Tempress Technologies, Inc.

Microhole Jet Drilling
System Configuration and Integration

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Abstract

Tempress' Mechanically-Assisted Jet Drilling project involves the development of a downhole intensifier (DHI) to boost the hydraulic pressure available in conventional coiled tubing to the level required for high-pressure jet erosion of rock. A review of high-pressure jet drilling and mechanically-assisted jet drilling was carried out to define the bottomhole assembly configuration and DHI performance specifications for coiled tubing drilling applications. Two BHA configurations were evaluated (1) mechanically-assisted jet drilling with the DHI deployed below a PDM drill motor and (2) high-pressure jet drilling with the DHI deployed upstream of a high-pressure jet drill. A hydraulic model of the DHI was coupled with a coiled tubing drilling circulation model to determine pressure and power available for jetting. Data on jet erosion of oil and gas producing formations and jet-assisted drilling was then applied to predict drilling rates. Other factors considered include steering, dogleg severity, extended reach, hole cleaning and coiled tubing pressure. The PDM would require heavy-duty bearings and a custom high-pressure seal. The drill motor/DHI combination BHA would also be longer than a conventional motor BHA, which would limit application to long-radius well curves. The DHI/jet drill combination would be much shorter than a conventional motor and would allow high speed drilling through short radius build sections. This configuration would also minimize mechanical loads and vibrations on the BHA. A design brief for a Microhole coiled tubing jet drilling tool capable of drilling 3-1/2-inch hole with 2-inch coil tubing is included.

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Executive Summary

The downhole intensifier under development by Tempress will generate high-velocity gas-shrouded fluid jets to enhance underbalanced coiled tubing directional drilling. A bottomhole assembly (BHA) review was carried out at the onset of this project to select the most promising configuration for commercial microhole drilling applications and to finalize hydraulic performance specifications. Two BHA configurations were evaluated; (1) mechanically-assisted jet drilling incorporating a steerable positive displacement downhole motor (PDM) above the downhole intensifier and (2) a high-pressure jet drilling tool located beneath the downhole intensifier.

A review of pressures required to erode conventional oil and gas producing formations has shown that 70 MPa (10,000 psi) jets will provide reliable jet erosion performance. Tempress has selected hydraulic performance specifications for a DHI that will provide this pressure when operated on coiled tubing drilling equipment under development as part of the Microhole Technology program. This equipment, including surface pumps, coiled tubing, orienters and positive displacement motors determines the pressure and flow available to power the DHI. The Tempress DHI is designed to operate on two-phase (water and nitrogen or air) to maximize hydraulic power available at the BHA and to allow underbalanced drilling operations. The tool will incorporate a gas separator to ensure that only water is intensified.

The mechanically-assisted jet drilling BHA would incorporate a conventional PDM, which turns the gas separator and DHI. A review of positive displacement motors has confirmed that these tools can be configured for reliable operation on two-phase flow. Current PDM seals and bearings restrict their use to relatively low differential pressures thereby restricting the intensified jet pressure and drilling performance. The PDM would need to be modified with a custom high-pressure seal and heavy-duty bearings. A dual-flow mechanical drill bit with high pressure jet ports and low pressure gas ports would also need to be developed for jet-assisted drilling. For steering applications this tool would incorporate a bent sub between the PDM and DHI assembly. Steering would be limited to large radius curves because of the length of the BHA and long bit-to-bend distance imposed by locating the DHI below the PDM. Applications would include rapid horizontal drilling, extended reach drilling, bicenter bit drilling and under-reaming.

The DHI could also be used to power a high-pressure jet drill. This configuration would employ a simple, compact BHA that could be used to drill ultra-short radius curves and horizontal wells. At 70 MPa, compact high-pressure rotary jetting tools are capable of drilling any moderate to high permeability formation, which effectively includes all conventional unfractured oil and gas producing formations. Jet drilling should only be considered for lateral well extensions within permeable producing formations. The high-pressure jet drill would use the degassed output from the gas separator and downhole intensifier to generate spinning, high-velocity jets. The gassy flow would be directed to the nozzle head where it shrouds the water jets for improved cutting performance. This configuration would incorporate a bent coupling between the DHI and jet drill for steering. The BHA would be much shorter than a PDM to allow steering through shorter radius curves than is currently possible with motors. Short-radius drilling is an important cost-reduction objective because all drilling can take place within the producing formation and because hole cleaning problems in the build section are minimized. The high-pressure jet drill would also extend lateral reach by eliminating the need to apply bit weight. This tool configuration should find broad application for underbalanced drilling of ultra-short radius and extended reach horizontal wells within production zones.

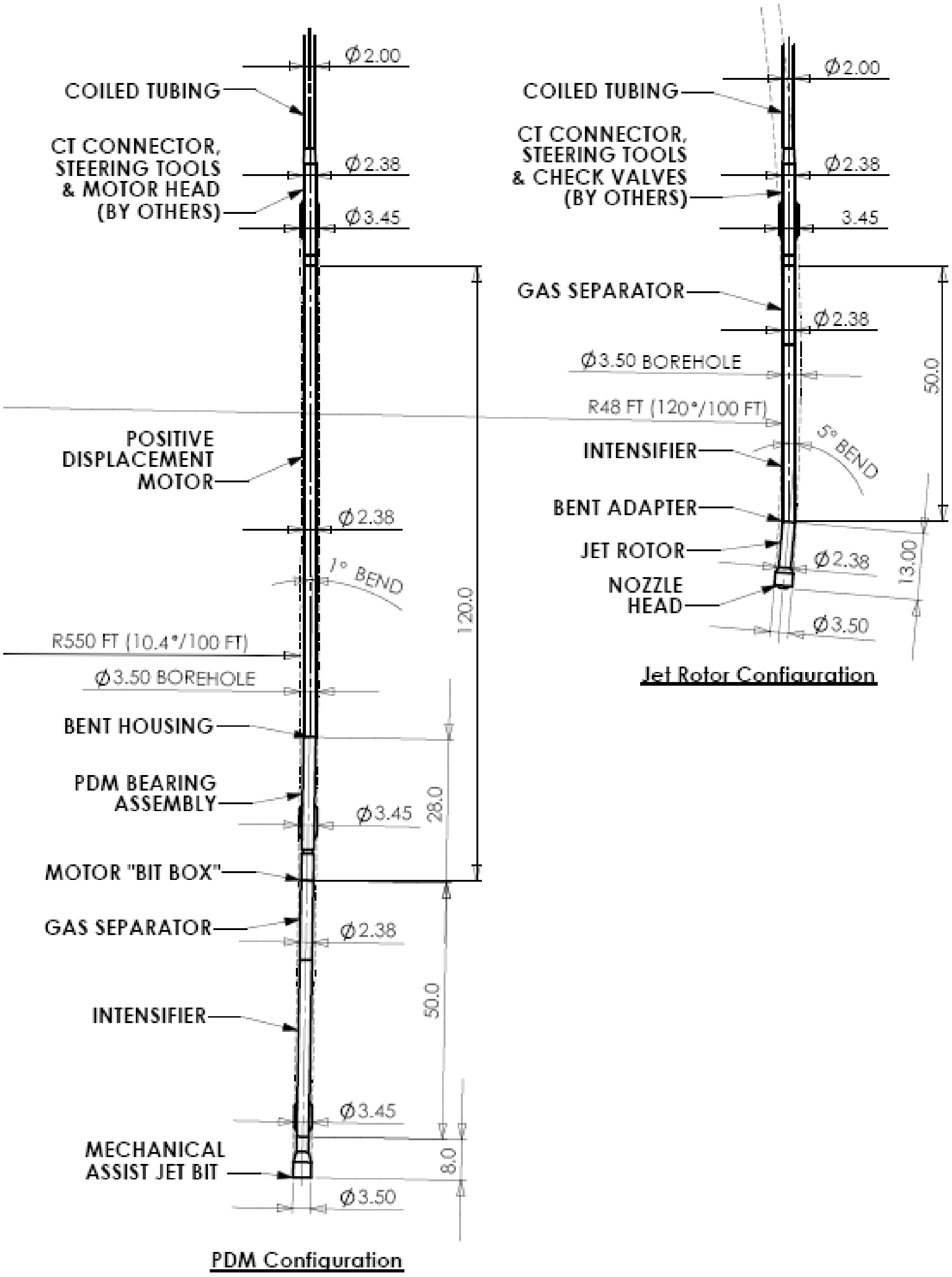
Introduction

The Tempress Microhole High-Pressure Jet Drilling project involves the development of a downhole intensifier for coiled tubing drilling applications. The intensifier will boost the pressure available at the end of the tubing to a level that is capable of eroding rock. The first task in the Microhole High-Pressure Jet Drilling project was to define pressure and hydraulic power requirements for effective jet erosion of rock. A numerical model of two-phase circulation during coiled tubing drilling and a two-phase hydraulic model of the downhole intensifier were then used to specify hydraulic operating parameters for these tools. Mechanically-assisted jet drilling and jet drilling applications were evaluated in terms of performance benefits and commercial potential. The BHA configurations are described for both applications.

The high-pressure flow can be used in two basic configurations:

1. High-pressure mechanically-assisted jet drilling uses the jets to reduce cutter loads and increase rate of penetration. In this configuration the intensifier would be run with a conventional positive displacement motor.
2. High-pressure jet drilling uses a jet rotor tool to drill rock without any mechanical cutters. These tools are much shorter than mechanical drill motors allowing drilling of short radius holes.

Two BHA configurations are illustrated in Figure 1. Each of the configurations uses two-phase flow to create underbalanced drilling conditions. A gas separator above the intensifier separates the water and gas in the bottomhole assembly so that only degassed water issues from the jets to maximum erosion performance. The downhole intensifier will use the energy in the separated gas-rich flow to pressurize the degassed water stream. The high pressure water will be converted to high velocity jets in nozzles incorporated into a drilling head or modified bit. The gas may also be discharged into the borehole at the bit face to “shroud” the jets thereby increasing their effective cutting range.



PDM Configuration

Jet Rotor Configuration

Figure 1. BHA configurations for high-pressure jet drilling.

Pressure and Power Available at the BHA

The use of small diameter coil causes frictional pressure losses that limit the pressure and hydraulic power available at the BHA. A two-phase coiled tubing drilling circulation model was expanded to determine the pressure and power while circulating commingled water and nitrogen for coiled tubing drilling of directional wells such as the example well shown in Figure 2. Circulating pressures are shown in Figure 3. The model accounts for circulating pressure losses and hydrostatic pressure changes in the coil and annulus. In this example, nitrogen is commingled to reduce the bottomhole pressure.

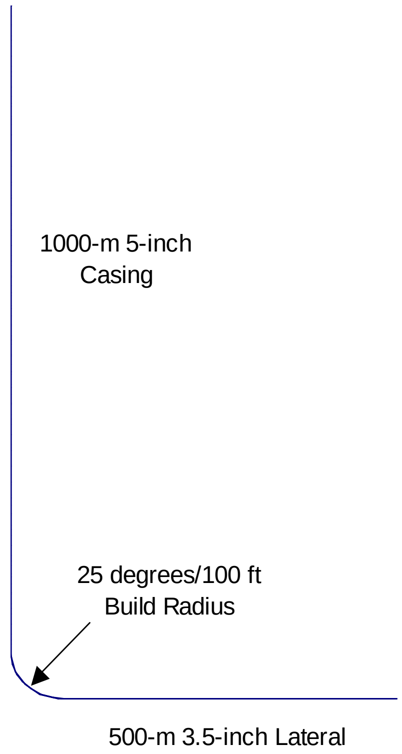


Figure 2. Example Microhole well.

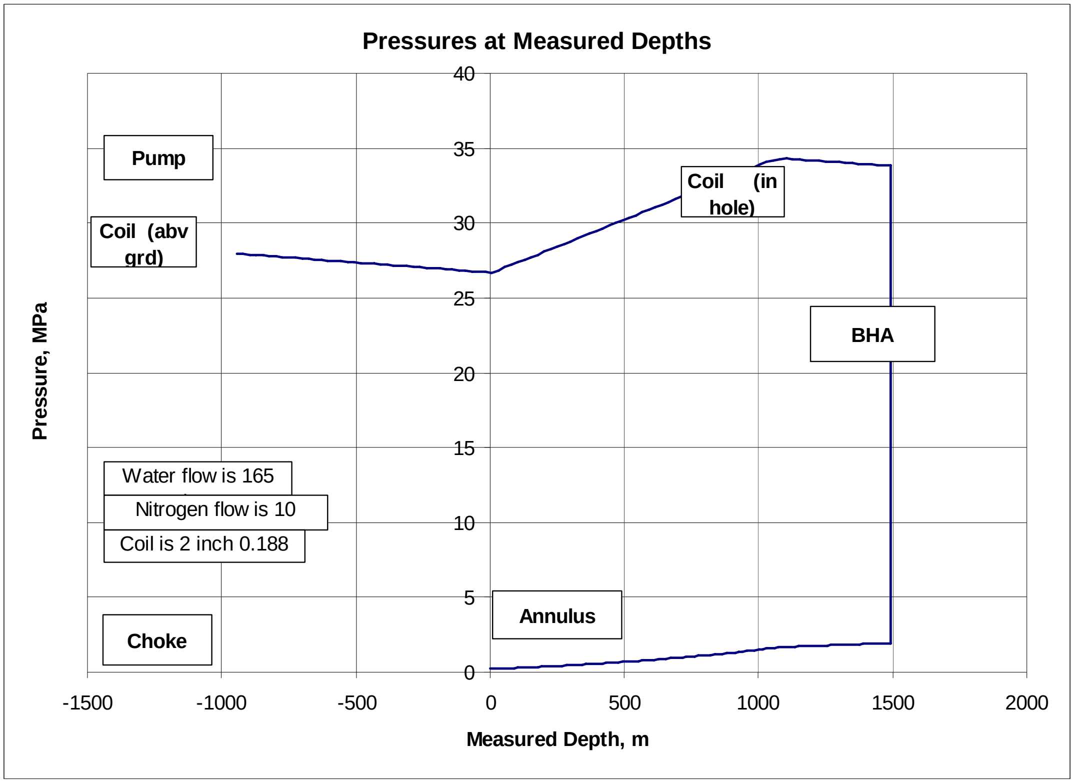
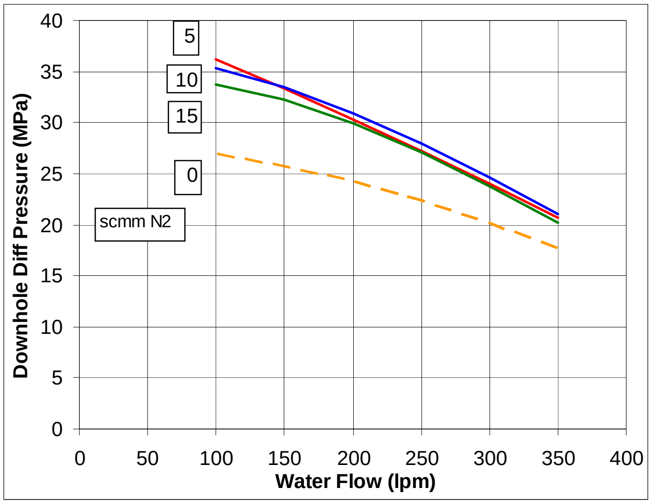


Figure 3. Circulating pressure in example well .

Figure 4 illustrates the effect of adding nitrogen on downhole pressure and power at various flow conditions in a hypothetical Microhole well. Injecting even small quantities of nitrogen into the drilling fluid (water) has several benefits, not least of which is the higher differential pressure available downhole. Underbalanced drilling makes it possible to increase the pressure differential from inside the coil to the borehole to ver 28 MPa (4000 psi) with 28-35 MPa (4000 – 5000 psi) surface pump pressure, by reducing fluid friction and lowering the density of fluid in the annulus. This analysis shows that the maximum power available occurs at 300 lpm water flow and 15 scmm nitrogen. The maximum pressure available at the BHA drops continuously with flow rate due to friction losses.



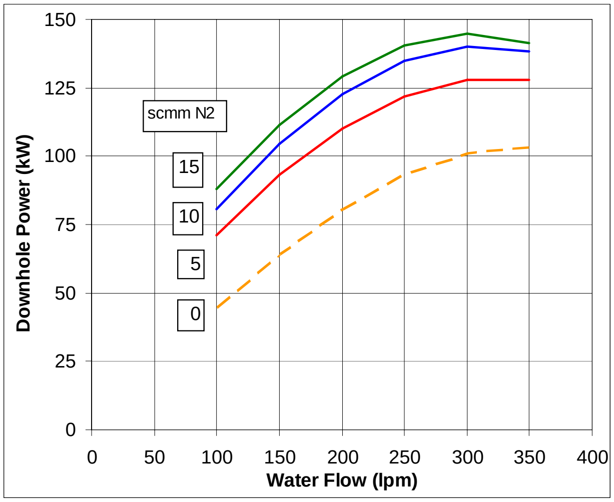


Figure 4. Effect of nitrogen flow on bottomhole differential pressure and hydraulic power with 4000 psi (28 MPa) surface pump pressure, 2" coiled tubing, 4.5" cased hole to 3280 ft (1000 m), 3.5" open hole to total measured depth of 6560 ft (2000 m) and kickoff at bottom of casing to 90° (horizontal) at 5000 ft (1524 m).

Cuttings Transport

The DHI is designed primarily for underbalanced drilling with energized fluids although drilling with clear water is also possible. Water plus a small amount (e.g 0.2wt%) of polymer would reduce friction pressure losses in the coil. Turbulent flow with low viscosity drilling fluid (water) should ensure that a cuttings bed does not build in the horizontal and inclined sections of the hole[1,2]. Adding nitrogen

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[1] Leising, L.J. and I.C. Walton (1998) "Cuttings transport problems and solutions in coiled tubing drilling," SPE39300, presented at IADC/SPE Drilling Conference, Dallas, March 3-6, Society of Petroleum Engineers, Richardson Texas.

[2] Okrajni, S.S. and J.J. Azar (1986) "The effects of mud rheology on annular hole cleaning in directional wells," *SPE Drilling Engineering*, August 297-308.

increases flow velocity and reduces fluid viscosity, which should further aid in cuttings transport as long as the flow does not stratify. These factors must be balanced with the surface pumping pressure capacity, coil size and hydraulic power requirements of the motor and DHI. Even when the flow is turbulent, some large cuttings may accumulate in the hole requiring wiper trips.

A plot of flow velocity for the circulation example shown in Figure 3 is provided in Figure 5. The minimum Reynolds number for this flow is 125,000 indicating extremely turbulent, mixed flow thoughout the well. In contrast, the minimum Reynolds number at the equivalent water-only flow rate is almost an order of magnitude smaller at 16,000 and drilling with mud or viscous polymer could result in laminar flow ($Re < 2000$).

At high gas flow rates and low mean velocity, the flow can stratify, which reduces the water velocity and cuttings transport. A Froude number analysis can be used to assess the potential for stratified flow. The Froude number describes the ratio of mixing to buoyancy forces at the interface of flow between fluids of different density. When the Froude number is greater than 2 the fluids will mix readily. Stratified flow is possible at Froude numbers less than 1. The minimum Froude number for flow in the horizontal well section is greater than 5 indicating that the potential for stratified gas/water flow is low.

Cuttings may also accumulate in casing where the flow area increases and velocity slows. The velocity and density of the mixed flow can be used to estimate the cuttings transport ratio[3] in the vertical section of the hole. A rule of thumb for adequate hole cleaning is that the upward flow velocity should be at least twice the slip velocity of the cuttings. Adding a small amount of gas substantially increases vertical velocity in casing, which enhances cuttings transport. In the example case, the minimum transport ratio for 2-mm diameter cuttings is 0.5, which should provide adequate hole cleaning in the casing. Pills of high viscosity fluid may be used to periodically sweep the casing if cuttings are not coming to surface.

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[3] **Transport ratio is the difference between annular velocity and slip velocity divided by the annular velocity.**

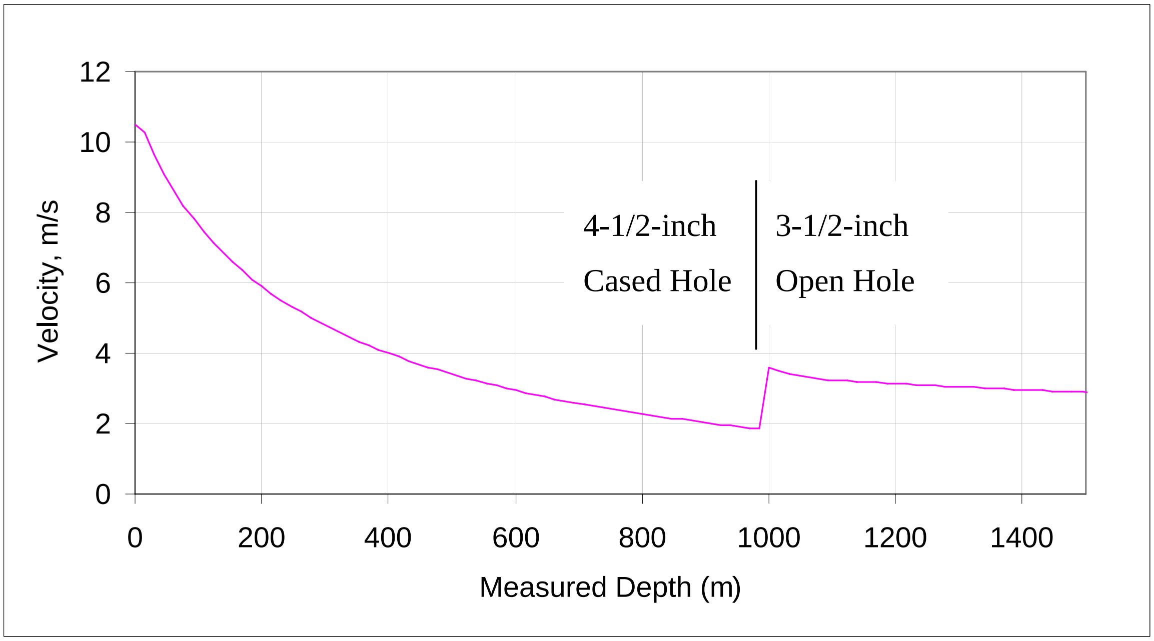

Figure 5. Flow velocity in example shown in Figure 3.

High-Pressure Jet Erosion of Rock

The DHI must generate sufficient pressure to enable effective erosion of rock for either mechanically-assisted jet drilling or jet-drilling. Jet drilling and erosion data consistently show that rock removal rates are linearly proportional to jet pressure above an initial threshold pressure. An analysis of this relationship shows that the specific productivity increases rapidly above the threshold pressure as is shown in Figure 6. The threshold pressure is inversely correlated with rock permeability as shown in Figure 7. The matrix permeability of oil bearing rock[4] is in the range of 10 to 10,000 mD while conventional gas formations may have a permeability as low as 1 mD. The threshold pressure for these formations is 60 MPa or less. Tempress has selected 70 MPa for operation of high-pressure jet drill. At this pressure, jet erosion will be effective in all conventional, unfractured oil and gas producing formations and will be effective in about half of sedimentary rock types. Over 75% of the formations drilled for oil and gas are impermeable shales[5], which are not effectively eroded by high-pressure jets. Jet drilling should only be considered for lateral well extensions in conventional producing formations.

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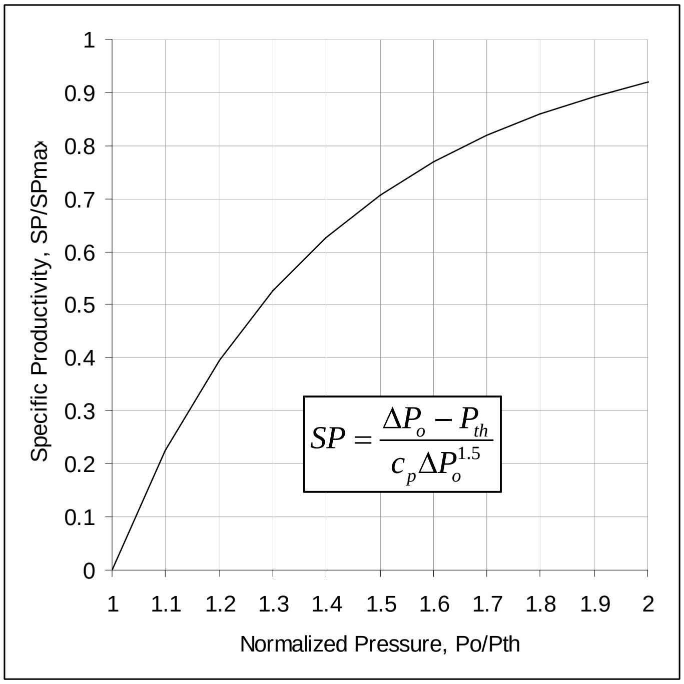
[4] **Bear, J (1972) *Dynamics of Fluids in Porous Media*, Dover Publications, New York.**

[5] **Steiger, R.P. and P.K. Leung (1992) "Quantitative determination of the mechanical properties of shales," *SPE Drilling Engineering*, September, p. 181.**



$$SP = \frac{\Delta P_o - P_{th}}{c_p \Delta P_o^{1.5}}$$

Figure 6. Jet erosion specific productivity as a function of pressure.

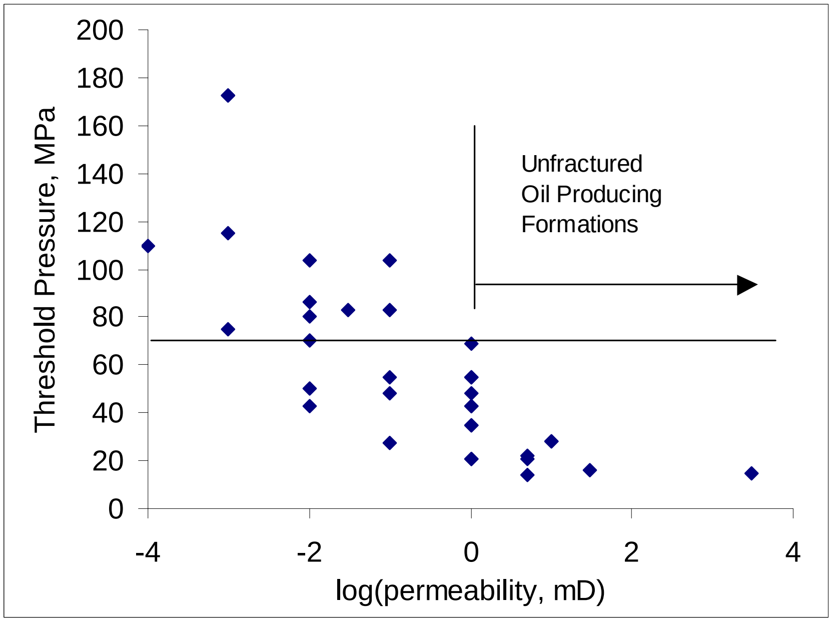


Figure 7. Relationship between rock matrix permeability and threshold pressure for twenty-eight rock samples[6].

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[6] **Data compiled from Kolle et al. (1992), Maurer et al. (1973) and Pols (1977)**

Downhole Intensifier Design

A schematic of an intensifier is shown in Figure 8. The intensifier operates by applying low pressure to a large area piston that drives a smaller area piston to boost the pressure. The DHI design uses a double-acting intensifier to provide continuous operation. The DHI can be described in terms of its area intensification ratio, which is the ratio of areas of the large piston and small piston. The output pressure is amplified in this ratio while the high pressure outlet flow is reduced in proportion to the intensifier area ratio. In practice, there are pressure losses through the fluid passages that reduce the pressure ratio and hydraulic efficiency of the tool.

Tempress has developed a detailed design for a double-acting DHI capable of providing 70 MPa to a high-pressure jet drill. The intensifier passage geometry has been incorporated into a two-phase hydraulic model that is used to evaluate shift timing, component motions and hydraulic efficiency. The intensifier incorporates long axial flow passages to port the flow to both sides of the intensifier. These passages are subject to turbulent friction pressure losses that cause the hydraulic efficiency of the DHI to decrease with increasing flow rate. At 70 MPa operating pressure, the maximum the power efficiency of the intensifier is limited to about 60%.

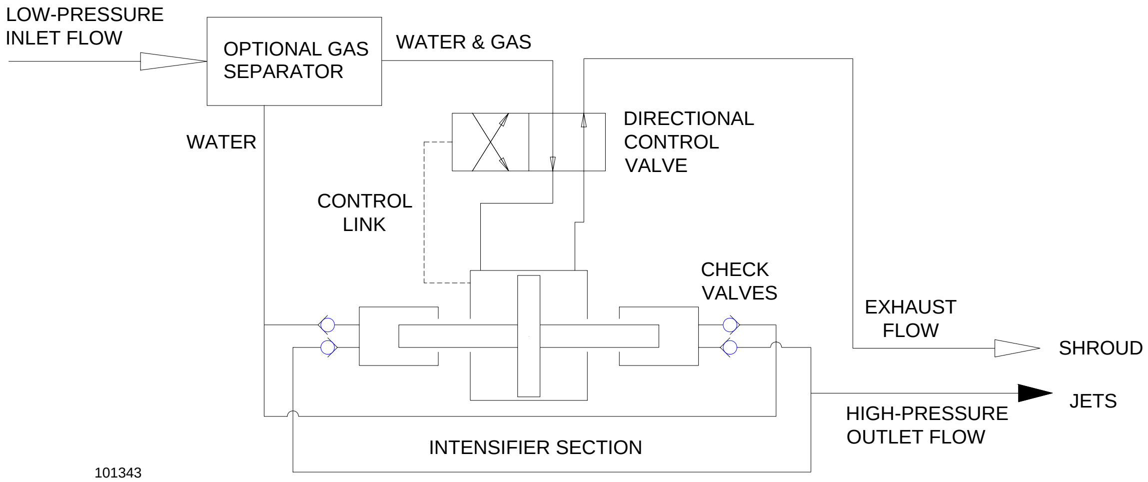

Figure 8. Downhole intensifier operating principles.

Nominal operating parameters for the DHI are provided in Table 1. More detailed data is provided in Appendix A. The tool will provide sufficient pressure to allow jet erosion in all conventional oil and gas producing formations. During mechanically-assisted jet drilling, the inlet pressure is reduced by up to 10 MPa by the pressure drop across the motor.

Table 1. Nominal downhole intensifier operating parameters.

Area Ratio	3.3:1
Water Flow	100 - 200 lpm
Gas Flow	10 scmm nitrogen
Inlet Pressure	30 MPa
Outlet Pressure	70 MPa
Outlet Flow	40-60 lpm
Outlet Power	50-75 kW

High-Pressure Jet Drilling

High pressure jet drilling would employ a jet rotor located below the downhole intensifier and gas separator. This configuration is much shorter than a downhole motor. Jet drilling at pressures of 30 to 100 MPa has been shown to be effective over a broad range of permeable and impermeable sedimentary rock types that may be encountered while drilling for oil and gas[7]. The pressure required for short radius lateral drilling within an oil producing formation will be lower than this range because these formations tend to have high matrix permeability which reduces the threshold pressure required for jet erosion.

A jet rotor for milling hard scale is shown in Figure 9. These tools have been tested at up to 90 MPa. A smaller rotor used for short radius drilling of rock is shown in Figure 10. These drills use the reaction thrust from off-axis jets to rotate the nozzle head. Proprietary pressure balanced seals and bearings provide free rotation of the rotor shaft. These tools have been used for milling hard scale and cement and for drilling sandstone. If left unchecked, reaction thrust rotation speed would be excessively high, causing overheating and rapid wear on seals and bearings. The jet rotor tools employ speed governors to control rotation rate.

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[7] **Maurer, W.C. J.K. Heilhecker and W.W. Love (1973) "High-pressure drilling,"** ***J. Pet. Tech*****, July, pp. 851-859.**

Figure 9. High pressure jet drill and 2-1/4" hole milled in hard carbonate scale at 35 MPa.

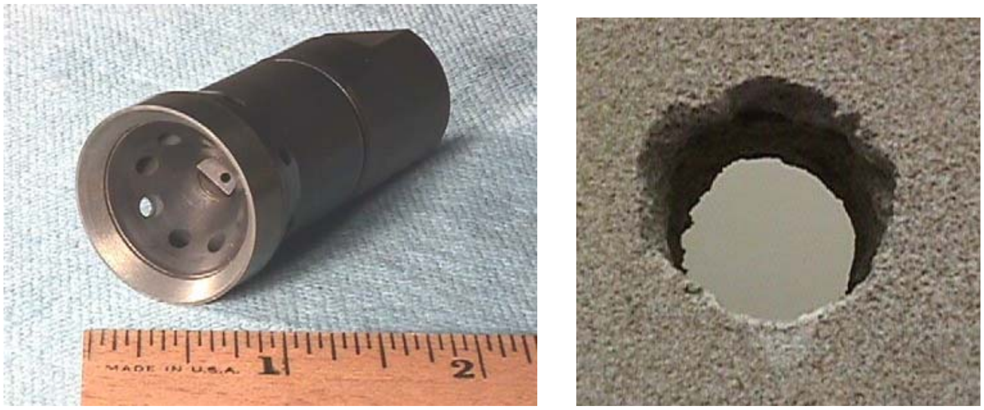

Figure 10. Compact jet drill and 1-1/4" hole drilled in Wilkeson sandstone at 70 MPa

Rate of Penetration

The rate of jet erosion is related to the specific productivity, which is determined from the ratio of volumetric rock removal rate to jet hydraulic power. The jet drilling rate is determined by

$$ROP = \frac{SP \cdot W}{\frac{\pi}{4} D_{hole}^2}, \tag{1}$$

where SP is the specific productivity, W is the jet hydraulic power and D_{hole} is the hole diameter. Data for specific productivity of jet drilling and rock erosion for ten moderate to high permeability ($k \geq 0.1$ mD) rock types is compiled in Table 2. The data was taken at different nozzle differential pressures and traverse rates.

Table 2. Threshold pressure and specific productivity of jet erosion in ten moderate to high permeability rock types.

	log(*k*, md)	P_{th}, MPa	dP_o, MPa	v_{tr}, m/s	*SP*, mm^3/J
West Texas Sandstone [a]	0.0	35	172	1	0.44
Wilkeson Sandstone [a]	-1.0	48	172	1	0.30
Indiana Limestone [a]	0.0	55	172	1	0.50
West Texas Sandstone [b]	1.0	28	55	78	0.50
Obernkirchen SS [c]	0.7	22	33	0.2	0.13
Gildenhausen SS [c]	3.5	15	30	0.22	0.21
Euville LS [c]	1.5	16	30	0.22	0.19
Indiana Limestone [d]	0.0	43	96	0.16	0.11
Berea Sandstone [d]	0.7	21	70	0.16	0.19
Wilkeson SS [e]	8	28	117	.025	0.07
				.076	0.18
				.25	0.50
				.76	1.07
				2.5	1.19
				7.6	0.90

[a] Jet erosion test (Kolle et al. 1992)

[b] High-speed jet drilling test (Tempress 2004)

[c] Jet drilling test, (Pols 1977)

[d] Jet drilling test (Maurer et al. 1973)

e Jet erosion tests (Crow 1973) permeability is estimated in this paper

Tempress jet rotor tools run at 2000-50,000 rpm, which is much faster than a PDM or the rotary speeds used by Pols (1977) and Maurer et al. (1973) for their jet drilling tests. Increased jet traverse rate has been shown to enhance on jet cutting productivity[8]. Data on depth of cut in a moderate permeability sandstone is shown in Figure 11 along with a model fit for cut depth, *h*.

$$h = \frac{c_h d_o (P_o - P_{th})}{P_{th}\left(1 + v_{tr}/v_c\right)^2}, \tag{2}$$

where c_h is a geometric constant, v_{tr} is the traverse rate and v_c is a critical velocity parameter. Jet erosion of permeable rock depends on the diffusion of jet stagnation pressure into the rock to generate

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[8] **Crow, S.C.(1972) "A theory of hydraulic rock cutting," Int. J. Rock Mech. Min. Sci., V.10, 567-584.**

tensile loads that break out the grains of rock. The pressure at a depth z in rock after a step change Δp in surface pressure is

$$p(z,t) = \Delta p \cdot erfc\left(\frac{z}{2\sqrt{Dt}}\right) \tag{3}$$

where erfc is the co-error function and D is the pore pressure diffusivity of the rock

$$D = \frac{k}{\mu\phi\beta} \tag{4}$$

where k is permeability in m^2, μ is the fluid viscosity in Pa-s, ϕ is porosity and β is the fluid compressibility in Pa^{-1}. The peak tensile stress beneath a fluid jet of diameter d_o impinging on a permeable half space occurs at a depth of less than one nozzle diameter. The critical velocity is proportional to permeability and inversely proportional to the jet size and the rock porosity,

$$v_c \propto \frac{k}{\phi d_o}. \tag{5}$$

The cut depth data provided in Figure 11 may be translated into a specific productivity value as shown in Figure 12. The specific productivity increases rapidly with a peak near the value of the critical velocity. At higher velocities the specific productivity drops off slowly. The jet drilling tool should be designed to operate at or above the critical velocity for maximum effectiveness.

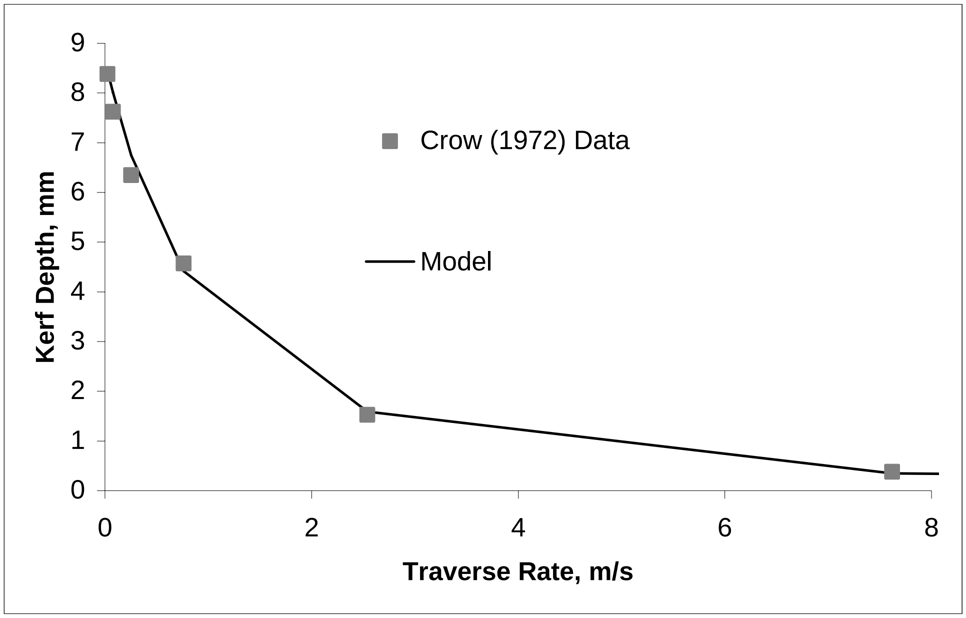

Figure 11. Effect of traverse rate on kerf depth in Wilkeson sandstone. (P_{th}=28 MPa, c_h=3.5 and v_c=1.9 m/s)

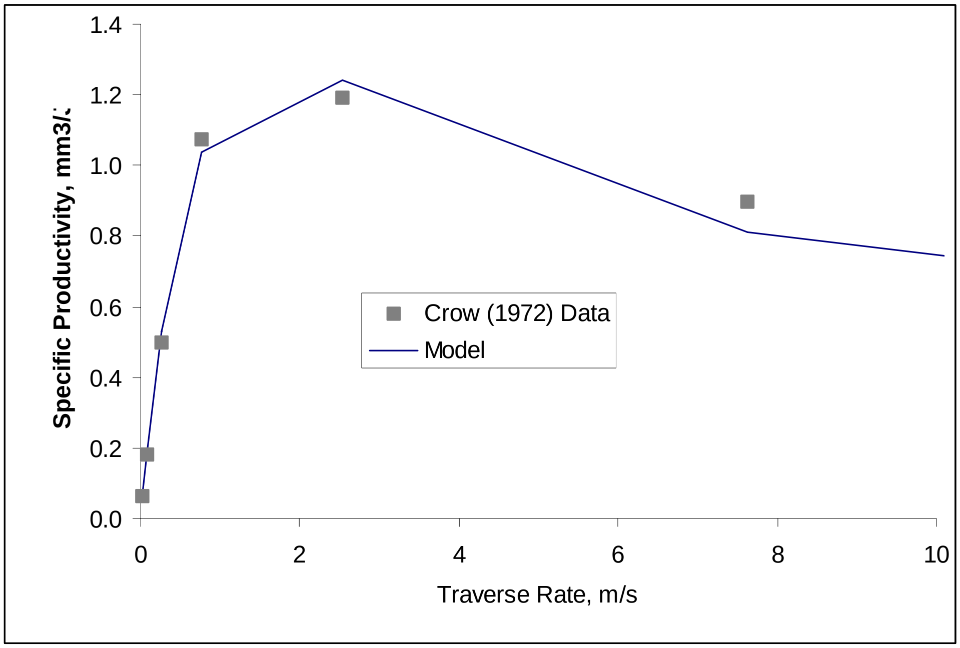

Figure 12. Effect of traverse rate on specific productivity in Wilkeson sandstone.

The downhole intensifier under development for this project will provide 70 MPa jets at 50 - 75 kW hydraulic power. The jet drilling tools can be designed to operate at around 2500 rpm which provides a traverse rate of 7.5 m/s on the circumference of a 57-mm diameter hole. This traverse rate is higher than the critical value for Crow's Wilkeson sandstone but still in the range where jet erosion is highly efficient. The threshold pressure and specific productivity data compiled in Table 2 was used to estimate high pressure jet drilling rates at 75 kW as shown in Figure 13. The drilling rates were corrected for rotary speed using equation 2. At 70 MPa jet pressure, the projected drilling rate averages 12 m/hr and ranges from 5 to 33 m/hr. Since most reservoir rock has substantially higher permeability than the samples tested, rates of penetration should be in the high end of this range in most cases. This was confirmed in the Tempress (2004) jet drilling test on permeable west Texas sandstone, which drilled a 28-mm hole at a rate of 137 m/hr with a 45 kW, 50,000 rpm jet drill.

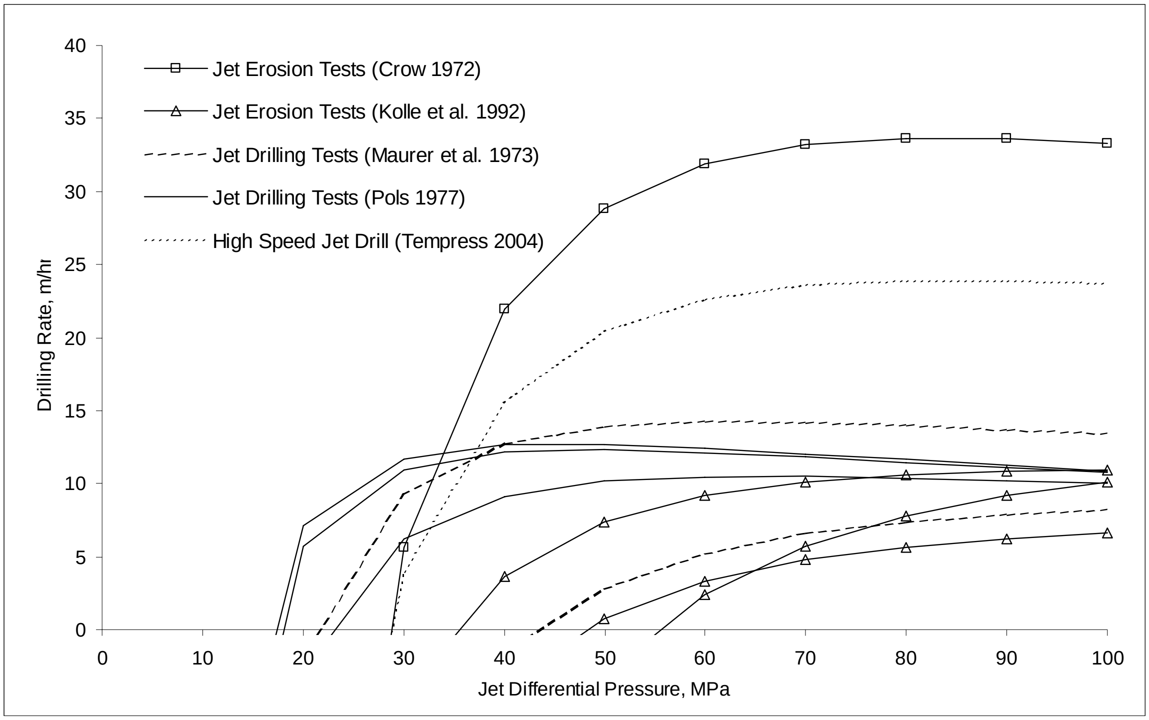

Figure 13. Relationship between jet differential pressure and predicted rate of penetration in a 89-mm diameter hole with a 75 kW jet drill operating at 2500 rpm.

Jet Dissipation Effects

Submerged, non-cavitating fluid jets are subject to rapid dissipation due to turbulent mixing of the fluid as illustrated in Figure 14. The maximum length of the submerged jet core produced by an ideal jet is just under seven nozzle diameters. Intense turbulence persists to a range of around 20 nozzle diameters. This relationship is predicted by boundary layer theory and has been confirmed experimentally by a variety of researchers. By contrast, water jets in air can be effective at ranges of over 1000 nozzle diameters. A comparison of jet velocity and stagnation pressure of water jets in air and submerged in water is shown in Figure 15. A jet discharged in air has an effective range that is one or two orders of magnitude greater than a submerged jet. Momentum transfer from the jet is proportional to the density of the dissipating medium. A model of shrouded jet range that assumes that pressure dissipates in proportion to the square root of the density of the ambient medium agrees reasonably well with the observations for air and water as shown in Figure 15. Under downhole conditions the gas is at higher pressure and has higher density so the effective jet range will be limited as shown in the figure. This model corresponds reasonably well with unpublished observations of jet shrouding.

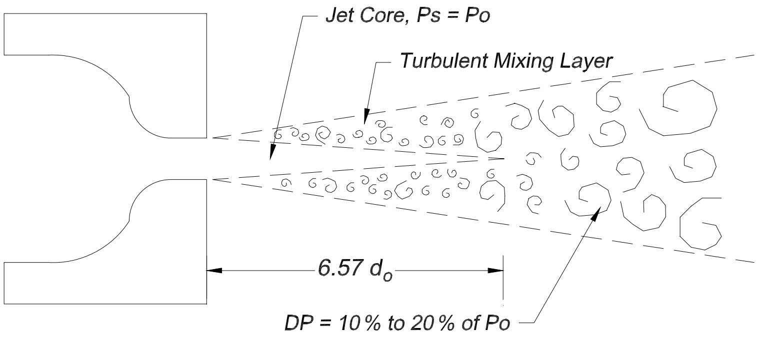

Figure 14. Turbulent dissipation of a non-cavitating jet[9].

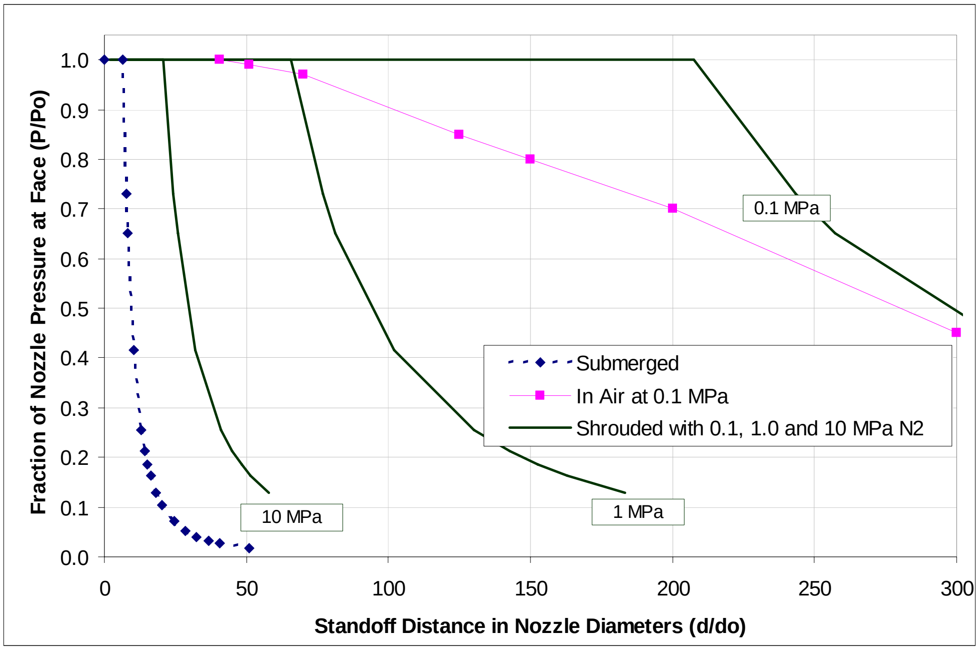

Figure 15. Dissipation of water jets in water, air[10] and effects of gas shrouding.

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[9] **Kolle, J.J., R. Otta and D.L. Stang (1991) "Laboratory and field testing of an ultra-high-pressure, jet assisted drilling system," SPE/IADC 22000.**

[10] **Yanaida, K and A. Ohashi (1980) "Flow characteristics of water jets in air,"** ***Fifth International Symposium on Jet Cutting Technology*****, Hanover, BHRA, Cranfield, Bedford, UK.**

Multiple Nozzle Head Design

The design of a jet-drilling rotor requires that the jets cut all of the rock face beneath the tool. As discussed above, the effective cutting range of a submerged, non-cavitating high-pressure water jet is limited by turbulent dissipation. Shrouding the jets with gas should increase the effective range but the limit is still determined by some multiple of the nozzle diameter. As illustrated in Figure 16, multiple smaller jets have a greater effective range than a single jet with the same total flow area and hydraulic power. This occurs because the hydraulic power is proportional to nozzle diameter squared while the range of the jets is proportional directly to nozzle diameter. The effective range increases as the square root of the number of jets so that four jets have twice the range of a single jet with the same flow area.

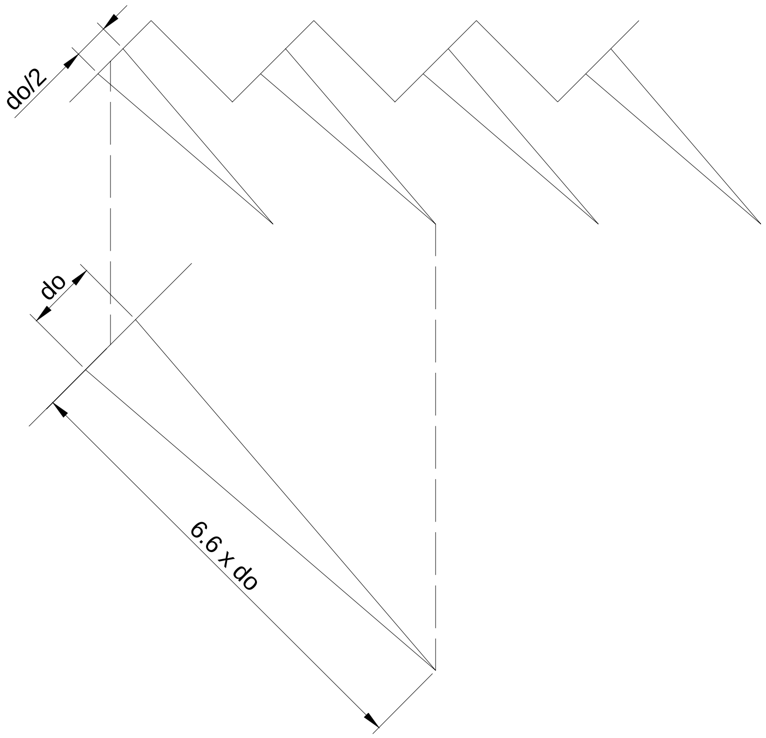

Figure 16. Four nozzles have twice the range of a single nozzle with the same total flow area.

In practice, the number of jets must be minimized to reduce fabrication costs. A practical design employs the minimum number of jets required to provide full coverage of the rock face given the hydraulic power available. The jets are oriented at the maximum practical angle from the hole axis to maximize the lateral range. Design of the jetting head also requires some assumption regarding the range of a shrouded jet. The range of a jet is

(6) $$R_o = 6.6 F_{shroud} \sin(\alpha) d_o \, .$$

where α is the inclination of the jet from the hole axis and F_{shroud} is a factor that accounts for the increased range of the jet due to shrouding. The total flow area is given by

$$TFA = N_o \frac{\pi}{4} d_o^2 , \tag{7}$$

where N_o is the number of nozzles. The flow area is related to the flow rate. A 50 kW, 70 MPa jet drilling nozzle head design with 8 nozzles is shown in Figure 17. The nozzle head incorporates a gage sleeve that prevents the tool from advancing until the gage is cut. This feature also controls overcut.

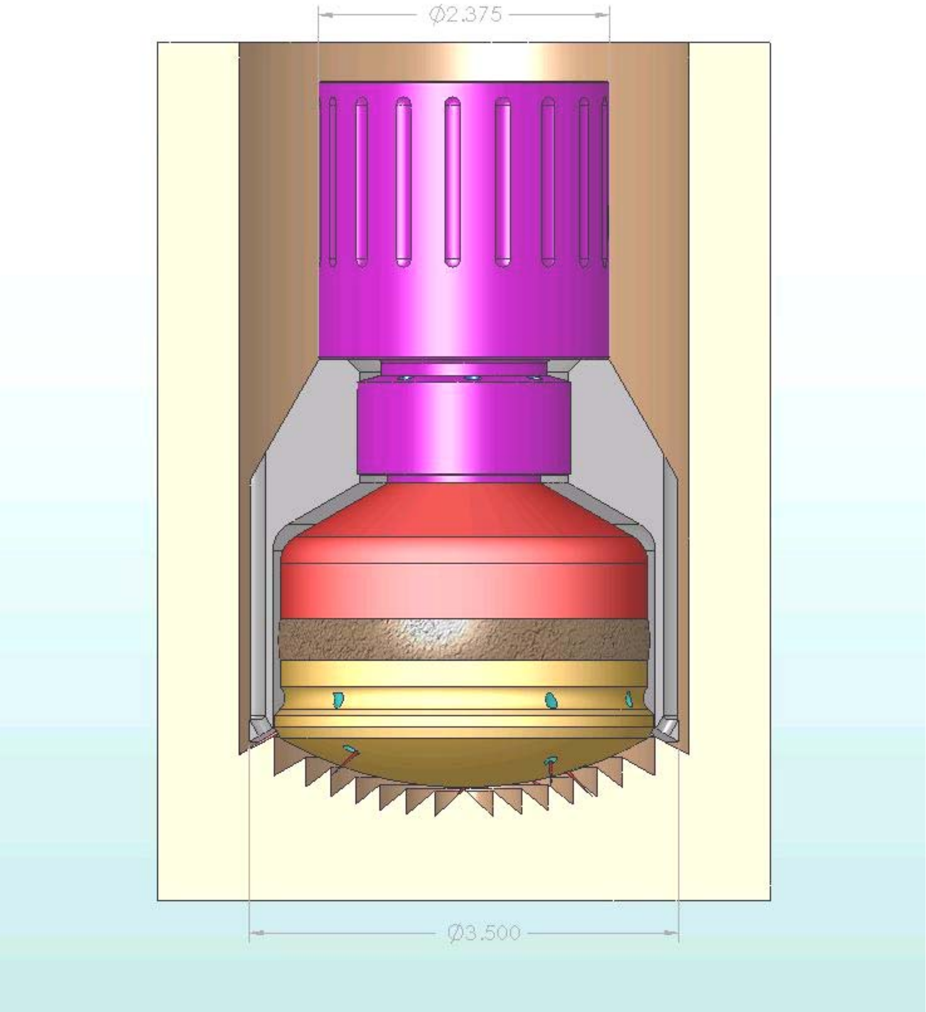

Figure 17. High-pressure jet drilling head with 8 nozzles.

Mechanically-Assisted Jet Drilling

Mechanically-assisted jet drilling places the DHI below a conventional PDM drill motor as illustrated in Figure 1. The pressure in the drilling fluid powers the intensifier. A mechanically-assisted jet bit as shown in Figure 18 incorporates high-pressure jets to cut the rock and mechanical cutters to cut the ridges of rock that remain. If the rock is too hard to cut with the jets, the mechanical cutters ensure that drilling continues. The mechanical cutting structure is designed for hard rock drilling and may incorporate surface-set cutters or small PDC cutters. Testing with a 70 MPa high-pressure jet drill with a jet power of 130 kW has demonstrated rate of penetration increases of a factor of five in sandstone and limestone[11]. The hydraulic power delivered to the bit face was also increased by a factor of five in these tests implying that the rate of penetration increase is proportional to power that can be delivered to the drill.

Figure 18 illustrates a dual-passage, high-pressure mechanically assisted jet bit. Fewer and larger nozzles are used than in the jet drilling bit shown in Figure 17. The high pressure nozzles are supplied with a separate high pressure tube connected to the intensifier. Low pressure ports for the gassy fluid are located to provide gas shrouding.

The mechanical power available from a small PDM is limited by both the torque capacity, which is proportional to the motor diameter, and the flow rate, which is proportional to diameter squared. Mechanical power capacity thus drops dramatically with motor size. Table 3 lists the motors investigated for this project. The maximum mechanical power capacity of a 2-3/8" motor is about 15 kW (20 hp). As summarized in Appendix A, it is possible to deliver up to 75 kW high-pressure jetting power in addition to the mechanical power available from the motors. This represents a five-fold increase in power at the bit face, which should provide a proportional increase in rate of penetration.

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[11] Cohen, J.H. C. Leitko and C.M. Hightower (2000) "High-pressure coiled tubing drilling motor," ETCE2000/Drill-10098, Proceedings of ETCE/OMAE Joint Conference, Feb 14-17, New Orleans, American Society of Mechanical Engineers.

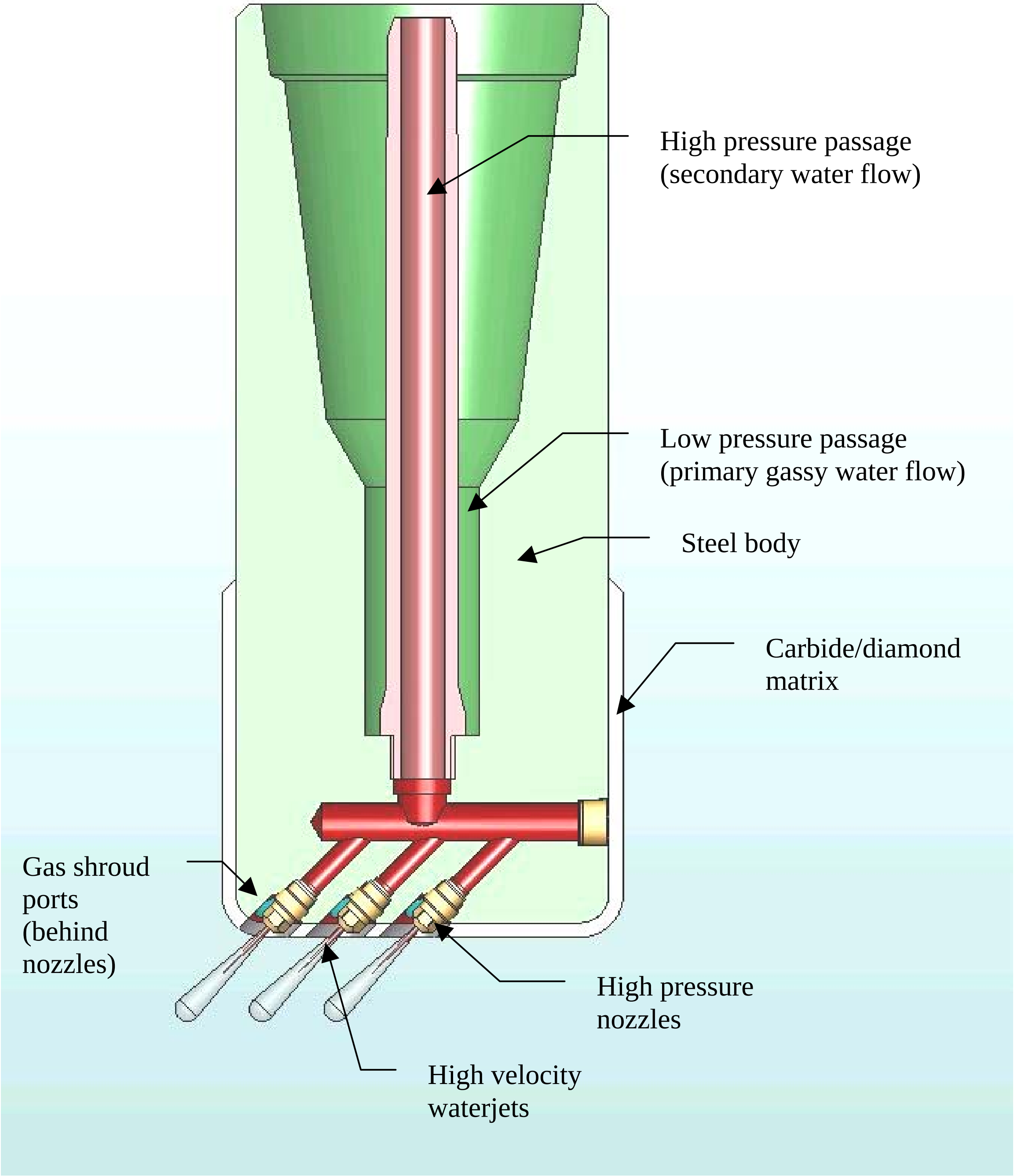

Figure 18. Mechanically-assisted jet bit.

Pressure Limitations of PDMs

Currently available PDM motors are not designed to operate on pressures above about 14 MPa (2000) psi, with most limited to 10 MPa (1500 psi). This is less than half the pressure required to run the intensifier at the power levels required for effective jetting. The main limitations of conventional PDMs are the seals, bearings and coupling shaft. It is possible to modify motors to run on water at 28 MPa (4000 psi) or higher using heavy-duty bearings and seals and a flexible coupling shaft. For example Cohen et al (2000)[6] discuss operation of a PDM at 70 MPa (10,000 psi).

Two basic types of PDM bearing assemblies are available, mud lubricated and sealed. Mud lubricated bearings use a portion of the drilling fluid to cool and lubricate multiple rows of angular contact ball bearings. These are simple and inexpensive but subject to rapid wear from drilling fluids. The pressure is contained by carbide lined annular clearance seals. Most motor manufacturers currently have at least some PDMs using this configuration. High pressure operation causes additional leakage through these seal passages and rapid erosive wear. High pressure in the motor also imposes additional thrust loads on the bearings leading to premature wear and loss of power.

The other basic type of PDM bearing is the sealed bearing package as used in many National Oilwell, Varco and Weatherford thru-tubing motors. These use oil or grease lubricated roller and/or angular contact ball bearings to carry thrust and radial loads. The seals must keep the lubricant in and the cuttings out. Since the seals are packed at surface ambient pressure, these seal packages often incorporate an annular compensator piston that balances the lubricant pressure with the drilling fluid pressure in the motor. The bottom seal must deal with the entire pressure difference from internal to external. In some National Oilwell motors, a bleed port and clearance seal are added to reduce that pressure differential. Small CAVO motors use graphite rope packing to seal the bearings with no pressure compensator or clearance seals. The ball bearings remain at surface ambient pressure. This simple solution is often good enough for CAVO's targeted well service applications. ThruTubing Solutions uses a sealed thrust washer bearing package that is said to be more resistant to impact from jarring tools. Sealed bearings are still subject to the extra pressure load imposed by high pressure motor operations.

The seal designs on commercially available PDMS will not provide the pressure capacity required for the downhole intensifier application.

Nitrogen Compatibility

Tempress surveyed 16 motor suppliers to evaluate nitrogen compatibility and performance characteristics of small-diameter motors that are suitable for microhole drilling. The results are summarized in Table 3. A number of these motors are specifically rated for nitrogen service. The nitrogen rated motors typically have a larger clearance between stator and rotor to allow for swelling of the elastomeric stator in the presence of nitrogen. The primary issues related to motor reliability with nitrogen are (1) overspeed of the motor when off-bottom and (2) increased vibrational loading because gas in the annulus reduces dampening.

The presence of gas makes PDM speed hard to control and monitor from the surface. If the bit stalls, the pressure change is difficult or impossible to detect on standpipe instruments due to the compressibility of the gas in the coiled tubing. When the bit releases, the motor will likely overspeed due to the stored energy in the gas. This also causes excessive vibration and damage to the BHA. With a downhole intensifier in series with the motor, the dangers of overspeed will be greatly reduced. Flow to the motor cannot rapidly increase as long as the intensifier is also using that flow to pressurize the degassed water.

Table 3. Survey of Microhole motors and steering tools.

Microhole

Survey of Supporting Technology

Key: good | less good | bad

Manufacturer	*Model*	*Type*	*Closest Sizes*	*Lobes*	*Stages*	*Max Power @ 40 gpm (water)*	*Differential Press*	*Speed*	*Sealed bearing?*	*Flex drive shaft?*	*Bent bearing housing?*	*Uniform rubber thickness?*	*Rated for N2?*	*Bore rotor? (alt config)*	*Sell compete motor?*	*Comments*
Downhole Motors			(inch)			(hp)	(psi)	(rpm)								
Baker Hughes	Navi-Drill X-treme AD	Moineau	2.125				1015	300	no		yes	yes	yes			AD = air drill
Baker Hughes	Navi-Drill X-treme	Moineau	2.375	5/6			905		no		yes	yes	yes			
BICO/Kaechele	SpiroStar SS100	Moineau	1.688	5/6	2.3	9.4	588	300	no[1]		yes	yes	yes		yes	@ 30 gpm
BICO/Kaechele	SpiroStar SS150	Moineau	2.875	5/6	3.5	9.1	885	90	no[1]		yes	yes	yes	yes	yes	@ 60 gpm
BICO	P150 Flex Drill	Moineau	2.375	7/8	2.5	5.5	300	230	no[1]		yes	no		yes	yes	
BICO	P360 Flex Drill	Moineau	2.375	1/2	7.0	17.0	950	850	no[1]		yes	no		yes	yes	
CAVO	4L-206-7	Moineau	2.062	4/5	7.0	24.1	1050	550	yes	yes	yes	no	yes	no	yes	$14,500
CAVO	5L-206-3	Moineau	2.062	5/6	3.0	5.0	450	160	yes	yes	yes	no	yes	no	yes	
Computalog (Precision)	Commander	Moineau	4.750	out of range												
Cougar Tool	Cougar	Moineau	2.875	2/3	7.0	13.0	960	360			yes	no		yes		
Cougar Tool	Cougar	Moineau	2.875	5/6	3.3	6.5	515	170			yes	no		yes		
Drill Motor Services	Standard	Moineau	1.688	5/6	2.3	11.0										
Drill Motor Services	Standard	Moineau	3.500	out of range												
Hailey Specialty Tools		Moineau														
Horizontal Tech	Vector/Trudril	Moineau	2.875	out of range												
Intn'l Dir Services	Accu-Drill 238 HS	Moineau	2.375	1/2	7.0	10.0	800	800				no				est performance
Intn'l Dir Services	Accu-Drill 238 MS	Moineau	2.375	5/6	2.5	7.4	400	300				no				est performance
National Oilwell Varco[2]	Standard	Moineau	2.125	5/6	6.0	19.4	780	600	yes		yes	no				est performance
National Oilwell Varco[2]	Standard	Moineau	2.375	1/2	7.0	19.9	910	1100	yes		yes	no				est performance
National Oilwell Varco[2]	Standard	Moineau	2.375	5/6	5.2	14.3	680	300	yes		yes	no				est performance
Schlumberger	PowerPak A213XP	Moineau	2.125	5/6	6	12.4	700	450	no		yes	no		no		XP = longer motor
Schlumberger	PowerPak A238	Moineau	2.375	5/6	2.5	4.5	245	270	no		yes	no		no		better fit in bend
Schlumberger	PowerPak A238XP	Moineau	2.375	5/6	5.2	10.9	570	285	no		yes	no		no		XP = longer motor
Smith Neyrfor	T2MK2	Turbine	2.875	-	-	110	1800	3000?			yes	-	yes			1500 scfm N2 + 20 gpm H2O
Thru Tubing Solutions	Titan	Moineau	2.125						yes			no	yes	no		non-rolling thrust bearing
Weatherford	CTD	Moineau	2.375	5/6	5.6	8.1	900	225	yes	yes?	no	no			no	
Weatherford	CTD	Moineau	2.125	5/6	5.8	10.2	348?	255	yes	yes?	no	no			no	
Weatherford	MacDrill	vane	2.125	-	-	19.9	2200	950	yes?		no	-	yes			
Wellco			4.75?	out of range												
Wenzel	Air/Nitrogen Power	Moineau	2.375	4/5	2	5.7		300	yes				yes			est performance
Rotor/Stators Only																
Dyna-Drill	DD287562.6	Moineau	2.875	5/6	2.6	4.2	390	55	no			no				
R&M Energy	475ERT4536	Moineau	4.750	out of range					-		-	yes		yes		
R&M Energy	238M1270 UF114	Moineau	2.375	1/2	7.0	19.7	1040	900	-		-	no		yes		$3,092
R&M Energy	238M5652 UF114	Moineau	2.375	5/6	5.2	15.7	900	250	-		-	no		yes		$8,732
Roper Pumps	238R1270	Moineau	2.375	1/2												
Roper Pumps	238R4560	Moineau	2.375	4/5												
Orienter Steering Systems																
AnTech	COLT	w/bent sub motor									yes					
Baker Hughes INTEQ	TinyTrak	w/flex subs & motor	2.375													
Baker Hughes INTEQ	CoilTrak	w/bent sub motor	2.375								yes					
Baker Hughes INTEQ	OrientXpress	w/bent sub motor	3.125	out of range					yes		yes					
Schlumberger	VIPER BHA	w/bent sub motor	2.875	out of range							yes		yes			
Schlumberger	SlimPulse BHA	w/bent sub motor	1.75								yes		yes			
Motor Steering Systems																
Baker Hughes INTEQ	VertiTrak	rib steer, push bit	6.75	out of range												
Baker Hughes INTEQ	**Microhole**	rib steer, push bit	2.375										yes			similar to VertiTrak
National Oilwell Varco	Hemi-Drill	rib steer, push bit?										yes?				
Motorless Rotary Steering Systems (RSS)																
Baker Hughes	AutoTrak	push-the-bit	4.75	out of range												
Halliburton	GeoPilot															
Precision Drilling	Revolution	point-the bit	4.75	out of range												
Pathfinder	3D RS	point-the bit	11.71	out of range												
Schlumberger	PowerDrive	push-the-bit	4.75	out of range												
National	Hemi-Drill															

Footnotes

[1] BICO plans sealed bearing motors in future that could raise pressure rating.

[2] National Oilwell Varco also supplies sealed bearing & drive shaft assemblies to build your own motor.

Directional Drilling Considerations

Mechanically-Assisted Jet Steering

There are operational challenges with locating the motor above the downhole intensifier. In particular, the distance from the bit to the bend in the motor housing is increased by the length of the intensifier. This reduces the possible dogleg severity (DLS) and makes short radius directional changes more difficult. In addition, the intensifier requires that the motor and steering tools operate at higher internal pressures than is customary.

Jet Steering

Jet drilling tools do not require side thrust to initiate changes of direction. Jet drilling heads utilize an enhanced form of point-the-bit steering. Since the jets cut ahead of the bit, a jet drilling tool with a bent housing preferentially enlarges the borehole on one side. The tool advances in the direction cleared by the jets. This technique has been used for many years to create horizontal directionally controlled micro-tunnels in soil for installation of underground utilities. This technique may enable side-tracks to be created from existing boreholes by pausing and jetting in the desired direction as selected by an orienter. It may then be possible for the bent jet drilling BHA to create a side-track without whipstocks or special side-track-finding tools.

Fluid jet drilling direction is influenced by variations in hardness of the formation. Fluid jets preferentially cut the softer material causing the drill to deflect in that direction. This effect allows geosteering in high permeability oil or gas producing zones or for coal bed methane extraction. In these cases, the tool is more likely to stay within the producing formation rather than drill out of it.

Dogleg Severity

Bent-housing motors create curved boreholes during oriented slide-drilling. To drill straight, the bent-housing motor must be rotated slowly by an orienter since coiled tubing cannot be rotated. The motor housing must bend in the opposite direction as it rotates through the angle build sections. The bending stress must not exceed the yield strength of the motor housing to prevent permanent damage to the motor. Figure 19 shows the maximum dogleg severity (DLS) possible with various bottomhole assembly diameters and lengths in a 3-1/2” borehole. The maximum allowable bending stress is held to half of the yield strength of steel commonly used in sour wells. For the purposes of this comparison, the BHA is considered to be straight and centralized at the upper and lower ends by a stabilizer and a bit respectively.

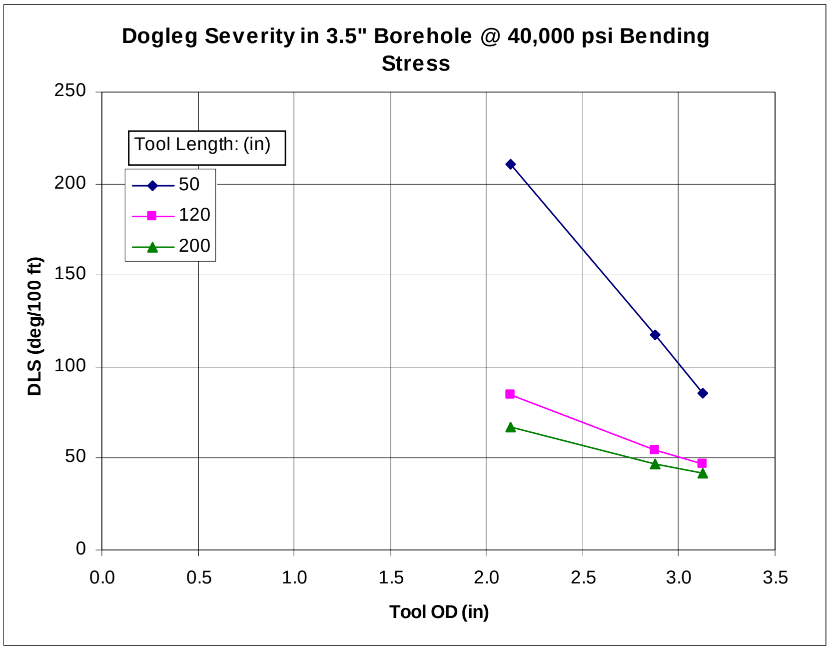

Figure 19. Effect of BHA tool diameter and length on acceptable dogleg severity

A typical 2-3/8” PDM can be 120” long. With motor head and orienter, the length can be 200” or more. The maximum DLS for this tool would be about 60º/100’. The mechanically-assisted jet BHA shown in Figure 1 has a DLS of only 10º/100’. These tools would not be suitable for drilling the curve section of the hole. The jet drilling BHA would be about 50” long and have an acceptable DLS of over 200º/100’. The jet drilling configuration can drill a curve with a radius of under 50’ allowing the tool to stay within a producing formation.

Simply by changing the adapter between the downhole intensifier and the jet drill, the tool can be converted from straighthole drilling to directional drilling. The adapter can be either straight or bent. An adjustable bent adapter is possible but beyond the scope of this project. Since the adapter is easily replaced, it may be better to have several adapters with different bend angles available while drilling. Since jet drilling requires almost no torque, hole straightness will be improved over PDM mechanical drilling.

Extended Reach Drilling

Both jet drilling approaches under development in this project will extend the reach of coiled tubing drilling by reducing the mechanical load required to drill. Figure 20 illustrates an analysis of coiled tubing lockup in a horizontal well using CoilCadE. Note that by reducing the thrust load from 2000 lbf (900 daN) for conventional mechanical drilling[12] to zero for jet drilling, the horizontal reach can be extended from about 1700 m to 2200 m, a 500 m (1600 ft) improvement.

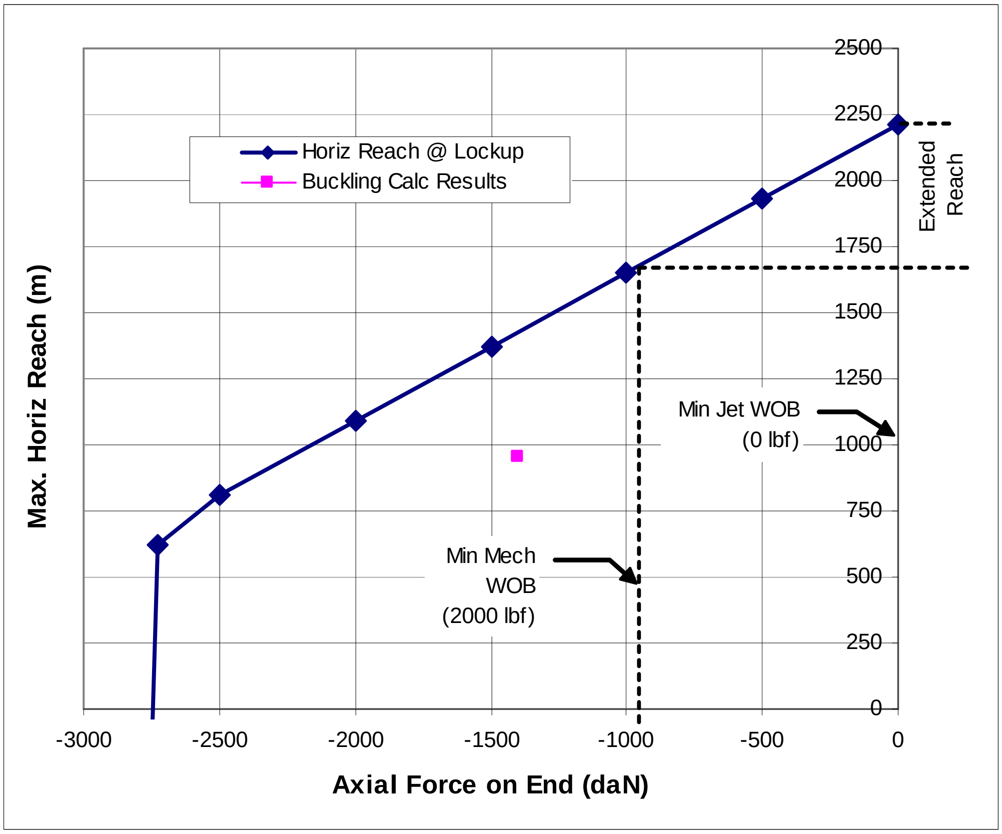

Figure 20. Horizontal reach at lockup due to helical buckling.

Conclusions

An analysis of high-pressure jet drilling and mechanically-assisted jet drilling was carried out to determine design specifications for the downhole intensifier and to determine the BHA components that will be required. A downhole intensifier model was coupled with a coiled tubing drilling circulation model to determine the nominal operating parameters. The analysis showed that flow rates and surface pressures are compatible with current coiled tubing drilling practices. Two-phase flow or

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[12] **http://www.oilfield.slb.com/media/services/resources/oilfieldreview/ors92/0792/p45_51.pdf**

clear water flow at the proposed rates will provide turbulent transport of cuttings in both the vertical and horizontal sections of the hole.

A review of jet drilling data shows that 70 MPa jets will allow high-pressure jet drilling at economic rates in conventional, non-fractured, oil and gas producing formations. The same jet pressure will allow mechanically-assisted jet drilling in a broader range of formations.

High-Pressure Jet Drilling

High-pressure jet drilling uses a compact BHA that will allow drilling of short radius laterals. The jet drilling head is easier to steer than a mechanical drilling head and requires nominal thrust for extended reach drilling. High-pressure jets preferentially cut the softer material ahead of the bit allowing the jet drilling tool to geosteer within producing formation. For example, the tool could be provided with a slight build tendency to track along the top of the producing formation. This approach will be limited to drilling lateral wells within conventional oil and gas producing zones with high matrix permeability.

Mechanically-Assisted Jet Drilling

The DHI can also be configured for mechanically-assisted jet drilling with a PDM. Mechanically-assisted jet drilling should increase drilling rates with small motors by a factor of five and increase the lateral reach of the drill by about 25%. The DHI will reduce bit vibration by reducing cutter loads and the intensifier hydraulics will limit overspeed of the motor when operating on two-phase flow.

Mechanically-assisted jet drilling requires development and operation of specialized high-pressure motors. The motor will be placed above DHI to limit the required motor operating pressure and to reduce motor complexity. In this configuration, the PDM operating pressure must be around 28 MPa (4000 psi) to generate 70 MPa (10,000 psi) jets. The required PDM operating pressure is more than twice the pressure rating of existing motors. This configuration also extends the BHA length and reduces steerability.

Appendix A: Design Brief

1. Performance Requirements

The following performance requirements are taken from the U.S. Department of Energy, National Energy Technology Laboratory (NETL), Microhole Technology Development II solicitation number DE-PS26-04NT15480-00:

- Borehole diameter: 3.50” (89 mm)
- Minimum depth: 2000 ft (610 m)
- Maximum depth: 5000 ft (1524 m)
- Minimum lateral offset: 1000 ft (305 m)
- Well location: United States

2. Design Operating Conditions

Three hypothetical cases are considered which cover a wide range of applications:

- **Case 1**: 2000 ft vertical depth, 1000 ft horizontal lateral
- **Case 2**: 3500 ft vertical depth, 1500 ft horizontal lateral
- **Case 3**: 5000 ft vertical depth, 2000 ft horizontal lateral

For analysis purposes, the borehole consists of the following:

- Casing: 5”, 13 lb/ft to kick-off depth
- Open hole: 3.5” below kick-off depth
- Dog-leg severity: 25 deg/100 ft (50 deg/100 ft maximum)

Interface Requirements

The jet drilling tool is part of a complete coiled tubing drilling system. The following system characteristics are assumed for this project:

- Drilling fluid: water plus nitrogen (underbalanced)
- Filtration: 100 microns
- Optional additives: solvents (diesel, xylene, terpenes), and friction reducers (polymers)
- Standpipe pressure: 4000 psi (28 MPa)
- Water flow: 26-55 gpm (105-210 lpm) depending upon design case and configuration
- Nominal gas flow: 353 scfm (10 scmm)

- Coiled tubing size: 2.00” OD (51 mm) by 0.188” (4.8 mm) wall
- Coiled tubing material: QT-800 (80,000 psi yield strength)
- Coiled tubing length: 8000 ft (2438 m)

Configuration Options

Two bottomhole assembly configurations will be developed. The first is a pure waterjet drill with minimal mechanical cutting ability. High pressure fluid jets provide 100% of the cutting. The second is a mechanically assisted jet drill. Fluid jets provide the primary cutting energy and a mechanical bit rotated by a downhole motor cuts sections that resist jet erosion. When the jets are cutting, motor pressure drop is minimal. When jets are unable to cut, motor pressure drop increases to maximum. In both configurations, the waterjet is shrouded by gassy flow to improve jet cutting range. The following table summarizes these configurations.

Feature	Pure Waterjet Drill	Mech. Assist Jet Drill
Drilling head (bit)	Multiple nozzle head with gas shroud ports	Diamond bit with high pressure jet nozzles and gas shroud ports
Drill head rotation	Jet thrust	Downhole motor
Intensification	Downhole intensifier	Downhole intensifier
Separation	Downhole gas separator	Downhole gas separator

3. Common Bottomhole Assembly Requirements

The following requirements are common to both bottomhole assembly configurations.

General Requirements

- Nominal tool outside diameter: 2.38” (60 mm)
- Overall length: to be determined
- Magnetic: OK
- Proof pressure: 1.5 times nominal operating pressures
- Reliability goal: 72 hours between maintenance
- Last chance screen: 200 micron

Environmental Requirements

- Corrosion: H_2S present
- Temperature: 32 to 300º F (0-150º C)

- Tolerant of ledges and edges in production tubing or casing

Gas Separator Requirements

- Purpose: Separate mixed nitrogen and water inlet flow into primary and secondary outlet streams
- Maximum inlet pressures (above ambient): 32 MPa (4700 psi)
- Inlet flow rates: 138-248 lpm (36-66 gpm)
- Inlet gas fraction (at inlet pressure): 10-25% (by volume)
- Primary outlet stream gas fraction (at pressure): 21-32% (by volume)
- Secondary outlet stream gas fraction: <1% (volume)
- Upper connection: to suit coiled tubing connector or optional steering tool (by others)
- Lower connection: dual passage, to suit downhole intensifier inlet

Intensifier Requirements

- Purpose: Use energy in primary stream to boost pressure of secondary stream
- Overall length: <5 ft (1.5 m)
- Theoretical intensification ratio: 3.29:1 (subject to revision)
- Maximum inlet pressures (above ambient): 32 MPa (4700 psi)
- Primary inlet: water only, gas only, or gas and water mixture
- Secondary inlet: water with <1% gas (by volume)
- Primary discharge pressure (above ambient): at least 0.5 MPa (70 psi)
- Secondary discharge pressure (above ambient, no motor load): at least 70 MPa (10,000 psi)
- Upper connection: dual passage, to suit gas separator
- Lower connection: dual passage, to suit jet rotor or jet bit (as required)

4. Mechanical Assist Jet Drill Requirements

The following requirements apply specifically to the mechanical assist jet bit configuration.

Downhole Motor Requirements

- Purpose: to provide mechanical rotation and torque for drilling
- Type: positive displacement, progressive cavity
- Steerability: optional bent axis bearing housing
- Length (with bearings): <10 ft (3.0 m)
- Speed: 500-1000 rpm

- Inlet flow rate: 120-250 lpm (32-66 gpm)
- Maximum torque: 157 N-m (116 ft-lb)
- Maximum pressure drop through motor: 7.1 MPa (1030 psi)
- Maximum internal pressure rating (above ambient): 5100 psi (35 MPa)
- Bearings: sealed, grease/oil lubricated, pressure compensated

Bit

- Purpose:
  1. mechanically drill rock that waterjets are unable to cut efficiently
  2. convert secondary fluid pressure into high velocity jets
  3. conduct primary flow to location adjacent to jet nozzles for shrouding jets
- Type: diamond, surface set or impregnated (to be determined)
- Body material: steel
- Bit diameter: 3.50” (89 mm)
- Connection: 2-3/8” API REG
- Gender: Pin up or box up (to be determined)
- Primary circuit inlet pressure (above ambient): 0.5 MPa (75 psi)
- Average secondary circuit inlet pressure (above ambient): 71 MPa (10,300 psi)
- Maximum secondary circuit inlet pressure (above ambient): 91 MPa (13,200 psi)

5. Pure Waterjet Drill Requirements

The following requirements apply specifically to the pure waterjet drill bottomhole assembly configuration.

Jet Rotor

- Purpose:
  1. conduct secondary flow from intensifier to nozzle head
  2. conduct primary discharge flow from intensifier to gas shroud ports
  3. allow rotation of the waterjet nozzle head
  4. limit maximum rotation speed
- Primary circuit inlet pressure (above ambient): 0.5 MPa (75 psi)
- Average secondary circuit inlet pressure (above ambient): 71 MPa (10,300 psi)
- Maximum secondary circuit inlet pressure (above ambient): 91 MPa (13,200 psi)

- Rotation speed: 2000-5000 rpm
- Connection: dual passage 1-1//2” (custom)

Nozzle Head

- Purpose:
    1. convert intensified secondary fluid pressure into high velocity jets
    2. conduct gassy primary flow to locations adjacent to jet nozzles to shroud jets
    3. use jet reaction thrust to rotate the jet rotor
    4. Estimated jet core reach: 13 times nozzle orifice diameter (with gas shroud)
- Jet core coverage diameter: 89 mm (3.5”)
- Pressures: same as jet rotor
- Secondary separation: Shroud gas flow taken from lowest density location in primary passage

Predicted Performance

Table 4 lists the expected downhole assembly performance predictions for each configuration. The results are predictions based on Tempress’ numerical computer models for borehole circulation and downhole intensifier performance using the operating parameters for the three cases described above and preliminary tool geometry. The predictions will be updated as the design develops.

Table 4 Downhole Intensifier Performance Predictions

Constants			
Pump press (surf)	*MPa*	28.0	(hold)
	psi	4060	
Gas flow (surf)	*scmm*	10	(hold)
	scfm	353	
Intensifier Piston Diameter	*mm*	25.4	
	in	1.00	
Intensifier Stroke	*mm*	155	
	in	6.10	
Intensifier Area Ratio	*:1*	3.29	

Variables		Mechanical Assist Jet Drill						Pure Waterjet Drill		
Case		**1**		**2**		**3**		**1**	**2**	**3**
Tool Depth	*m*	610		1067		1524		610	1067	1524
	ft	2000		3500		5000		2000	3500	5000
Lateral Offset	*m*	305		457		610		305	457	610
	ft	1000		1500		2000		1000	1500	2000
Mechanical Load on Bit		Min	Max	Min	Max	Min	Max	-	-	-
Water Pump Flow (surf)	*lpm*	122	100	165	140	207	175	124	167	210
	gpm	32	26	44	37	55	46	33	44	55
Total Flow @ end of coil	*lpm*	161	138	203	177	245	212	163	205	248
	gpm	42	36	54	47	65	56	43	54	66
Press @ end of coil (abv amb)	*MPa*	29.9	30.4	31.9	32.7	32.7	34.4	29.9	31.8	32.6
	psi	4340	4408	4626	4742	4747	4988	4333	4614	4722
Downhole Ambient Pressure	*MPa*	1.0	0.8	2.0	1.7	4.2	3.4	1.0	2.0	4.2
	psi	138	122	284	241	605	486	140	289	615
Motor Differential Pressure	*MPa*	0.3	7.1	0.3	7.1	0.3	7.1	-	-	-
	psi	49	1030	49	1030	49	1030	-	-	-
Motor Speed	*rpm*	1100	800	1425	1090	1700	1300	-	-	-
Motor Torque	ft-lb	0	116	0	116	0	116	-	-	-
	N-m	0	157	0	157	0	157	-	-	-
Motor Power	*kW*	0.0	13.2	0.0	17.9	0.0	21.4	0.0	0.0	0.0
	bhp	0.0	17.7	0.0	24.1	0.0	28.7	0.0	0.0	0.0
Intensifier Inlet Pressure	*MPa*	29.3	22.9	31.1	25.2	32.0	26.9	29.5	31.4	32.2
	psi	4249	3321	4510	3654	4640	3893	4278	4557	4669
Intensifier Cycle Rate	*Hz*	13.3	11.9	16.5	14.9	19.2	17.6	13.3	16.7	19.4
Nozzle Flow	*lpm*	43	38	54	48	63	57	43	55	63
	gpm	11	10	14	13	17	15	11	14	17
Nozzle press (abv amb)	*MPa*	70.5	54.4	70.7	56.1	70.0	57.1	70.5	70.6	70.5
	psi	10,223	7,888	10,252	8,135	10,150	8,280	10,223	10,237	10,223
Nozzle Quantity		3		3		3		8	8	8
Nozzle diameter	*mm*	0.97		1.09		1.17		0.60	0.67	0.72
	in	0.0383		0.0427		0.0461		0.0234	0.0263	0.0283
Nozzle Total Flow Area	*mm*^{2}	2.23		2.77		3.23		2.23	2.81	3.26
	in^2	0.00345		0.00430		0.00500		0.00345	0.00435	0.00505
Jet power	*kW*	50.1	34.4	63.2	45.0	72.9	53.9	50.5	64.1	74.5
	hhp	67.3	46.2	84.8	60.4	97.9	72.3	67.8	86.0	100.0
Total Power Delivered to Bit or Nozzle Head	*kW*	50.1	47.6	63.2	62.9	72.9	75.3	50.5	64.1	74.5
	hp	67.3	63.8	84.8	84.5	97.9	101.1	67.8	86.0	100.0