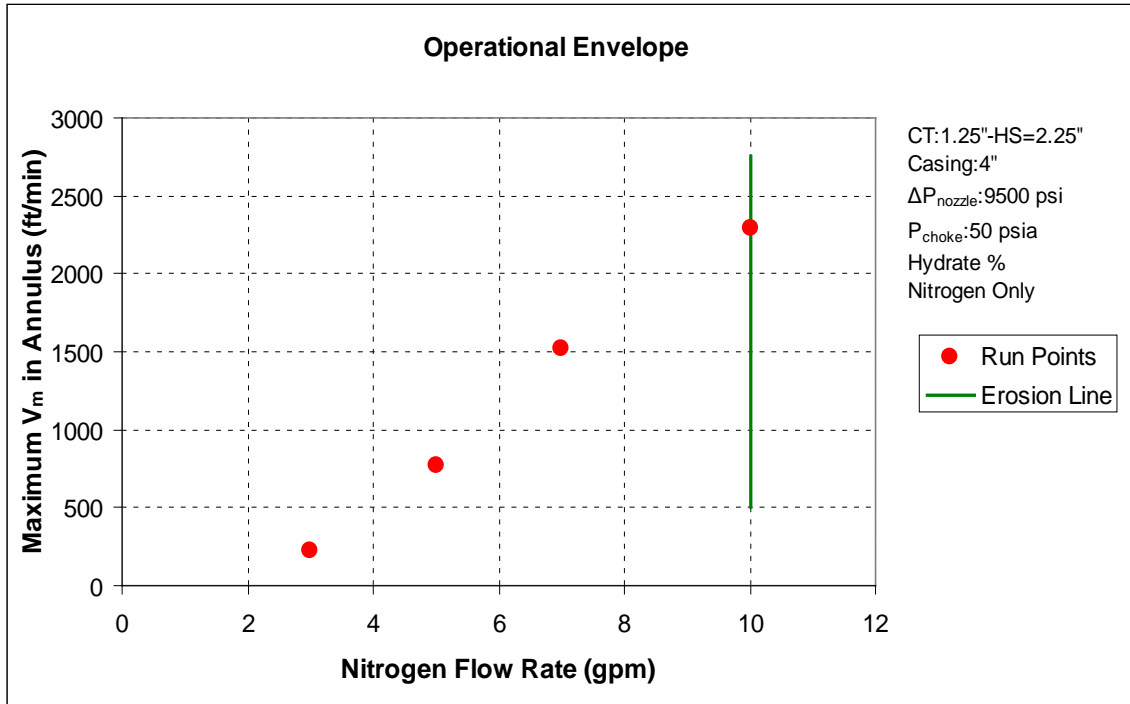


Figure 21: Operational Envelope for N₂ (4" Casing, Nitrogen Only)

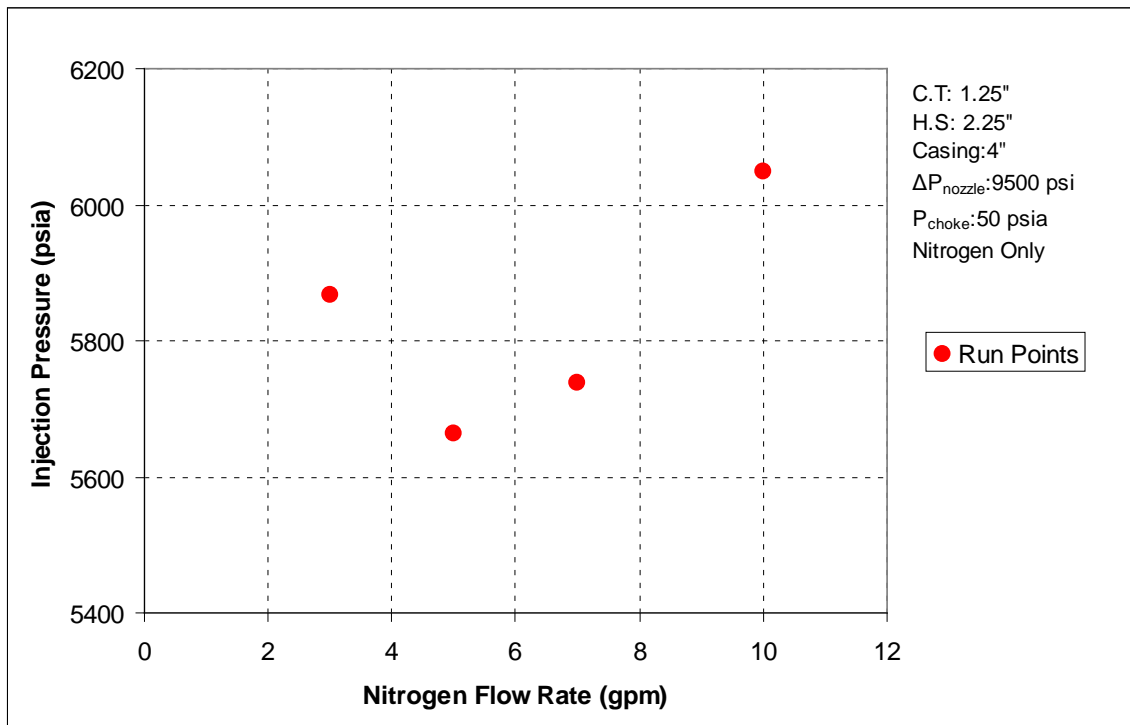


Figure 22: Flow Rate vs. Inj. Pressure for N₂ (4" Casing, Nitrogen Only)

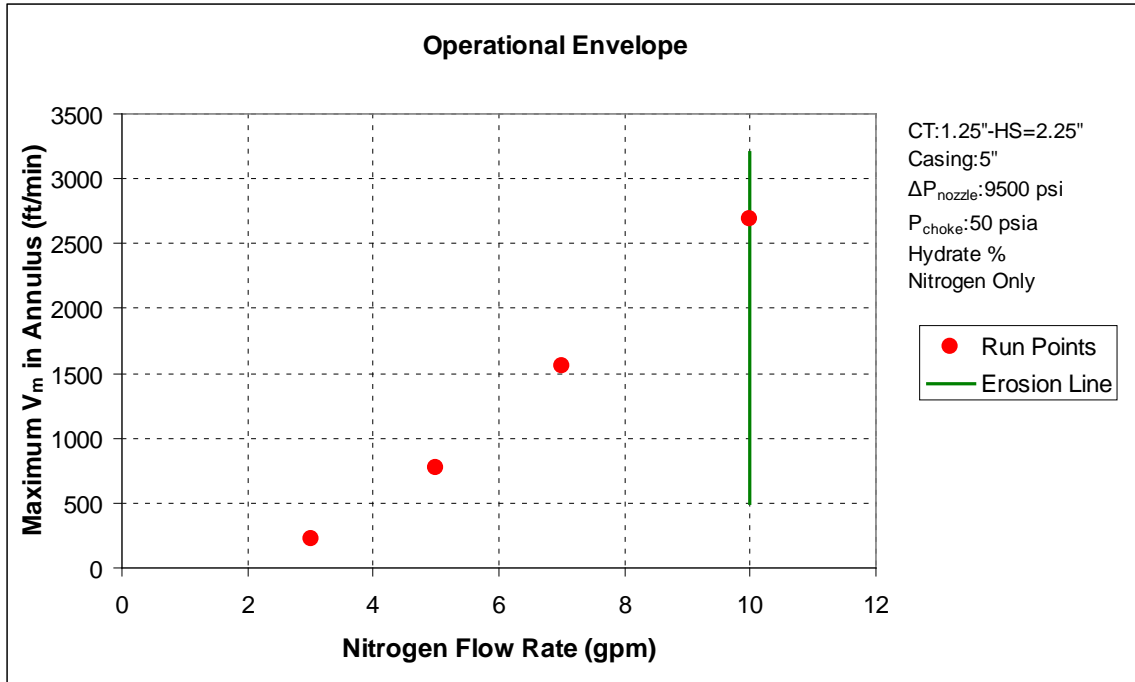


Figure 23: Operational Envelope for N₂ (5" Casing, Nitrogen Only)

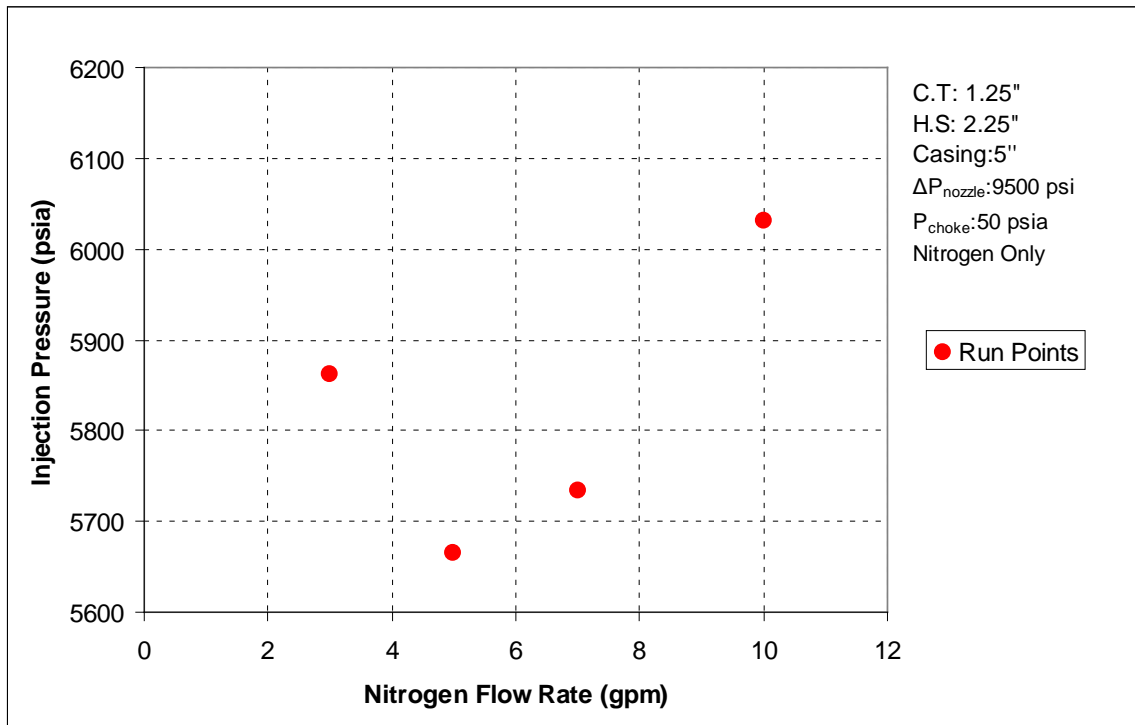


Figure 24: Flow Rate vs. Inj. Pressure for N₂ (5" Casing, Nitrogen Only)

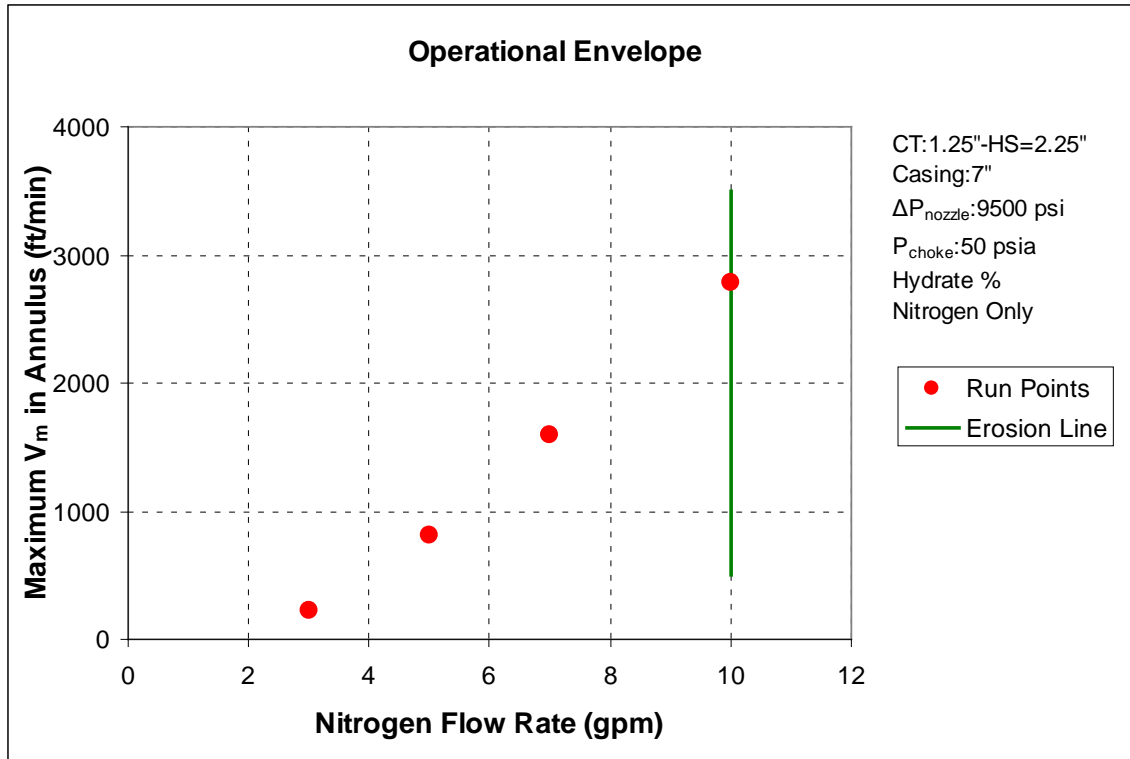


Figure 25: Operational Envelope for N₂ (7" Casing, Nitrogen Only)

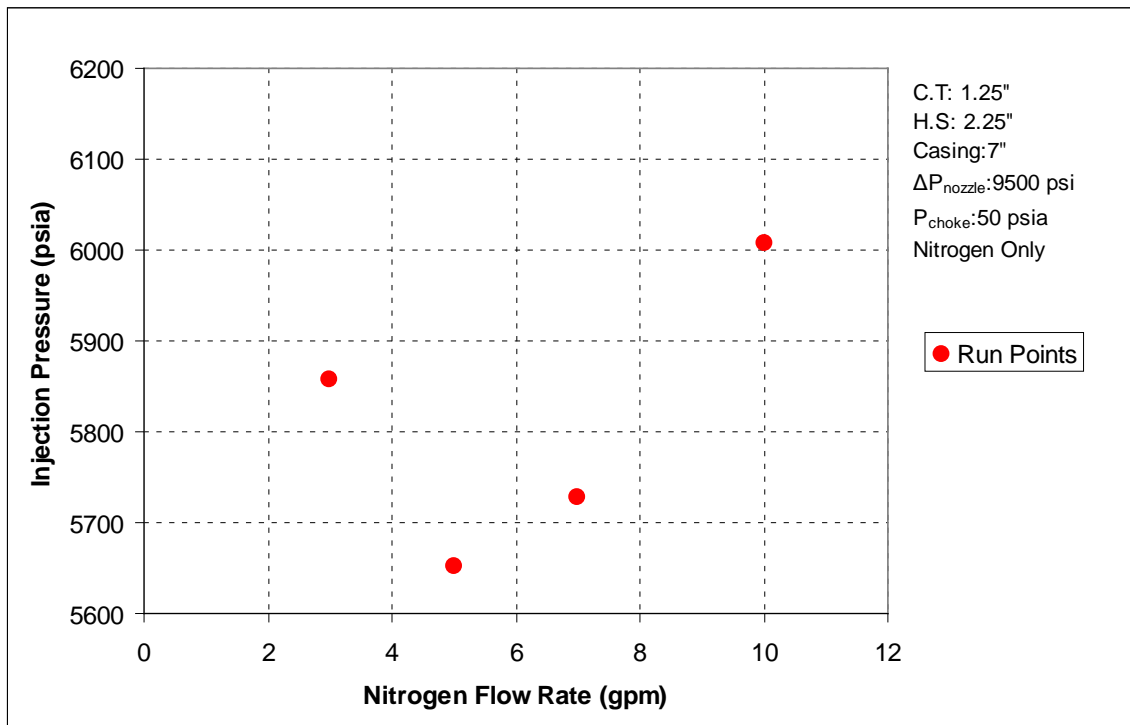


Figure 26: Flow Rate vs. Inj. Pressure for N₂ (7" Casing, Nitrogen Only)

3.3 Cutting Transport Analysis

In this part, cutting transport analysis is made for different casing sizes used for the first 29,000 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 75 or 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.

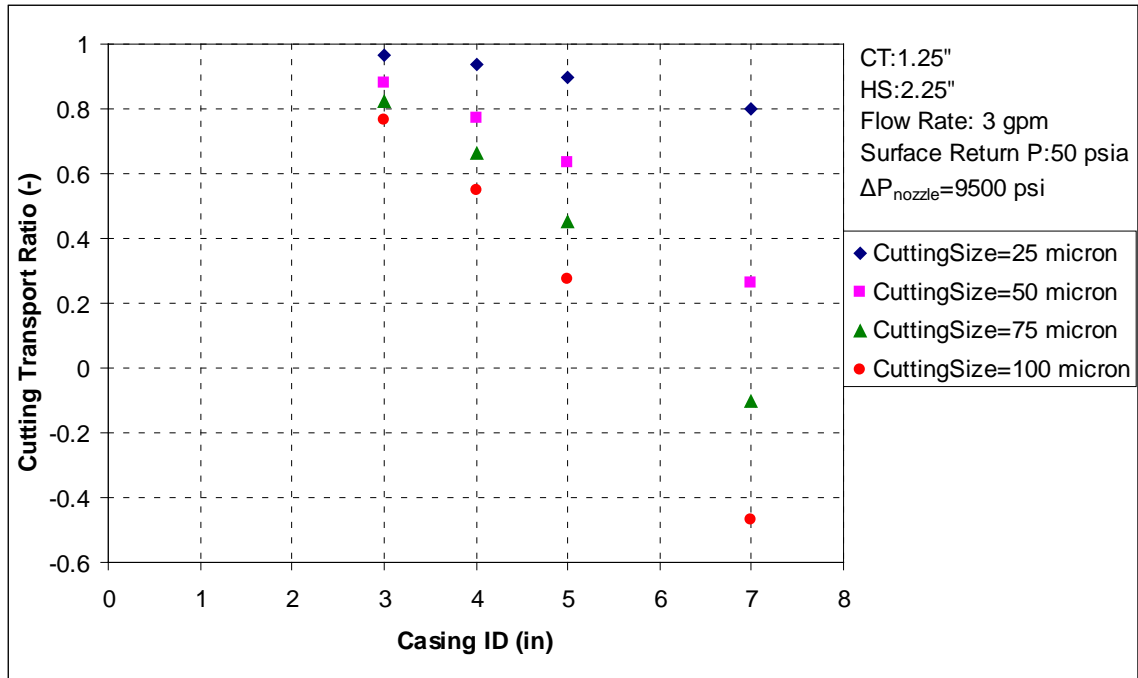


Figure 27: CTR vs. Casing ID (Nitrogen Only, $Q_{N_2}=3$ gpm)

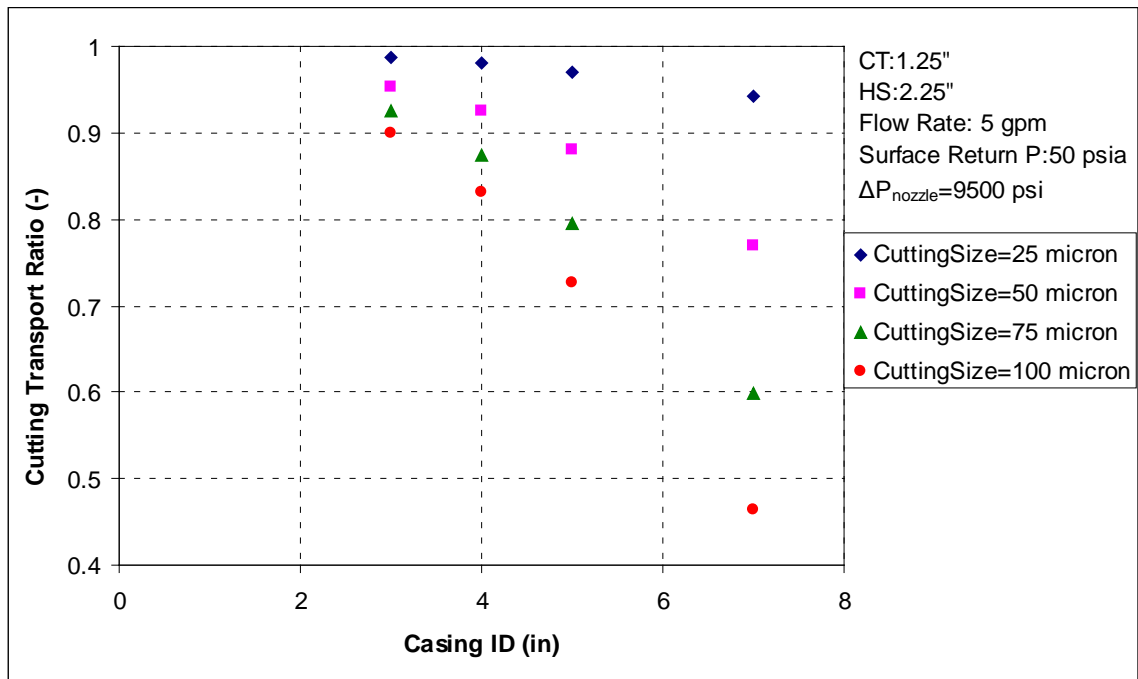


Figure 28: CTR vs. Casing ID (Nitrogen Only, $Q_{N_2}=5$ gpm)

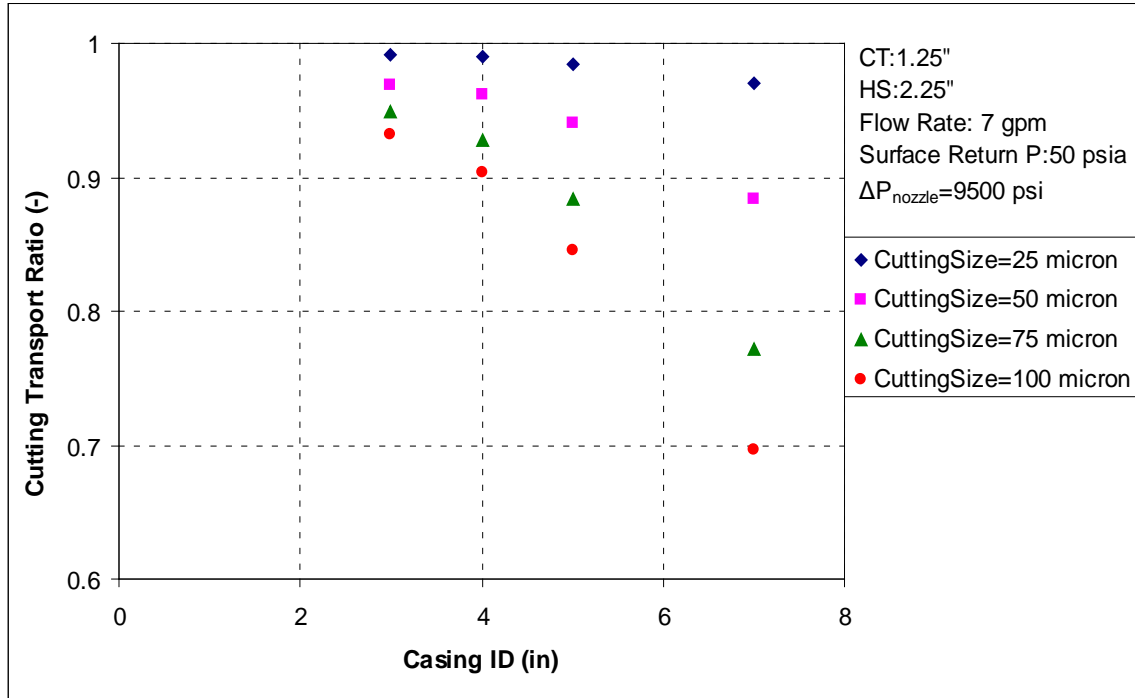


Figure 29: CTR vs. Casing ID (Nitrogen Only, $Q_{N_2}=7$ gpm)

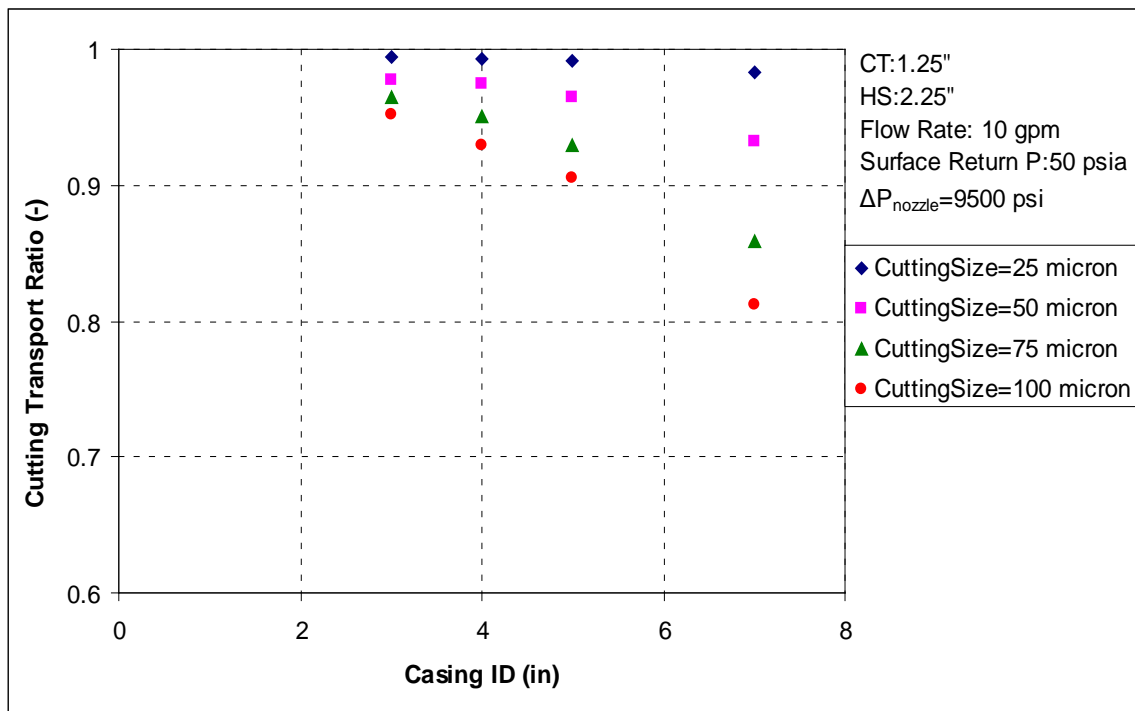


Figure 30: CTR vs. Casing ID (Nitrogen Only, $Q_{N_2}=10$ gpm)

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 29,000 ft (kick of point) of the well. Different sizes of casings used for the first 29,000 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 these cases, pressure drop at the nozzle was fixed to 9,500 psi for all runs. Also in this part, nitrogen changed its phase to gas around the bottom of the well in the tubing except with water addition condition and 3 gpm injection rate. 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'' (N₂ 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.

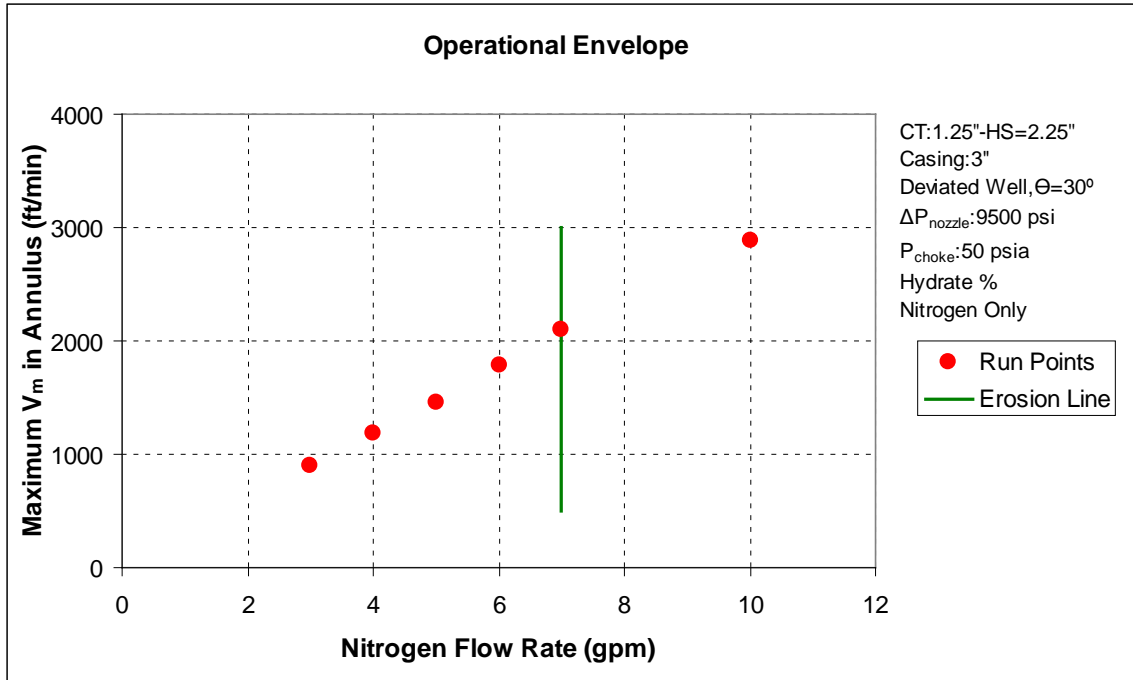


Figure 31: Operational Envelope for N₂ (3" Casing, N₂ Only, Deviated Well)

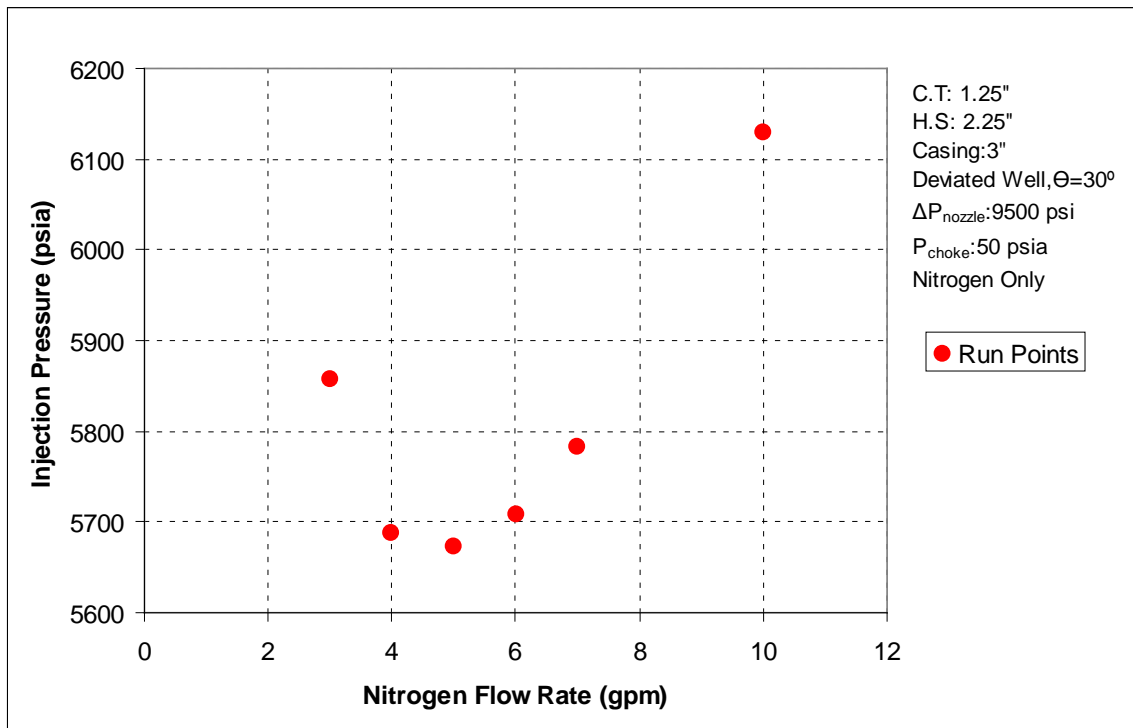


Figure 32: Flow Rate vs. Inj. Pressure for N₂ (3" Casing, N₂ Only, Deviated Well)

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 9500 psi occurs at the nozzle. Also due to the surface coiled tubing facility, 175 psi total pressure drop occurred at the surface. Pressure outputs are given in Table 7.

Table 7: Output Pressure Values
(N₂ Only, 3'' Casing, Q_{N₂}=7 gpm, Deviated Well)

Injection Pressure (psia)	5782
BHP Upstream Nozzle (psia)	10030
BHP Downstream Nozzle (psia)	530

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 29,000 ft due to the beginning of 3'' casing and then started to increase while reaching surface.

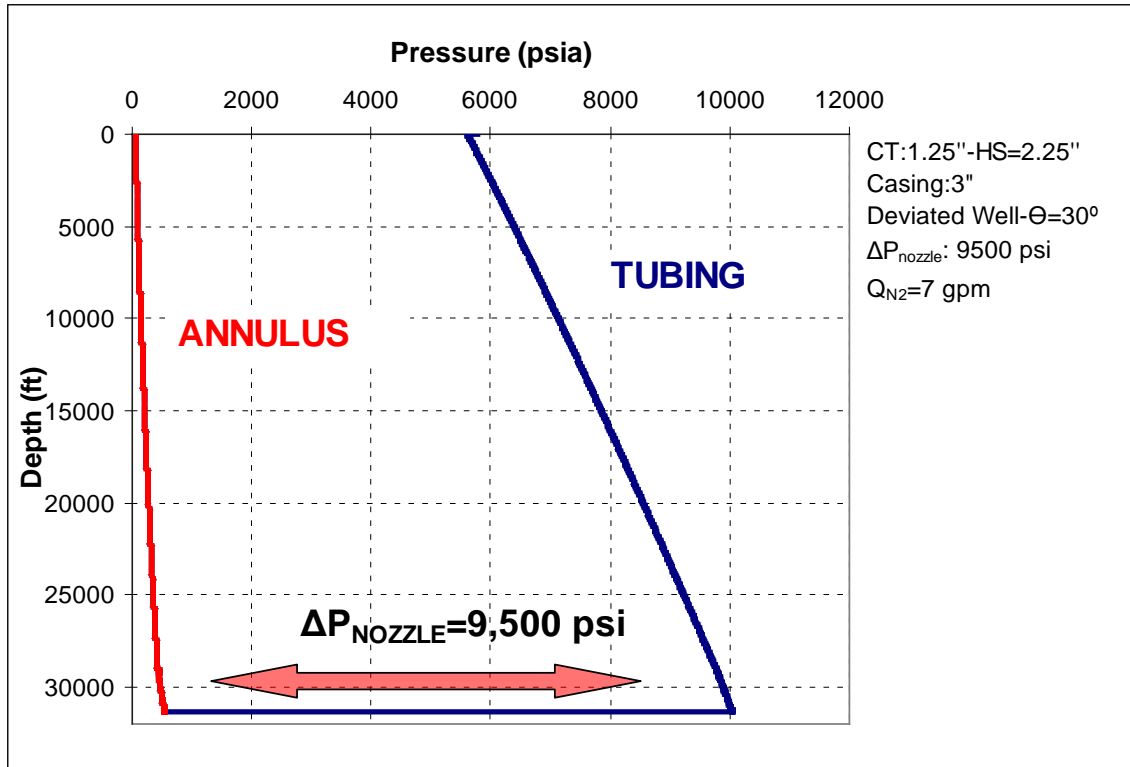


Figure 33: Pressure vs Depth (N₂ Only, 3'' Casing, Deviated Well)

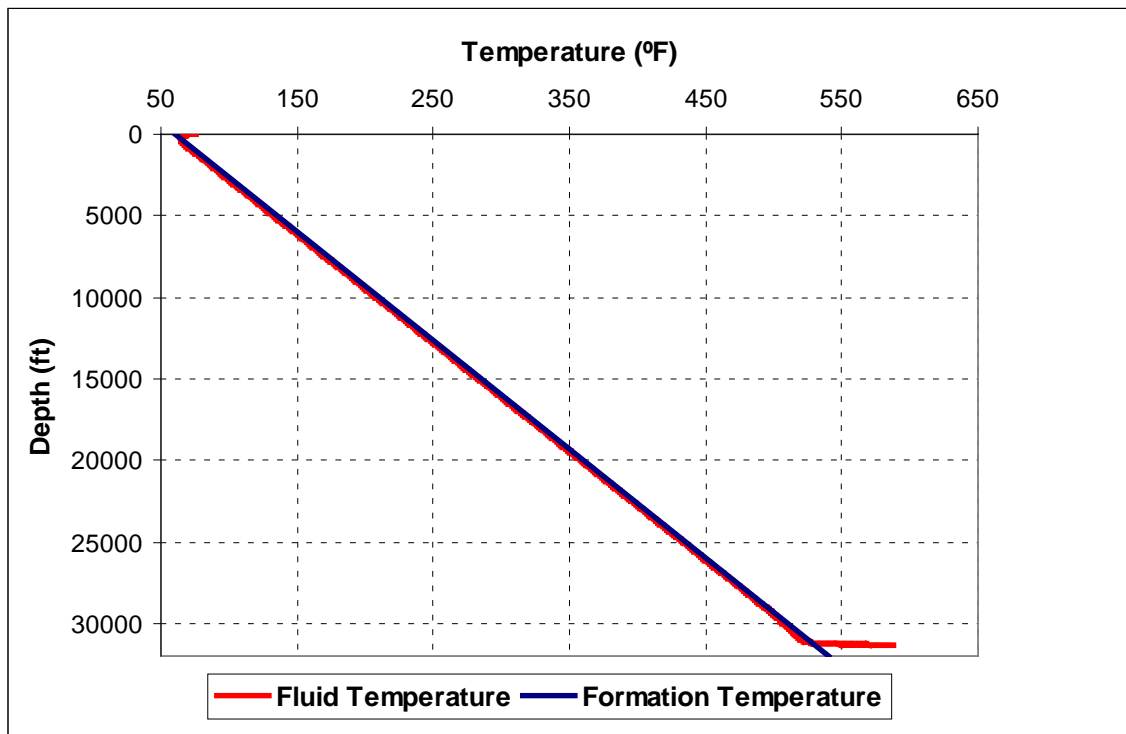


Figure 34: Temperature vs. Depth (N₂ Only, 3'' Casing, Deviated Well)

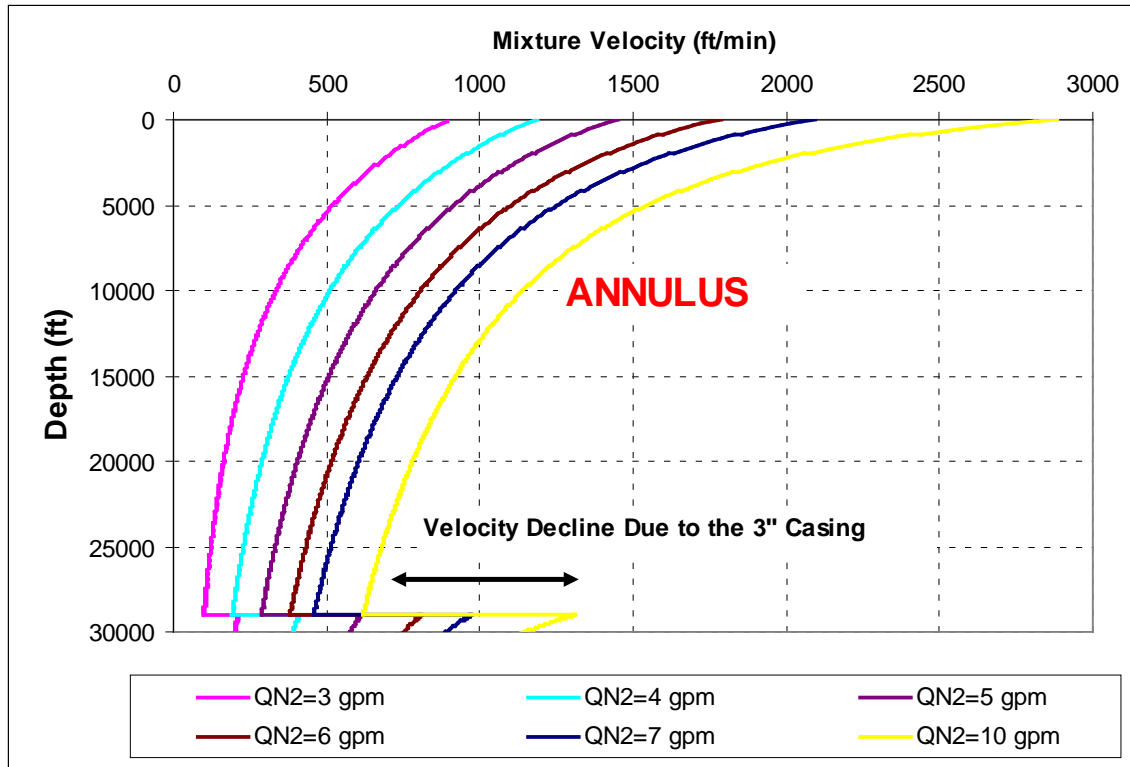


Figure 35: Velocity Profile (N₂ Only, 3'' Casing, Deviated Well)

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 29,000 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.

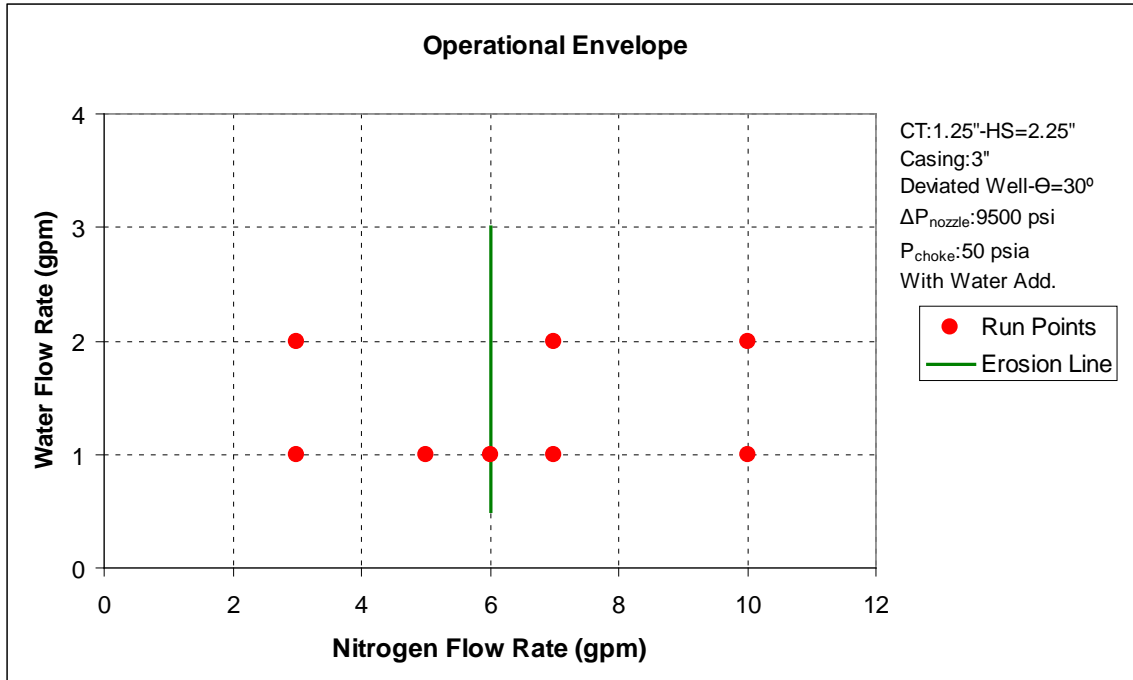


Figure 36: Operational Envelope for N₂ (3" Casing, With Water, Deviated Well)

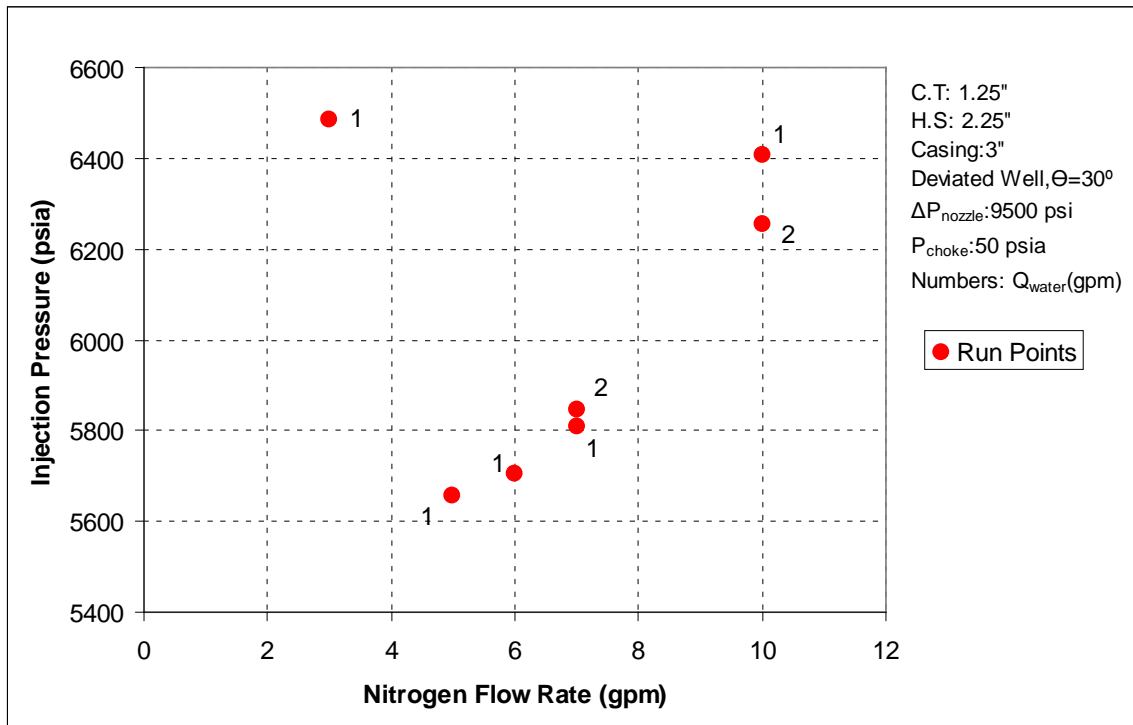


Figure 37: Flow Rate vs. Inj. Pressure for N₂ (3" Casing, With Water, Deviated Well)

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 9,500 psi occurs at the nozzle. Also due to the surface coiled tubing facility, 770 psi pressure loss occurred at the surface. Pressure outputs are given in Table 8.

Table 8: Output Pressure Values
(N₂ with Water Add., 3'' Casing, Q_{N₂}=7 gpm, Q_w=1 gpm, Deviated Well)

Injection Pressure (psia)	5809
BHP Upstream Nozzle (psia)	10232
BHP Downstream Nozzle (psia)	732

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 29,000 ft and then mixture velocity increases while reaching surface.

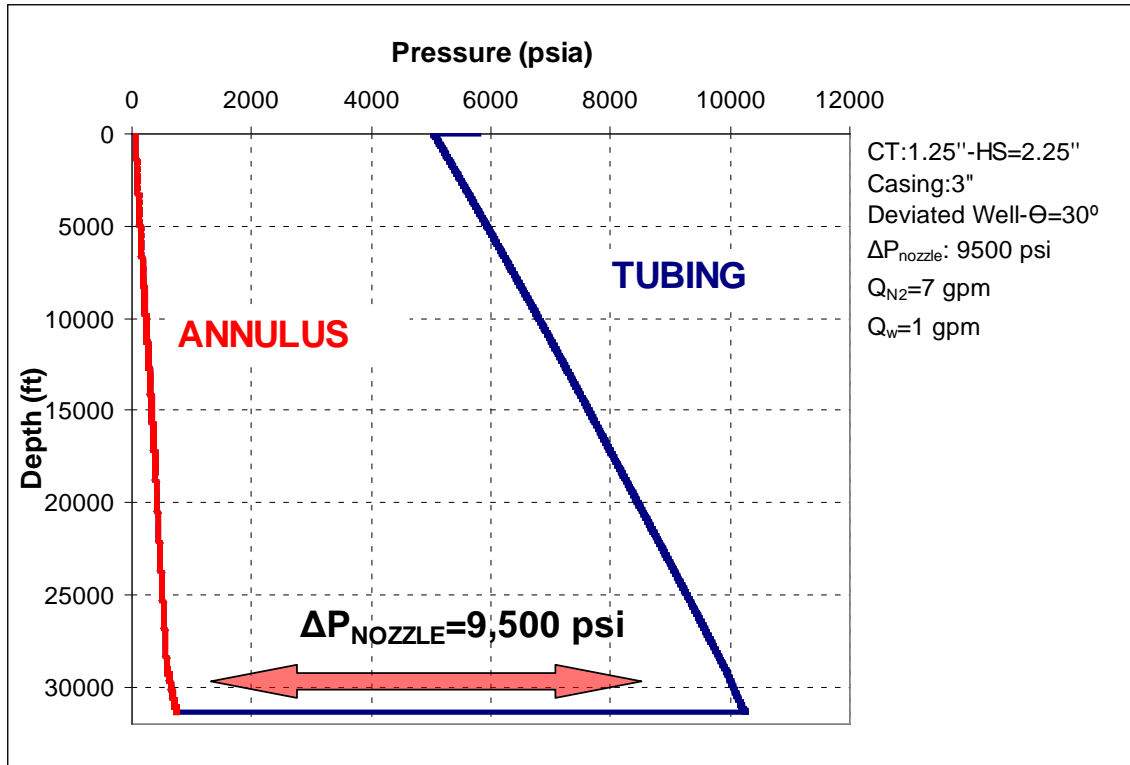


Figure 38: Pressure vs Depth (N₂ with Water, 3'' Casing, Deviated Well)

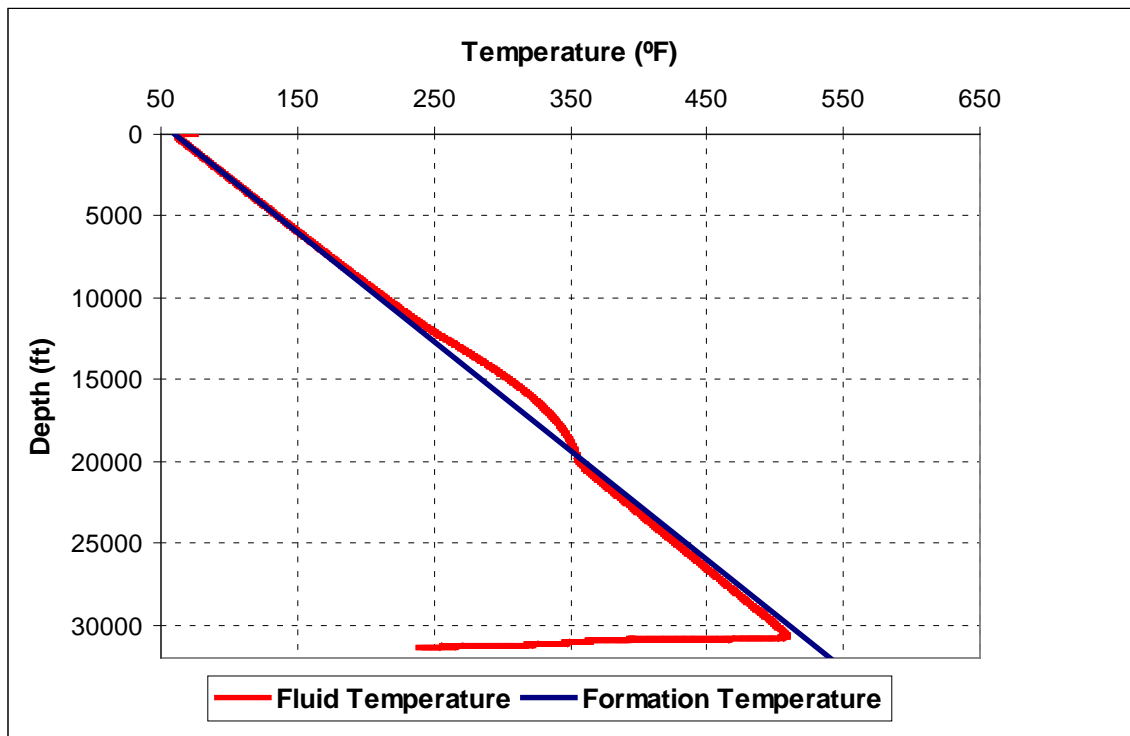


Figure 39: Temperature vs. Depth (N₂ with Water, 3'' Casing, Deviated Well)

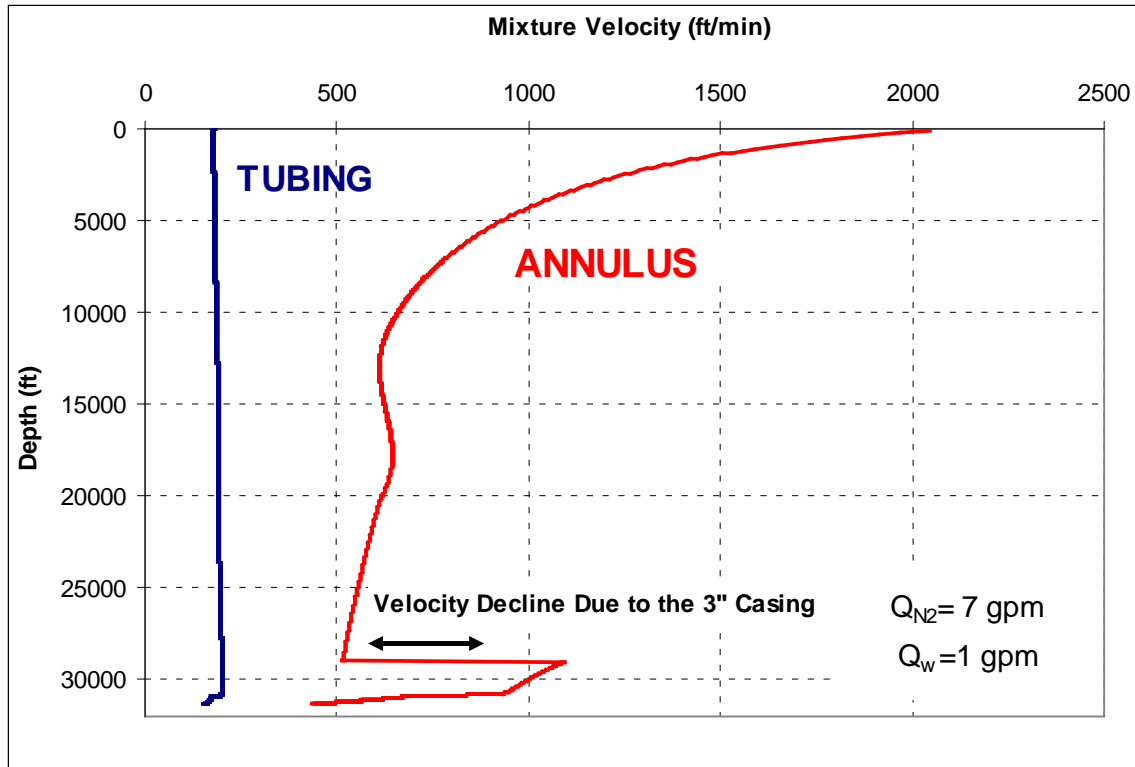


Figure 40: Velocity Profile (N_2 with Water, 3'' Casing, Deviated Well)

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.

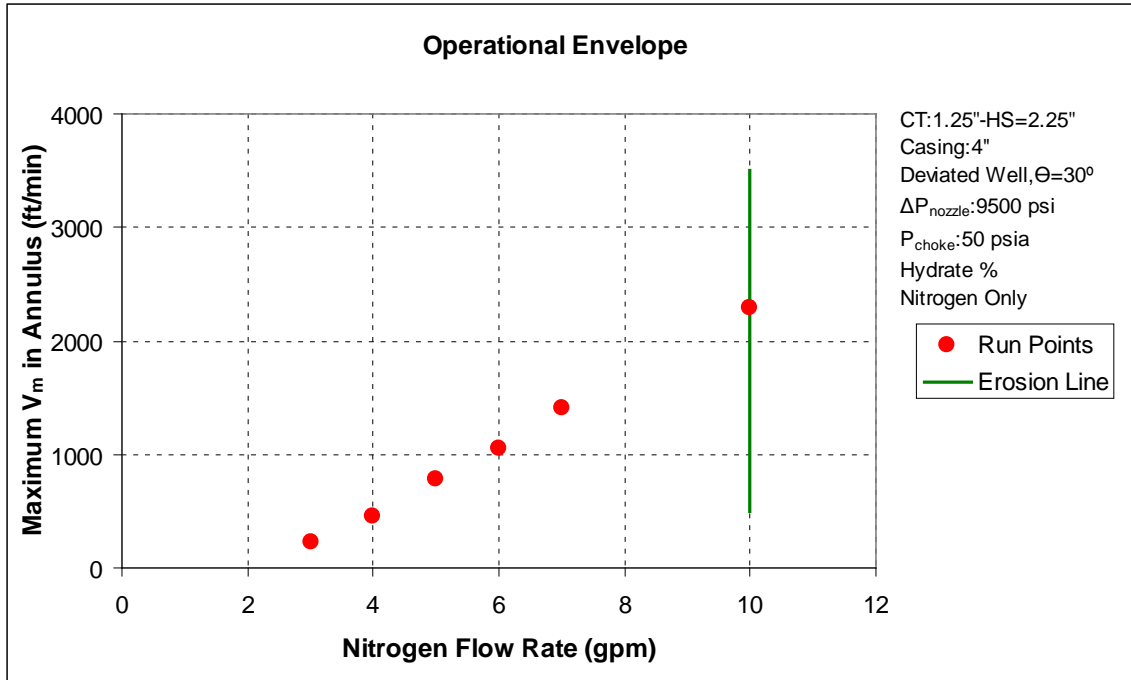


Figure 41: Operational Envelope for N₂ (N₂ Only, 4" Casing, Deviated Well)

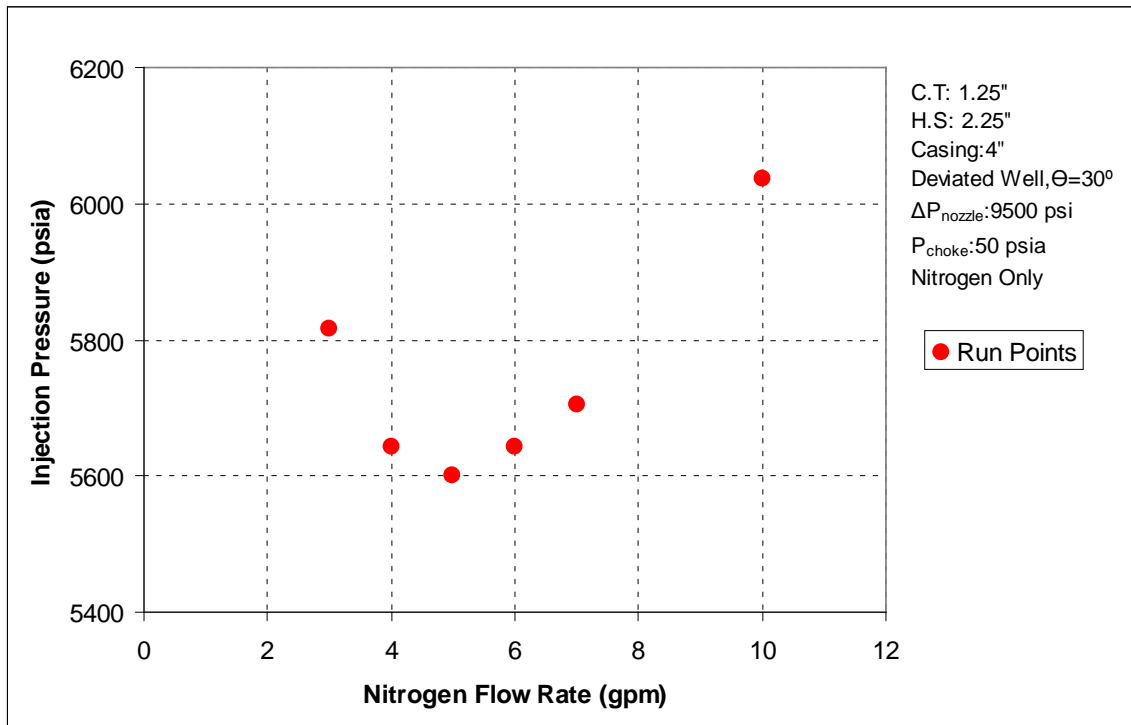


Figure 42: Flow Rate vs. Inj. Pressure for N₂ (N₂ Only, 4" Casing, Deviated Well)

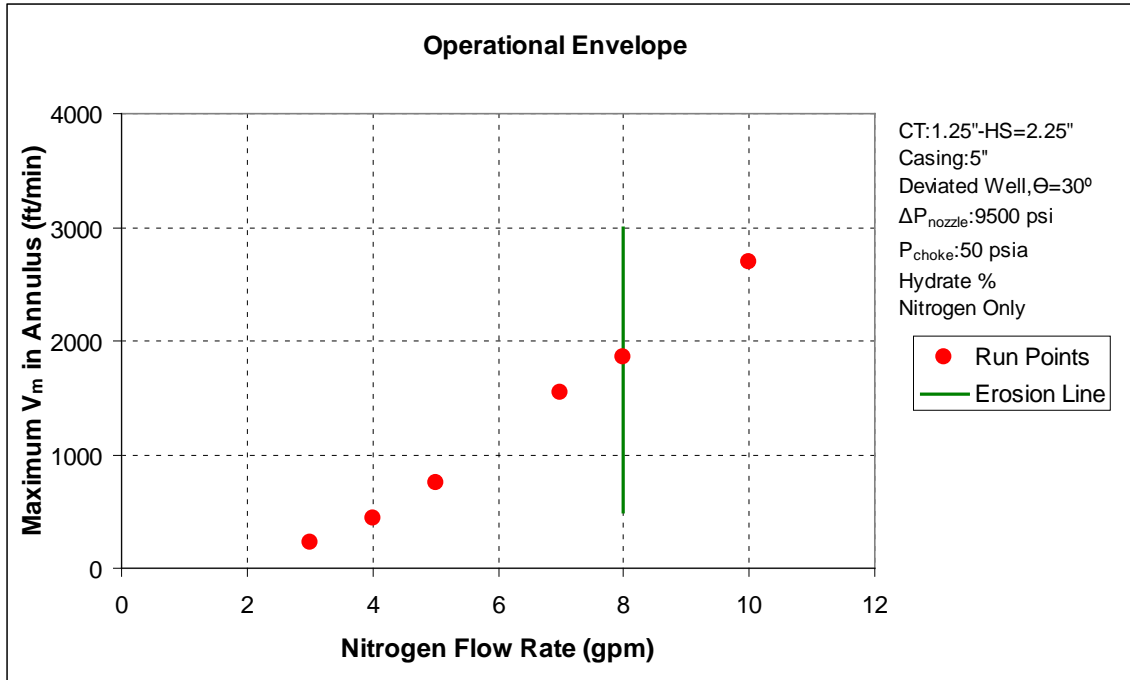


Figure 43: Operational Envelope for N₂ (N₂ Only, 5" Casing, Deviated Well)

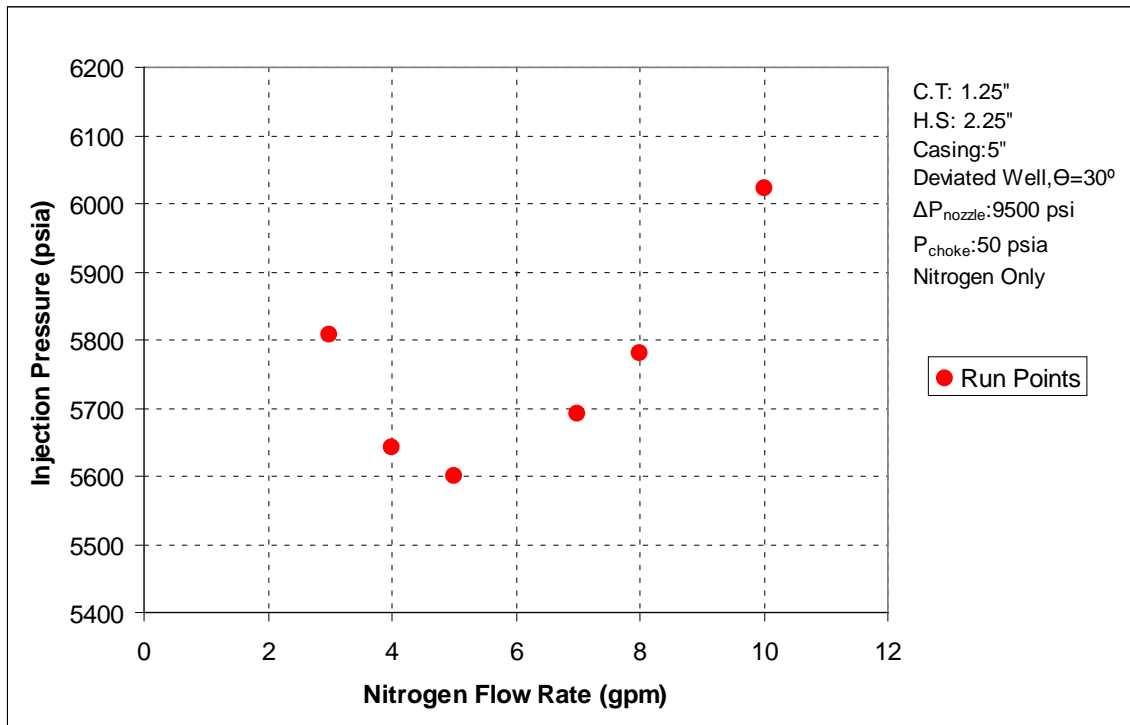


Figure 44: Flow Rate vs. Inj. Pressure for N₂ (N₂ Only, 5" Casing, Deviated Well)

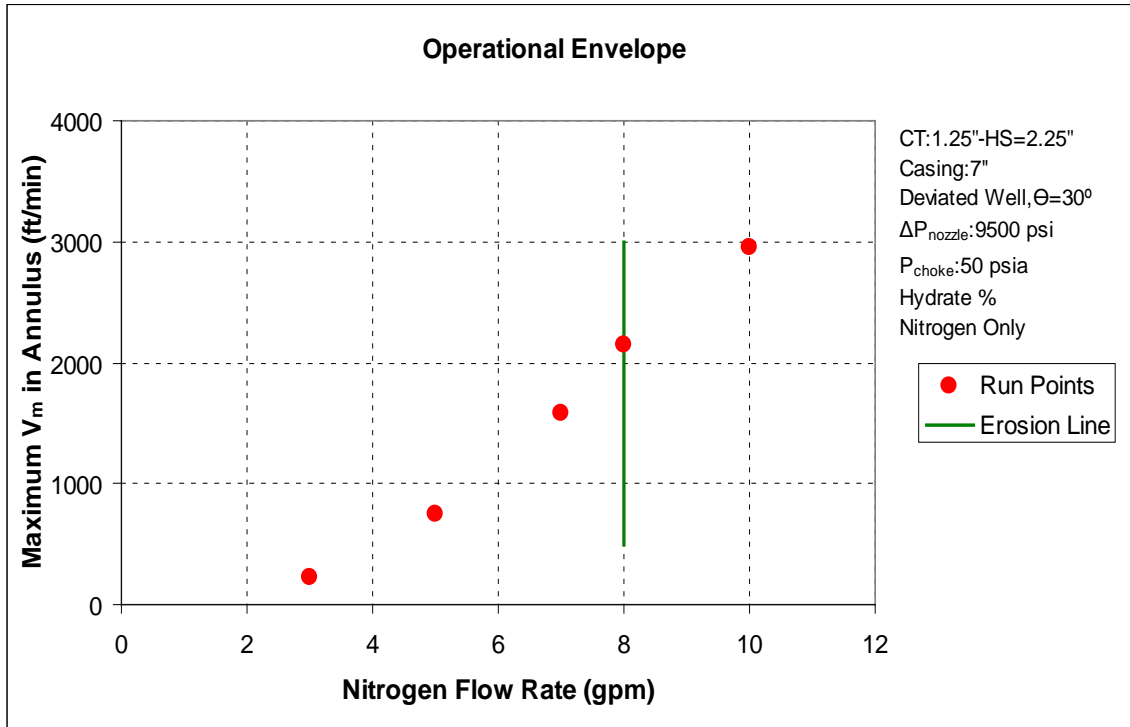


Figure 45: Operational Envelope for N_2 (N_2 Only, 7" Casing, Deviated Well)

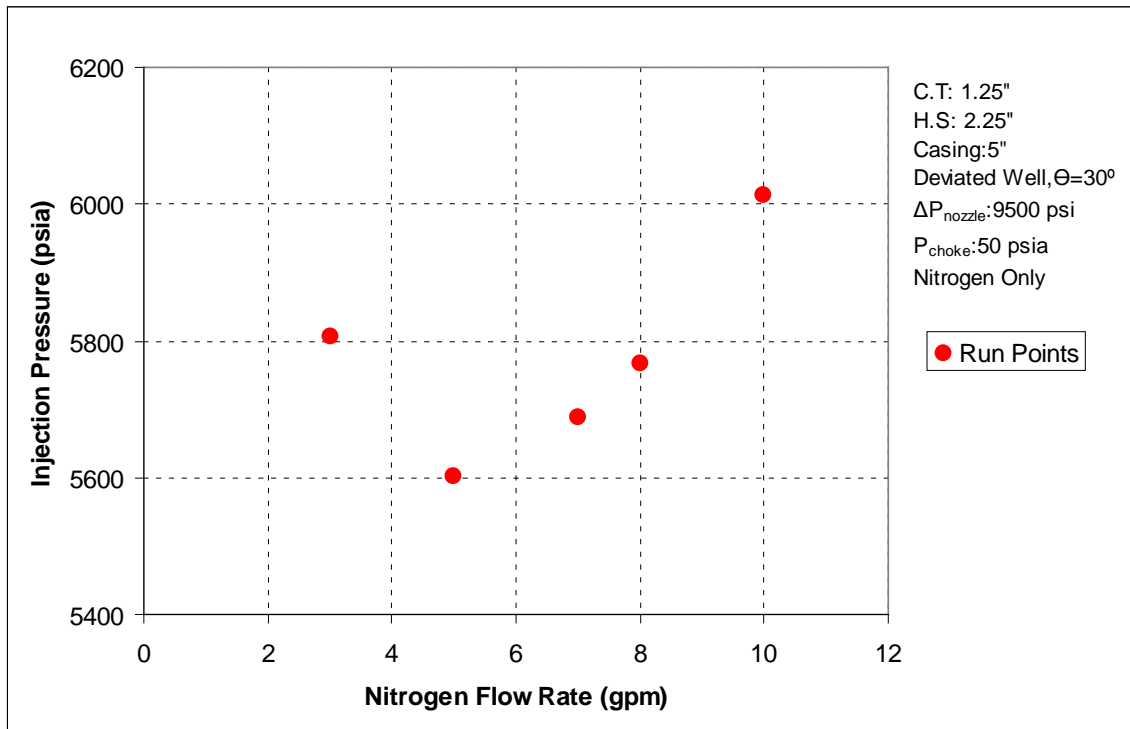


Figure 46: Flow Rate vs. Inj. Pressure for N_2 (N_2 Only, 7" Casing, Deviated Well)

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 75 and 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.

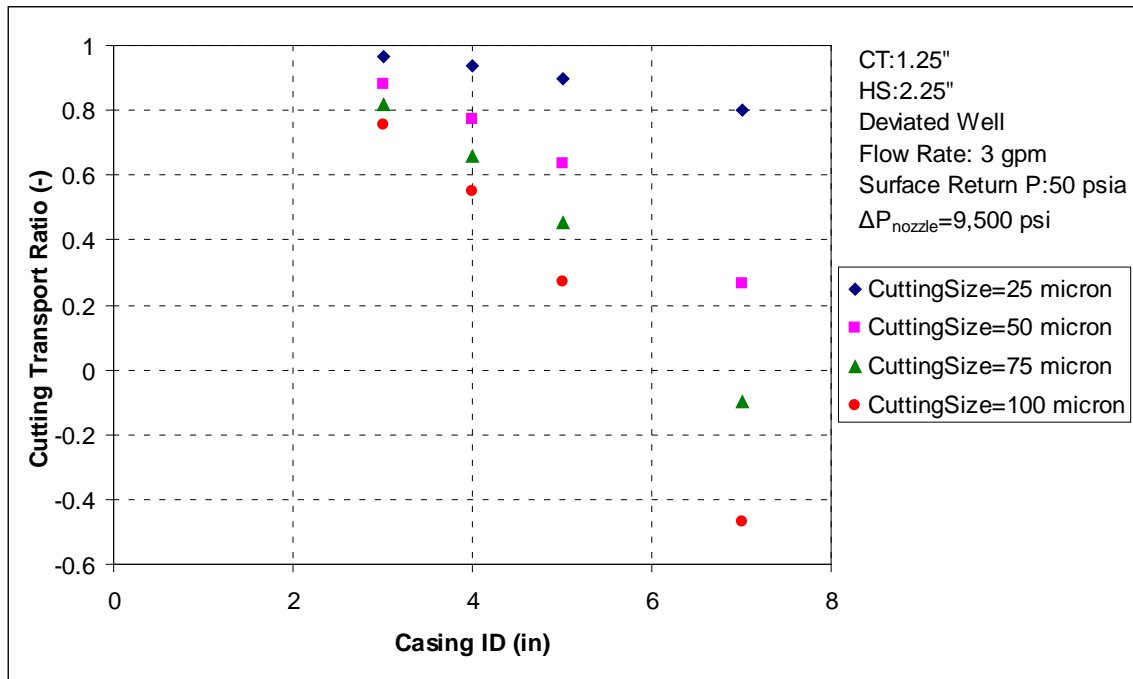


Figure 47: CTR vs. Casing ID (Nitrogen Only, $Q_{N_2}=3$ gpm, Deviated Well)

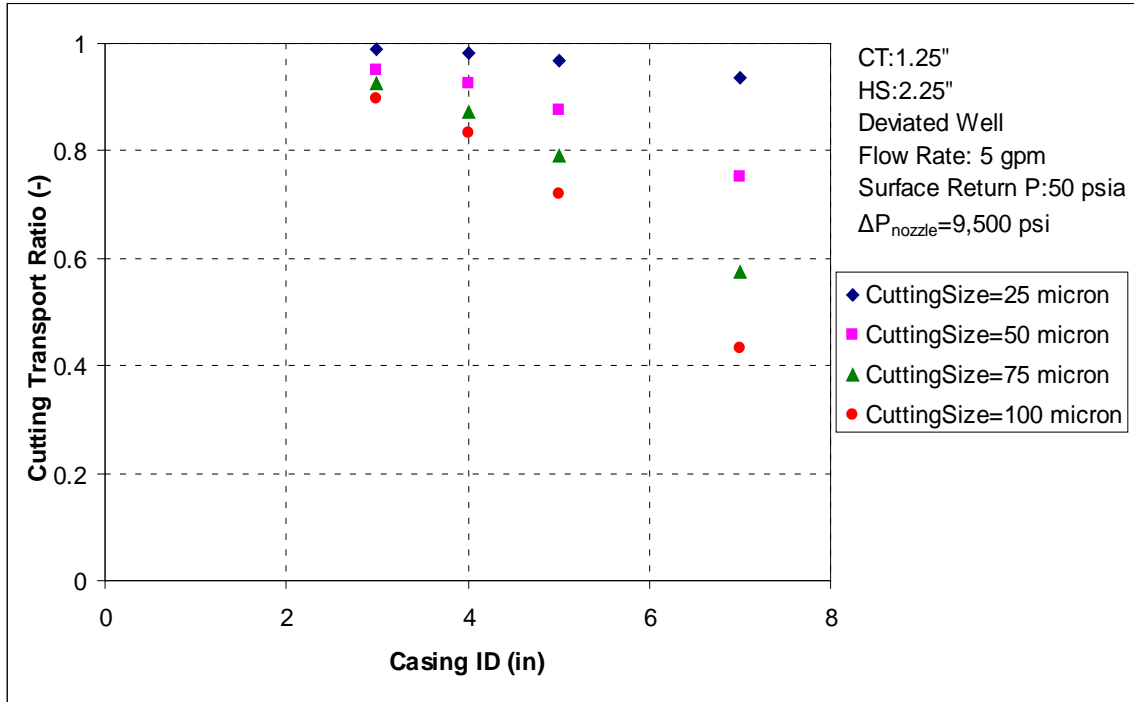


Figure 48: CTR vs. Casing ID (Nitrogen Only, $Q_{N_2}=5$ gpm, Deviated Well)

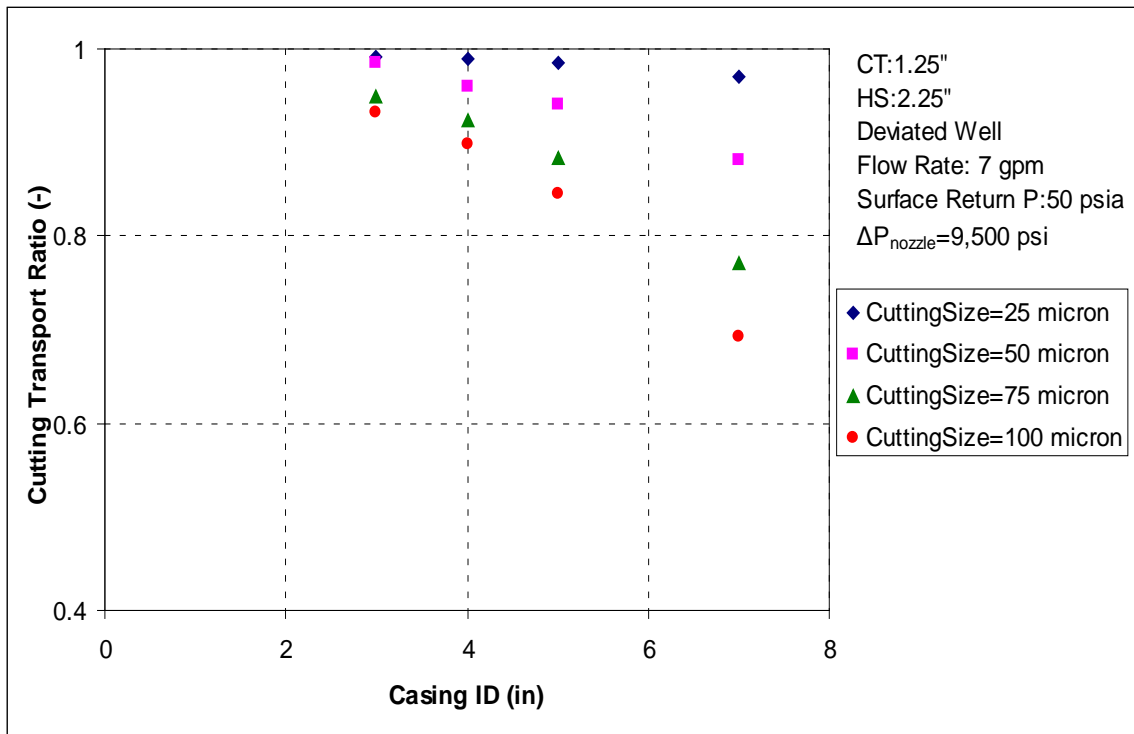


Figure 49: CTR vs. Casing ID (Nitrogen Only, $Q_{N_2}=7$ gpm, Deviated Well)

5. CONCLUSIONS

Simulations of drilling operation with supercritical fluid; N₂ has been carried out utilizing WellFlo Version 8.0.13 for 30,000 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 30,000 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 8,200 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.
- Small amount of temperature increase was observed around the nozzle for nitrogen only conditions

- 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 was observed around the nozzle.

Simulations with Different Casing and Cutting Sizes

In these simulations, different sizes of casings were used for the first 29,000 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 9,500 psi.
- Nitrogen changed its phase to gas around the nozzle in the tubing for all runs except 3 gpm.

- Increasing casing sizes decreased the needed injection pressures.
- 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 29,000 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.
- 9,500 psi pressure drop was used at the nozzle.
- Nitrogen changed its phase to gas around the nozzle in the tubing for all runs except 3 gpm.
- 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 (°F)

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 N₂ (gpm)	Q Water (gpm)	Maximum Mixture Velocity Annulus (ft/m)	Mixture Velocity Annulus (ft/m) 30,000 ft	Liquid Fraction After Nozzle (30,000 ft)	Liquid Velocity Tubing (ft/m)	Total Hydrate (%)	Solid Phase (%)
2	-	1180	49	0	40	-	-
3	-	1697	106	0	63	-	-
4	-	2134	154	0	84	-	-
5	-	2773	198	0	107	-	-
7	-	4253	256	0	147	-	-
10	-	5677	317	0	210	-	-
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	-	6291	11013	2813	535	567	0.939
3	-	5672	10063	1863	534	561	0.97
4	-	5579	9858	1668	535	561	0.979
5	-	5621	9849	1649	538	563	0.984
7	-	5856	10008	1808	544	571	0.987
10	-	6462	10452	2252	556	586	0.99
Coiled Tubing O.D: 1.25 inch –Bore Hole Size: 2.25 inch-Nitrogen with Water Addition							
Q N₂ (gpm)	Q Water (gpm)	Maximum Mixture Velocity Annulus (ft/m)	Mixture Velocity Annulus (ft/m) 30,000 ft	Liquid Fraction After Nozzle (30,000 ft)	Liquid Velocity Tubing (ft/m)	Total Hydrate (%)	Solid Phase (%)
3	1	1625	49	1	99	-	-
5	1	2319	82	0.09	144	-	-
5	2	2436	78	1	166	-	-
7	1	3347	113	0.08	186	-	-
7	2	3347	112	1	215	-	-
10	1	5464	172	0.15	260	-	-
10	2	5440	171	0.2	295	-	-
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	1	5150	9766	4766	460	449	0.967
5	1	4537	8623	3623	420	405	0.972
5	2	5105	9959	4959	462	453	0.98
7	1	4578	8420	3420	401	385	0.979
7	2	5059	9398	4398	438	427	0.985
10	1	4734	8015	3015	364	349	0.989
10	2	5359	8860	3860	400	389	0.99

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

Casing Size:3'', Nitrogen Only							
Q N₂ (gpm)	Q Water (gpm)	Maximum Mixture Velocity Annulus (ft/m)	Mixture Velocity Annulus (ft/m) 30,000 ft	Liquid Fraction After Nozzle (30,000 ft)	Liquid Velocity Tubing (ft/m)	Total Hydrate (%)	Solid Phase (%)
3	-	910	218	0	63	-	-
5	-	1489	615	0	105	-	-
7	-	1935	917	0	147	-	-
10	-	3015	1233	0	210	-	-
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	-	5894	10392	892	535	562	0.967
5	-	5728	10014	514	536	562	0.988
7	-	5839	9985	485	540	565	0.992
10	-	6154	10028	528	546	573	0.994
Casing Size:3'', Nitrogen With Water Addition							
Q N₂ (gpm)	Q Water (gpm)	Maximum Mixture Velocity Annulus (ft/m)	Mixture Velocity Annulus (ft/m) 30,000 ft	Liquid Fraction After Nozzle (30,000 ft)	Liquid Velocity Tubing (ft/m)	Total Hydrate (%)	Solid Phase (%)
3	1	963	86	0.09	90	-	-
5	1	1516	307	0.12	138	-	-
5	2	1563	182	0.24	162	-	-
7	1	2144	484	0.08	179	-	-
7	2	2123	385	0.12	211	-	-
10	1	3203	650	0.07	246	-	-
10	2	3259	583	0.09	274	-	-
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	1	6526	11874	2374	392	377	0.955
5	1	5721	10274	774	271	255	0.986
5	2	6046	11182	1682	253	343	0.978
7	1	5851	10145	645	243	226	0.991
7	2	5890	10436	936	290	278	0.988
10	1	6315	10195	695	230	213	0.993
10	2	6403	10350	850	264	252	0.991

Table A-2: Continuation

Casing Size: 4''							
Q N₂ (gpm)	Q Water (gpm)	Maximum Mixture Velocity Annulus (ft/m)	Mixture Velocity Annulus (ft/m) 30,000 ft	Liquid Fraction After Nozzle (30,000 ft)	Liquid Velocity Tubing (ft/m)	Total Hydrate (%)	Solid Phase (%)
3	-	223	224	0	62	-	-
5	-	773	754	0	106	-	-
7	-	1517	1346	0	149	-	-
10	-	2292	1783	0	213	-	-
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	-	5867	10356	856	534	562	0.938
5	-	5664	9918	418	535	560	0.981
7	-	5737	9827	327	538	562	0.99
10	-	6049	9862	362	543	568	0.993
Casing Size:5''							
Q N₂ (gpm)	Q Water (gpm)	Maximum Mixture Velocity Annulus (ft/m)	Mixture Velocity Annulus (ft/m) 30,000 ft	Liquid Fraction After Nozzle (30,000 ft)	Liquid Velocity Tubing (ft/m)	Total Hydrate (%)	Solid Phase (%)
3	-	226	226	0	62	-	-
5	-	768	750	0	106	-	-
7	-	1551	1366	0	149	-	-
10	-	2694	1931	0	213	-	-
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	-	5861	10347	847	534	562	0.9
5	-	5665	9920	420	535	559	0.97
7	-	5734	9822	322	537	561	0.985
10	-	6031	9834	334	543	568	0.991

Table A-2: Continuation

Casing Size:7''							
Q N₂ (gpm)	Q Water (gpm)	Maximum Mixture Velocity Annulus (ft/m)	Mixture Velocity Annulus (ft/m) 30,000 ft	Liquid Fraction After Nozzle (30,000 ft)	Liquid Velocity Tubing (ft/m)	Total Hydrate (%)	Solid Phase (%)
3	-	227	227	0	62	-	-
5	-	810	787	0	106	-	-
7	-	1601	1400	0	149	-	-
10	-	2778	1954	0	210	-	-
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	-	5858	10344	844	534	562	0.799
5	-	5651	9900	400	535	559	0.942
7	-	5727	9815	315	537	561	0.97
10	-	6007	9824	324	542	567	0.983

Table A-3: Output for Drilling 30,000 ft (Different Casing Sizes, Deviated Well)

Casing Size:3'', Nitrogen Only							
Q N₂ (gpm)	Q Water (gpm)	Maximum Mixture Velocity Annulus (ft/m)	Mixture Velocity Annulus (ft/m) 30,000 ft	Liquid Fraction After Nozzle (30,000 ft)	Liquid Velocity Tubing (ft/m)	Total Hydrate (%)	Solid Phase (%)
3	-	896	199	0	62	-	-
4	-	1188	388	0	84	-	-
5	-	1452	570	0	106	-	-
6	-	1785	734	0	127	-	-
7	-	2095	857	0	148	-	-
10	-	2885	1079	0	211	-	-
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	-	5858	10484	984	552	583	0.965
4	-	5687	10166	666	553	581	0.982
5	-	5672	10066	567	554	582	0.988
6	-	5709	10029	529	557	584	0.991
7	-	5782	10030	530	559	587	0.992
10	-	6130	10118	618	566	596	0.994
Casing Size:3'', Nitrogen with Water Addition							
Q N₂ (gpm)	Q Water (gpm)	Maximum Mixture Velocity Annulus (ft/m)	Mixture Velocity Annulus (ft/m) 30,000 ft	Liquid Fraction After Nozzle (30,000 ft)	Liquid Velocity Tubing (ft/m)	Total Hydrate (%)	Solid Phase (%)
3	1	972	83	0.11	90	-	-
3	2	1099	83	0.2	119	-	-
5	1	1522	289	0.07	139	-	-
6	1	1805	374	0.06	160	-	-
7	1	2045	436	0.06	180	-	-
7	2	2178	358	0.07	212	-	-
10	1	2938	562	0.06	240	-	-
10	2	3025	512	0.07	274	-	-
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	1	6485	12015	2515	400	385	0.956
3	1	6710	12951	3451	445	436	0.955
5	1	5655	10339	839	282	265	0.986
6	2	5706	10247	747	264	247	0.989
7	1	5809	10232	732	256	238	0.991
7	2	5844	10534	1034	302	289	0.99
10	3	6253	10303	803	246	228	0.993
10	1	6406	10500	1000	280	267	0.993

Table A-3: Continuation

Casing Size:4''							
Q N₂ (gpm)	Q Water (gpm)	Maximum Mixture Velocity Annulus (ft/m)	Mixture Velocity Annulus (ft/m) 30,000 ft	Liquid Fraction After Nozzle (30,000 ft)	Liquid Velocity Tubing (ft/m)	Total Hydrate (%)	Solid Phase (%)
3	-	224	212	0	62	-	-
4	-	455	429	0	84	-	-
5	-	779	703	0	107	-	-
6	-	1060	904	0	128	-	-
7	-	1412	1102	0	150	-	-
10	-	2298	1415	0	213	-	-
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	-	5815	10420	920	552	582	0.938
4	-	5643	10101	601	552	580	0.969
5	-	5601	9957	457	553	580	0.981
6	-	5643	9927	427	555	582	0.986
7	-	5705	9910	410	557	584	0.989
10	-	6036	9968	468	564	592	0.993
Casing Size:5''							
Q N₂ (gpm)	Q Water (gpm)	Maximum Mixture Velocity Annulus (ft/m)	Mixture Velocity Annulus (ft/m) 30,000 ft	Liquid Fraction After Nozzle (30,000 ft)	Liquid Velocity Tubing (ft/m)	Total Hydrate (%)	Solid Phase (%)
3	-	226	215	0	62	-	-
4	-	444	419	0	83	-	-
5	-	750	680	0	105	-	-
7	-	1547	1160	0	150	-	-
8	-	1854	1293	0	170	-	-
10	-	2702	1488	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	-	5808	10410	910	552	582	0.9
4	-	5643	10106	606	552	579	0.948
5	-	5601	9965	465	553	580	0.969
7	-	5691	9889	389	557	583	0.985
8	-	5781	9900	400	559	586	0.987
10	-	6021	9944	444	564	592	0.991

Table A-3: Continuation

Casing Size:7''							
Q N₂ (gpm)	Q Water (gpm)	Maximum Mixture Velocity Annulus (ft/m)	Mixture Velocity Annulus (ft/m) 30,000 ft	Liquid Fraction After Nozzle (30,000 ft)	Liquid Velocity Tubing (ft/m)	Total Hydrate (%)	Solid Phase (%)
3	-	227	215	0	62	-	-
5	-	747	678	0	105	-	-
7	-	1579	1364	0	150	-	-
8	-	2143	1360	0	171	-	-
10	-	2947	1523	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	-	5805	10407	907	552	582	0.798
4	-	5601	9966	466	553	580	0.937
5	-	5687	9884	384	557	584	0.97
6	-	5767	9880	380	559	586	0.978
7	-	6014	9934	434	564	591	0.984

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, N₂ Only				
Q N2 (gpm)	Q Water (gpm)	Frictional Pres. Loss (psi/ft)	Hydrostatic Pres. Loss (psi/ft)	Total Pres. Loss (psi/ft)
2	-	15.1	0.2	15.3
3	-	34	0.2	34.2
4	-	58.1	0.2	58.3
5	-	92.2	0.2	92.4
7	-	173.9	0.2	174.1
10	-	364.4	0.2	364.6
Coiled Tubing O.D: 1.25 inch –Bore Hole Size: 2.25 inch, N₂ 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	367	850	1217
5	1	458	371	830
5	2	671	602	1273
7	1	538	140	677
7	2	815	234	1049
10	1	693	21	714
10	2	1052	45	1097

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	-	34.2	0.2	34.4
5	-	91	0.3	91.3
7	-	174.2	0.2	174.4
10	-	353.2	0.3	353.5
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	330.9	828.8	1159.7
5	1	459.1	418.5	418.5
5	2	660.9	616.8	1277.7
7	1	573	198.8	771.8
7	2	834	287	1121
10	1	781.2	45.9	827.1
10	2	1079.2	85.9	1165.2
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	-	33.2	0.2	33.4
5	-	91.7	0.3	92
7	-	176.3	0.2	176.5
10	-	357.4	0.2	357.6
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	-	33.2	0.3	33.5
5	-	91.7	0.3	92
7	-	176.4	0.2	176.6
10	-	358.1	0.2	358.3
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	-	33.3	0.2	33.5
5	-	91.9	0.2	92.1
7	-	176.5	0.2	176.7
10	-	347.6	0.2	347.8

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	-	33.3	0.2	33.5
4	-	59.2	0.2	59.4
5	-	91.7	0.2	92
6	-	130.5	0.2	130.7
7	-	175.4	0.2	175.6
10	-	354.2	0.2	354.4
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	332.2	828.2	1160.4
3	2	499.3	1015.4	1514.7
5	1	461.7	412.8	874.5
6	1	518.2	285.4	803.6
7	1	574.3	195.3	769.6
7	2	836.4	280.8	1117.2
10	1	760.3	52.3	812.6
10	2	1079.1	86.2	1165.2
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	-	33.4	0.2	33.6
4	-	59.5	0.2	59.7
5	-	92.4	0.2	92.6
6	-	131.6	0.2	131.8
7	-	177	0.2	177.2
10	-	357.9	0.2	358
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	-	33.4	0.3	33.7
4	-	57.6	0.2	57.8
5	-	89.5	0.2	89.7
7	-	177.3	0.2	177.5
8	-	228.6	0.2	228.8
10	-	358.5	0.2	358.7

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	-	33.5	0.2	33.7
5	-	89.5	0.2	89.7
7	-	177.4	0.2	177.6
8	-	229	0.2	229
10	-	358.8	0.2	359

APPENDIX C

Additional Runs to Fill the Gaps

In this part, WellFlo simulation results are given for drilling 31,000 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 29,000 ft (kick of point). After 29,000 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 (31,000 ft)

	Water Only	N₂ & Water
Depth (ft)	31,000	31,000
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	6000
Cutting Size (micron)	25	25
ROP (ft/hour)	400	400

1. Water Only (31,000 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 is 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.

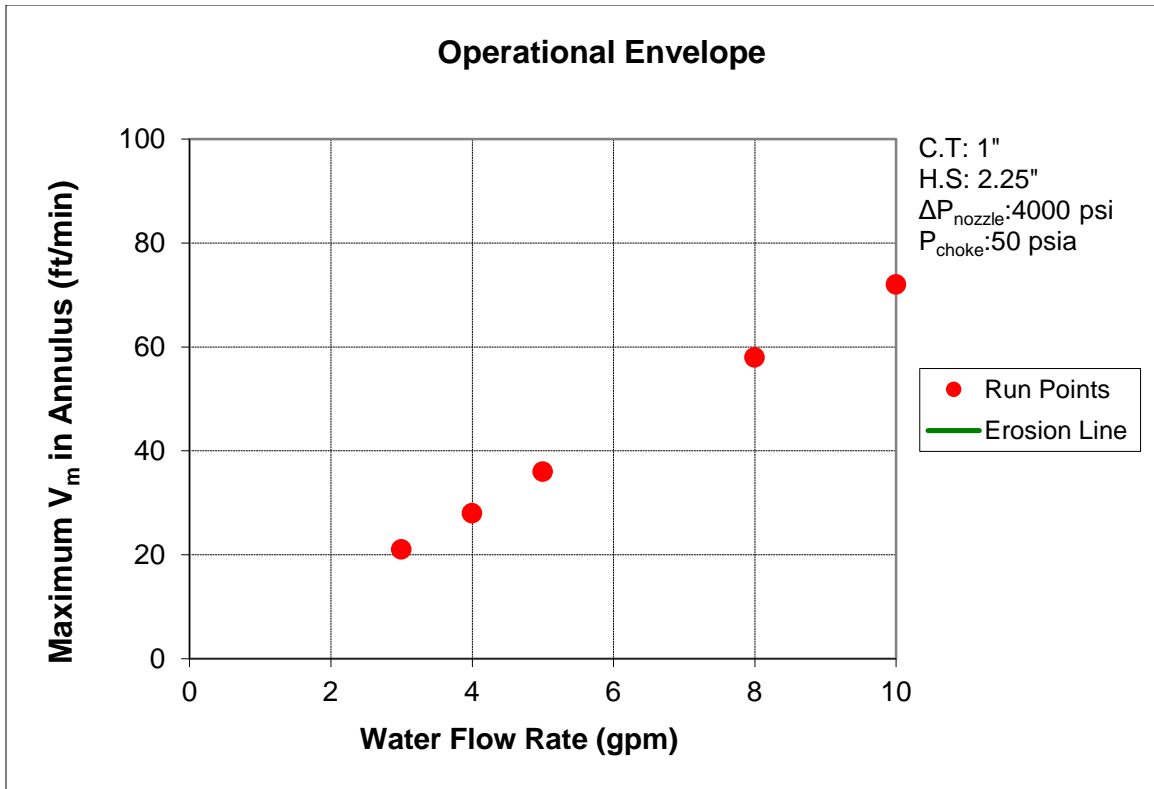


Figure C-1: Operational Envelope for Water Only (CT: 1"-HS:2.25", 31,000 ft)

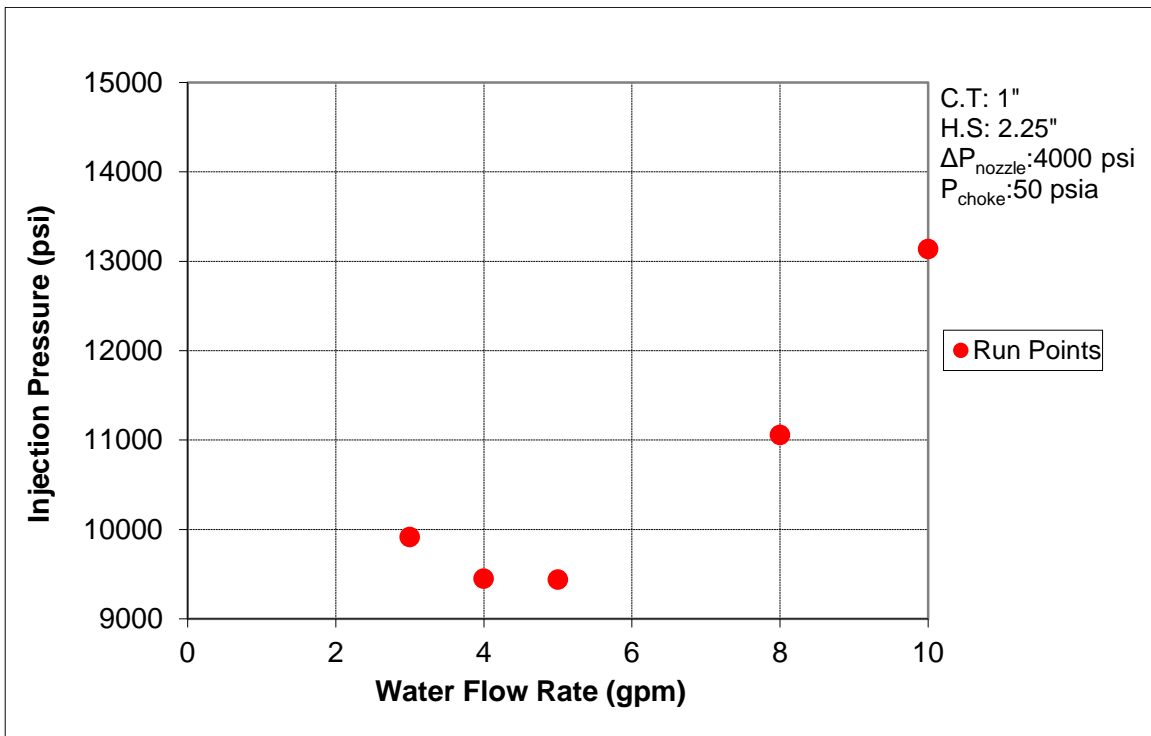


Figure C-2: Flow Rate vs. Inj. Pressure for Water Only (CT: 1"-HS:2.25", 31,000 ft)

Example pressure and temperature profile graph water only case is 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, 31,000 ft)

Injection Pressure (psia)	9439
BHP Upstream Nozzle (psia)	20,168
BHP Downstream Nozzle (psi)	16,168

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.

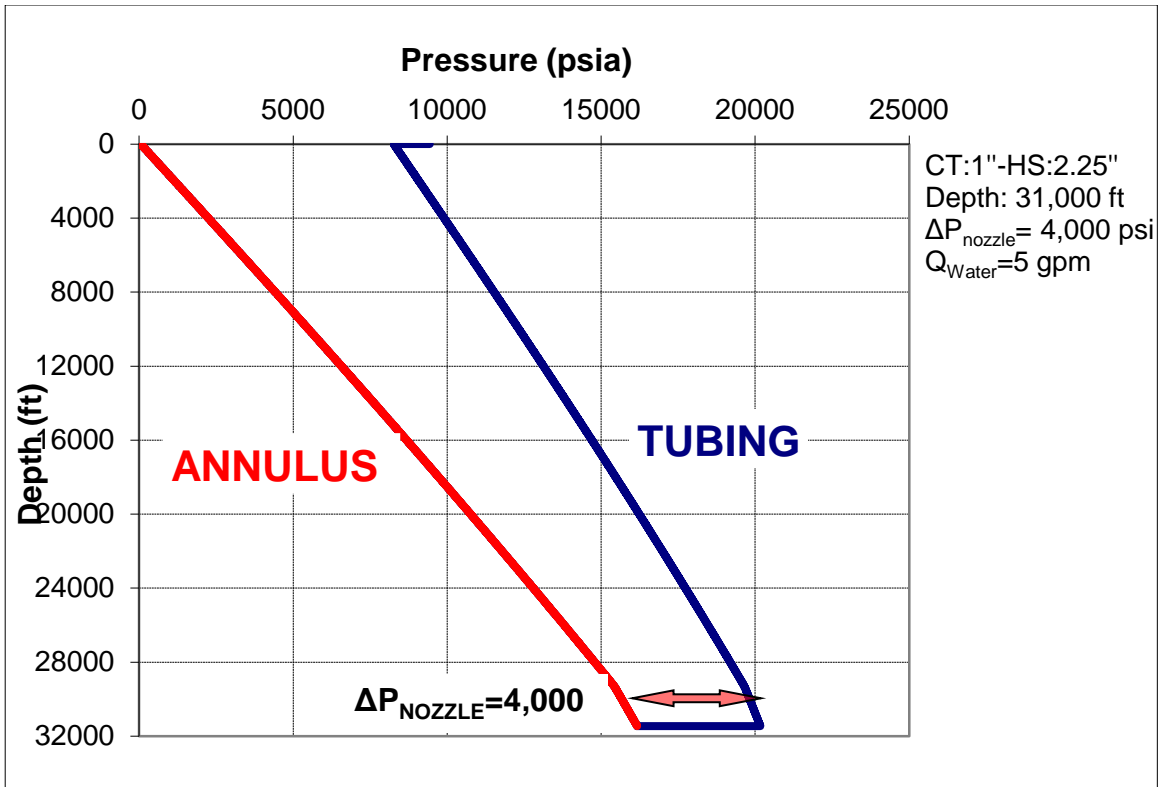


Figure C-3: Pressure vs Depth (CT:1", H.S:2.25", Q_w : 5 gpm, 31,000 ft)

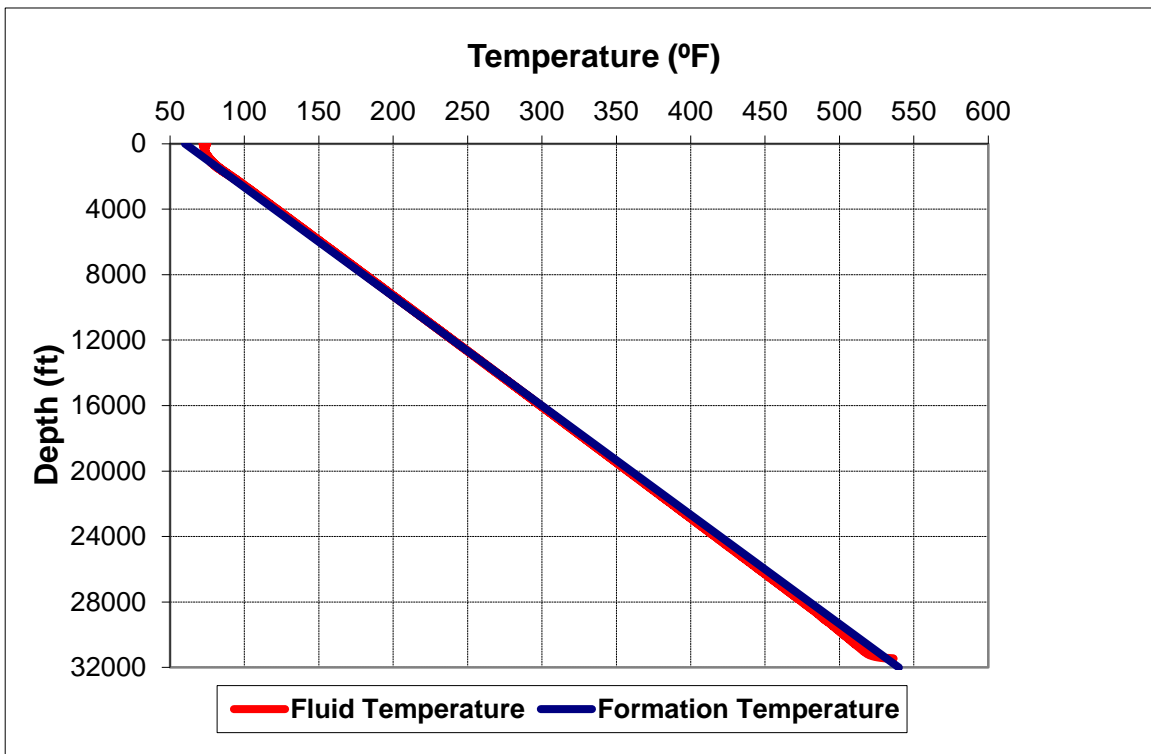


Figure C-4: Temperature vs. Depth (CT:1", H.S:2.25", Q_w : 5 gpm, 31,000 ft)

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.

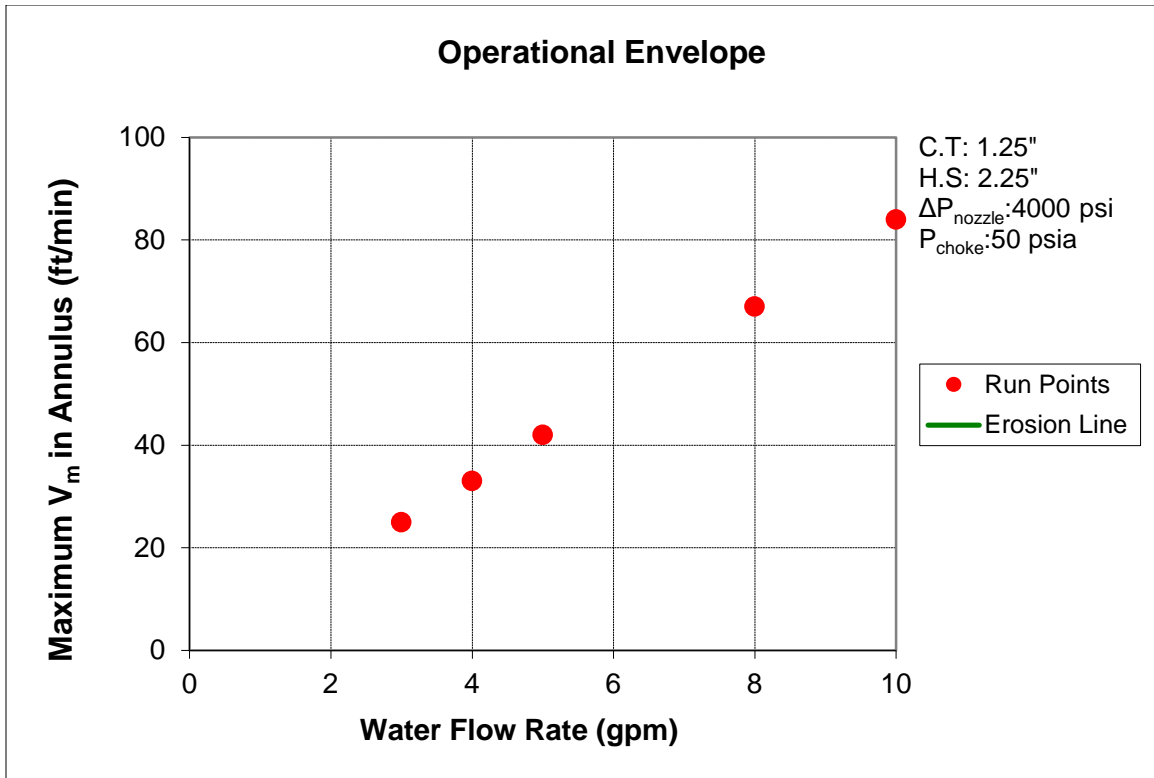


Figure C-5: Operational Envelope for Water Only (CT: 1.25"-HS:2.25", 31,000 ft)

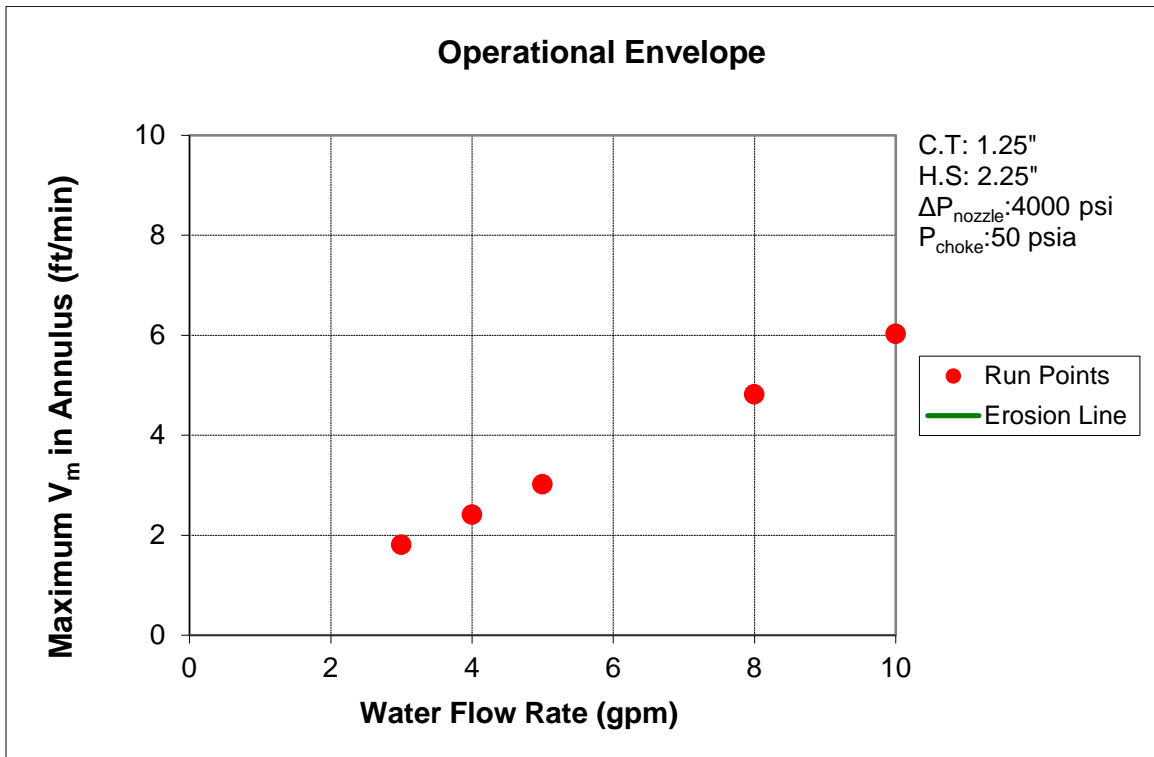


Figure C-6: Flow Rate vs. Inj. Pressure for Water Only (CT: 1.25"-HS:2.25", 31,000 ft)

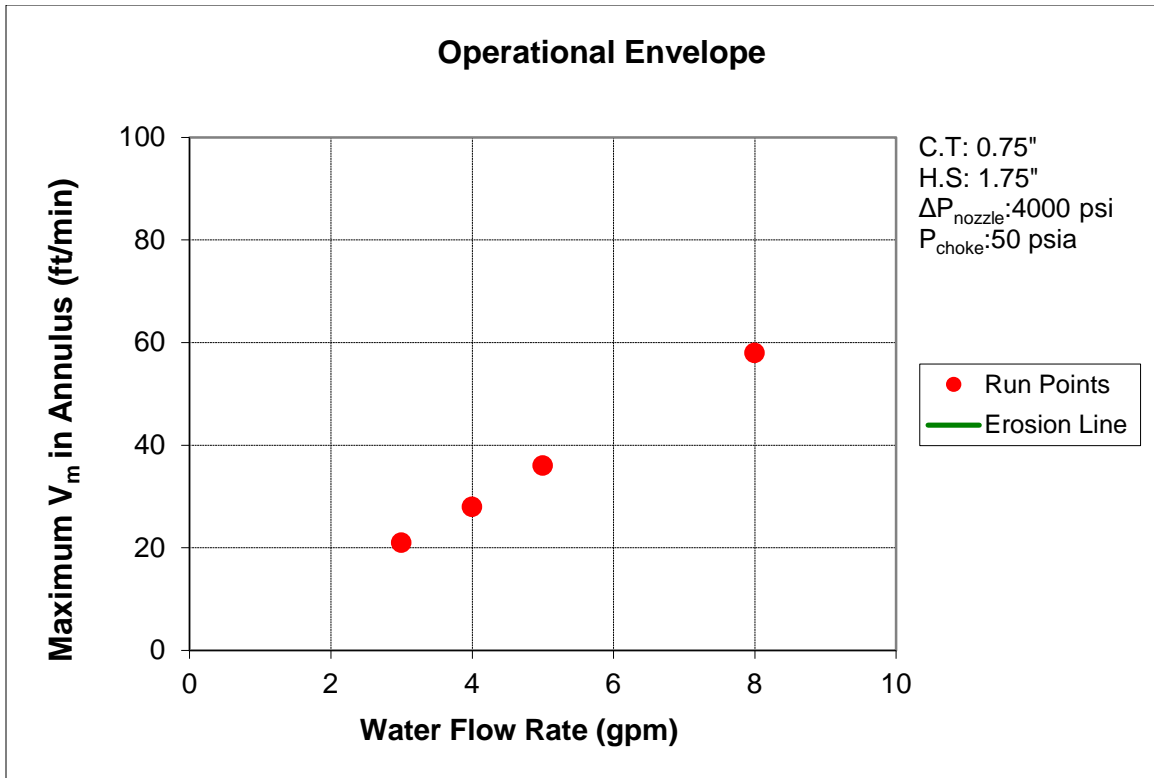


Figure C-7: Operational Envelope for Water Only (CT: 0.75"-HS:1.75", 31,000 ft)

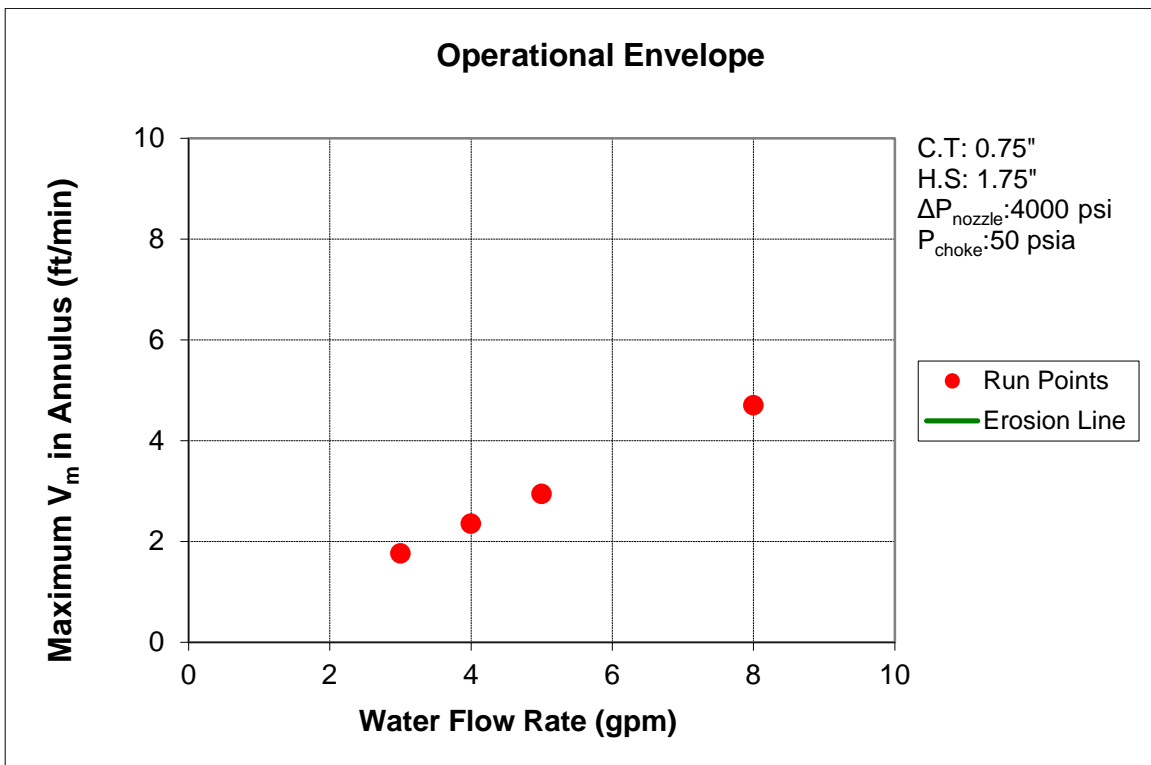


Figure C-8: Flow Rate vs. Inj. Pressure for Water Only (CT: 0.75"-HS:1.75", 31,000 ft)

2. Nitrogen with Water Addition (31,000 ft)

In this part, WellFlo simulation results are given for drilling 31,000 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 6,000 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 after conclusions.

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.

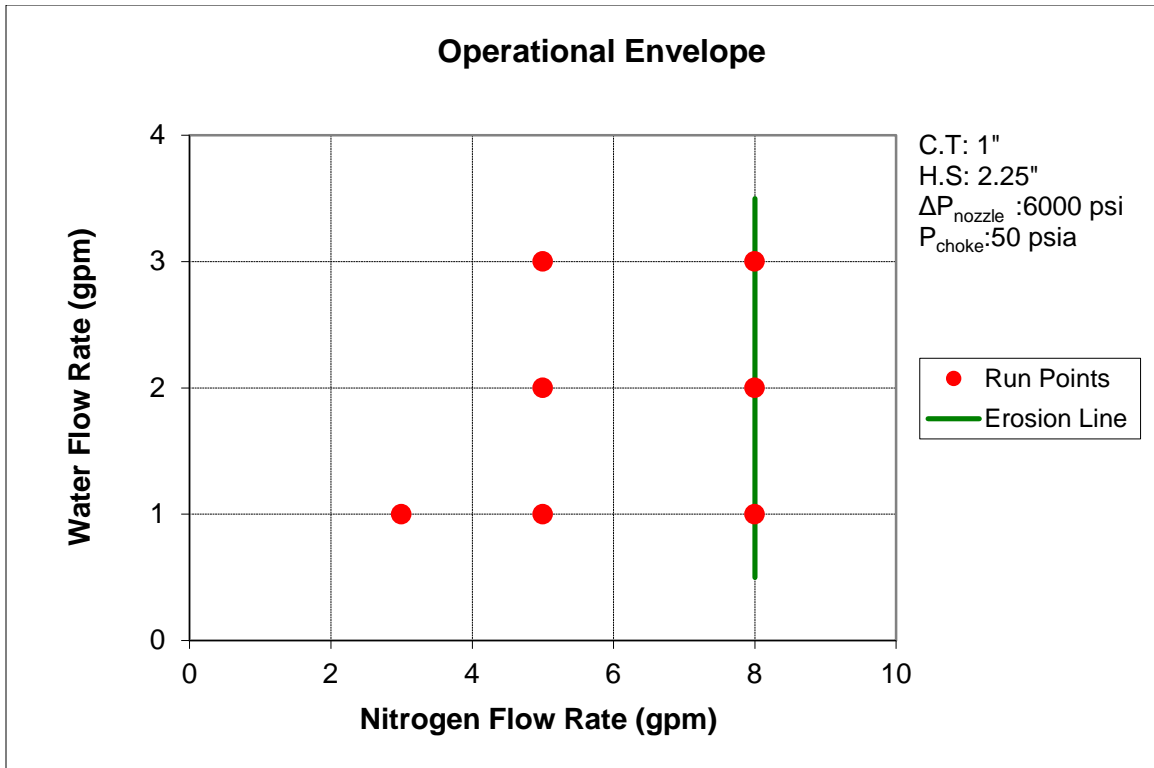


Figure C-9: Operational Envelope for N₂ with Water (CT: 1"-HS:2.25", 31,000 ft)

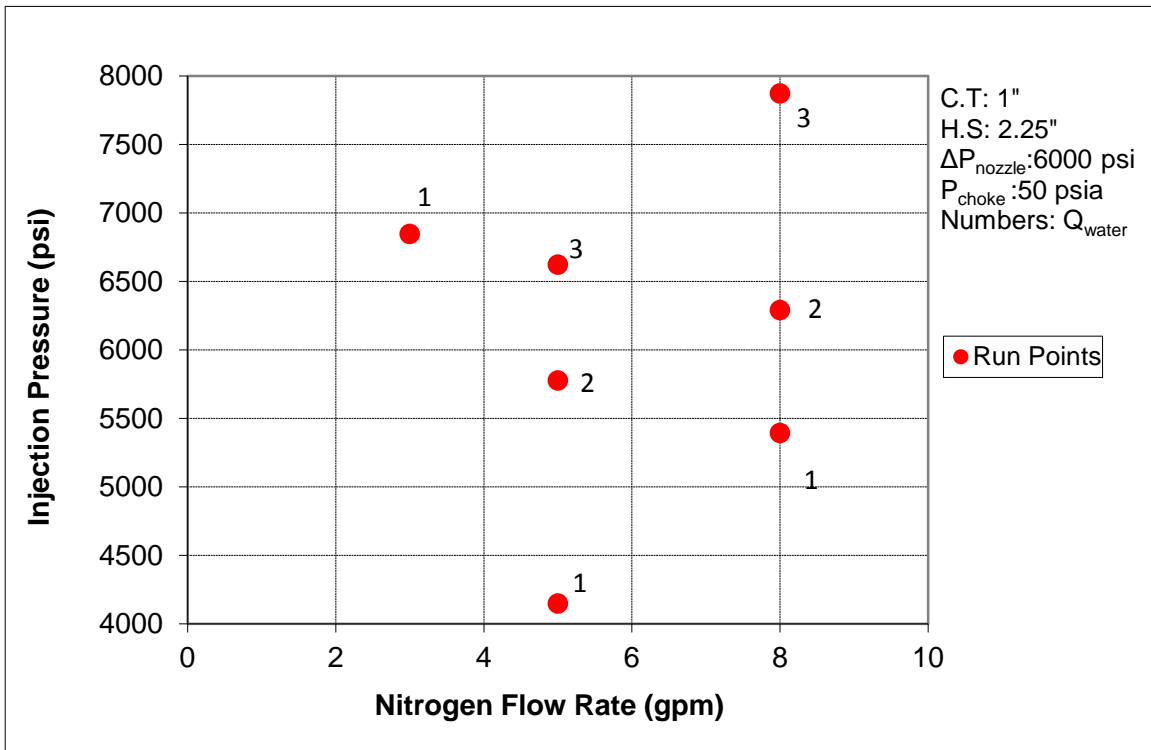


Figure C-10: Flow Rate vs. Inj. Pressure for N₂ with Water (CT: 1"-HS:2.25", 31,000 ft)

Example pressure and temperature profile graph for nitrogen with water addition case is 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 6,000 psi occurs at the nozzle. Pressure outputs are given in Table C-3.

Table C-3: Output Press. Values (Nitrogen with Water, $Q_{N_2}=5$ gpm, $Q_w=1$ gpm, 31,000 ft)

Injection Pressure (psia)	4148
BHP Upstream Nozzle (psia)	7229
BHP Downstream Nozzle (psi)	1229

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.

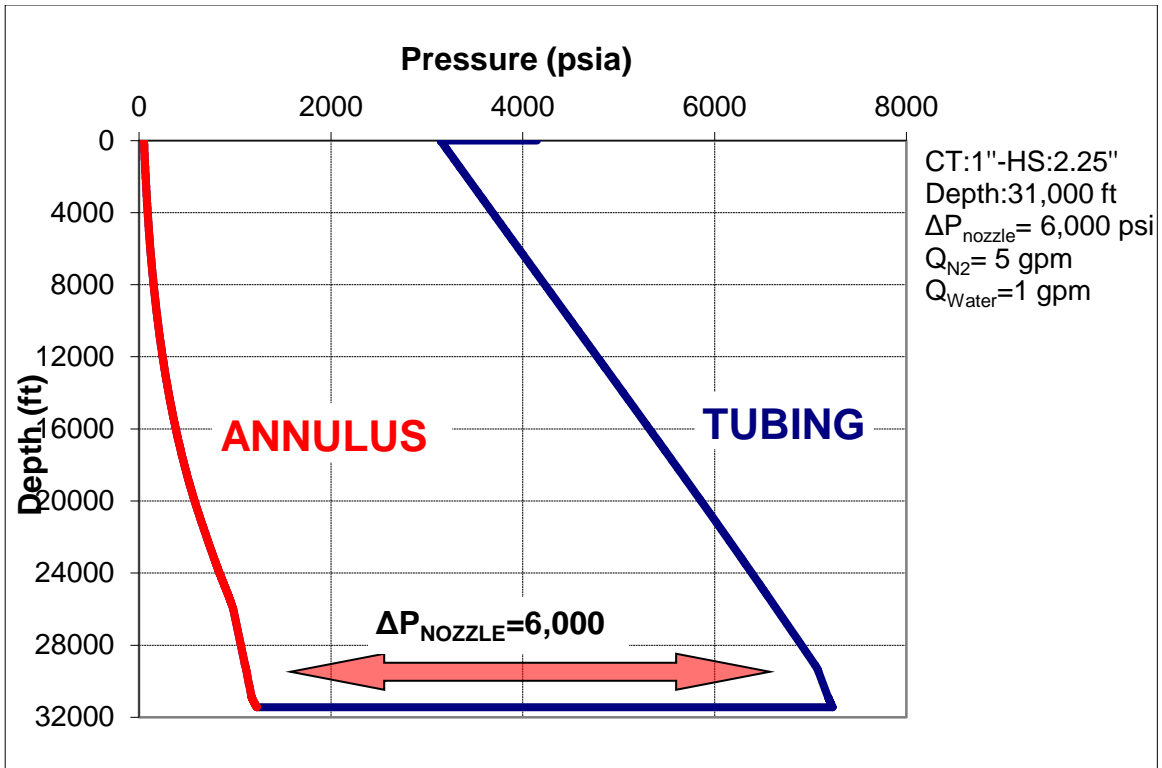


Figure C-11: Pressure vs Depth (CT:1", H.S:2.25", Q_{N_2} : 5 gpm Q_w : 1 gpm, 31,000 ft)

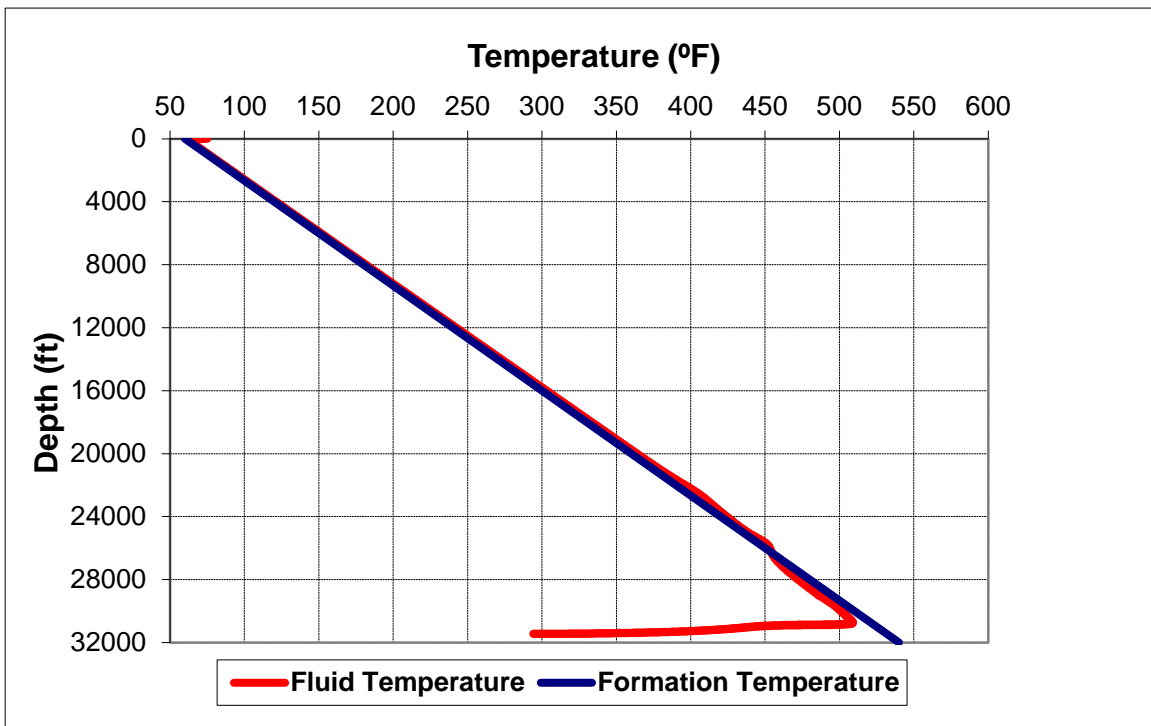


Figure C-12: Temperature vs Depth (CT:1", H.S:2.25", Q_{N_2} : 5 gpm Q_w :1 gpm, 31,000 ft)

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.

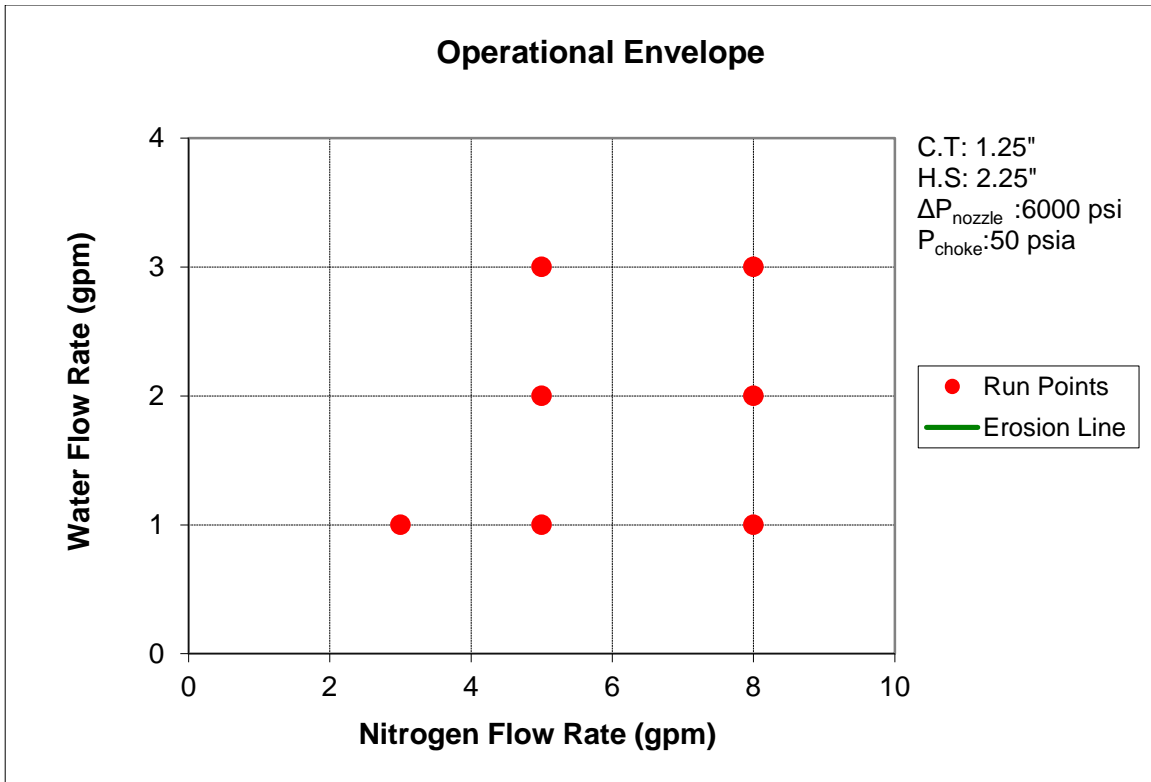


Figure C-13: Operational Envelope for N₂ with Water (CT: 1.25"-HS:2.25", 31,000 ft)

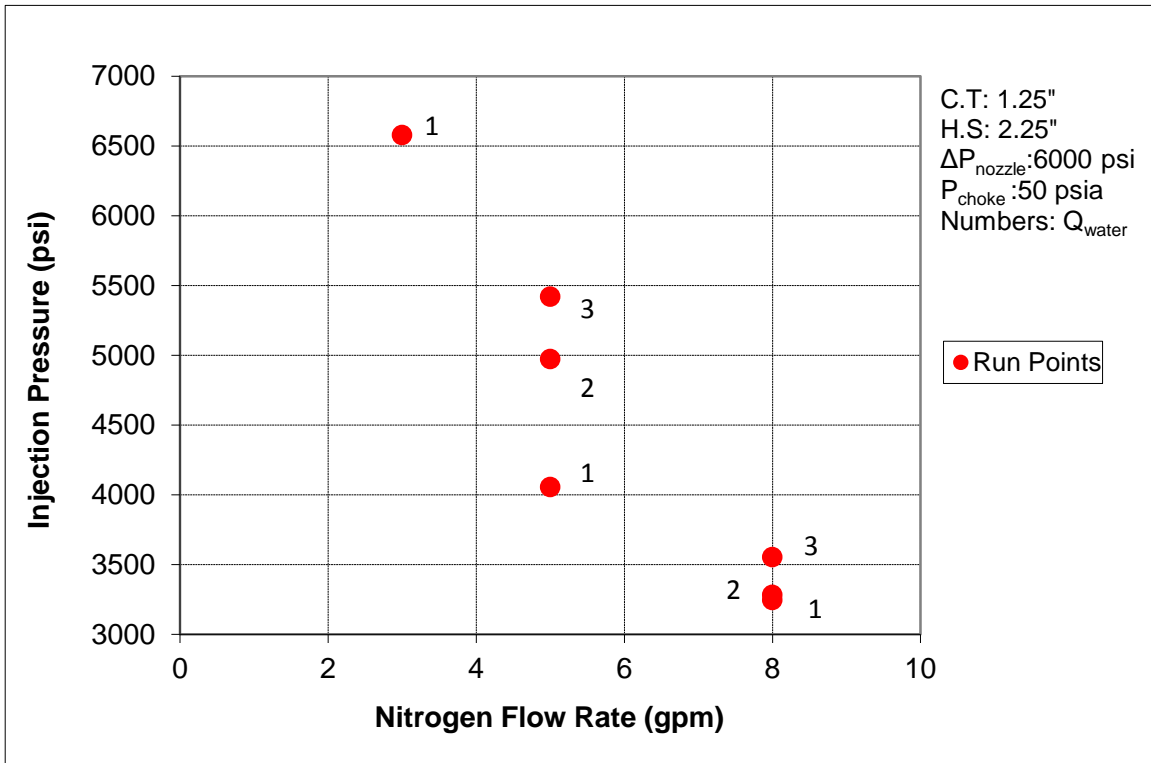


Figure C-14: Flow Rate vs. Inj. Pressure for N₂ with Water (CT:1.25"-HS:2.25", 31,000 ft)

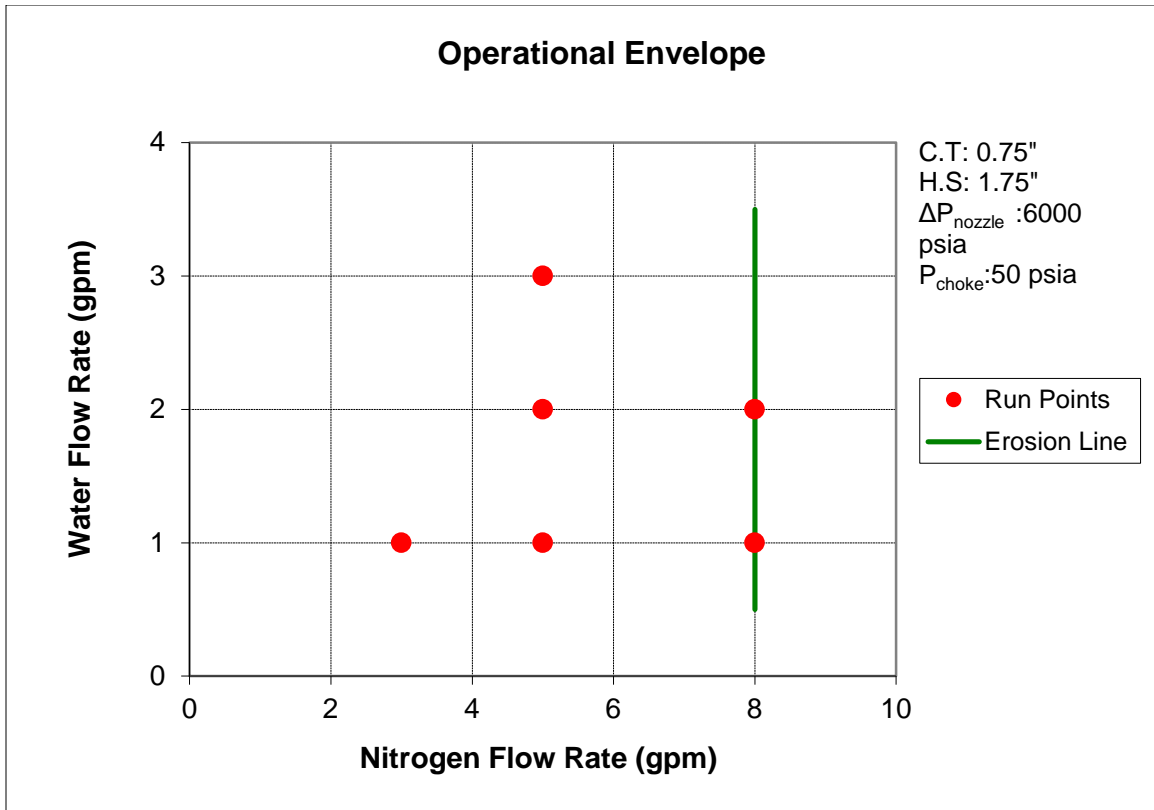


Figure C-15: Operational Envelope for N₂ with Water (CT: 0.75"-HS:1.75", 31,000 ft)

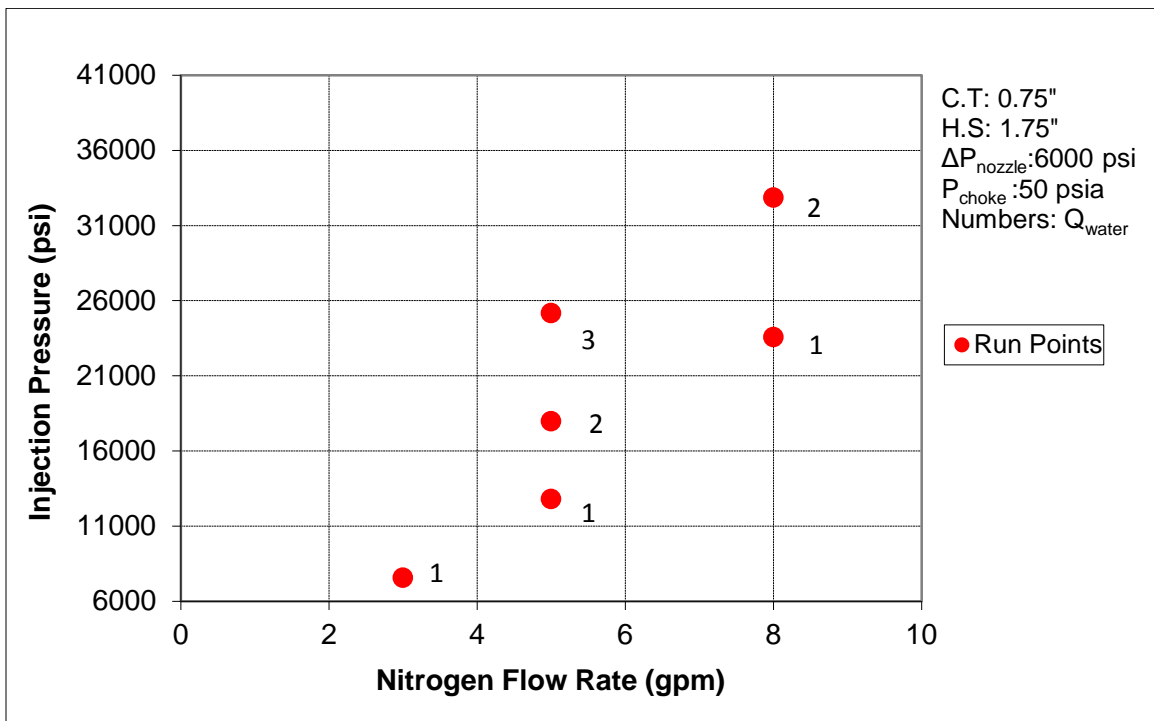


Figure C-16: Flow Rate vs. Inj. Pressure for N₂ with Water (CT: 0.75"-HS:1.75", 31,000 ft)

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 29,000 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 31,000 ft (Water Only)

Coiled Tubing O.D: 1 inch –Bore Hole Size: 2.25 inch							
Q N₂ (gpm)	Q Water (gpm)	Maximum Mixture Velocity Annulus (ft/m)	Liquid Fraction After Nozzle (31,000 ft)	Liquid Velocity Tubing (ft/m)	CTR (25 Micron)	CTR (100 Micron)	
-	3	21	1	107	0.805		
-	4	28	1	142	0.849		
-	5	36	1	178	0.877		
-	8	58	1	286	0.92		
-	10	72	1	357	0.936		
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	9914	21869	17869	533	538	
-	4	9449	20853	16853	532	536	
-	5	9439	20168	16168	531	536	
-	8	11055	18980	14980	531	535	
-	10	13137	18548	14548	533	537	
Coiled Tubing O.D: 1.25 inch –Bore Hole Size: 2.25 inch							
Q N₂ (gpm)	Q Water (gpm)	Maximum Mixture Velocity Annulus (ft/m)	Liquid Fraction After Nozzle (31,000 ft)	Liquid Velocity Tubing (ft/m)	CTR (25 Micron)	CTR (100 Micron)	
-	3	25	1	63	0.807		
-	4	33	1	84	0.851		
-	5	42	1	105	0.878		
-	8	67	1	168	0.921		
-	10	84	1	210	0.936		
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	9364	21863	17863	532	537	
-	4	8521	20856	16856	531	536	
-	5	8022	20164	16164	532	537	
-	8	7607	18996	14996	531	535	
-	10	7832	18561	14561	530	534	

Table C-4: Continuation

Coiled Tubing O.D: 0.75 inch –Bore Hole Size: 1.75 inch							
Q N₂ (gpm)	Q Water (gpm)	Maximum Mixture Velocity Annulus (ft/m)	Liquid Fraction After Nozzle (31,000 ft)	Liquid Velocity Tubing (ft/m)	CTR (25 Micron)	CTR (100 Micron)	
-	3	21	1	220	0.792		
-	4	28	1	293	0.84		
-	5	36	1	366	0.874		
-	8	58	1	584	0.918		
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	12145	20182	16182	532	537	
-	4	14751	19416	15416	532	537	
-	5	18506	18919	14919	534	538	
-	8	35669	18106	14106	533	537	

Table C-5: Output for 31,000 ft (Nitrogen with Water Addition)

Coiled Tubing O.D: 1 inch –Bore Hole Size: 2.25 inch							
Q N₂ (gpm)	Q Water (gpm)	Maximum Mixture Velocity Annulus (ft/m)	Liquid Fraction After Nozzle (31,000 ft)	Liquid Velocity Tubing (ft/m)	CTR (25 Micron)	CTR (100 Micron)	
3	1	171	1	150	0.638		
5	1	350	0.28	265	0.87		
8	1	2607	0.06	411	0.984		
5	2	270	0.34	300	0.901		
5	3	315	0.34	371	0.919		
8	2	3131	0.07	467	0.982		
8	3	4259	0.08	524	0.986		
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	6847	12056	6056	468	461	
5	1	4148	7229	1229	311	294	
8	1	5393	6387	387	196	175	
5	2	5777	9179	3179	411	400	
5	3	6622	9091	3091	417	408	
8	2	6291	6487	487	239	221	
8	3	7872	6542	542	243	230	
Coiled Tubing O.D: 1.25 inch –Bore Hole Size: 2.25 inch							
Q N₂ (gpm)	Q Water (gpm)	Maximum Mixture Velocity Annulus (ft/m)	Liquid Fraction After Nozzle (31,000 ft)	Liquid Velocity Tubing (ft/m)	CTR (25 Micron)	CTR (100 Micron)	
3	1	173	1	90	0.643		
5	1	225	0.29	150	0.932		
8	1	1655	0.08	223	0.968		
5	2	264	0.34	177	0.875		
5	3	280	1	201	0.856		
8	2	1449	0.13	263	0.96		
8	3	1070	0.17	313	0.947		
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	6578	12050	6050	478	468	
5	1	4056	8071	2071	370	351	
8	1	3247	6488	488	235	214	
5	2	4974	9782	3782	446	434	
5	3	5421	10724	4724	474	466	
8	2	3284	6700	700	280	264	
8	3	3555	7123	1123	351	331	

Table C-5: Continuation

Coiled Tubing O.D: 0.75 inch –Bore Hole Size: 1.75 inch							
Q N₂ (gpm)	Q Water (gpm)	Maximum Mixture Velocity Annulus (ft/m)	Liquid Fraction After Nozzle (31,000 ft)	Liquid Velocity Tubing (ft/m)	CTR (25 Micron)	CTR (100 Micron)	
3	1	986	0.15	398	0.919		
5	1	4685	0.05	508	0.983		
8	1	8763	0.03	643	0.992		
5	2	6162	0.08	564	0.983		
5	3	6470	0.09	629	0.982		
8	2	11019	0.05	717	0.992		
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	7548	6746	746	272	256	
5	1	12789	6566	566	223	204	
8	1	23579	6817	817	235	213	
5	2	17978	6718	718	258	243	
5	3	25168	6813	813	276	265	
8	2	32859	6979	979	252	238	

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 (31,000 with 500 ft CT at Surface)

	Water & N₂
Depth (ft)	31,000
Formation	Sandstone
Geothermal Gradient (°F/ft)	0.015
Surface Temperature (°F)	60
Injected Fluid Temperature (°F)	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 for 31,000 ft run. Water was injected into the system with different amounts of nitrogen. Number near the run points are amount of nitrogen flow rate with water. 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.

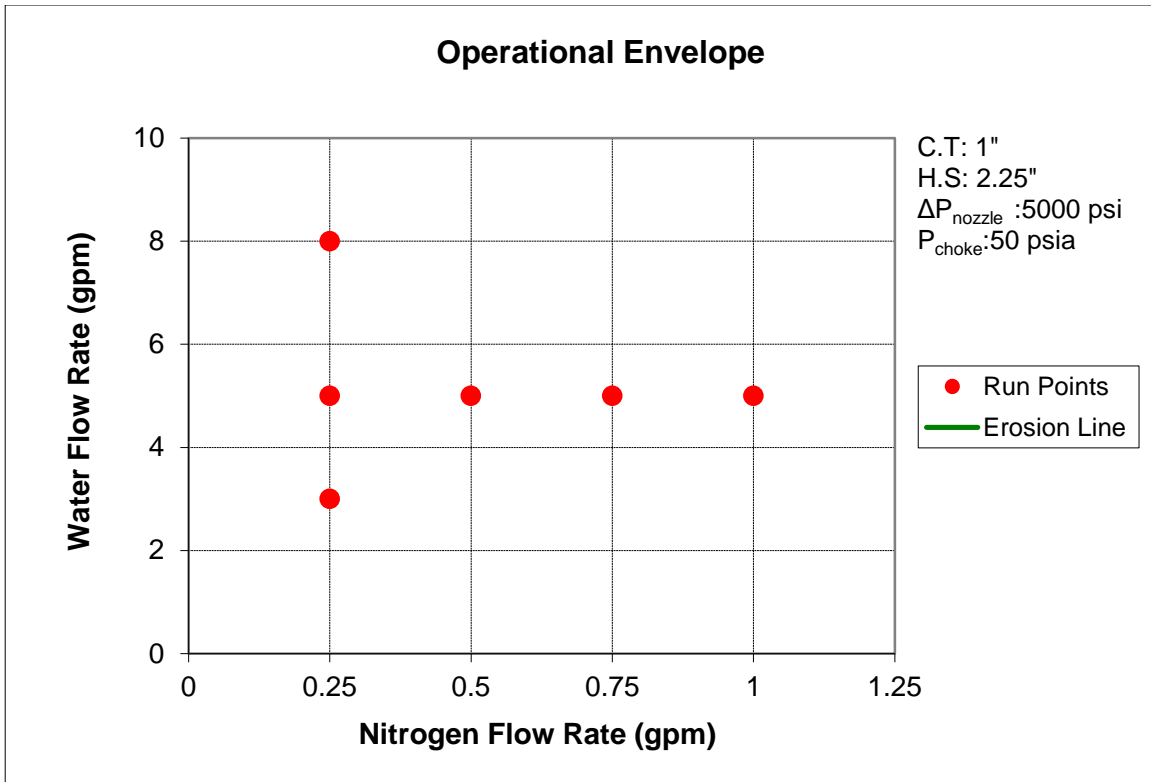


Figure D-1: Operational Envelope for Water with N₂ (CT: 1"-HS:2.25", 31,000 ft)

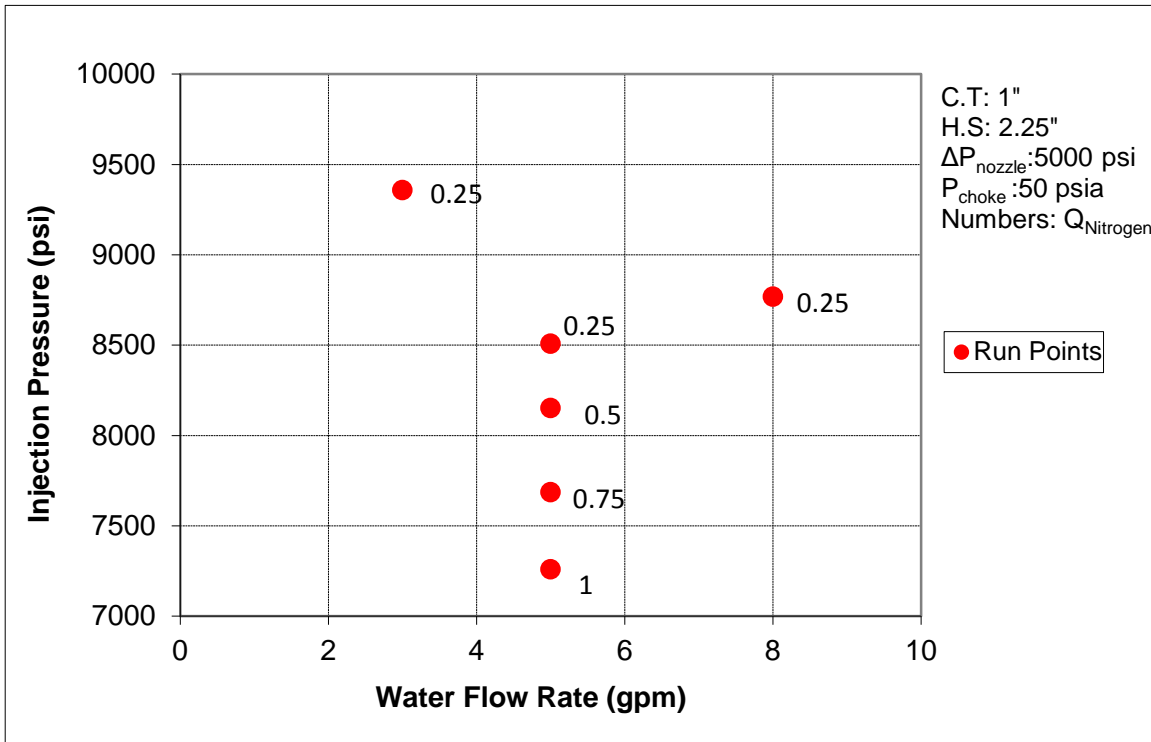


Figure D-2: Flow Rate vs. Inj. Pressure for Water with N₂ (CT: 1"-HS:2.25", 31,000 ft)

Example pressure and temperature profile graphs 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_{N_2} :0.25 gpm, 31,000 ft)

Injection Pressure (psia)	8,508
BHP Upstream Nozzle (psia)	20,132
BHP Downstream Nozzle (psi)	15,132

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.

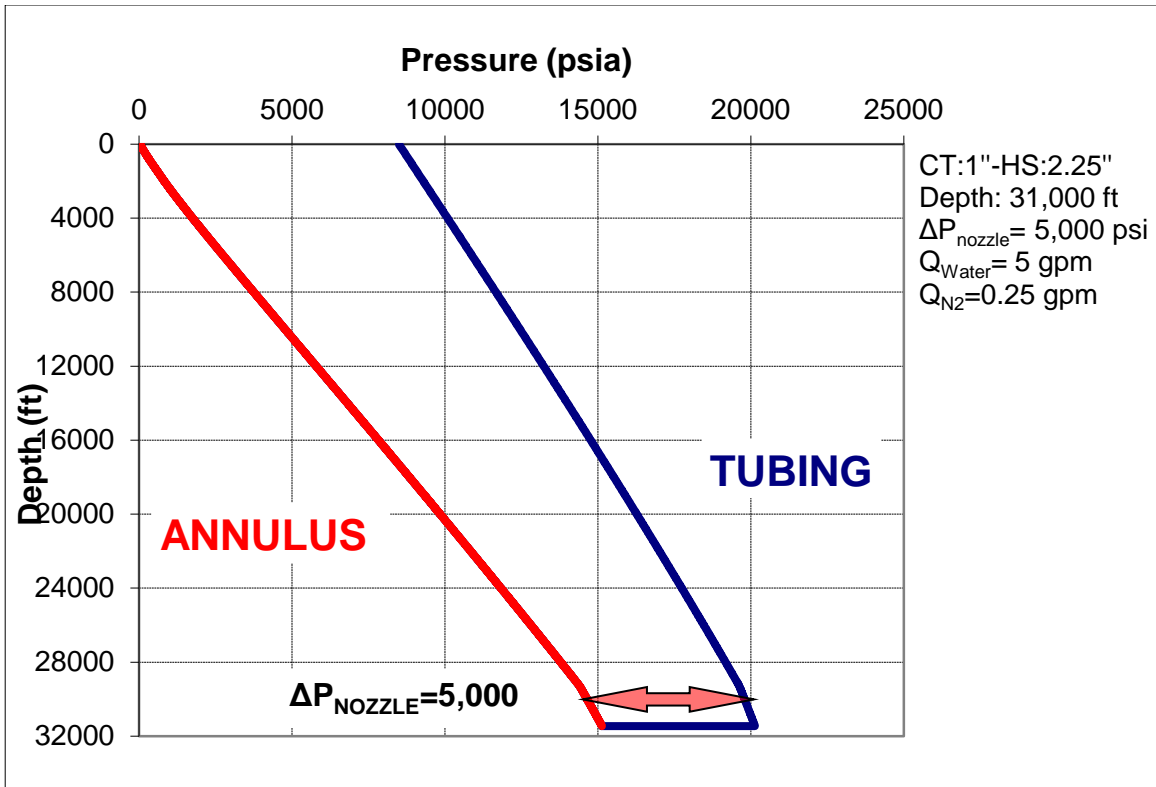


Figure D-3: Pressure vs Depth (CT:1", H.S:2.25", Q_w : 5 gpm Q_{N_2} : 0.25 gpm, 31,000 ft)

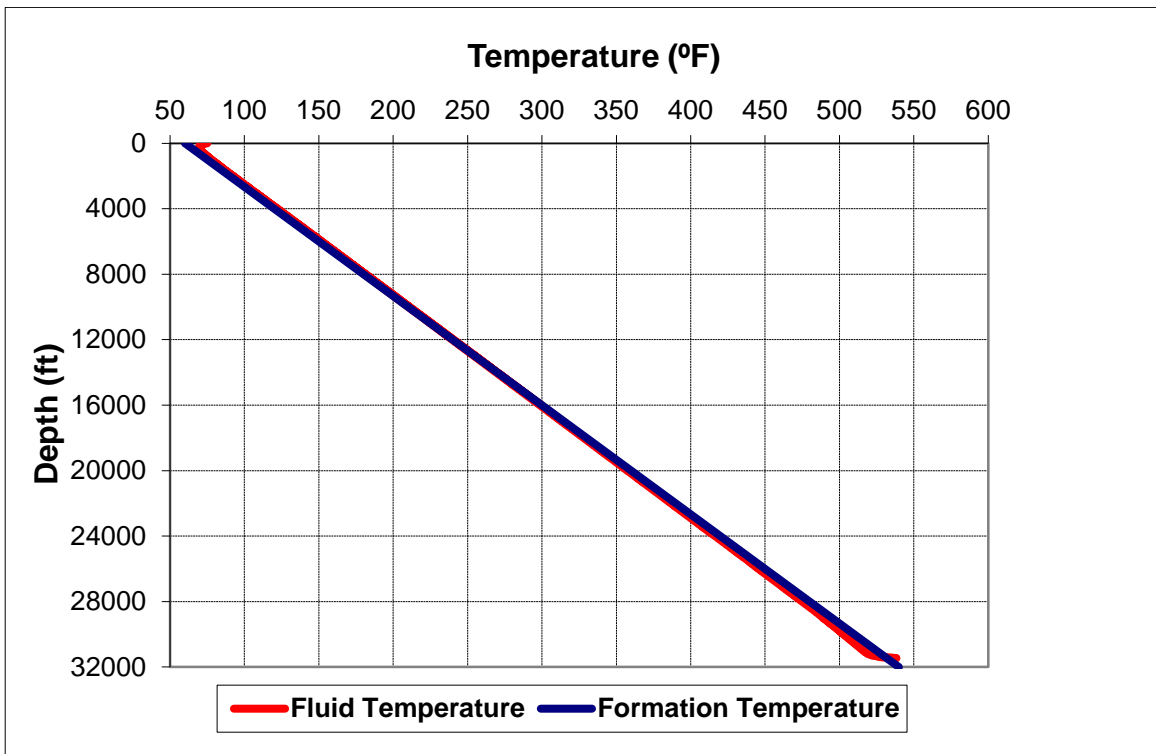


Figure D-4: Temperature vs Depth(CT:1", H.S:2.25", Q_w :5 gpm Q_{N_2} :0.25 gpm,31,000 ft)

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.

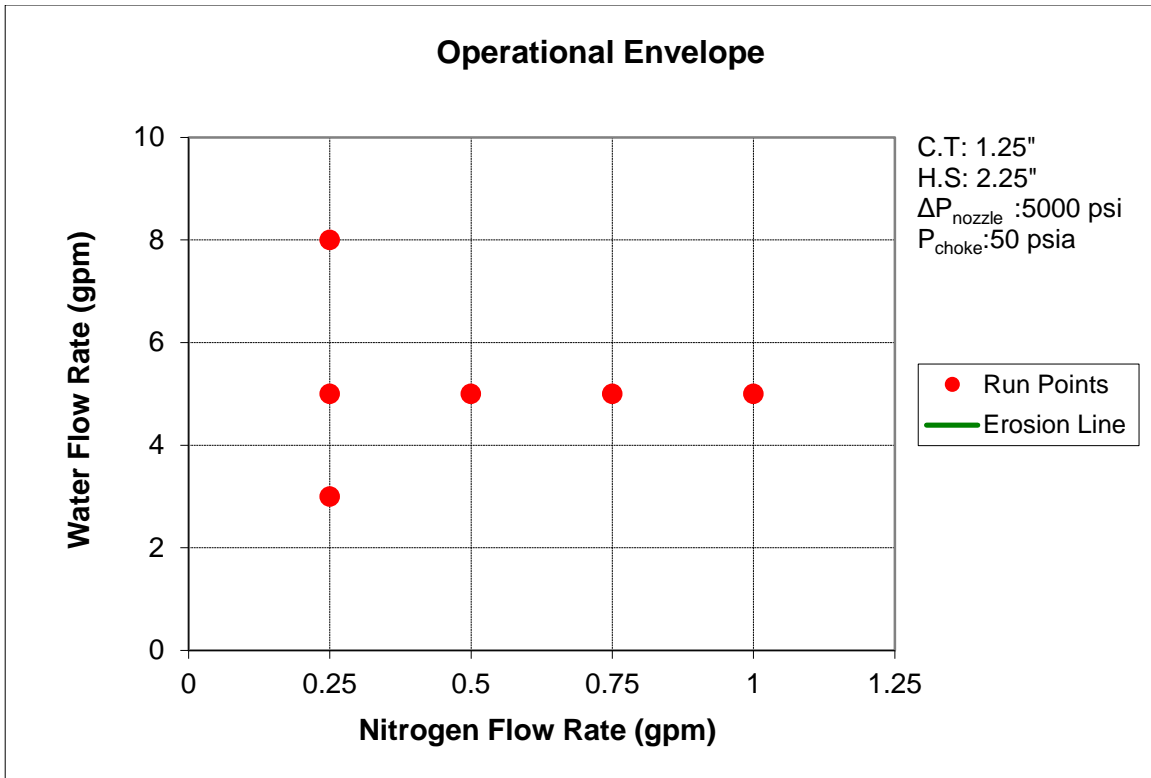


Figure D-5: Operational Envelope for Water with N₂ (CT: 1.25”-HS:2.25”, 31,000 ft)

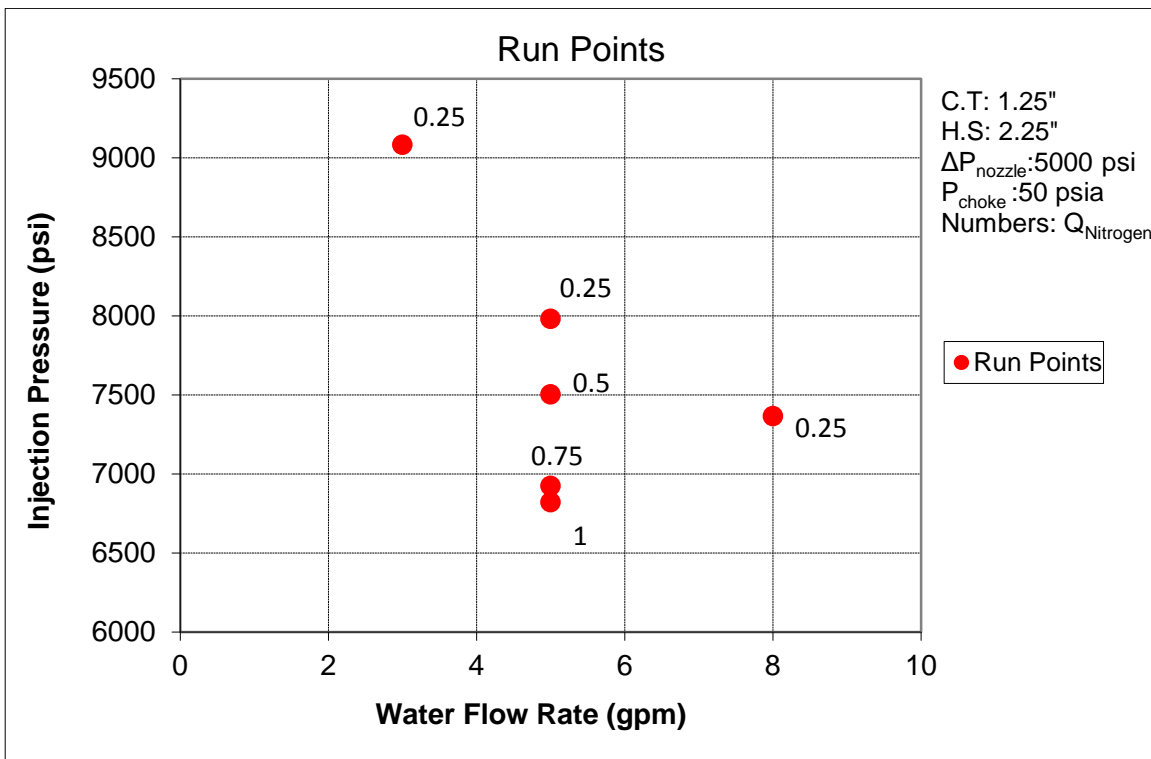


Figure D-6: Flow Rate vs. Inj. Pressure for Water with N₂(CT: 1.25”-HS:2.25”,31,000 ft)

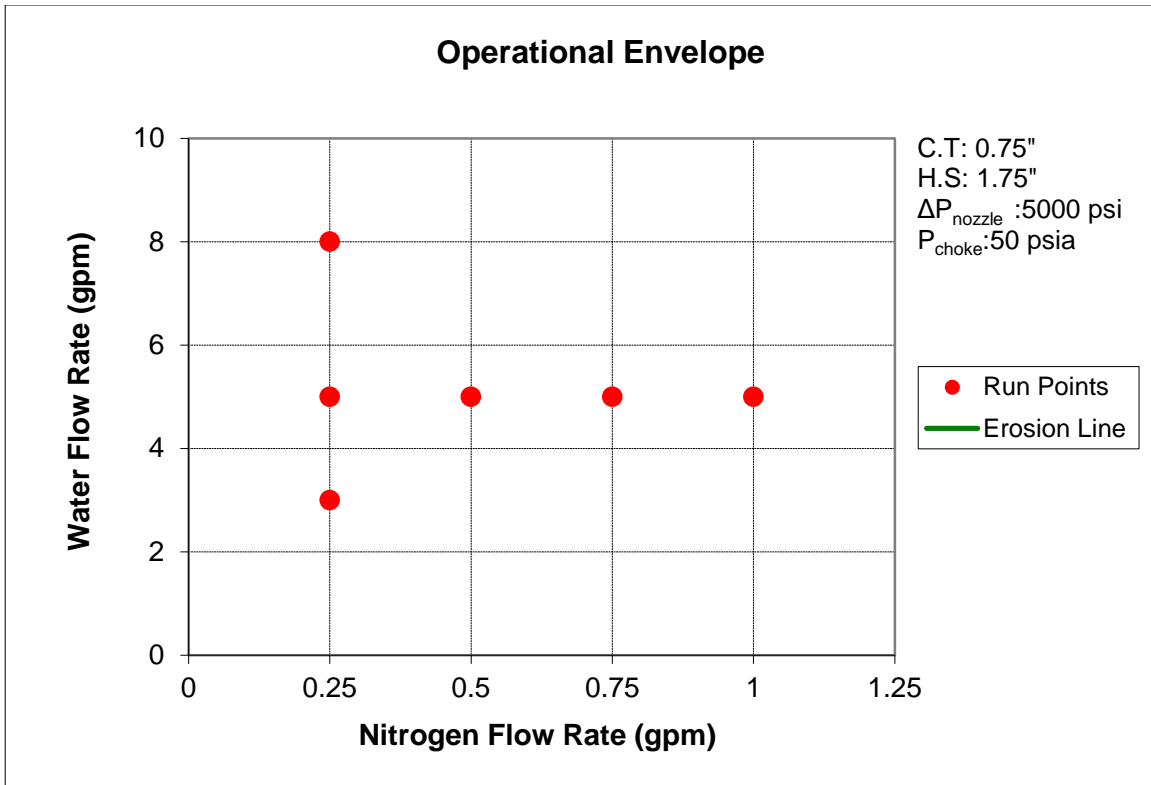


Figure D-7: Operational Envelope for Water with N₂ (CT: 0.75”-HS:1.75”, 31,000 ft)

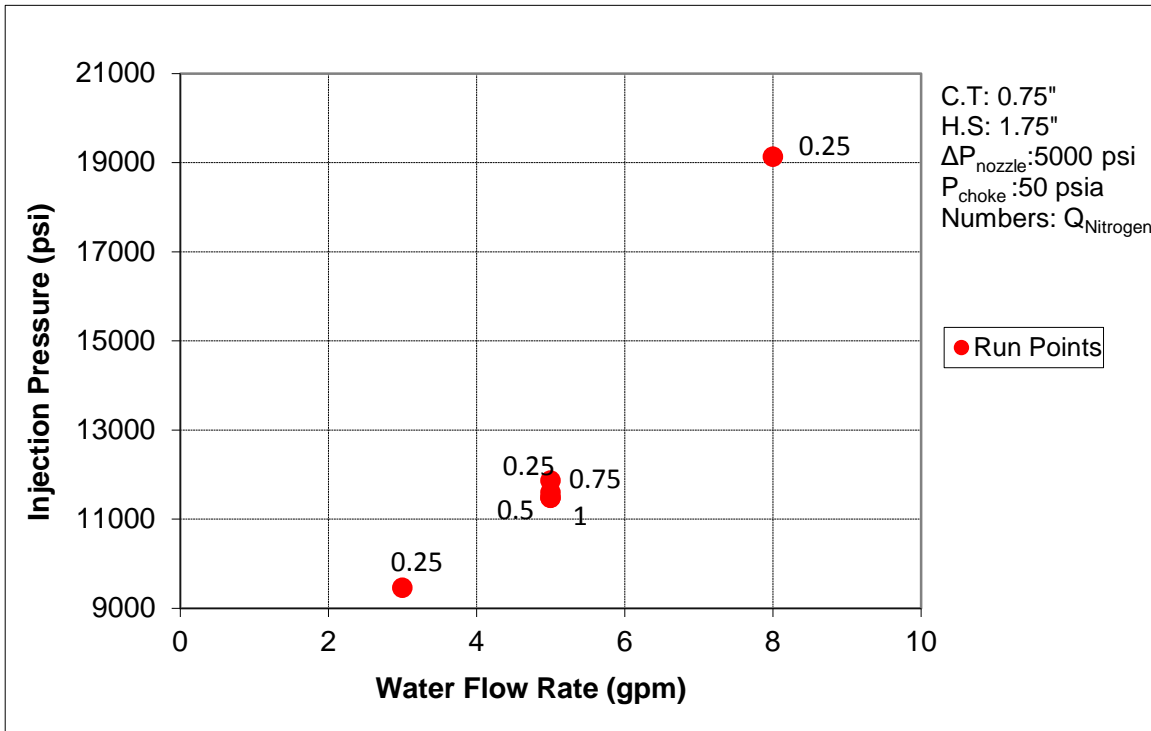


Figure D-8: Flow Rate vs. Inj. Pressure for Water with N₂(CT: 0.75”-HS:1.75”, 31,000 ft)

Conclusions

- ✓ 31,000 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 29,000 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 N₂ Addition (31,000 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 (31,000 ft)	Liquid Velocity Tubing (ft/m)	CTR (25 Micron)	CTR (100 Micron)	
3	0.25	23	1	116	0.799		
5	0.25	38	1	189	0.875		
8	0.25	60	1	297	0.92		
5	0.5	39	1	197	0.872		
5	0.75	53	1	206	0.867		
5	1	73	1	216	0.862		
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	9359	21371	16371	533	538	
5	0.25	8508	20132	15132	533	538	
8	0.25	8769	19249	14249	532	537	
5	0.5	8153	19491	14491	532	536	
5	0.75	7687	18688	13688	533	538	
5	1	7261	17906	12906	531	536	
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 (31,000 ft)	Liquid Velocity Tubing (ft/m)	CTR (25 Micron)	CTR (100 Micron)	
3	0.25	29	1	69	0.802		
5	0.25	44	1	111	0.877		
8	0.25	70	1	175	0.921		
5	0.5	45	1	116	0.874		
5	0.75	75	1	122	0.869		
5	1	52	1	126	0.866		
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	9081	21313	16313	533	538	
5	0.25	7981	20219	15219	533	538	
8	0.25	7366	19377	14377	533	538	
5	0.5	7503	19485	14485	532	536	
5	0.75	6925	18611	13611	533	538	
5	1	6821	18304	13304	533	538	

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 (31,000 ft)	Liquid Velocity Tubing (ft/m)	CTR (25 Micron)	CTR (100 Micron)	
3	0.25	38	1	240	0.786		
5	0.25	62	1	387	0.869		
8	0.25	99	1	606	0.917		
5	0.5	65	1	403	0.864		
5	0.75	69	1	420	0.859		
5	1	73	1	437	0.855		
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	9454	19648	14648	532	536	
5	0.25	11859	18874	13874	532	536	
8	0.25	19127	18291	13291	533	537	
5	0.5	11595	17954	12954	533	536	
5	0.75	11468	17164	12164	532	536	
5	1	11479	16478	11478	531	535	