Advanced Mud System
for
Microhole Coiled Tubing Drilling

Final Technical Report

Performance Period: 8/2/04 to 12/1/08

Principal Investigator:
Kenneth D. Oglesby, P.E.

Report Issued Date: 16 March 2009
DOE Award No.: DE-FC26-04NT15476

Submitting Organization:

IMPACT Technologies LLC
PO Box 35505, Tulsa, OK 74153-0505

DISCLAIMER

ABSTRACT

An advanced mud system was designed and key components were built that augment a coiled tubing drilling (CTD) rig that is designed specifically to drill microholes (less than 4" diameter) with advanced drilling techniques. The mud system was tailored to the hydraulics of the hole geometries and rig characteristics required for microholes and is capable of mixing and circulating mud and removing solids while being self contained and having zero discharge capability. Key components of this system are two modified triplex mud pumps (High Pressure Slurry Pumps) for advanced Abrasive Slurry Jetting (ASJ) and a modified Gas-Liquid-Solid (GLS) Separator for well control, flow return and initial processing.

The system developed also includes an additional component of an advanced version of ASJ which allows cutting through most all materials encountered in oil and gas wells including steel, cement, and all rock types. It includes new fluids and new ASJ nozzles. The jetting mechanism does not require rotation of the bottom hole assembly or drill string, which is essential for use with Coiled Tubing (CT). It also has low reactive forces acting on the CT and generates cuttings small enough to be easily cleaned from the well bore, which is important in horizontal drilling.

These cutting and mud processing components and capabilities compliment the concepts put forth by DOE for microhole coiled tubing drilling (MHTCTD) and should help insure the reality of drilling small diameter holes quickly and inexpensively with a minimal environmental footprint and that is efficient, compact and portable. Other components (site liners, sump and transfer pumps, stacked shakers, filter membranes, etc..) of the overall mud system were identified as readily available in industry and will not be purchased until we are ready to drill a specific well.

TABLE OF CONTENTS

LIST OF GRAPHICAL MATERIALS

19. HPSP First Prototype under modifications after Test.

20. Compact Mud Processing Unit, from TriFlow International

21. Kemtron Compact Separation Unit (no tank)

Additional Figures for MST's work are included in Appendix C.

Table 1 Hydraulic Model- Pump Rates versus StandPipe Pressures by Case (with Figure 7)

INTRODUCTION

Traditionally, the oil and gas industry had drilled large diameter (6-1/4 thru 13-3/8 inches diameters and more) holes with rigs and equipment that are big, heavy and expensive to operate and maintain. They are based on 1950s technology, with only some modifications such as PDC bits and better hydraulics (ie higher pump pressures and rates). They follow the 'crush and grind' method of making and cleaning new hole. That method requires heavy pipe to create the weight (force) on the bit and high torque for the rotary action to stress and relieve the rock into chips. The newer bits require less weight on bit and higher rotation speeds. The pumped mud (water and occasionally diesel/oil with chemicals) provides cooling to the bit and a way to clean drilled cuttings out of the hole to the surface. Rig sizes are very large and normally require more than 10 truck loads to move (some newer rigs require less loads) to the next well. Mud system volumes are typically thousands of barrels. The required surface location of such rigs is on the order of 5-20 acres.

The industry has moved slightly toward 'slimhole' drilling, which is typically considered anything less than 6-1/4" down to and including 4-3/4" diameter bits. These are most typically used for directional or horizontal wells or where the hole or set casing conditions require smaller sizes.

Conversely, Micro-hole sized drilling offers operators the potential to drill wells less expensively allowing a way to acquire geological or geophysical data, or develop reserves that might otherwise go untested. Microhole sizes are typically considered 4" diameter and less with a goal of 1" diameter for some applications. The relative sizes of the diameters discussed are shown in Figure 1 (taken after DOE). Such smaller holes require less mud volume, less chemicals, less materials to build, operate and maintain the rig, less disposal of drill cuttings and less energy to drill. The total system mud volume can be less than 200 bbls, even down to 50 bbls. The 'mud' fluids must be specialized or at least a tailored premium mud due to the reduced clearances in the hole and hydraulic concerns.

The corresponding rig to drill microholes will be smaller, lighter, more portable, and have a significantly smaller environmental footprint than conventional rigs. The surface location size can be down to about 1 acre. Such a small rig can be heliportable or, at least, take only 2 to 3 truck load to move. This will allow access to areas that were previously too environmentally sensitive or remote. Microhole drilling could truly be the quantum shift needed in drilling methods in order to drill more wells for less investment, access portions of reservoirs that would otherwise never be produced, and move the U.S. toward less dependency on foreign energy.

A natural addition to microhole drilling is the use of coiled tubing (CT, continuous coiled pipe) for the drilling process. This is especially true for use with the advanced drilling techniques discussed in this research. Such Coiled Tubing Drilling (CTD) is being done in Canada and on the north slope of Alaska. Such a proposed 1st generation hybrid conventional mast and CT rig is shown in Figure 2. This example type is a hybrid combination of a traditional rig utilizing a mast for handling jointed pipe with coiled tubing and it is not a true CTD rig.

DOE NETL and the Los Alamos National Laboratory (LANL) developed their Microhole Rig (trailer mounted rig shown in Figure 3 (coil and hydraulics unit trailer only)) to test the microhole drilling premise. The mud trailer is not shown. This effort used conventional bits, mud pumps and 1” coiled tubing to drill down to about 1400 feet in multiple areas. This work showed that such holes can be drilled, but with problems identified. In particular, the high flow rates needed for conventional mud pumps to generate sufficient torque to drill with the bit eroded the hole, caused slow drilling and created hole problems. Harder rock could not be efficiently drilled. Cleaning or removing the solids built up from the used mud proved challenging in that it could not be removed using conventional systems. New methods are needed for microhole coiled tubing drilling in order to advance its capabilities and resulting economics.

This project presents the design of an advanced mud and cutting system for microhole coiled tubing drilling (MHCTD) within the DOE’s Microbore Technology Development solicitation. The proposed system was designed to:

1. be compatible with and enhance the use of coiled tubing for drilling;
2. include equipment and methodologies to mix, pump and circulate the drilling fluids downhole;
3. separate, clean and store the returned fluids;
4. perform these functions in an underbalanced condition;
5. with zero discharge; and at reduced levels of overall environmental impact.

The set pump requirements were 350 gpm at 1000 psi and 15 gpm at 5000 psi. In addition to performing the above functions, the project was granted the latitude to investigate and develop advanced abrasive slurry jetting (ASJ) as a drilling mechanism to be applied with MHCTD, which logically tied ASJ to the mud system.

As with any emerging technology, design and implementation is an iterative process. It will take a systems approach and merging of traditional and new concepts. This report is the culmination of Budget Phase I and Phase II of this project which was to prototype and test the key components of the system- a patented abrasive pumping system (HPSPs-High Pressure Slurry Pumps) in a plunger pump version; mud processing equipment (patented pending Gas-Liquid-Solid (GLS) separator and DryFilters); the patent pending abrasive nozzle and fluids; and the overall system layout.

EXECUTIVE SUMMARY

Impact Technologies LLC (Impact) and Missouri University of Science and Technology (MST) developed an advanced mud system for microhole coiled tubing drilling as part of the DOE's Microhole Technology Development Solicitation. A previous report (Phase I Final Report, 9 May 2005) presented the basic design(s) and concepts for the system proved the concept was feasible and recommended proceeding to the Phase II. The goal of Phase II was to manufacture and test prototypes of the designs and concepts. This report covers both Phase I and II tasks and results.

The system as conceived and presented herein includes the following components:

1. pump(s) to convey drilling fluids downhole;
2. sub-system to process the returned well fluids; and
3. method to drill a hole in rock with an abrasive laden fluid.

The resulting system is compact, portable, and readily adaptable to current microhole coil tubing rigs. The ability to drill rock with an abrasive laden fluid represents a significant shift in drilling methods and has numerous congruencies with CTD and microhole drilling. The accumulation of this work represents significant advances in the capabilities of microhole CTD in many applications and industries, as well as for drilling larger bores.

This research defined operating parameters for the entire mud system considering the intended movement toward microholes, coiled tubing rigs and the anticipated shifts in drilling technology. This included investigating mud properties for microholes and confirming drilling hydraulics through computer modeling. The resulting predicted performance allowed specifications of flow rates and pressures (aside to the DOE specifications) which ultimately determined types and sizes of equipment to be considered. Needed and appropriate answers were obtained and no impediments to the ability to drill small holes with coiled tubing and the functioning mud system were found.

Abrasive slurry jet (ASJ) cutting and drilling is a logical adjunct to MHCTD but is a technology unto itself. Through a university research sub contract, significant progress was made toward applying ASJ and the more advanced FLASH ASJ system to MHCTD. An extensive literature search provided a springboard to focus ASJ toward the drilling of wells. Laboratory tests demonstrated the feasibility to cut a hole in rock larger than the nozzle diameter and without rotating the nozzle or drill string. This was accomplished by utilizing supercritical carbon dioxide as the slurry carrier fluid and specialty nozzles. This new process- method and equipment- is patent pending and is being trademarked as FLASH ASJ drilling. A new method of metering and delivering abrasives to the drilling fluid was also developed. The process requires no rotation (for small microholes), has low reactive forces and torque, utilizes lower pressures and thus is a milestone in the advance of ASJ and the direct applicability to MHCTD.

Mud pumps are a key component of MHCTD and have some unique specifications resulting from the DOE defined operating parameters (350 gpm at 1000 psi and 15 gpm at 5000 psi). Developing a true high pressure slurry pump (HPSP) was a key goal of this project for ASJ and FLASH ASJ drilling and cutting. These specific functions are now patented with additional patents pending prior to the project. As described in the tasks and results section, the first HPSP (Hydraulic driven piston pump, developed under a DOE sponsored Stripper Well Consortium project) was designed, fabricated and tested. Two other versions were built for this project and will be tested soon. All pumps have been modified to handle both ASJ and the FLASH ASJ fluids. Thus, we now have several options available for delivering abrasives at high pressures for drilling, providing an important advance in the technology for MHCTD.

Another significant development for advanced mud processing was a patent pending compact 3-phase gas-liquid-solid (GLS) separator that can concentrate the solids stream under backpressure for more compact processing and well control. This is important for underbalanced drilling conditions, as proposed with the FLASH ASJ, air drilling and nitrogen based drilling systems.

Searches inside and outside of the oil and gas industry found several mud processing units available that meet the project specifications (200 bbls and 500 gpm). There was, however, room for significant improvement to tailor a unit for true MHCTD in that no unit efficiently recovers sub-20 micron particle sizes and all such units are set up for cascading failure if any upstream processing step fails. A back flow DryFilter system was designed and developed to overcome the existing failure mode. Standard tankage (only) to meet the DOE specifications (200 bbls volume) is readily available in the industry. However, ASJ and FLASH ASJ systems do not require such volumes and, when combined with the use of non-traditional tankage materials, they will provide another significant step towards the reduced size MHTCTD rig of the future.

As the industry pushes harder to find more barrels of oil and gas per exploration and development dollar, all methods and equipment need to be continually reviewed and optimized. It is clear that these new emerging technologies of ASJ and FLASH ASJ drilling systems, HPSP pumps and GLS (with related systems) could find an application in MHCDT, but are a work in progress and will require significant effort to be commercialized. This project reports on the design and testing of the key components of ASJ and FLASH ASJ drilling systems including the HPSP, mud (abrasive slurry) mixing and processing system, state of the art 3-phase GLS separator and associated tanks and equipment- all in fulfillment of the requirements of this project.

EXPERIMENTAL

Experiments in this project included development of the specialized fluids and nozzle (combined later known as the FLASH ASJ system, US Trademark applied) performed by the Missouri University of Science and Technology (MST) at Rolla as related to Abrasive Slurry Jetting. It also includes the design, development, fabrication and testing of the HPSP at Impact. Much of this work is still confidential and/or proprietary. The results and discussion of these experiments are given in Tasks 7 and 8 of the Results and Discussion section below and in Appendix C, the final report from MST. They will not be repeated herein.

RESULTS AND DISCUSSION

Tasks 1 – 6 were performed in the analysis and feasibility studies of Phase I and are listed here with the summarized results for continuity. For a full discussion of the tasks performed and detailed results see the Budget Period I Final Report of 9 May 2005.

Task 1 -Review of the Overall Mud System and needs for each technology (Drilling Synergy)

The specific items in the overall MHCTD process were reviewed to better define the overall microhole drilling mud system and determine their key optimum characteristics. An idealized MHTCTD rig's surface and downhole components are shown in Figure 4. A generalized mud system's surface flow schematic is shown in Figure 5. These show that the key mud system components are fluids, pumps (including mixing), flowback tanks and processing (separation, treating) and well control. But these are impacted by other factors in the MHTCTD system.

This task process consisted of-

1. first identifying the wellbore geometries and construction;
2. mud type, fluid and physical properties;
3. coiled tubing characteristics, limitations, types and availability;
4. advanced drilling techniques applicable to MHCTD;
5. separation technologies; along with
6. environmental impact reduction methods.

The key factors that impact wellbore hydraulics were then set to model the process based on fluids, pump rates and the resulting standpipe/pump pressures needed to clean the hole during drilling. All work was preformed to be synergistic with current CTD operations and ASJ practices.

Mud types were reviewed with various mud companies and consultants. General mud types identified were (1):

1. Fresh water bentonite systems (spud mud category)
    a. Viscosity 37-45 cps
    b. Weight 8.9-9.2 ppg
    c. Fluid loss 8-25 cc
    d. Solids content 5-8%
2. Low Solids Systems
    a. Low bentonite, non dispersed, no polymers
    b. Viscosity 33-37 cps
    c. Weight 8.4-9.2 ppg
    d. Fluid loss 8-20 cc
    e. Exhibit high YP/PV ratios, shear thinning
    f. Higher penetration rates
3. Low Solids Polymer Muds
    a. Viscosity 38-45 cps
    b. Weight 8.8 – 9.5 ppg
    c. Fluid loss 10- 15 cc

4. KCL Polymer Muds
    a. Higher shear capability
    b. Higher cost
    c. Viscosity 34-45 cps
    d. Weight 9- 9.4 ppg
    e. Fluid loss 8- 15 cc
    f. Solids content 4-6 %
    g. Power Law terms of N'=0.30 and K'=0.01797

5. Salt Water (Brine) Muds
    a. Viscosity 38- 50 cps
    b. Weight 9.7- 10.3 ppg
    c. Fluid loss 8- 10 cc
    d. Solids content 6-10%
    e. Lower penetration rate than other fluids
    f. Lower potential of hole problems due to clay swelling

6. Oil based Emulsion systems
    a. Usually diesel based
    b. Oil:water % are 70:30 to 90:10
    c. Viscosity 38- 60 cps
    d. Fluid loss 5- 25 cc
    e. Weight 9- 20 ppg
    f. Rigs must be set up to use oil based fluids
    g. Higher cost to maintain in good shape
    h. Penetration rates are normally much higher with oil based muds

7. Air Drilling (Dusting)
    a. Air volume depends on hole & drill pipe size and depth
    b. Minimum volume rule it 3000 feet/minute annular velocity for hole cleaning
    c. Normally high penetration rates
    d. Compressor Units are for 1800- 3500 scfm
    e. High water influx sections can stop air drilling (convert to foam or mud)

8. Mist Drilling
    a. Air volume usually 30-35% higher than Dusting if higher liquid rates
    b. Air rates normally 400-800 scfm for 8" holes
    c. Lower penetration rate than dusting
    d. Water sensitive sections can cause serious problems
    e. High water influx sections can stop drilling
    f. Liquid/water injection rates should start at 1.4 times the Hole Size (inches)=gpm
    g. Must break foam before separation
    h. Foamer (soap) injection rates of 0.5 to 1.5% of fluid injection rate.

9. Gasified liquids include nitrified water or oil based muds

10. Gas systems, nitrogen or carbon dioxide without any or with minor liquids and foams

11. Silicates (PQ corp) , potassium, Formate brines (EcoForm) or other speciality muds.

Hydraulics are affected by wellbore geometry; CT size (ID and OD), type and pressure ratings; flow rate; maximum pressures; and mud (liquid and gases) type, viscosity and density. Successful hydraulics are the combination of all the listed factors that lead to the ability to drill the bore and clean the wellbore of cuttings.

Coiled tubing was investigated for its availability, diameters, materials, pressure ratings and cycle life.

Typical available CT nominal sizes for microholes are: 3", 2.875", 2.375", 2.0", 1.75", 1.50", 1.25", 1.0", ¾", ½", ¼", 1/8". The smaller sizes below ¾" are mostly available in stainless steel for chemical injection. The targeted sizes for microholes in this project are 1.25" to 1.75".

Materials for CT include steel alloys, chrome steel and composites. Steel alloys are lower cost but have a lower cycle life due to pressure cycles and bend/unbend cycling. Chrome CT has better corrosion resistance and higher cycle life. Composites have thicker walls, unknown abrasive characteristics (Hydril personally commented that in their tests that their composites performed better in abrasive wear than the steel connections). Programs for predicting the cycle life of CT are available.

The DOE published a White Paper on Coiled Tubing in 2005. The tubing is made at several manufacturing stations synchronized to form and weld steel strips into tubing on a continuous basis. It comes in a range of alloys with tensile strength from 70,000 to 120,000 lbs. and sizes from 1 inch to 4 ½ inches OD. Companies providing such coiled tubing include:

Quality Tubing is a National Oilwell Varco company formed in 1976 and is the leading manufacturer of coiled tubing. They manufacture a wide range of standard and custom made products. They can manufacture up to 30,000 feet of continuous coiled tubing.

Precision Tubing (www.precision.com) was formed in 1990. They manufacture coiled tubing primarily for use as offshore flow lines.

Fine Tubes (www.finetubes.co.uk) is a British company specializing in Stainless, Nickel, and Titanium alloy tubing.

Several companies (Hydril, FiberSpar, etc...) make composite or fiberglass coiled tubing, some with fibers for communication, but none are in commercial use at present.

Coiled Tubing comes in various yield strengths 70,000, 80,000, 90,000, 100,000 psi for standard alloys and in Chrome. Specification information for the 80,000 and Chrome follow:

National OilWell Varco's QT-16Cr coil tubing has a Minimum Yield Strength of 90,000 psi, Minimum Tensile Strength of 110,000 psi, Modulus of Elasticity of $28x10^6$ at 70 degree F, and a material density of 0.284 lbs/cubic inch. It also has significantly less corrosion by wet carbon dioxide in synthetic sea water than standard coil tubing. It also has about a doubling of the cycle life than standard QT900 coil tubing. Sizes and Internal Yield Pressures (thickest wall) are 1.000"OD/16,200 psi, 1.25/ 21,740, 1.5/ 20,400, 1.75/ 15,000, 2.0/ 13200, 2.375/ 11,100 and 2.875" OD / 9,200 psi.

Varco's QT800 tubing is a lower grade, but still high strength, alloy with properties of Minimum Yield Strength of 80,000 psi, Minimum Tensile Strength of 90,000 psi, Maximum Rockwell Hardness of C22. It is available in sizes and Internal Yield Pressures (at thickest wall) ratings of 0.75" OD/ 19,200 psi, 1.0/ 19,200, 1.25/ 21,760, 1.5/21,120, 1.75/ 18,100, 2.0/ 15,840, 2.375/ 13,340, 2.625/ 12,070, 2.875/ 11,020, 3.25/ 9,750 and 3.5" OD/ 9,050 psi.

Operating winding and unwinding coiled tubing while under pressure (as when drilling) significantly shortens the operating life cycle of the tubing. This has been studied significantly at the University of Tulsa.

Underbalanced and Managed Pressure systems have shown the capability to drill faster and without damaging the targeted production formation in many cases. This process is basically drilling with the well flowing or nearly flowing or bottom hole pressure balanced as the bore is drilled. Prediction (models) and control (downhole, blow-out preventors (BOPs), fluids (air, nitrogen, foams, oils) and procedures for the process have advanced considerably in the last decade. The key is in the monitoring and control of the processes and the equipment at the surface.

The Society of Petroleum Engineers has a specific 2008-2009 Distinguished Lecturer on Managed Pressure Drilling. Don M. Hannegan, Director, Emerging Technologies-Controlled Pressure Drilling at Weatherford International Ltd., made a world-wide tour talking about the state of Managed Pressure Drilling (MPD). From his talk on the SPE website (www.spe.org) it was found that MPD is an "advanced form of primary well control typically employing a closed, pressurizable fluid system that allows greater and more precise control of the wellbore pressure profile than mud weight and mud pump rate adjustments alone. As opposed to a conventional open -to-atmosphere returns system, MPD enables the circulating fluids system to be viewed as a pressure vessel. Influx not invited". His listing of conventional Well Control Variations of MPD include

- PMCD (Pressurized Mud Cap Drilling)
- CBHP (Constant Bottomhole Pressure)
- HSE (Returns Flow Control up drill pipe)
- RC (Reverse Circulation) and

• DG (Dual Gradient, several methods)

Companies in this under/near balanced and managed pressure effort are Weatherford International and Blade Energy (http://www.blade-energy.com/), although many other companies are advancing this technology now.

However, methods to control and separate the gases, liquid and solids under pressure are somewhat limited and/or very expensive.

Advanced drilling methods considered were CTD (a given for MHTCTD and ASJ), underbalanced and managed pressure (air, nitrogen, oils, gases) drilling, ultra-high rotational speed bits and motors, high pressure water jetting, abrasive water jetting, abrasive slurry jetting, laser, plasma, cavitation and a combination of other high energy and mechanical methods. Water jetting has been proposed to assist bit drilling since the 1950s where it was practiced by many major oil companies and reported by Maurer (2) and others. However, it required very high pressures (10,000-50,000 psi) which rotated jointed pipes could not tolerate, small orifices at the bottom of the drill string that would plug up with even small fines/ scale and high rates which would hydraulically limit its application.

Its sister cutting method, abrasive water jetting (AWJ) was developed for faster cutting on the surface. In this method high pressure water is pumped through a nozzle, air with abrasives are inducted into that jet stream and then all mixed fluids and solids are focused through another nozzle toward the target. The combination of high pressure and dual lines (one with air), while possible on the surface, is not practical for downhole drilling.

Abrasive slurry jetting (ASJ) was developed to improve the efficiency of AWJ. It was proven to be up to 4 times more efficient in cutting (18), but had the disadvantage of pumping a solids laden fluid (slurry) through a pump or requiring a batch system. Pumping a slurry through a pump to get to sufficient pressures wears the valves, seats and plungers out prematurely causing high pumping costs. Batch slurry systems are difficult to maintain for continuous drilling operations. Impact's patented High Pressure Slurry Pumps (HPSPs in piston or plunger, crank or hydraulic driven versions) overcomes such pump component wear problems by protecting the valves and seats with a cushion of clean fluid. This allows for longer life and lower pumping costs. Pressures with slurries can reach any pressure capable of a clean fluid pump, although at a lower recommended stroke rate.

Flash ASJ (developed post Budget Phase I) utilizes a supercritical fluid as a carrier for the abrasives. With specialty downhole tools developed for these fluids, the resulting cutting stream is powerful and efficient. The efficient cutting and drilling of FLASH ASJ systems means lower pump, standpipe and coil pressures than waterjetting, abrasive waterjetting, and typical ASJ drilling. In addition, the return flow is mostly gaseous allowing for underbalanced or managed pressure applications. Drilled particle sizes for ASJ and FLASH ASJ will be extremely small (less than sub-20 microns) for easier removal out of the hole.

Other high energy systems such as ultra-high speed rotation (motor and bits), laser, plasma, cavitation or other means to provide future cutting capabilities were studied, but were not addressed specifically in this project. High temperatures and high torque means are not addressable by current bit and coil technology. However, the downhole tools (inverted motors) that Impact developed for ASJ drilling are directly applicable to these future advanced drilling systems.

Environmental protection and Zero Discharge capabilities were studied as primary and secondary containment of any spills around the well site during the drilling process. The primary containment methods are the blow out preventors (BOP), separators, tanks, valving and piping in the process. However mechanical systems do fail and backup provisions are required. Further, advanced methods to minimize the environmental impact were investigated, including site liners, tank size and rig layout, recycling fluids and better well control on flow back. Ahead in the secondary protections is a dirt or mobile temporary (water or foam filled bladder) dike system that is needed around all well functions. Polypropylene liners covering the well site across the dike system is the next level of secondary containment. Sump pumps within the liner are also needed to pickup and transfer any spilled fluids. Tertiary containment methods include vacuum truck to pick up a spill that escapes the primary and secondary containment methods.

Minimizing the size of the tankage and operation would also be an environmental saving. This saves in materials (steel, etc…), fluids (muds, chemicals, diesel, etc…), energy (diesel, power) and disposal volumes. This can be accomplished by going to a mostly gaseous 'mud', utilizing the smallest bore possible (microholes) and utilizing coiled tubing systems for a smaller rig footprint. This smaller size would allow higher mobility, fewer truck loads in moves and be heliportable for remote locations.

Separation of solids below 20 microns is a continuing problem in allow recycling of the liquids. Solids build up in the drilling process when fines are generated at the cutting tip, by larger chips being ground down by the rotating pipe and by the flow process up the well annulus (collisions to rock wall, pipe and other solids). Typical screen shakers cannot remove these fines from the liquid, even with flocculants (polymers, etc…). Pumping these solid laden fluids through desander/ desilter hydrocyclones ise common in the oilfield and in various industries, but such actions remove particles only down to about 20 microns when they are working properly. Centrifuges can remove particles down to 2 micron sizes but they are inefficient and prone to plugging. This whole process is subject to cascading failure when any upstream step does not work properly. Downstream steps get plugged up often due to larger particles not removed in upstream operations. Even then they operate at less than maximum efficiency most of the time if the pumps are not properly matched to and operating with the separation equipment (9,10,11,12, 13). Combination tankage and processes (shakers, hydrocyclones and centrifuges) that meet the DOE specifications of 200 bbls volume and for water or oil based muds are currently available for purchase or rental.

Backflow stainless steel filters and membranes (Texas A&M, Dave Burnett) were identified as the last processing step needed to remove sub 20micron size particles, as post processing with or without the above existing methods. In such filtering processes, the mixture passed through a fine mesh/porous material. A filter cake builds up that then filters even smaller particles than the mesh/ porous material, at the cost of lower rates, high surface areas or higher pressures. Backflow or recycling of the filter media is important due to reduced disposal volumes, media cost and time considerations. Since not all fluids in the cycle need to be filtered every cycle, a 5-10% volume rate of the total circulation rate is acceptable and desired. This can be accomplished further by concentrating the solids in upstream steps prior to filter/ membrane process polishing.

A hydraulic modeling study was performed to evaluate the required rates and pressures, within the capabilities of the microhole wellbore configuration and coiled tubing sizes. That effort is summarized in Table 1 and Figure 7. As can be seen for surface drilling and pipe setting, higher rates and more forgivable pressure responses are possible. No rate exceeds 350 gpm for this effort with a premium mud. As microhole bores are utilized with premium muds the pressure-rate operating range is very narrow and requires careful control to keep within the capabilities of the coiled tubing, while still cleaning the hole. This makes use of conventional motors and bits problematic. Gaseous systems are required to aid in hole cleaning.

Task 2 – Abrasive Slurry System Design

This work was performed under a subcontract with the Missouri University of Science and Technology (MST) (previously known at the University of Missouri-Rolla (UMR)) at their Rock Mechanics and Explosives Research Center under the supervision of Dr. D. A. Summers.

The review of applicable published literature in the area of high pressure water jetting and abrasive jetting with submerged jets found that while some work in this area had occurred, it had not progressed enough for direct application to MHCTD. However it was promising enough that it should be further investigated in an attempt to integrate ASJ into MHCTD. A summary of this literature review is also included in the Bibliography section and further discussed in Appendix B.

In these earlier studies, MST laboratory tests demonstrated that a 5.08 cm (2.0 in) diameter hole can be abrasively water jetted in rock and the resulting hole is larger than the 0.11 cm (0.043 in) nozzle diameter and up to 4.45 cm (1 ¾ inch) diameter drill string. And, this can be done without rotating the nozzle or drill string. These are both key issues and accomplishments for CT drilling since the CT drill string cannot be rotated. Testing showed that the system can work under water. Additionally, the performance of the ASJ system was improved by developing an abrasive injection circuit (Abrasive Inlet Mixer subsystem) that allows more continuous and metered delivery of abrasives into the flow stream. FLASH ASJ fluid system were not tested in this earlier MST work.

Task 3 deleted by DOE on original contract

Task 4 - Pump Sub-system

The system specifications originally set by DOE were: 500 gpm at 1000 psi and 15 gpm at 5000 psi. The higher rate was later modified by DOE to 350 gpm. This set operating pump range can be seen in Figure 6. The top line represents the DOE rate-pressure requirements. The true MHT section, based on the hydraulic study, is shown in the lower rate area. The ASJ and FLASH ASJ operating area for MHTs are also given. The higher rates are only for hole cleaning in larger bores, as seen in drilling the surface pipe and in existing well deepenings. As a note, these set pumping conditions were exceptionally high for the new FLASH ASJ system which needs less than 75 BPD of liquid and more toward the lower 25 BPD liquids.

Impact's task was to identify available industry pumps and any modifications required to meet the DOE specifications. The investigators met with several pump manufacturers, including National (3,4), White Star (14), Kerr (7,8), Tulsa Triplex (13) , Gardner Denver 5,6) and others (15,16,17). Impact's set requirements were: dual pumps with minor/ no fluid end change for the range of operation, light weight for portability, compact size/ footprint and met the DOE specifications. Solids handling capabilities in the pump were preferred.

Intermittent versus continuous service type pumps were evaluated. A shorter drilling time on a well allows the use of lower end pumps. Intermittent pumps are lighter than continuous service pumps, which saves on mobility and space. In addition, it is expected that ASJ methods do not need even those high rates, as proposed originally by the DOE. From this effort intermittent pumps were selected. Further, an advanced rig would be fully electric and would have electrical generation capabilities for greater control and power of the drilling process. Thus these pumps would be electrically powered.

The available pumps identified were:

Kerr 3500 series
National JWS185
Gardner Denver TEE series
Tulsa Triplex TT series

Two (2) Kerr 3500A series pump power ends were chosen for this project. New fluid ends based on the patented High Pressure Slurry Pump (HPSP) design were utilized to obtain the (modified) 350 gpm combined rates and pressures specified by the project. In fact the HPSPs were designed for up to 15,000 psi at 15 gpm (30 gpm together). They are specifically designed for Abrasive Slurry Jet (ASJ) and FLASH ASJ drilling capabilities.

Task 5—Returned Well Fluids Processing Unit Sub-system

A key component of the "Advanced Mud System for MHD" is the returned well fluids processing unit. As specified by DOE, the "system" must be able to mix, circulate, clean, and store 31.8 m^3 (200 bbls) of water or diesel based mud; be able to process 31.5 lps (500 gpm, 17,142 BPD); perform while drilling under balanced; and have zero discharge. The "mud processing unit" or the returned well fluids processing unit discussed herein handles all of these functions except delivering and circulating high pressure drilling fluids, which is handled by the mud pump(s). This work did not originally include a well control element or system and purposely left it removed. It was later added back in to make a more complete system specifically for the ASJ and FLASH ASJ drilling fluids.

Much of the work in Task 5 consisted of contacting experts and vendors of mud and processing units (in and out of the oil and gas industry) and evaluating products for applicability to MHCTD. For the flow conditions developed by DOE and other tasks of this solicitation, several components of available mud processors approached the DOE MHCTD specifications. Equipment from Kemtron (9,10, in Houston, TX) and Tri-Flo (11,12 in Conroe, TX) met all of the operating parameters and conditions, but vary from each other in how the shakers and tankage are configured. Either can be modified for MHCTD and pricing is comparable (See Figures 20 and 21). Final selection was delayed until other contemplated design concepts are matured within Budget Phase II for this solicitation. These contemplated concepts include:

1) making the unit more portable than even existing models;
2) eliminating steel tankage and piping for bladder systems;
3) modularizing unit components, pumps, prime movers, tanks;
4) automating functions such as tank fluid levels, mud property measurements, screen and cone maintenance;
5) lift systems for packaged mud products; and
6) improved sub-20 micron solids separation.

The recommended mud processing equipment is well suited to removing solids and tankage can be designed and plumbed to allow continuous mud processing included times while not drilling. Many of these units are currently available in the industry for rental.

Per Kemtron (9,10), shakers can remove particles down to 140 microns (scalper screens much higher sizes only); Desanders remove down to 70 microns; Desilters down to 20 microns; and centrifuges, when working, can get down to 2 microns sizes. Shaker screens normally start at 20 mesh for the scalper screen, and 210 mesh for the second screen. Later hydrocyclone units become plugged up if any prior step does not remove the larger particles. The author calls this 'cascading failure'. For convenience, the conversions between mesh, micron/micrometers and inches are:

40 mesh = 0.0118 inches = 300 micrometer
80 mesh = 0.007 inches = 178 micrometers
200 mesh = 0.0029 inches = 74 micrometers
1 micrometer = 0.00003937 inches
1 inch = 25400 micrometers

Specifically, Kemtron (Houston, www.kemtron.com) and Tri Flow International (Conroe, TX) were found to have the small combination tanks and processing units needed for MHTCTD as they target the smaller trenchless utility drilling applications for installing cables and pipes in road and river crossings. Mud Technology International, Inc, www.mud-tech.com also has oilfield 450 to 1000 gpm mud cleaning/ processing systems with tanks.

Other interesting shakers only for ASJ and FLASH ASJ solids recovery and reuse are:

Sieve Shaker, by W.S. Tyler. For small volumes, this is a batch processing method where the mixture is dumped onto the top of a stack of 6 circular screens and shook. The screens are 12 inches in diameter and 2 inches deep with mesh from large down to 25 micron. The mechanical version RX-30 is $2,235. For wet service there is an additional charge of $1,032. The maintenance kit is $300. They also make a fully electronic version that requires less maintenance for $5,570.

"Washing Machine" Vibro-energy Round Separator by MI Sweco. These come in varying sizes and with one to four screens, providing 2 to 5 stream outlet. Although they don't recommend 4 screens unless the first screen is very large. It is a continuous feed, wet or dry. The 48 in model with one screen weighs 725 pounds and costs around $12,000. The same size with four screens weighs 1,025 pounds and costs around $22,000.

Sub 20 micrometer particles are a concern and can be handled by centrifuges and filters/ membranes. Centrifuges are problematic to operate since they fail/ plug often in the authors experience. It is still important to note that not all the circulated fluid must be processed to this low level of solids on every cycle. Only 10% of such volumes are required or other methods of concentration can be utilized to minimize the volumes processed. Oilfield centrifuges are readily available for rental. Such centrifuge and filtering sources are - Proguard Filtration Systems, www.nowata.com Engineering Fluid Solutions, LLC, automatic HydraKleen liquid-solid separators, www.efsfilter.com; membrane system per Dave Burnett, Texas A&M; www.internetmesh.net, precision micro-etch in stainless steel sheets and micro-mesh electroformed screens down to 0.0003"; www.hydac.co; Lakos, www.lakos.com has separation units; West Phailia, www.wsus.com has centrifuges and decanters; Oiltools International, 405-670-6537; 3M high flow Liquid Filtration, 800-648-3550; Hydro Carbon Flow specialists, zero discharge systems with vacuum units and cutting holding boxes, www.hydro-carbon.com; and Envir Voraxial Technology, www.evtn.com has a horizontal powered centrifuge.

Further complicating the problem, sub-2 micron particles cannot be removed by traditional methods. Only filters and membranes can target these small particles by developing a filter cake that provides additional filtration below the media sizing. This is at a cost of reduced flow rates, higher surface areas or higher pressures.

Tankage only is readily available for rental. Tank only rental companies, specializing in oilfield rentals, include Magnum Mud Co. (http://www.magnummud.com/) and many other frac tank service providers.

For emergency and added storage capability bladder tanks with limited processing are available by SEI Industries www.sei-ind.com/enviro in types onion, terra and pillow styles and include transfer pumps and filters.

Liners and Bladders:
High density polypropylene can be used for the primary tankage, emergency storage tanks and containment liners around the drilling rig to form a zero-discharge operation. Products are polypropylene 20, 30, 40 mils thick, and a reinforced 30 or 40 mil polypropylene geo-membrane. Smaller sizes, such as the 40 ft. by 40 ft. size for MHTCTD rigs can be fabricated at the vendor's facility, folded and shipped, weighing only 250 to 450 lbs., depending on material thickness and density. Larger sizes are fabricated (heat welded) on site from rolled product. Most vendors will either ship the liner to be installed by the purchaser or within some geographic limitations, provide for the installation. While some vendors have provided liners for drilling pads, more common applications are oilfield reserve pits, remediation pads, salt water disposal pits, wastewater lagoons, ponds, and oilfield frac pits. Most vendors do not provided berm material or pipe boots (exceptions discussed below).

The websites of a number of vendors were visited and four vendors were contacted for their specifications, prices, services, products and installation. Few, if any, of their customers reused the liners, particularly when used as a drilling pad liner, mostly due to driving over the unprotected liners. It is recommended that a polyfiber or geotextile (thick light-weight fabric cushion material) covered with plywood or fiberboard be laid down on top of the liner in high traffic areas to allow use. Specific comments, products, services and prices from the four vendors were:

Unit Liner Company, http://www.pitliner.com/, contact Dick Taber.
Most of their liners are fabricated in the field with 22 ½ ft rolls, but they could fabricate and ship a 40 by 40. Cost for 40 mil is 70 cents/ft^2 ($1120). Thirty mil is 38 cents. The 40 mil would weigh around 400 lbs. and could be shipped for a couple of hundred dollars. They only install within 500 miles or so from Shawnee, but the cost for three men and a truck is $130/hr including travel. They have sold liners for drilling pads to Apache Corp. for drilling on Indian land. They use a bobcat or equivalent with a blade to make the berm, lay the liner down and secure it with dirt on the outside of the berm. For the conductor, he said they just cut "a pie shaped wedge and let it drape into the cellar". Other than a small bobcat with a blade (rental item), nothing special is required to install it.

Just Liners, http://www.justliners.com/, contact Joe Finley
Just Liners sells comparable products as Unit Liner above at similar prices. But he recommended a product called JPL 24 which is a reinforced polyethylene that is about

half of the weight and half the price (39 cents/ft^2), although clearly not as strong as the 40 mil polypropylene. He indicated that they sold quite a bit of that product for use in Alaska and California, but didn't say in what kind of application. They would build the berms and secure the edges in the same fashion as the others with a blade. For the conductor he suggested a boot be constructed similar to a roof vent, but hadn't done that before.

Environmental Protection, Inc. http://www.geomembrane.com, contact Brad Diarment. EPI also sells the same products as the first two at comparable prices, but recommended a 40 mil reinforced polypropylene geomembrane. Much stronger and much pricier at \$1.60/ft^2 (\$2,560 for 40 by 40). And like several others, he recommended the geotextile heavy fabric (1/8 inch) and ply wood in heavy traffic areas. One interesting add-on service they offer is a Technical Service Representative that would, among other things, instruct the customer's foreman on how to install pipe boots.

Interstate Products, Inc. http://www.interstateproducts.com contact Scott Sagalo. Interstate Products was the only one I came across that could manufacture the complete system with built in berms and pipe boot. They can manufacture drive thru berms from 4 to 18 inches high, filled with foam or water. The recommended liner was Seimens XR-5 a 30 ounce, 30 mil polypropylene geomembrane. It would be manufactured at the vendor's shop and shipped on a pallet (it would weigh 480 lbs). The installation consists of basically unfolding it. The delivered price would be around \$10,000 for the 40 by 40 foot liner. At that price, mats would be needed so that it could be reused. Any repairs would be done with a heat welded patch, in the field or back in their shop.

Not called were: Griffolyn Products Reef Industries, Inc. at 800-231-6074; In-Line Plastics, LC www.in-lineplastics.com at 800 364-7688 (reinforced 100 mills thick).

The liners can be formed around the well head conductor, down sumps and draped over dikes. They can be cut and resealed on the edges repeatedly. Method to weld the edges onsite are available. Portable dikes would allow moving them between sites. Cleanup of the liner would be a continuing problem. Sump pumping and "squeeging" would be initial steps, but full cleaning would generate additional liquids requiring processing and/or disposal.

Budget Period I Conclusions

Satisfactory hydraulics are possible within true MHT systems in both mud and gasified systems. Pump operating range required for these MHT systems are 0.63 – 18.9 lps (10-300 gpm) with 6.9 – 34.5 MPa (1000 - 5000 psi) capabilities with those respective rates. Gas injection of 0- 0.94 m^3/s (0-2000 scfm) allows underbalanced drilling operations in microholes. Processing of returned fluids at the 31.5 lps (500gpm) specified rate is possible. Nodal analysis / hydraulic modeling should be strongly considered for each specific application in both the planning and execution phases since each well and rig configuration is different and the operating ranges are so narrow in MHT systems.

An Abrasive Slurry Jetting (ASJ) (or later developed FLASH ASJ) should be applicable to MHCTD after demonstrating a nozzle prototype that is capable of jetting a hole larger than itself without rotating and while submerged in water with back pressure. Also a low cost batch abrasive slurry mixing and deliverability method was demonstrated, but still requires optimization.

Compact, light weight and modular components with twin pumps are desired for redundancy, portability, and flexibility. Two Kerr KA3500 pumps with Impact modified HPSP fluid ends were identified that suit this MHTCTD application. Prime movers for these pumps were selected to be electric driven.

A compact mud processing system is possible. Through contacts with experts- including a mud engineering consultant, mud companies and mud processing companies- both inside and outside the oil & gas industry, trenchless systems, and other industries, key processing systems were identified as approaching the specifications of rate and processing- Kemtron, Tri-Flo and Impact's DryFilter. Modifications are needed for weight, size, ASJ processing and sub-20micron solids removal. Modular systems and non-metal tankage and plumbing are anticipated to produce high savings in portability (size and weight).

Budget Period II Results and Discussion

Manufacture and Prototype Testing

Task 7 – Build and Test the Abrasive Nozzles

This work was done by Dr. Summers at MST and involved building and testing nozzles, then bench testing under various conditions of back pressure, noting penetration rates and diameters as a function of pressure and slurry concentration. Fluids studied included- water only, gelled water, gasified (CO_2) water and supercritical carbon dioxide. The full Final Report from MST is included in Appendix C. That full discussion will not be repeated here. It is sufficient to note that a new method (fluids, nozzles and operation) was developed, still needing optimization, that can make a significant change in drilling wells, especially MHTCTD wells.

Task 8 – Build and Test Pump

A prototype HPSP in a hydraulically driven piston version was built, fabricated, assembled and tested under another DOE funded project. That pump can be seen in Figure 18. The Impact test facility can be seen in Figures 16 and 17. The first HPSP plunger version for this project was built by Danco, a local Tulsa OK machine shop, and fabricated at Impact's shop to cover a range of project parameters. The second version of the plunger HPSP was built and is ready for modification (for FLASH ASJ fluids) and nearing completion. All pumps will be under testing and field trial with FLASH ASJ systems soon under a DOE SBIR grant project to drill 2000 foot geophone VSP wells.

The power drives for the two pumps in this project are expected to be on an electric drilling rig setup (or at least with an electrical generator) with 460 AC voltage available. They are:

Toshiba Variable Frequency Drive (VFD, AC-DC-AC) with a 60:1 turndown. It controls a 200 horsepower 460VAC, 400 amp 12 pole Westinghouse electric motor. This gives the capability to power the HPSP fluid end version 3 plunger type / Kerr power end pump with full torque and smooth control from 500+rpm down to about 20 rpm. This pump and power skid can be seen in Figures 12, 13 and 14.

The Aberdeen Dynamics Hydraulic Power Unit (HPU), Figure 9, consists of a 200 horsepower 460VAC Worldwide electric motor which drives two (2) 3000 psi Parker variable displacement P2 radial piston hydraulic pumps, a Parker proportional valve, SAI positioned and an ETACH encoder/tachometer to a SAI GM5A 190 horsepower hydraulic motor. This allows full and continuous control of the HPSP fluid end version 2 plunger/ Kerr power end pump from zero to 500 rpm speeds. This dual skid unit can be converted to a diesel driven hydraulic pump, if desired. It can be seen in Figures 8, 10 and 11.

These pumps introduce a new method to drill and cut materials in many industries.

Task 9 – Intentionally left blank

Task 10 – Finish and Test Return Well Fluids Processing Subsystem (RWFPS)

It was decided that only two key items were absolutely required for ‘mud’ processing for true MHTCTD rigs- a primary/ initial separator and a final sub-20 micron filter/ membrane. Everything else is available as rental from industrial suppliers.

All well control equipment was specifically excluded from this original project proposal and effort. However, later developments of the advanced ASJ and FLASH ASJ processes were naturally underbalanced or managed pressure drilling, and a return cyclonic separator was determined to be essential. Impact has such a unit based on a patent pending Gas-Liquid-Solids (GLS) design by Impact and a patent pending multiple GLCC series design by Multiphase System Integration (MSI). It was built under an Oklahoma Center for the Advancement of Science and Technology (OCAST) partial grant through the University of Tulsa. It was modified for this project for full portability, control and erosion prevention. This unit can handle 1 MMSCFPD of gas and 250+ gpm of low viscosity mud (water). Two units would be needed for the original DOE specifications, but not for the ASJ or FLASH ASJ drilling methods. It would provide environmental safety as a first responder well control device. It would provide flow and well hydraulics control by placing backpressure on the well. Under modification it would provide dust control through the addition of water and a variable diameter Churn Riser (in a later study for OCAST with the University of Tulsa). Thus it benefits the MHTCTD rig process by better controlling the underbalanced system while still allowing initial separation to take place. This trailer mounted GLS separator is shown in Figure 15.

Impact's Dry Mud Filter was designed, the stainless filters obtained from Federal Screen Products (stainless steel filters of 25 and 5 micron sizes) and a prototype container was built. But the full filter system was not made operational due to other membrane systems becoming available. In either method a filter cake would buildup on the 5 to 25 micron rated screen would remove ALL (even sub 2 micron) particles very slowly. Further ASJ and FLASH ASJ drilling systems will generate a lower overall volume of sub-20 micron particles higher concentration, and thus less of a perceived need of the DryFilter development.

Tankage, shakers, hydrocyclones (desanders, desilters) and other items can be rented as needed for the field test. Specifically Kemtron or Tri-Flo combination units would suffice when inserted between the GLS separator and the final filters/ membranes.

Task 11 – Combine, Test and Evaluate All System Units

Optional. Not done due to budget, time and no specific well to test.

Task 12 – Final Reporting and Conclusions

As part of the DOE Microhole program, numerous interim presentations were made at the quarterly review Petroleum Technology Transfer Council (PTTC) meetings in Houston, Texas on 17 August 2005, 16 November 2005, 22 March 2006 and 16 August 2006. In addition, presentations have been made to i2E, an Oklahoma business development group, Tulsa Engineering Foundation, Engineering Society of Tulsa, Stripper Well Consortium and other groups. This final report completes the requirements of this project.

GRAPHIC MATERIALS AND TABLES

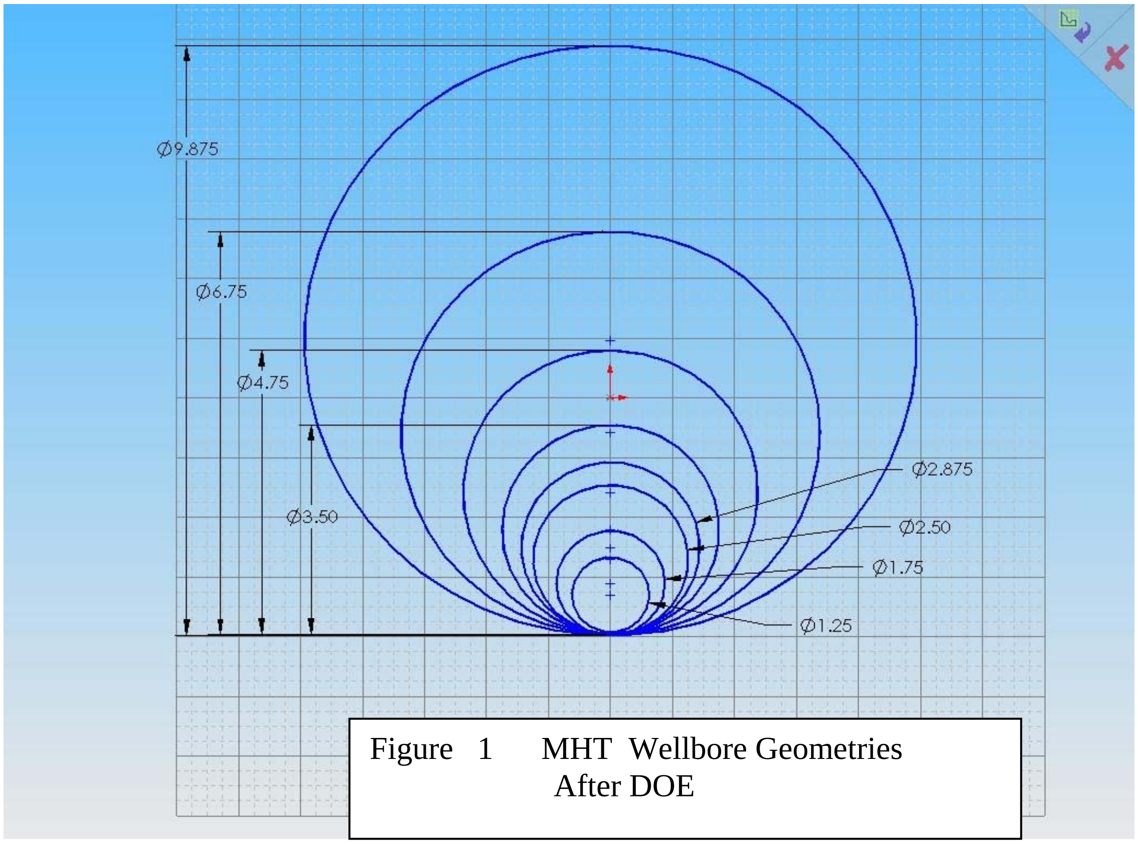

Figure 1 MHT Wellbore Geometries After DOE

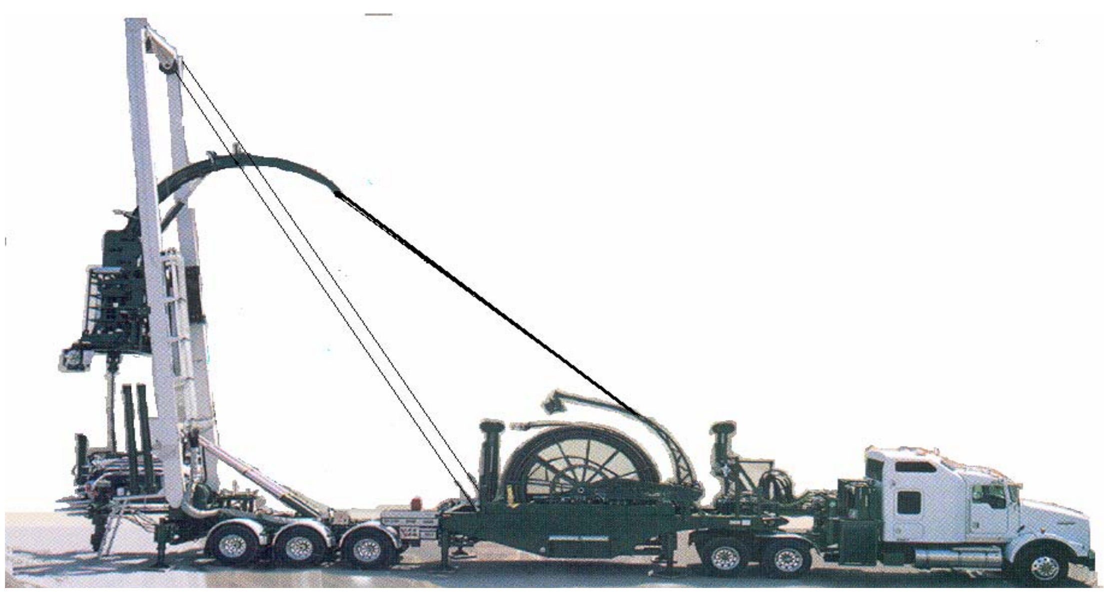

Figure 2 Hybrid Conventional Mast-Coiled Tubing Rig

Figure 3 DOE Los Alamos National Laboratory Microhole CTD Rig

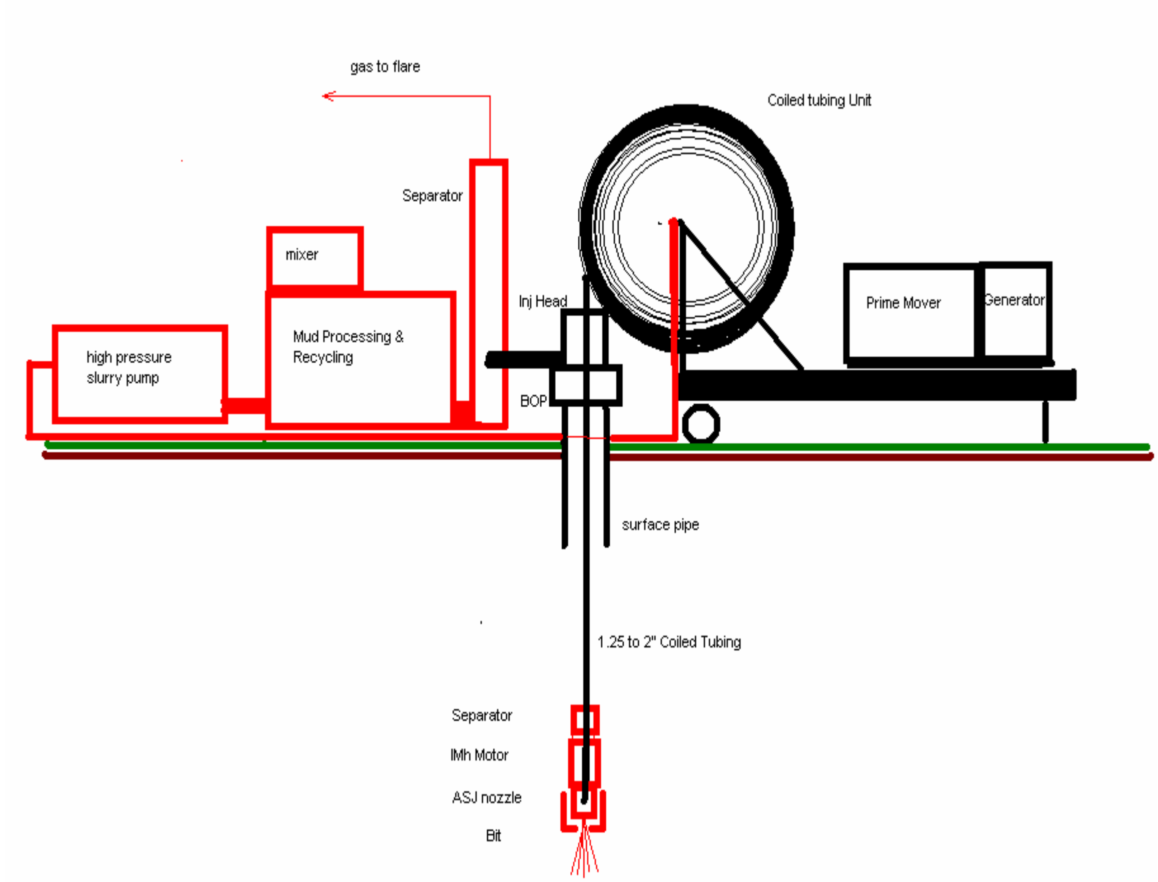

Figure 4 Idealized Microhole Coiled Tubing Drilling Rig Components

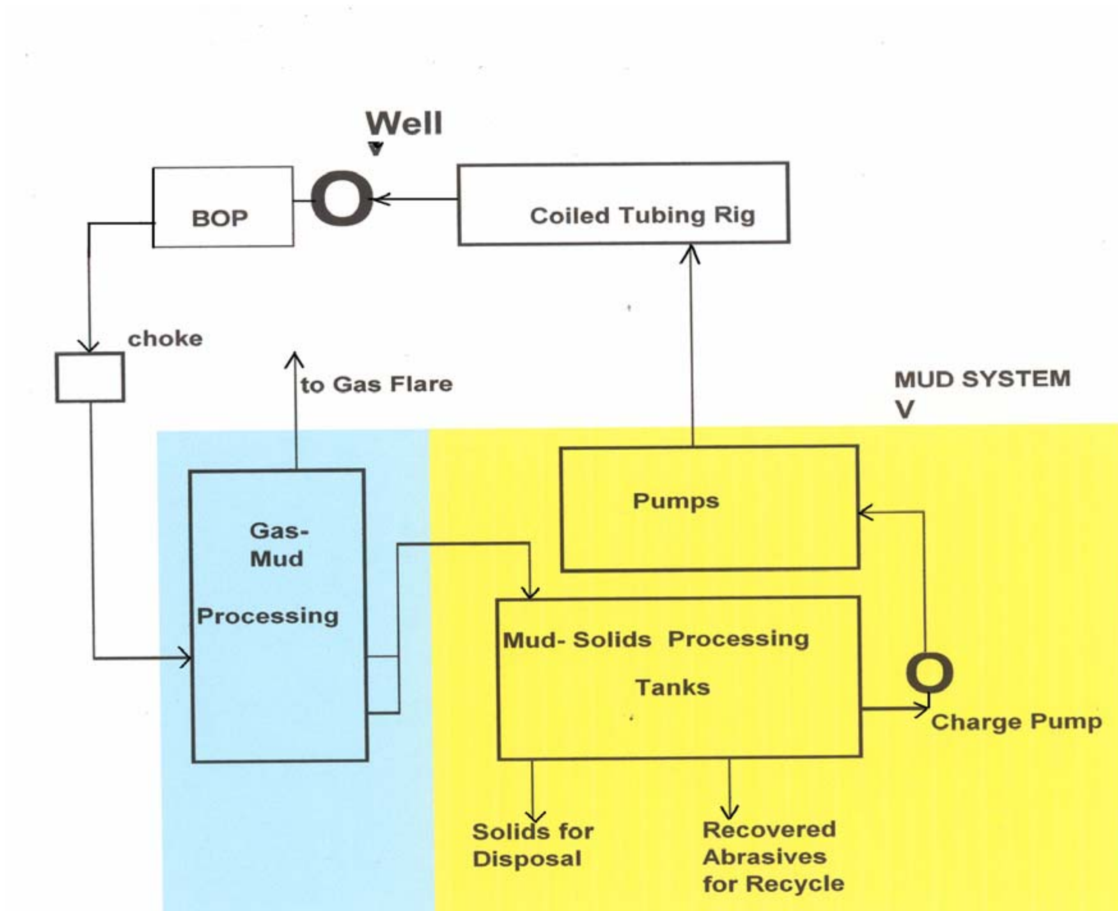

Figure 5 Project Mud System Flow Schematic (Blue and Yellow included)

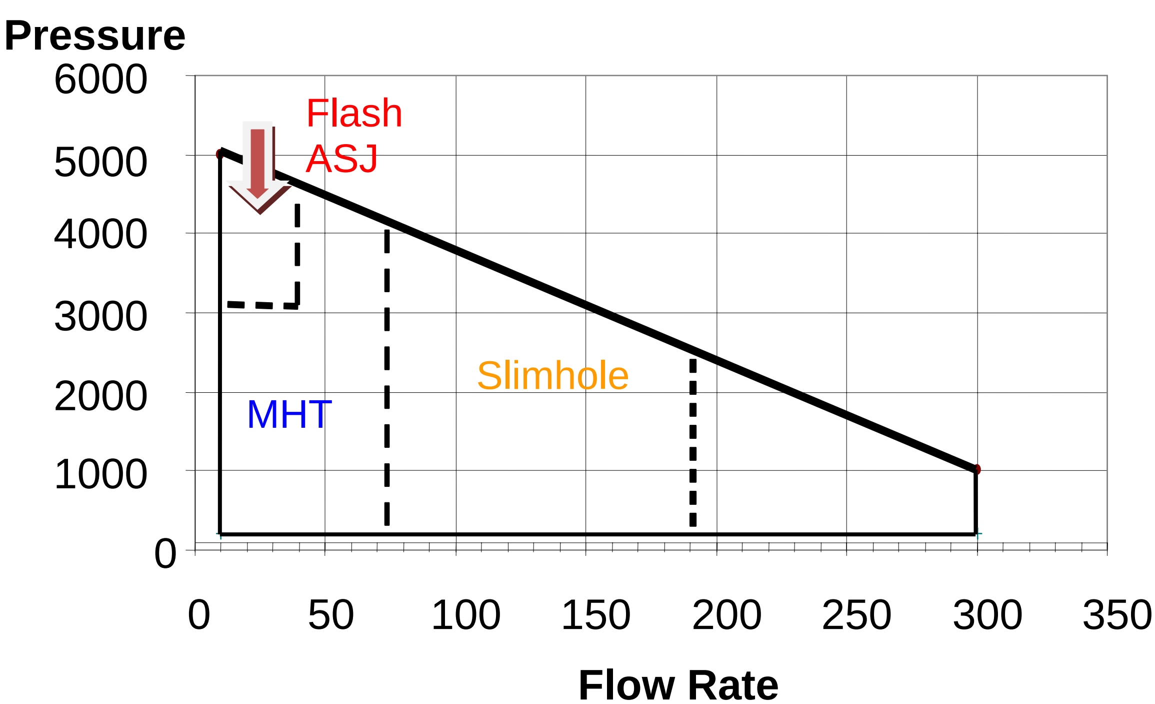

Figure 6 DOE MHT Pumping System, Total Operating Range

DOE Mud System
Pressures for various flow rates and systems
Summary of Runs

Case / Flow Rate	0	10	15	25	50	75	100	200	300	400	500	GPM		
S1							98	425	850	1420	2308	PSI	120gpm to clean @146psi	all la
S2							90	350	830	1400	2119	PSI		turbl
S3					31	70	100	390	780	1300	2135	PSI		turbl
S4							85	350	780	1350	2162	PSI		all tu
S5								355	788	1425	2151	PSI		all tu
P1				150	210	325	533	1493	2838	4543		PSI	no hole cleaning below 50gpm	turbu
P2				225	300	400	600					PSI		turbu
P3				380	800	1250	1701	5036				PSI		
P4		3000	5000									PSI	review for ASJ capability	
L1				300	700	1300	2000	5000				PSI	15gpm willnot clean vertical	30gp
L2				475	1125	2005	3300					PSI		
L3				300	500	800	1400					PSI		

Case Descriptions:

S1 500' surface casing point, 3.5" jointed DP, 9.875" hole, lite mud system
S2 500' surface casing point, 3.5" jointed DP, 9.875" hole, premium mud system
S3 500' surface casing point, 3.5"jointed DP, 6.75" hole, premium mud system
S4- 500' surface casing point, 3.5 jointed DP, 6.75" hole, water
S5- 500' surface casing point, 3.5" jointed DP, 9.875" hole, water

P1- 5000' casing point with 6.75" hole, 2.875"CT, premium mud, 3.5" BHA
P2- 5000' slimhole with 4.75" hole, 2.875"CT, premium mud, 3.5" BHA
P3- 5000' microbore with 3.5" hole, 2.375"CT, premium mud, 2.875" BHA
P4- 5000' microbore with 2.5" hole, 1.75"CT, premium mud, 2.0" BHA

L1- 1000' horizontal lateral microbore of 3.5"hole, 1.75"CT at 5000"TVD in 5.5" casing
L2- 1000' horizontal lateral, microbore 2.5" hole, 1.75" CT at 5000' TVD in 5.5" casing
L3- 1000' lateral of 3.5" microbore, 2.375"CT at 5000'TVD in 5.5" casing

Table 1 Hydraulic Model- Pump Rates versus StandPipe Pressures by Case (with Figure 7)

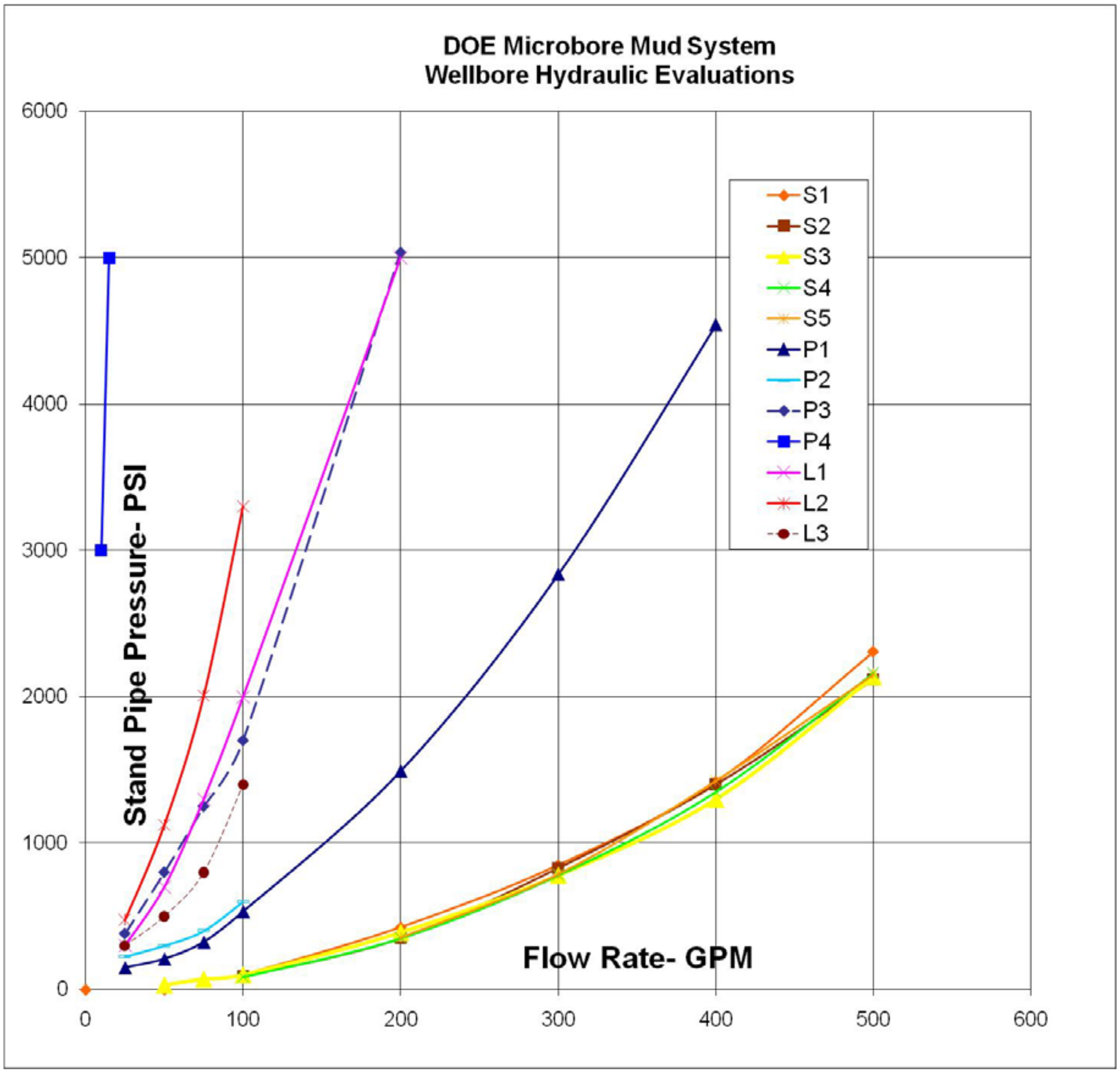

Figure 7 Plot of Flow/Pump Rate versus Stand Pipe Pressures by Hydraulic Model Case (with Table 1)

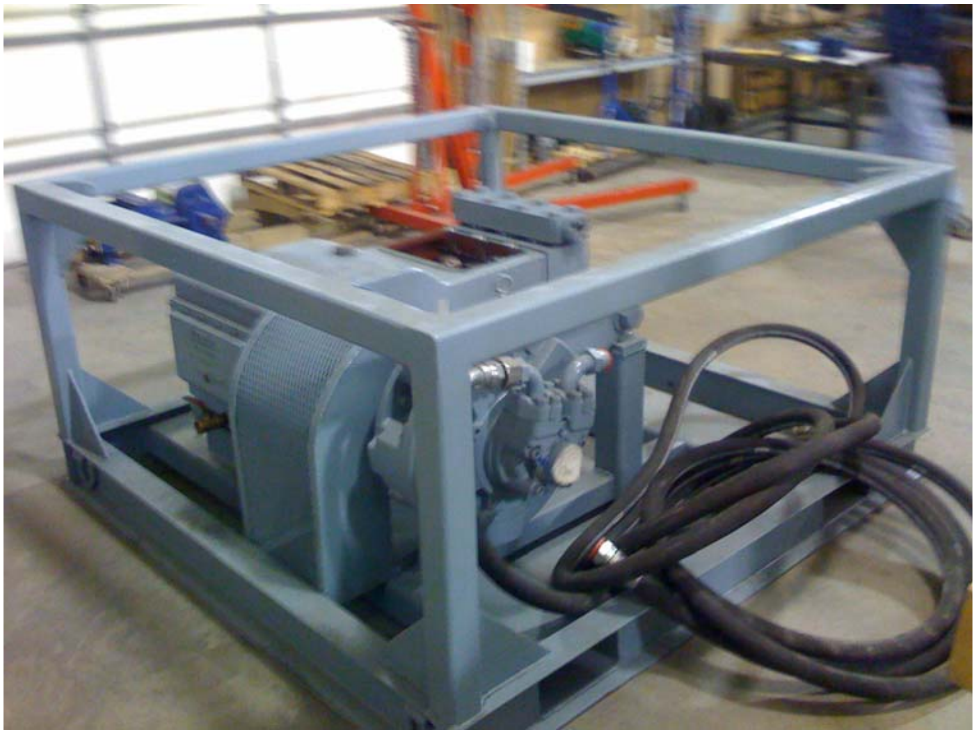

Figure 8 High Pressure Slurry Pump – Hydraulic Driven

Figure 9 Aberdeen Dynamics Electric-Hydraulic Power Unit

Figure 10 Second View- High Pressure Slurry Pump- Hydraulically driven

Figure 11 Third View of High Pressure Slurry Pump- Hydraulic Driven

Figure 12 Variable Frequency Electric Driven High Pressure Slurry Pump

Figure 13 VFD version of HPSP, second view

Figure 14 VFD Electric Driven HPSP, third view

Figure 15 Trailer Mounted Gas-Liquid-Solid (GLS) Cyclonic Separator

Figure 16 Impact Test Facility near Tulsa, Oklahoma, View to West

Figure 17 Impact Test Facility View to the South

Figure 18 First Prototype High Pressure Slurry Pump (HPSP) under Test

Figure 19   HPSP First Prototype under FLASH ASJ modifications after Testing.

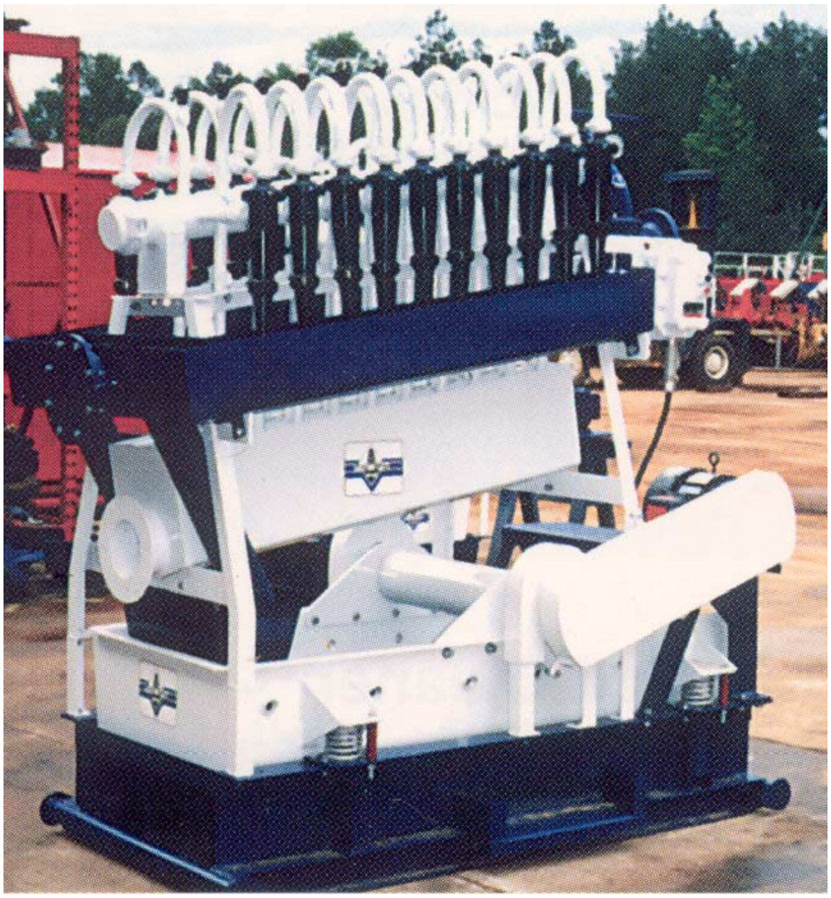

Figure 20 Tri-Flo Compact Separation Unit (no tank)

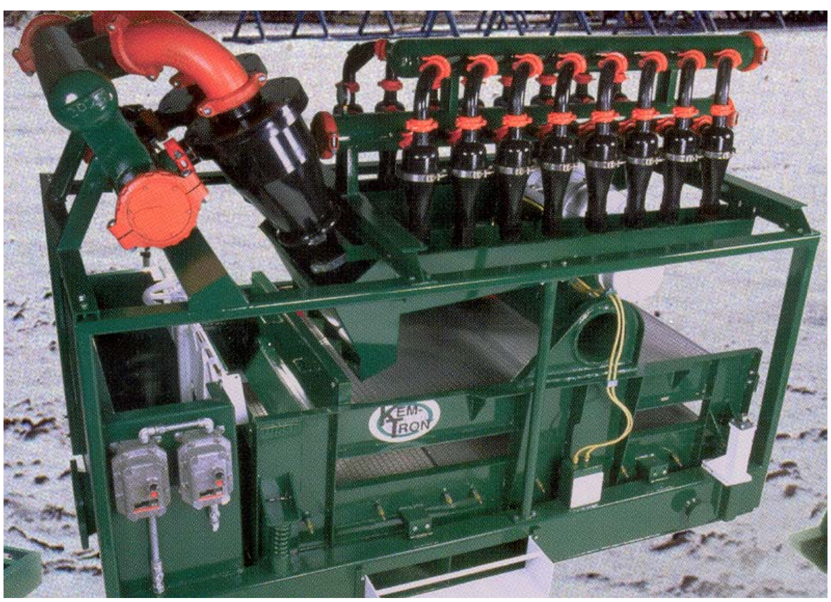

Figure 21 Kemtron Separation Unit

PROJECT MILESTONES   Summary

● Task 7 – Build and Test the Abrasive Nozzles
These nozzles were built and bench testing was performed at the Missouri University of Science and Technology. In fact, a new patent pending ASJ fluid and nozzle design was developed for truly advanced and efficient drilling.

● Task 8 – Build and Test Pump
Two (s) patented High Pressure Slurry Pumps (HPSPs) were built at Impact's shop and in Danco Pump and Supply's machine shop in Tulsa, Oklahoma. The first is a Aberdeen Dynamics 200 horsepower electric- hydraulic unit driving a Kerr KA3500 pump with a patented Impact HPSP fluid end. The second is a Toshiba-Westinghouse VFD electric motor driving a Kerr KA3500 pump with a patented Impact HPSP fluid end. Combined, the two pumps are designed to pump over 350 gpm at 1000 psi and 30 gpm at 15,000 psi. The FLASH ASJ system does not require and cannot use anywhere near the 350 gpm rates for microholes.

A HPSP prototype (from Impact's Advanced ASJ Drilling System for the Stripper Well Consortium) was tested in January 2008 at Impact's yard. That test was successful, but it was found that a better inlet mixing system was required for steady solids concentrations while drilling. That has been constructed in one version and designed in another version.

● Task 10 – Finish and Test RWFPS
Originally the returns system was specifically stated that it did not include well control items. In that direction, a trailer with a backflow DryFilter (of Impact design, staged micron/ mesh ratings) was laid out with pumps and tankage on a 20 foot trailer with inflatable rubber tubes for emergency storage. That system design was drafted for construction / fabrication, but not built. With the advent of the FLASH ASJ system this trailer based design was modified.

That returns system included a back flowable DryFilter that was useable for any mud (fresh water, brine, air, underbalanced) system and could reduce solids to sub 20 micron and even sub 2 micron acceptable levels for reuse. Only about 10% of the return liquids required such a low particle filtration on each pass. Such a filter system could be used instead of or post processing with existing shakers, hydrocyclones/ desanders/ desilters. It would replace problematic centrifuges. However, the DryFilter was prototyped only and was not built because other membrane and filtering sources became available and FLASH system would greatly reduce the volume of fluids requiring treatment.

With the advent of the new nozzle and FLASH ASJ fluid systems developed at MST, which are by nature underbalanced or mamaged pressure balanced, it was decided that higher efficiency and greater adaptability would be gained by utilizing a patent pending Gas-Liquid-Solid separator combined with a patent pending multistage series towers and controls. This unit was built under an OCAST grant with the University of Tulsa, and modified for this project. This inclusion allowed a first level well control device that also performed efficient gas removal and solids concentration. The solids concentration allowed more efficient post processing for removal. The gas handling capabilities meant it was specifically capable of controlling underbalanced (oils, air, nitrogen or Flash ASJ) systems. This unit can be seen in Figure 15.

Post liquids processing to remove the solids could still be by the DryFilter or by other means identified, such as commercially available membranes and/or specialty centrifuges identified. Tankage for 200 bbls volume was readily available for rental in the industry. These rental equipment items were specified and rental sources identified.

● Task 11 – Combine, Test and Evaluate All System Units

This was not done since no specific well was identified as needing the overall system units and thus rental items (tanks, liners, membranes/centrifuges,…) were not obtained for a test. Individual components were tested to the extent possible.

● Task 12 – Final Reporting and Presentations

- Final Status Report for Budget Phase I, 31 March 2005
- Status Reports and Presentations to DOE as required by the Project CORE
- Petroleum Technology Transfer Council (PTTC) Presentations for DOE
    - Microhole Technology Integration Meeting, Tulsa
    - 17 August 2005,
    - 16 November 2005,
    - 22 March 2006 and
    - 16 August 2006
- Other presentations-
    - i2E, an Oklahoma business development group, 3 July 2007 & 19 September 2007 in Tulsa, OK
    - Tulsa Engineering Foundation/ Engineering Society of Tulsa, Tulsa, OK
    - Stripper Well Consortium at RMOTC, Casper, Wyoming on September 2007 and Wichita, Kansas on 30 October 2007
- Final Report submitted on 16 February 2009

CONCLUSIONS

Significant advances to the fluids, pumping and returns handling allow a new drilling system for microhole coiled tubing drilling, MHTCTD. The major components of this new system are new patent pending down-hole nozzles and ASJ and FLASH ASJ (trademark applied) fluids; two patented high pressure slurry pumps (HPSPs) capable of 350 gpm at 1000 psi and 30 gpm at 15,000 psi, designed to pump any type of mud, including water or oil based, underbalanced/ managed pressure, ASJ slurries (solids in liquids) and FLASH ASJ systems; a patent pending Gas-Liquid-Solid multi-stage cyclonic separator built for well control, gas separation and solids concentration; and a new backflow DryFilter system (designed but not completed). These advances were developed specifically for efficient microhole (low volumes, low rates) coiled tubing (lower pressure, low torque, low weight on bit and no string rotation) drilling.

REFERENCES

1. Discussions with Mike Beyhan, consultant to Anchor Mud Company
2. Maurer W.C., *Advanced Drilling Techniques*, 1st ed.; Petroleum Publishing Co.
3. National Pump Company pump catalog
4. Discussions with Gary Lake and Kenny Lopez at National Pumps
5. Gardner Denver pump catalog
6. Discussion Bill Marshall at Gardner Denver, Tulsa OK
7. Kerr Pumps catalog and technical manual
8. Discussions with Mike May at Kerr Pumps, Sulphur OK
9. Kemtron Product brochures, www.kemtron.com
10. Discussion with Rachel Watson, Dilip Shah, Joe Poppelreiter at Kemtron, Houston Tx.
11. Triflo Product brochure, www.triflow-intl.com
12. Discussions with James Griffin, Bob Scofield, Jerry Turk, Eddy Dow and Ed Moe at Triflo, Conroe, Tx
13. Discussions with Trevor Young, Tulsa Rig Iron Company (Tulsa Triplex), Kiefer OK
14. Discussions with White Star Pump, Shaun White, Houston , Tx
15. Telephone conversations and email with Yarom Polsky and Bart Patton at Schlumberger.
16. Phone and email with Matthias Moeller, Thorsten Regener Karsten Fryer, John MacPherson at Baker Oil Tools
17. Discussions with Charles Hailey with Hailey Oil Tools, Oklahoma City, OK
18. Discussions with Dr. David Summers, Missouri University of Science and Technology, Rolla, MO.

BIBLIOGRAPHY

Note: All bibliographical references listed below are from Dr Summer's (MST) literature search and review in Task 2 of this project.

Theoretical and Basic Studies

1. Fairhust R.M. "Abrasive Water jet Cutting", M.Sc. Thesis, Cranfield Institute of Technology, January 1982.

2. Leach S.J. & Walker G.L. "Some Aspects of Rock Cutting by High Speed Water jets," Phil Trans Royal Society, London, Vol 260A, 1966, pp.295 – 308.

3. Selberg B.P. and Barker C.R. "Dual-orifice Waterjet Predictions and Experiments," Erosion: Prevention and Useful Applications, ASTM STP 664pp. 493 – 511.

4. Barker C.R. and Selberg B.P. "Water Jet Nozzle Performance Tests,"Paper A1, I 4th International Symposium on Jet Cutting Technology, Canterbury, UK, April 1978.

5. Kovscek P.D., Taylor C.D., and Thimons E.D. Techniques to increase water pressure for improved water jet assisted cutting, USBoM RI 9201, 1988, 10 pp.

6. Lohn P.D. and Brent D.A. "Improved Mineral Excavation Nozzle Design Study," Interim Report, July 1975 – March 1976, Contract JO255024, April 1976, for the US Bureau of Mines.

7. Lohn P.D. and Brent D.A. "Inlet- Nozzle Performance Study," Final Report, July 1976 – June 1977, Contract JO255024, July 1977, for the US Bureau of Mines.

8. White, Frank M., "Viscous Fluid Flow", Second Edition McGraw-Hill (especially pp 470-476).

9. Tesar V. Basic Fluid Mechanics – A Hypertext textbook, Czech Technical University in Praha (see http://web.cvut.cz/fme/k212/personnel/tesar/skripta/obsah%5ea.htm)

10 Erdman-Jesnitzer, F., A.M. Hassan, H. Louis, "A Study of the Effect of Nozzle Configuration on the Performance of Submerged Water Jets", 4th International Symposium Jet Cutting Technology, Paper A2, BHRA, 1978.

11. Brandt, C., H. Louis, J. Olsen and G. Tebbing, "Influence of Nozzle Geometry on Abrasive Water Jets", 5th Pacific Rim International Conference on Water Jet Technology, February 3-5, 1998, New Delhi, India, pp 330-345.

12. Yazici S. Abrasive Jet Cutting and Drilling of Rocks, PhD Dissertation, UMR, June 1989, 191 p.

13. D.A. Summers, R.D. Fossey, J.W. Newkirk, G. Galecki, UMR; M. Johnson, NSWC; G. Olson, DAC, " Results of Comparative Nozzle Testing Using Abrasive Waterjet Cutting," 2001 American Waterjet Conference, Minneapolis, MN, August 18-21, 2001.

Applications of Submerged Jets.

14. Yahiro, T. and Y. Yoshida, "On the Characteristics of High Speed Waterjet in Liquid and its Utilization in an Induction Grouting Method", Second International Symposium on Jet Cutting Technology, Cambridge, UK, 1974, pp G4-41 to E4-62, paper G4.

15. Savanick, G. "Borehole Mining of Deep Phosphate Ore in St. John County, Florida, Mining Engineering, February 1985, pp 144-148. 1985, pp 144-148.

16. Alba, H., C. Brandt, H. Brewer, N. Eickelpasch, H. Kalwa, H. Louis, W. Reiter, "The Application of Abrasive Water Suspension Jets (AWSJ) for the Dismantling of Nuclear Power Plants", Proceedings International Symposium on New Applications of Waterjet Technology, October 19-21, 1999, pp 443-450.

17. Bach, F., "State of the Art of Thermal and Hydraulic Cutting Techniques in Aqueous Environment with Special Consideration of Decommissioning Tasks for Nuclear Faculties", Lehrstull fur Werkstofftechnologie, Fakultal Maschinenbau Universitat Dortmund.

18. Blickwedel, H., R. Decker, H. Haferkamp, and H. Louis, "Submerged Cutting with Abrasive Waterjets", 8th International Symposium on Jet Cutting Technology, Durham, UK, BHRA, 1986, paper 27, pp265-268, ISBN 0-947711-17-1 (abrasive waterjets were used to cut structured steel under water successfully).

19. Echert, D., M. Hashish and M. Marwin, 1987, "Abrasive Water Jet and Water Jet Technique for Decommissioning Nuclear Facilities", Proceedings 4th U.S. Water Jet Symposium, Berkeley, Water Jet Technology Assn.

20. Echert, D., M. McDonald and D. Monserud, "Underwater Cutting by Abrasive-Waterjet", Oceans 89, Part 5, pp 1562-1566. Available from IEEE Service Center, Piscataway, NJ, publication N89CH2780-5.

21. Echert, D., M.C. McDonald and D.O. Monserud, 1989, "Underwater Cutting by Abrasive Water Jet", Proceedings of Conference Oceans '89, Seattle, pp 1562-1566.

22. Haferkamp, H., H. Lewis and G. Meier, "Cutting of Contaminated Material by Abrasive Waterjets Under the Protection of Water Shield", Proceedings of the 9th Symposium on Jet Cutting Technology, Sendai, Japan, 1988, paper F1, pp 271-288.

23. Haferkamp, H., H. Louis and G. Meier, "Abrasive Waterjet – an Adaptable Tool for Different Purposes in Hazardous Environments", Proceedings of Second International

Conference on Decommissioning Offshore and Nuclear Works, Manchester, UK, April 1990, pp 28-34.

24. McGough, M., W. Austin, G. Kneth, "Underwater Plasma Arc Cutting in Three Mile Island's Reactor", Welding Journal, Vol. 68, No. 7, June 1989, pp 22-27 (a five axis teleoperator delivered plasma arc cutting, rotary grinding and abrasive waterjet cutting of end effector complex geometry sectioning was completed in a mockup facility at pressure conditions simulating a hole in the reactor vessel, prior to actual in-vessel operation. This paper presents the details of the in-vessel cutting efforts).

25. McGough, M.S., W.K. Austin and G.J. Knetl, "Underwater Plasma Arc Cutting in the Three Mile Island Reactor Welding Journal, Vol. 68, No. 7, July 1989, pp 22-27.

26. Reiter, W, H. Kalwa, H. Brehmor, "Dismantling of the Core Shroud Bottom and the Thermal Shield of the Pressure Vessel of the VAK Using Water Jet Cutting Techniques, Proceedings of the Annual Meeting on Nuclear Technology '98, Munich, Germany, May 26-28, 1998, pp 479 (in German).

27. Usii, Shinichi, Toshihiro Komiyo, "Development of Spent-Controlled Rod Cutting Equipment by Abrasive Waterjet", Fapig (Tokyo), No. 156, 2000-11, pp 3-9 (in Japanese) (300Mpa abrasive waterjet cuts remotely underwater).

28. Martinec P., Foldyna J., Sitek L., Scucka J., Vasek J.,"Abrasives for AWJ Cutting," Institute of Geonics, Academy of Sciences of the Czech Republic, Ostrava, 80 pp.

29. Domann, H., C. Von Minder, (1991) "Abrasive Jet Cutting Down to 600 m Water Depth, Proceedings 3rd International Symposium on Underwater Technology, Geesthacht, paper 19, pp 1-8.

30. Haferkamp, H., H. Louis and G. Meier, "Deep Sea Application of Abrasive Water Jets: Feasibility and Limitations", paper E3, Proceedings of the 10th International Symposium on Jet Cutting Technology, 1990, Amsterdam, Holland, pp 513-523.

31. Alberts, D. and M. Hashish, "An Observation of Submerged Abrasive Suspension Jet Cutting for Deep Ocean Applications", 8th American Water Jet Conference, Houston, Texas, 1995.

32. Bailey, M., 1992, "In Deep Water with Diajet", BHR Group News, No. 2.

33. Odds, D.J.H., "Water Jetting Under the North Sea", Fourth International Symposium on Jet Cutting Technology, 1978, paper H3, pp H3-39 to H3-46.

34. Oil States MCS, promotional literature, Abrasive Water-jet cutting for platform removal and well abandonment, Oil States MCS, Houston, TX 1997, 7 pages.
see also http://www.oilstates.com/osmcs.html

35. Raghavan, C., "Offshore Platform Decommissioning with UHP Abrasive Waterjets", 5th International Conference on Water Jet Technology, February 3-5, 1998, New Delhi, India, pp 396-406, Allied Publishers, New Delhi.

36. Raghavan, C., J. Olsen, C. Anderson and L. Lander, "Method and Apparatus for Cutting Metal Casings with an Ultra High Pressure Abrasive Fluid Jet", U.S. Patent 5,381,631.

37. Meyer T. and Hood M. "Waterjet drill for tight radius drilling operations", 16th International Conference on Water Jet Cutting, 16-18 October, 2002, Aix-en-Provence, France, pp. 463 – 476.

38. Meyer T., Carvanas P., Alehossein H., Hood M., Adam S., and Gledhill M. "The Effect of Nozzle Design on the Erosion Performance of Cavitating Water Jets," International Symposium on New Applications of Water Jet Technology, October 19-21, 1999, Ishinomaki, Japan, pp. 33 – 41.

39. Mazurkiewicz M. & Davey C., "High pressure liquid jet mill for creating ultra-fine particles of materials, International Conference on Water Jet Cutting, 16-18 October, 2002, Aix-en-Provence, France, pp. 547 - 556.

40. Shimizu, S. and L.Z. Wu, "Erosion due to Premixed Abrasive Waterjet", 12th International Conference on Jet Cutting Technology, Rouen, France, 1994.

41. Shimizu, S., "Erosion due to Premixed Abrasive Waterjet Under Submerged Conditions", 4th Pacific Rim International Conference on Water Jet Technology, Shimizu, Japan, 1995.

<u>Parametric Studies</u>

42. Miller, A., D. Daly and S. Connors, "Reach Enhancement of a Submerged Waterjet Using Air Shrouding", Proceedings of the Ninth American Water Jet Conference, Aug. 23-26, 1997, Dearborn, Michigan, paper 24, pp 347-363.

43. Savanick G.A., Krawza W.G., and Swanson D.E. "An abrasive jet device for cutting deep kerfs in hard rock," 3rd American. Conference on Water Jet Cutting, Pittsburg, PA, pp. 101 – 122.

44. Savanick G.A. & Krawza W.G., "An abrasive waterjet rock drill," 4th American Water Jet Conference, Berkeley, CA, August 1987, pp. 129 – 132.

45. Savanick G. "An abrasive-enhanced water-jet drill and kerf-cutter for hard rock." Proceedings of the Conference on Shaft Drilling Technology, Las Vegas, Nevada, April 24-26, 1991.

46. Miller A.L Kugel R.W. and Savanick G.A. “The dynamics of multi-phase flow in collimated jets,” 5th American Water Jet Conference. August 29-31., 1991, Toronto, Canada, pp. 179 – 189.

47. Miller A.L. and Archibald J.H., “Measurement of particle velocities in an abrasive jet cutting system,” Proceedings of the 6th American Water Jet Conference, August 24 – 27, 1991, pp. 291 – 304.

48. Alberts, P.G., M. Hashish and R.C. Lilley, “Experimental Studies of Deep Ocean Cutting with Abrasive Jet Systems”, 12th International Conference on Jet Cutting Technology, Rouen, France, 1994 (presents the results of investigations of the use of VHP, direct-pumped abrasive suspension jets and modified entrainment-type AWJ for cutting up to 600 m of water).

49. Okita Y., Nakamura K., Nishimoto K. and Yanasaka N., “Performance of Abrasive suspension jet nozzles with a singular annular conduit.” 6th Pacific Rim International Conference on Water jetting Technology, Sidney, Australia, October 9 – 11, 2000, pp 111 – 114.

50. Howells, W.G., “Enhancing Waterjetting by the Use of Water Soluble Additives in Water Jet Applications”, Construction Engineering, A.W. Momber, Editor, A.A. Balkema, Publisher, Rottendam, Netherlands, (1988) ISBN 9054106480.

51. Howells, W.G., “Polymer Blasting with Super-water”, from 1974-1989 A Review, International Journal of Waterjet Technology, Vol. 1, No. 1, March 1990, pp 1-16.

52. Howells, W.G., “Super-water”, Jetting Applications from 1974-1999, Proceedings of the 10th American Waterjetting Conference, Aug 14-17, 1999, Houston, Texas, pp 363-380.

53. Domann, H., E. Aust, G. Schultheiss, “Waterjet Cutting Investigation on Underwater Process Technology and Application”, Schweissen und Schneider, Vol. 42, No. , December 1990, pp 646-650 (in German) (Underwater cutting of high strength low alloy steels).

54. See references 22, 23 and 30.

55. Surle, R.J., 1991, “Hyperbaric abrasive-Water Cutting Trials for Offshore Industrial Applications”, Proceedings of 10th International Symposium on Jet Cutting Technology, (ed. E. Saunders) Elsevier.

56. See reference 31

Other References not cited in the precis
57. Albertson, M.L., Y.B. Dai, R.A. Jensen and Hunter Rouse, “Diffusion of Submerged Jets”, Proceedings American Society of Civil Engineers, Vol. 74, No. 10, December 1948 (Good treatment of high velocity submerged jet – analytical and engineering data).

58. Andersen, C.B., “Underwater Cutting”, Svejsning, Vol. 15, No. 2, pp 13-16, 1988 (in Danish) (also, plasma and waterjet cutting techniques and equipment described depths to 60 m).

59. Baumann, V., “The Execution of Soil Improvement Method Utilizing Water Jet”, paper III-3, International Symposium on Water Jet Technology, Tokyo, Japan, December 1984, Water Jet Technology Society of Japan.

60. Brandt, C., H. Louis, G. Meier, G. Tebbing, “Abrasive Suspension Jets at Working Pressures up to 200MPa, Proceedings of the 12th International Symposium on Jet Cutting Technology, Rouen, France, 1994, Cranfield, UK, BHR Group Limited, 1994.

61. Cheung, J., G. Hurlburt, 1976, “Submerged Water-Jet Cutting of Concrete and Granite”, Proceedings 3rd International Symposium on Jet Cutting Technology, Chicago, Illinois, BHRA, 1976, paper E5, pp 49-62.

62. Cobb, G.C. and Zublin, C.W., Petroleum Engineer International, October 1985, pp 159-166.

63. Conn, A.F. and V.E. Johnson, Jr., “The Fluid Dynamics of Submerged Cavitating Jet Cutting”, Proceedings of the Fifth International Symposium on Jet Cutting, paper A1, pp 1-14.

64. Damon, H.E., E. Aust and J. Alba, Experimental Research on Jet Cutting for Subsea Applications”, Proceedings of the 10th International Symposium of Jet Cutting Technology, Amsterdam, Holland, 1990, paper E1 (comparative AWJ steel cutting laboratory tests at simulated depths of submergence up to 150 m).

65. Eddingfield, D. and M. Albrecht, “Effect of an Injected Shroud on the Breakup Length of a High Velocity Waterjet”, Erosion Protection and Useful Application, ASTM STP m664, Ed. By W. Adler, Amer. Soc. for Testing and Materials, pp 461-472, 1979.

67. Gelfort, E., J. Mischke, H. Blickwodel, and H. Haferkamp, “Submerged Cutting of Nuclear Fuel Elements by High Speed Water Jets”, papers presented at 8th International Symposium on Jet Cutting Technology, Durham, England, 1986, paper 32, pp 315-322.

68. Guo, N., A. Laurinat, H. Louis and G. Meier, 1992, “Assistance for the Application of Abrasive Water Jets”, Proceedings of International Conference on Geomechanics, 91, Hradec (ed. Z. Rakowski), A.A. Balkema, Rotterdam-Brookfield.

69. Howes, J., “Flying High with the Jet Set”, Oilman, Oct. 1987, pp 44. (Describes abrasive jetting equipment and its application to concrete and steel cutting and cleaning apparatus off shore. One example given is the removal of one of Conocos V-fields accommodation jacket platforms.)

70. http://www.norse-group.no/right.htm

71. http://web.cvut.cz/fme/k212/personnel/tesar/skripta/i12na.htm
Basic Turbulent Shear Regions, Turbulent Submerged Jet.

72. http://www.ec-decom.be/europe/related/contractor/u/uwth/fi1d0069.htm
Contract no. FI1D-0069; reference no. EUR 12684; working period July 1987 - March 1989; contractor(s) University of Hanover, Germany.
A special cutting head for underwater use was designed and built. Tests were carried out to find out useful parameters for submerged cutting. With regard to the production of secondary waste the abrasive flow rate had to be minimized. It seems to be useful to realize this demand by using a small water jet nozzle (up to 0.4 mm diameter) and a high pressure (up to 4000 bar) with an optimal abrasive flow rate of about 5 g/s. In case of a higher ambient pressure a decrease of the cutting performance was measured. But this decrease is not important regarding decommissioning because the ambient pressure is less than 2 bar. An air mantle nozzle was adapted to the cutting head to improve the working distance under water. The air mantle surrounding the abrasive jet lowers the friction between jet and surrounding water and increases the cutting efficiency in case of greater working distances.

73. Kulumuck, K, G. Chahine and, and C. Frederick, “Influence of Ambient Pressure and Nozzle Shape on Submerged Waterjet and Spreading”, paper 16, 7th American Waterjet Conference, Seattle, Washington, 1993, pp 231-262.

74. Labus, T.J. and J.A. Hilloris, IITRI Research Report DG103 (Final Report) ITT Research Institute, Chicago, Illinois, January 1976.

75. Lalande A. and J. Allen, “Method and Apparatus for Removing Mud from Around and Inside of Casing”, U.S. Patent 5,360,292.

76. Liu, B., Yang, Q., Jia, B. and Zhang, D., “Submerged Cutting Experiments with the Premixed Abrasive Jet”, 12th International Conference on Jet Cutting Technology, Rouen, France, 1994, p 701.

78. Mei, F. and Y. Wu, “On Study of Underwater Cutting – Using Waterjet Techniques”, International Conference on Underwater Welding, March 20-21, 1992, New Orleans, Louisiana, published by American Welding Society, pp 40-53.

79. Meier, G., G. Pilot and H. Layer, 1992, “Abrasive Jet Cutting Technology from the Stage of Laboratory into Real Application”, final report, res. contract, no. F12D-0009.

80. Melaugh, J.F., “The Effects of Confining Pressure on the Jet Erosion Cutting of Rock”, M.S. Thesis, The University of Tulsa, 1972.

81. Murai, H., S. Shitzu, A.L. Wu and H. Noguchi, “Structure of Submerged Water Jet and Erosion of Materials – Compared with Jet in Air”, 4th Pacific Rim International Conference on Waterjet Technology, Shenzu, Japan 1995.

82. Pardley, P.H., C. Eng, “Underwater Application of Continuous Water Jet”, 3rd International Symposium Jet Cutting Technology, paper G1, BHRA, March 1976.

83. Rouse, H., 1966, “Jet Diffusion and Cavitation”, Journal of the Boston Society of Civil Engineers, Vol. 53, No. 3, 255-271.

84. Sato, H., H. Soyma, Y. Yamauchi, R. Oba, R. Oshima, “A Study of Peening by Submerged Ultra-high Speed Water Jet”, in Jet Cutting Technology, Vol. 13 ed. By A. Lichtarowicz, Kluwer Academic Publishers, 1992, pp 413-424.

85. Shen, Z. and Q. Sun, Study of Pressure Attenuation of a Submerged Non-Free Jet and a method of Calculation of Bottom hole Hydraulic Parameters, SPE Drilling Eng., pp 68-76, March 1988.

86. Sonson, E. F. Anderson and R. Fabbri, 1989, “High Pressure Jetting of Shifting Offshore Structures”, Proceedings Offshore Technical Conference, Houston, Texas, Vol. 1, 511-517.

87. Summers D.A. and Zakin J.L. The Structure of High Speed Fluid Jets and their use in cutting various soil and material types,” Final Report to U.S. Army Mobility Equipment Research and Development Center, DAAK02-74-C-0006, April 30, 1975, 220 pp.

88. Summers, D.A. and Sebastian, Z., “Considerations in the Use of Waterjets to Enlarge Deep Submerged Cavities,” 5th Int. Jet Cutting Symp., Hanover, W. Germany, June, l980.

89. Summers D.A. & Lehnhoff T.F. “The design of a water jet drill for development of Geothermal resources,” Final report DOE EY 76 S 02 2677.M003, Sept. 1978, 224 pp.

90. Summers, D.A., Lehnhoff, T.F., and Weakly, L.A., “Development of a Water Jet Drilling System and Preliminary Evaluations of its Performance in a Stress Situation Underground,” 4th International Symposium on Jet Cutting Technology, Canterbury, England, April, l978.

91. Brandt C., Brandt S., Louis H., Milchers W., and Ch von Rad, “Application of abrasive water suspension jets for nuclear dismantling,” 14th International Conference on Jetting Technology, Brugges, Belgium, 21 – 23 September 1998, pp. 467 – 476.

92. Cheung, J., G. Hurlburt, 1976, "Submerged Water-Jet Cutting of Concrete and Granite", Proceedings 3rd International Symposium on Jet Cutting Technology, Chicago, Illinois, BHRA, 1976, paper E5, pp 49-62.

93. Anon, "Conjet repairs pipelines on the sea floor," Jet News, April 1995, p. 3

94. You Ming-quing, Sing Yufeng, Liu Wei, Au Hoshen, "A study of DIAjet nozzle wear," Proceedings of the 13th International Conference on Jet Cutting Technology, Publication 21, Cagliari, Sardinia, 29 – 31, 1996, pp. 45 –

95. Domann H., Aust E., Alba H. "Experimental Research on Jet Cutting for sub-sea applications" Proceedings of the 10th International Conference on Jetting Technology, 1991, pp. 489 – 498.

96. Alba H. "Abrasive Sub-sea cutting", promotional videotape, Alba Industries, Hinterdan Kirschkaten 32, D-23560 Lubeck.

Note: These following references are from another Task 2 report by Dr Summers (UMR):

97. May P.R. *Origins of Hydraulic Mining in California*, 1970, 1st ed: Holmes Book Co. Oakland, CA.

98. Maurer W.C., *Advanced Drilling Techniques*, 1st ed.; Petroleum Publishing Co.

99. Killalea M. 1989, High Pressure Drilling System Triples ROPs, Stymies Bit Wear, *Drilling, March/April.*

100. Deily F.H. J.K. Heilhecker, W.C. Maurer and W.W. Love 1977, A Study of High Pressure Drilling, *Drilling Technology Conference, New Orleans, LA.*

101. Summers D.A. C.R. Barker and H.D. Keith 1979*, Preliminary Evaluation of a Water Jet Drilling System for Application in In-situ Gasification*, Contract Final Report to Sandia Laboratories, April, 66 pp.

102. Barker C.R. and K.M. Timmerman 1981, Water jet Drilling of Long Horizntal Holes in Coal Beds, *Proceedings 1st U.S. Water Jet Symposium*. April, Golden CO III.2.1 to III-2.10.

103. Dunn P and T Meyer 1999, High Pressure Waterjet Drilling Technologies for In-seam Drainage. In *Proceedings of the International Symposium on New Applications of Water Jet Technology*, Ishinomaki, Japan, 391-398.

104. Anon 1986, Hydrodemolition Speeds Bridge Deck Reconstruction, *Roads, and Bridges Magazine*, March.

105. Hashish M. 2000 Advances in Surface Preparation, Jet machining and Food Processing, in *Proceeding of the 6th Pacific Rim International Conference on Water jet Technology*, October 9-11, Sydney, 18 – 30.

106. Summers D.A. J. Yao, J.G. Blaine, R.D. Fossey and L.J. Tyler 1992 Low Pressure Abrasive Waterjet Use for Precision Drilling and Cutting of Rock in *Proceedings of 11th International Symposium on Jet Cutting Technology*, September, St Andrews, 233- 251.

107. Fairhurst R. M. R.A. Heron and D. H. Saunders 1986 DIAjet – A New Abrasive Waterjet Cutting Technique, *Proceedings of 8th International Symposium on Jet Cutting Technology*, September, Durham, 395 – 402.

108. Mann M.D. 1998 *High Pressure Jet Pump Conveyance Optimization*, MS Thesis, Department of Mining Engineering, University of Missouri-Rolla.

109. Summers D.A. 1995 *Waterjetting Technology*, 1st ed, E & FN Spon, London.

LIST OF ACRONYMS AND ABBREVIATIONS

ASJ- Abrasive Slurry Jetting
CCT- Composite Coiled Tubing
CT- Coiled Tubing
CTD- Coiled Tubing Drilling
DOE- Department of Energy
FLASH ASJ- patent pending drilling fluids, solids and pumping systems
MHCT- Microhole Coiled Tubing
MHCT D- Microhole Coiled Tubing Drilling
MHT- Microhole Technology
MST – Missouri University of Science and Technology
TVD- True vertical depth
UBD- underbalanced drilling
UMR- University of Missouri at Rolla

Fpm- feet per minute
Ft- foot
Gpm- gallons per minute
Psi- pounds per square inch pressure
In- inch
KPa- Kilo Pascals
K- Power Law constant for mud rheology
MPa- Mega Pascals
lps- liters per second
m- meter
m^3- cubic meter
N- Power Law exponent for mud rheology
Pa- Pascals
Scfm –standard cubic foot per minute

APPENDIX LIST

A. Contact Information for Investigators
B. UMR Literature Search and Review
C. Missouri University of Science and Technology Final Report

APPENDIX A
CONTACT INFORMATION

IMPACT Technologies LLC
Kenneth D. Oglesby, P.E.
918.627.8035
kdo2@impact2u.com

Missouri University of Science and Technology
Dr. David A. Summers
573. 341.4368
dsummers@mst.edu

APPENDIX B
Literature Search by Dr. D. Summers at MST

A Summary of the Existing Literature Concerning Submerged and Sheathed High Pressure Waterjets and Ways of Enhancing Their Performance

Introduction

The literature describes both laboratory investigations and studies of practical applications of submerged jets in the field. For ease of interpretation the literature reviewed has been divided into segments, bringing together the references in to three groupings. Although some studies cross over from one section to another, they have been listed where it was felt most appropriate.

The initial segment covers laboratory investigations, including theoretical fluid mechanical studies as well as experimental parametric evaluations. These studies of the fluid mechanics of turbulent submerged jets are discussed below under “Theoretical and Basic Studies”.

Descriptions of practical applications of submerged jets include slurry jetting for civil engineering applications such as the emplacement of grout; the decommissioning of nuclear facilities and for deep ocean applications such as the maintenance and decommissioning of offshore oil platforms. These applications are discussed below under “Applications of Submerged Jets”

The “Parametric Studies” section includes studies of: air shrouds around waterjets and abrasive waterjets; direct injected abrasive jets; the effect of confining pressure on jet erosion; the use of chemical additives to enhance the reach of waterjets and abrasive jets; optimization of nozzle design for submerged jets; cutting of rocks, concrete and steel with submerged jets; and the diffusion of submerged jets.

Theoretical and Basic Studies

The cutting process discussed is one in which high-pressure waterjets are mixed with an injected abrasive to form a slurry jet that is accelerated to a designed velocity at which it strikes the target and begins to cut. Although the initial design for the abrasive slurry jet has been assigned to Fairhurst (1) in 1982, there was a significant body of work available prior to that time. The initial study by Leach and Walker (2) included work on nozzle design and the need for high levels (around 0.15 micron) of surface finish and smoothness of flow in nozzle construction. Selberg and Barker (3, 4) validated these conclusions and showed that jet throw could be significantly increased, where care is taken with the entrance flow path. The importance of having a straight section to stabilize flow was shown by Kovscek et al (5) who showed that a 10 cm straight section ahead of the nozzle was effective, a distance not available in this case.

Lohn and Brent (6, 7) analyzed the fluid mechanics related to the energy losses incurred by a waterjet cutter operating in the confines of a well casing. They designed improved nozzles and an efficient means of changing the direction of water flow immediately upstream of the nozzle, using turning vanes and showed that they could achieve equivalent performance as a “straight” inlet to a throw distance of 30 ft. White (8) analyzes viscous fluid flow. Tesar (9) analyzes the turbulence engendered by the issuance of a waterjet into water.

Erdmann-Jesnitzer et al (10) examined the effect of nozzle configurations on the performance of a waterjet under water. The study revealed that nozzles with a conical contraction angle of 60 degrees and a straight section half the diameter of the orifice exit are the most suitable for cutting with a submerged waterjet.

Brandt et al (11) studied the acceleration of abrasives in suspension jet nozzles. The study showed that the cutting efficiency of short nozzles is higher than that of long nozzles and that increasing the length of the cylindrical part of the nozzle increases the jet coherence. Yazici (12) found that the use of long nozzle designs had little benefit in drilling operations where the nozzle was very close to the target, although Summers et al (13) have shown that where the jet is allowed to properly accelerate a 700 bar ASJ will give as much energy to abrasive at the same water and abrasive feed rates as a 2,800 bar conventional abrasive waterjet system (AWJ).

<u>Applications of Submerged Jets</u>

Yahiro and Yoshida (14) found that grouting operations with a slurry jet is aided by the addition of air to the jet. Their work involved the optimization of downhole induction grouting with a 2-mm diameter, 700 bar jet surrounded by an annular airflow of up to 250 cfm. Their data showed nearly a 500% improvement in downstream centerline jet impact pressures at a standoff distance of 15 cm. Although the waterjet reach improved steadily as the flow increased from zero to 180 cfm, a trend of asymptotically diminishing returns also appeared i.e. up to 400% improvement was measured with airflows of only 21 cfm. Beyond 180 cfm the added air destabilized the waterjet.

Savanick(15) showed that an air shroud increased the useful range of a 2.5-cm diameter submerged waterjet to about 5.4 m in a borehole phosphate mining operation. In this operation phosphate was mined remotely from the surface through a 72 m-deep borehole .The submerged cutting jet pressure ranged from 70 to 133 bar and the corresponding flow rate was 1700 to 2000 lpm. The air shield pressure was 175-bar and the corresponding air shield flow rate was 150std cfm.

Alba et al (16), Bach(17),Blickwedel et al(18).Eckert et al (19, 20, 21), Haferkamp et al(22, 23), McGough et al (24, 25) , Reiter et al(26) And Usii et al(27) discuss the application of abrasive suspension jets for the dismantling of nuclear power plants. This work demonstrated that it is possible to increase the working distance of the submerged jet by using an air shield.

An important problem in these applications is the lifetime of the nozzle which is limited because of wear. It is necessary to choose the cutting parameters to achieve a balance between the cutting efficiency (which is normally associated with higher wear) and nozzle life. The nozzle must last long enough to complete the cutting job.

The selection of the abrasive might be useful in achieving the balance described above. Recently Martinec et al (28) investigated the cutting efficiency and wearing effects of a series of abrasives used in abrasive jet cutting. Garnet was found to be the most efficient cutting abrasive, followed by olivine. However, olivine gave a 25% longer nozzle life than olivine, and can be significantly cheaper to purchase. Thus, in certain cases, olivine abrasive can be a suitable, less expensive alternative to garnet abrasives for cutting metals.

Domann et al (29),Haferkamp et al (30) ,Alberts et al (31), Bailey(32), and Olds (33) discuss subsea applications of waterjets. These applications include cleaning and cutting under water. Cutting applications include severing pipes under the seabed. Cemented pipe strings which have been severed by an abrasive jet are shown by Oil States MCS (34) and Raghavan (35). These pipe strings are severed below the mud line when the offshore platforms are decommissioned. The literature search revealed no instances where uncemented, nested pipe strings have been severed by an abrasive jet.

Raghavan et al (36) have patented a method and apparatus for using an abrasive jet to cut piles and conductors under offshore oil production platforms.

In a related field Meyer et al (37, 38) have been drilling coal at depth and have found that cavitation around the submerged jet can impact performance. Because Mazurkiewicz (39) has shown that cavitation is a very powerful crusher of particles, the effect of cavitation on ASJ performance underwater, briefly discussed by Shimizu (40, 41) needs further investigation.

Parametric Studies

Miller et al (42) demonstrated the use of an air shroud to increase the reach of a submerged water jet using an air shroud flow rate of 280 cfm. Improvement with waterjet reach was found to correlate strongly with volume flow rate of air at standoff distances between 10 and 180 nozzle diameters from the nozzle. At greater standoff distances no improvement was measured.

Savanick et al (43) demonstrated that it is possible to increase the effective reach of an abrasive jet by collimating it i.e. by enclosing it in a pipe (44, 45). This phenomenon was used to build an abrasive jet drill one-inch-diameter holes in hard rock to a depth of 4.5-m. Miller et al described the physics of three-phase flow in a collimating pipe (46) and measured the velocity of abrasives in the collimation pipe (47).

Ultrahigh–pressure, direct-pumped abrasive suspension jets were compared with entrainment-type abrasive waterjets for cutting under up to 6000 m of water by Alberts et al(48). This paper showed that the abrasive suspension jet system is more effective and easier to operate in the laboratory and potentially in the field.

Okita et al (49) evaluated nozzle wall wear of three types of abrasive suspension jet nozzles: a conventional suspension jet nozzle and two nozzles with a conventional suspension jet nozzle fitted with annular conduits.
Howells (50, 51, 52) reviewed the use of polymeric additives for jet collimation and abrasive suspension. Jets collimated with chemical additives carry further than ordinary jets and thus have been useful in fire fighting. Polymers have also been useful for suspending abrasive particles and to form a coherent suspension jet.

Dormann et al (53) describe underwater research with abrasive jets aimed at development of undersea robots. Cutting was performed to a simulated depth of 600 m. Haferkamp et al (54) discuss the deep sea applications of abrasive waterjets produced by injection of the abrasives at the cutting head. This research points up the limitations of this kind of abrasive jet at greater water depths and indicates that premixed jets such as the DIAJET are more suitable for working in the deep sea. Surle (55) performed abrasive jet cutting tests in a pressure chamber. This research indicates that abrasive jet cutting is reliable at depths up to 400 to 500m and that the direct injection of pressurized slurry is more efficient and practical to use than other methods of transporting abrasive to the cutterhead.

Alberts and Hashish (56) evaluated the performance of directly pumped abrasive suspension jets in a test chamber that simulated ocean depths up to 6100 m. They recommend using an air shroud around the submerged jet.

Bibliography

Note: all bibliography references from this section are fully reported in the BIBLIOGRAPHY section of this report.

APPENDIX C

The Use of Dispersed Abrasive Slurry Jet System for Rock Drilling

A Final Report to

Impact Technologies LLC

by

D. A. Summers, R. Fossey, G. Galecki, P. Nambiath

High Pressure Waterjet Laboratory
Rock Mechanics and Explosives Research Center
Missouri University of Science & Technology

Executive Summary

The High Pressure Waterjet Laboratory (HPWL) at the Missouri University of Science & Technology (Missouri S&T) has developed a novel tool for drilling through rock, using a new nozzle configuration and cutting fluid. Laboratory experiments have demonstrated that the high-velocity, abrasive-laden jet produced can drill a hole through a variety of rock types that is larger than the drilling nozzle assembly, allowing the drill to advance, without rotation, into the hole created. Within the period of this work the following improvements to the technology have been achieved:

- Parameters have been identified, and experiments have demonstrated that this hole can be increased in size (from an originating jet with a diameter of 0.039 inches) to more than 2-inches in diameter.
- By changing the driving fluid to liquid carbon dioxide, an accelerated jet is produced that increases the rate of penetration and reduced the specific energy of penetration to 110 joules/cubic cm.
- In the short laboratory tests ROP of up to 8.9 ft/min in limestone, 15.0 ft/min in Missouri dolomite, and 3 ft/min in basalt have been achieved.
- Experiments to develop optimal operating conditions for the new nozzle design and new injection system will be required and these will provide data on component wear and operational lifetime to feed the cost model for this system.
- The simplicity of the design and the relatively low cost of the components (nozzle bodies cost around $100) and a life anticipated to be around 40 hours with current materials, suggest that operational costs will be at an acceptable level.

The above figure for preliminary drilling efficiency is not yet optimized, but gives some measure of the level of energy required for drilling in some of the rocks that may be encountered in establishing an oil well.

Table of Contents

List of Figures

List of Table and Charts

1.0 Abrasive Slurry Jet (ASJ) Drilling Overview

The use of high-pressure waterjets to effectively drill holes through rocks is constrained by the pressures required if the jets are to have the capabilities of penetrating all the rocks likely to be encountered in a hole. The pressures needed to penetrate the hardest rocks raise the required operating pressure above that viable with existing tubulars, and the process is economically challenged by the cost of the ultra-high pressure systems that would be needed. However the development, in 1980, of a method for injecting abrasive into the fluid jet stream, made it possible to cut a much greater range of material at lower, though still considerable pressure. That development has led on to the still growing industry known as abrasive waterjet (AWJ) cutting and the capability of precision cutting in a range of materials that includes metals and glass as well as the full suite of rocks.

AWJ technology adds the abrasive to the cutting jet stream at the nozzle, and requires a dry feed of the abrasive to that point, using air as the carrier fluid. This imposes some logistical design problems in developing an AWJ drill capable of drilling deep into the Earth, and some performance issues since the air used as a carrier fluid to bring the abrasive to the nozzle must also be accelerated in passing through the mixing chamber.

Both these problems were solved by the development of the ASJ system in 1984, when Fairhurst enclosed the abrasive within a pressure vessel, and through control of feed water flowing into that chamber, was able to mix abrasive into the feed line between the high pressure water pump and the primary nozzle (Fig. 1).

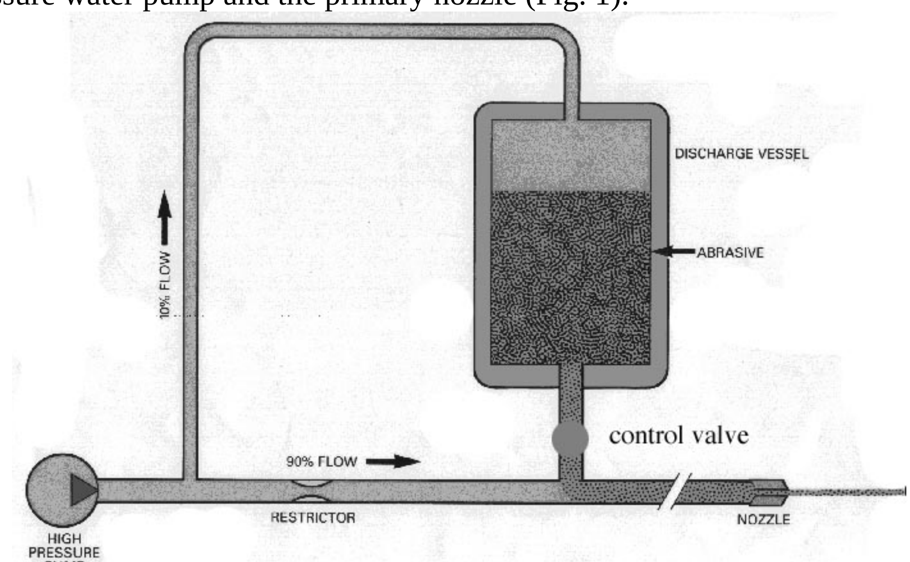

Figure 1. Initial configuration for an ASJ flow circuit

The removal of the air carrier fluid from the system, and the concurrent acceleration of the water and abrasive through the cutting nozzle gave a system that was much more efficient in energy transfer between the water and the abrasive. The result was a jet that could cut through the hardest rock, with a driving pressures of 5,000 psi. The cutting stream from this system, as originally configured, was a narrow jet (typically less than 0.1-inch in diameter) that, while it could cut more than 12-inches into rock, did so with a slot that was not much wider than the jet (Figure 2). Such a slot, or hole, is too small for the supporting nozzle that forms the jet to advance into the hole that has been cut.

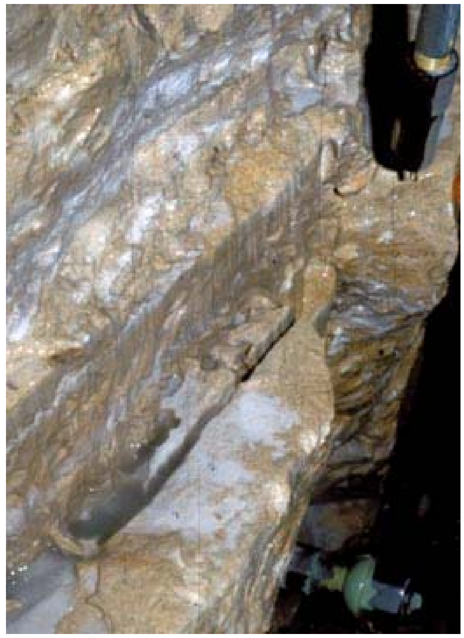

Figure 2. Slot cut through dolomite by an ASJ – although the slot is 12-inches deep it is only about 0.1-inches wide.

To create a hole of sufficient diameter it was necessary that the nozzle be rotated, with the jet offset and inclined outward from the main axis of the drilling assembly and the hole being drilled (Figure 3).

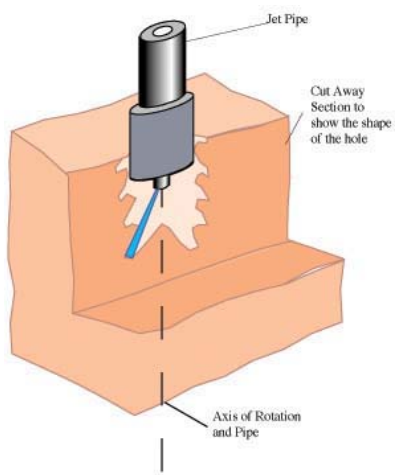

Figure 3. Angled rotation of a jet to create a hole wide enough for the nozzle head.

In the earliest configuration of these nozzles the rotation was provided by firmly attaching the nozzle to the feed pipe, and, with a high-pressure swivel at the entry to that pipe, rotating the entire assembly around its axis.

While this method of rotation can be effective in drilling small holes of limited distance (for example those used for blasting or rock support in mining applications) it becomes an expensive option in drilling deeper holes, since the tubular steel that supports the nozzles must still be broken and remade, as with conventional drilling systems, and this detracts from some of the potential benefits of this new tool. These benefits include a relatively low reaction force imposed back on the drill string through the nozzle as the jet cuts, and an ability to cut forward through rock of varying geology and maintain hole alignment while doing so. These advantages make the marriage of high-pressure drilling and coiled tubing a potentially very successful one, but require an alternate means for generating the larger hole size needed, since coiled tubing itself does not rotate.

There are a number of options that can be considered for resolving this problem, and these will be described in turn, with potential advantages and disadvantages.

Option A – Electric motor drive

Mounting a rotary coupling within in a hollow core electric motor that will provide the rotary motion to the nozzles, and which can be attached to the lower end of the coiled tubing. These motors, such as those built by Kollmorgen, have been used to provide rotation in confined space, Figure 4.

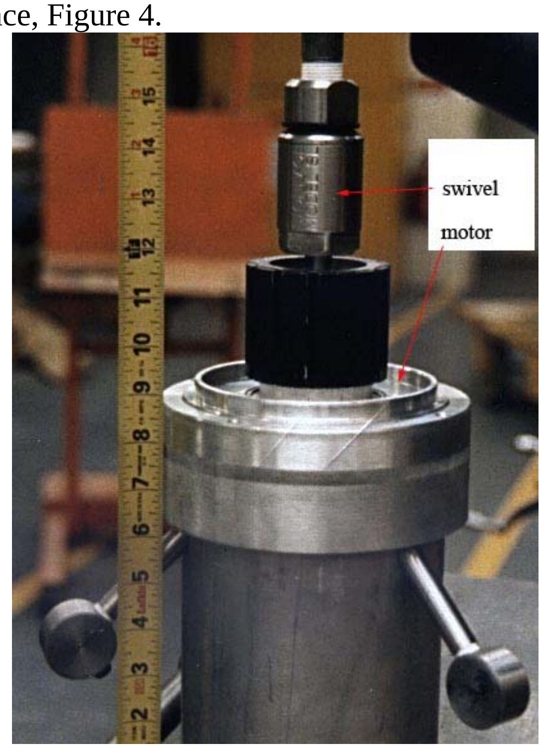

Figure 4. Configuration where a hollow core electric motor surrounds a high-pressure waterjet rotary swivel

While such combinations exist and have been used, in the above case to develop a tool that was used to remove high level radio-active waste, these have only been operated without abrasive in the feed fluid, and the motor sizes that are available in the sealed conditions that would be required for down-hole operation are very restricted. It should be noted however, from the illustration, that rotary swivels to allow motion of the nozzles around the axis of the system are quite small, and can now be obtained with a diameter of less than an inch.

Given the abrasive nature in which the motor is likely to be placed, it is considered that while this is an option, it is an expensive alternative to other possible solutions.

Option B – rotation with a hydraulic motor

An alternative configuration could replace the electrical motor with a hydraulic motor, and there are a variety of such tools that have been developed over time, where the driving fluid can be the mud used to remove the cuttings from the drilling operation, and to keep the drill bit clean, in conventional drilling operations. These motors, in general, are larger than the electrical equivalent, and remain a relatively expensive option.

Option C- self-rotating nozzle assemblies.

One of the advantages of using a fluid jet cutting system is that, with the nozzle assembly held above the rock surface, there is no over-riding frictional forces that will drag on the drive mechanism and require a high level of torque to ensure nozzle rotation. As a result the reaction forces that the jets impose on the nozzle assembly can be used to provide the driving force for the nozzle rotation, negating the need for a driving motor. This principle has been adopted by the high-pressure waterjet manufacturing industry, which has built nozzle and drilling assemblies, where this reaction force is the sole driving force for rotation of the heads. The resulting tools have been successfully used in surface applications, such as, for example, in the cleaning of heat exchanger tube bundles, but have had limited application for drilling applications. They have not been used in drilling deep wells of small diameter, where fluid resistance to motion in the bottom of the well would brake the rotation speed and could lead to the nozzle ceasing to rotate. Nevertheless, where down-hole fluid density is not high, as would be the case with a gaseous carbon dioxide exhaust gas, then the restriction on motion is not likely to be great, and self-rotating nozzles could be used.

The small size of the swivel that would be required to allow this rotation, their relatively low cost (due to widespread use in other industries) and the simplicity of operation makes this a viable candidate for consideration in the design. Most of the swivels that have been used, however, have only been applied with water flowing through the swivel. It has been found that where abrasive is used within this cutting fluid, the passage through the swivel itself should be straight, and a special seal should be placed to stop abrasive entering the passageways containing the bearings. When such precautions are taken then swivel life can be acceptable for this current application.

Option D – Non-rotating dispersing abrasive jets

One of the properties of a liquid carbon dioxide jet that is directed out of a high-pressure line is that as the fluid gasifies in the nozzle assembly it expands in volume, so that the resulting jet that issues from the orifice is larger in diameter than that orifice, and the resulting hole created is also consequently larger (Figure 5).

Figure 5. Carbon dioxide jet carrying abrasive and cutting into Roubideaux sandstone. The orifice diameter is 0.044 inches, jet pressure 3,000 psi, the hole diameter is 0.875 inches, and ultimate depth was 2.75 inches in four seconds.

Production of this jet, using a liquid carbon dioxide feed to the nozzle, and gasification of this fluid within the nozzle itself (a proprietary technology) gives an additional acceleration to the abrasive that is transported to the nozzle in the liquid CO2. As a result the cutting stream is able to cut through rock to significant depth, but concurrently at relatively large nozzle diameters. The concept of being able to use an abrasive laden carbon dioxide fluid as the drilling medium for this application would therefore appear to be of considerable potential benefit, since, in the process, the ability to drill a larger hole than the orifice could mean that it would be un-necessary to rotate the bit, and this in turn would reduce considerably the complexity and cost of the drilling head assembly.

Accepting that this is the potentially most favorable of the options that can be developed a program was undertaken to evolve the design of a system that could achieve the required potential as a means of drilling small diameter holes from coiled tubing. The evolution of this tool can be separated into two parts, the first the evolution of the high pressure slurry pump (HPSP), and the second a methodology for generating a design for a drilling nozzle assembly that will allow creation of a hole that is consistently, regardless of material, of the size required (2.125-inches diameter).

1.2 Large diameter hole drilling with a static drilling head

Nozzle designs that disperse a fluid jet so that it covers a much larger area than the dispersing orifice and nozzle assembly are used in industry for a variety of purposes. Conventional fan shaped nozzles, however, generally have a design that leaves a thin metal thickness at the orifice to give the sharp edge for best jet production. This layer is very vulnerable to wear when the waterjet contains abrasive, so that the functional lifetime of the nozzle is measured in minutes.

An alternative approach is to swirl the fluid as it approaches the nozzle (Figure 6), so that the fluid acquires an angular momentum that it retains passing through the accelerating cone and focusing throat of the orifice. As the resulting jet emerges with this retained component of velocity, the resulting jet is dispersed (and will hereafter be referred to as a Dispersed Abrasive Slurry jet or DASjet for short) (Figure 7).

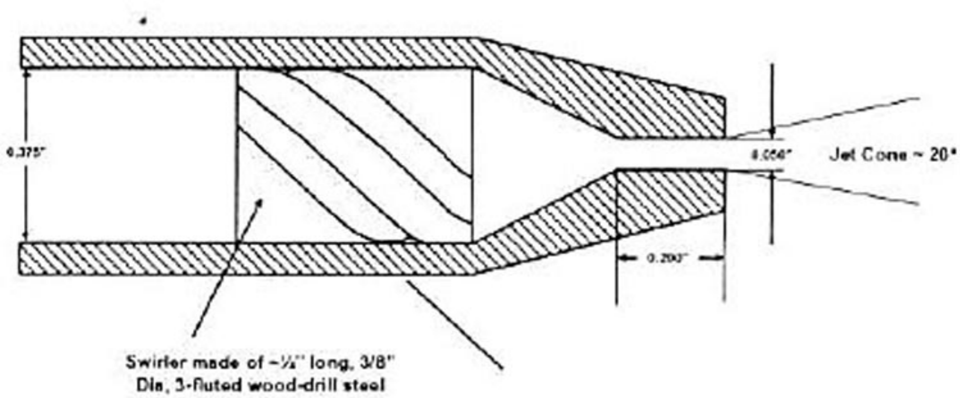

Figure 6. Simplified nozzle assembly to generate a dispersed abrasive slurry jet.

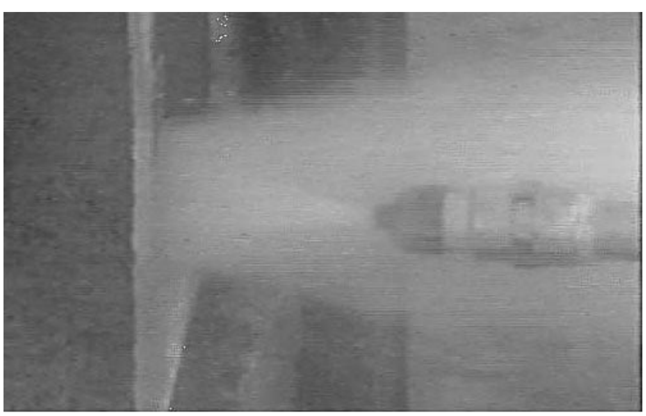

Figure 7. Dispersed Abrasive Slurry jet cutting into concrete, the size of the hole generated can be seen by the edges of the rebounding jet.

This design has a significant benefit for the current purpose because it no longer requires the sharp, thin edge to the orifice of the earlier fan jet designs, but rather has a substantial throat section, which can withstand the additional erosion it becomes subject to form the rapidly moving abrasive particles. In addition the abrasive stream produced is sufficiently dispersed that it will drill holes of diameter 2.0-inch and greater through a variety of rock (Figure 8).

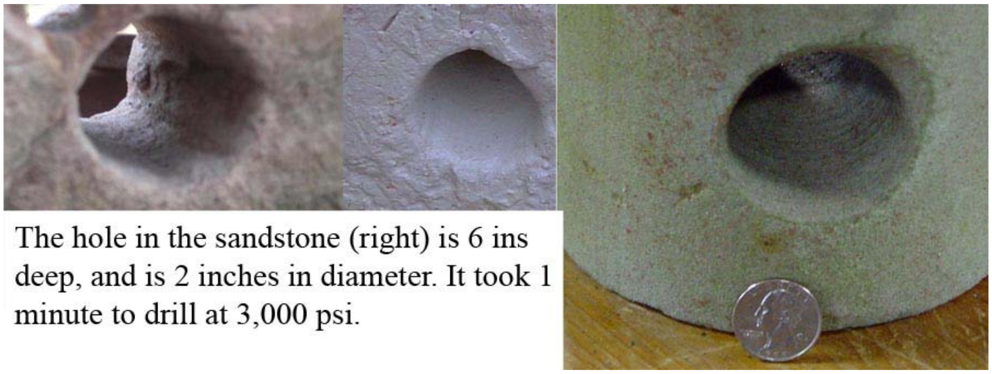

Figure 8. Holes drilled in Roubideaux sandstone, a dolomite and Berea sandstone by a DASjet.

Note that in these early developments of the design tests were carried out with water as the carrier rather than carbon dioxide. The relatively low water flow volume, and operating pressure of this system meant that the holes that were drilled were created with relatively low levels of specific energy (energy required per unit volume of rock removed), the sandstone in Figure 8, for example being removed with a specific energy of around 600 joules/cc.

There are a number of parameters that can be investigated in the control of the shape of the dispersed stream that comes from these nozzles. Two factors were studied, the angle of swirl induced in the water flow into the nozzle and the conic angle of convergence in the cone section leading into the throat of the nozzle.

Increasing both angles were found to significantly improve the overall dispersal of the abrasive to a greater range of diameter than shallow angles (Figure 9), and holes larger than 2-inches in diameter could be generated.

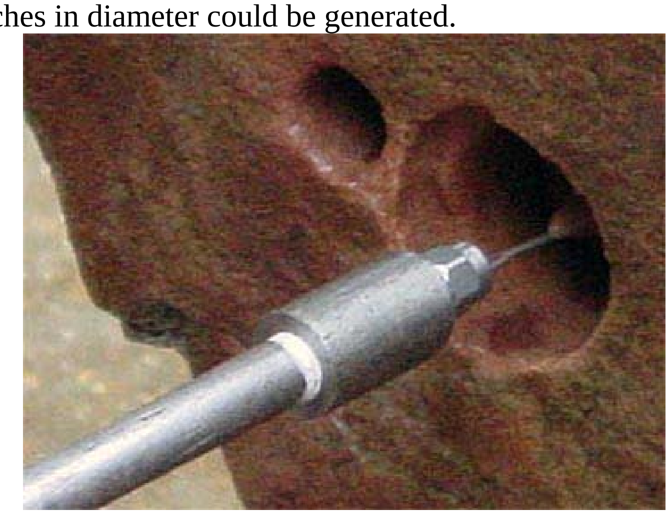

Figure 9. Relative hole diameters with a shallower (left) and steeper (right) turning vane assembly leading into the cone. The high pressure tubing is 1-inch in diameter.

One disadvantage to the use of this system with a high-pressure water carrier for the abrasive is that the resulting hole created becomes full of fluid, and as hole depth increases, so the back pressure in the hole will reduce the relative pressure differential that defines jet velocity, while concurrently the presence of that water between the nozzle and the rock surface will decelerate the individual particles as they pass through it. Thus as back pressure in the system increases with depth, this water-based conventional system will drill holes of reducing diameter.

With a conventional water carrier the nozzle design was changed to include a diverging conic section beyond the throat of the nozzle(Figure 10). One advantage of this design, which carries the diverging cone out to the desired diameter for the hole, is that the drill can no longer advance until the rock ahead of the cone is all removed, and where this is the largest diameter of the entire assembly, then the hole can be gauged to the required diameter as the jet is drilling it. (Keeping the hole at the required diameter is a little more of a concern with a waterjet system than with a conventional mechanical bit, since the cutting takes place away from the mechanical components of the system).

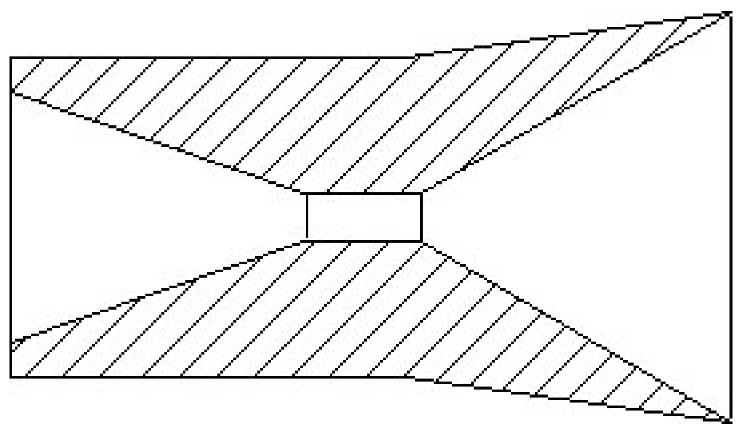

Figure 10. Schematic of a nozzle design with a secondary cone to ensure adequate hole diameter.

While this system gives a hole of the required diameter, it remains susceptible to a reduction in cutting power with depth, because of the attenuation in particle energy as the particle moves through the fluid between the orifice and the rock surface.

An alternative fluid – the use of the liquid carbon dioxide – as the carrier fluid, with the transition of the fluid from liquid to gas within the cutting nozzle overcomes this disadvantage.

The change has the further advantage of clearing the borehole of the cuttings and spent material since the gaseous carbon dioxide, in the larger volume of the transition, has enough kinetic energy as it flows between the annulus and the rock wall to carry all the material out of the hole. As a result the fluid between the nozzle and the rock surface becomes just the gas, and there is no significant loss in kinetic energy when the abrasive travels from the orifice to the rock. This was demonstrated in drilling holes that started initially underwater, and where the expanding gas cleared the zone between nozzle and rock very rapidly. As a result there was no significant difference between the depth of cut where the nozzle was originally underwater, as when it was in air. Unfortunately the turbulence of those tests meant that it was not possible to record the drilling of the holes in the way that was developed to assess the performance of the carbon dioxide jets.

1.3 Testing the concept of carbon dioxide abrasive cutting (COOAC)

In order to assess the performance of the liquid carbon dioxide as a replacement for the water, a number of different tests have been carried out. The tests were carried out in a number of different rock types (and a steel plate). In order to assess the performance of the jets a novel test configuration was created in which the jet was oriented to drill at the side of a block of rock, rather than through the center. In this way as the jet penetrated through the rock, the rebounding jet from the bottom of the hole would project out into the free space, and indicate, by the location of the rebound, where the bottom of the hole was (Figure 11). The drilling events were recorded using a standard digital video camera (from which the images shown were taken). This camera takes 30 images per second and thus, as the drilling is recorded, penetration rates can be established.

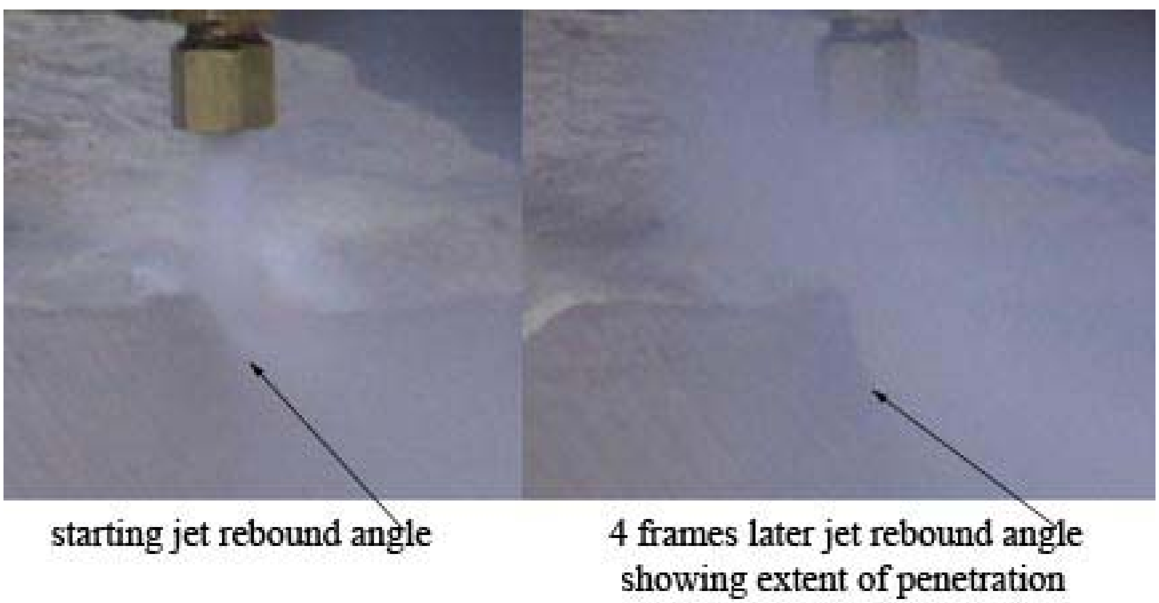

Figure 11. Two frames of video of an abrasive-laden CO2 jet drilling in limestone. The brass fitting is 0.5 inches across to give a measure of scale.

In Figure 11, for example, the hole has deepened from 0.33 to 0.5 inches in 4 frames or 0.12 seconds. This gives an ROP of 1.4 inches/second or 85 inches/minute. In this manner it has been possible to derive the ROP as jets of differing configuration were used to drill through various rock types, and the specific energy of drilling could also be established, knowing the pressure of the jet, and the flow rate of fluid to determine input energy, and the hole diameter and ROP to determine the volume of rock removed.

Consider, for example a test carried out with a 0.03-inch diameter nozzle, at a pressure of 3,000 psi. The hole that was drilled in this early test was 1 cm deep and 2 cm in diameter, giving a total hole volume 3.1 cu. cm. and it was drilled in 6 frames of video. This translates to 0.18 seconds of cutting, and the jet would flow at 1.28 gpm for an equivalent hydraulic horsepower of 2.24. Multiplying by time, and converting into joules leads to a specific energy value of 106 joules/cc. Holes drilled as the system design was improved were significantly deeper (Figure 12).

Figure 12. Hole drilled in Joachim Limestone, to a 4.5 inch depth at 4,000 psi jet pressure and 0.039 inch nozzle diameter.

Because of limitations in the capabilities of the initial system, in which only short batch tests of the drilling capabilities of this new concept could be tested, drilling runs were limited in both jet pressure, nozzle size and system operating time. As a result most holes were drilled with the COOAC running for only a few seconds. In that time it was found possible to drill through rocks in a suite of tests that included Berea sandstone, Joachim limestone, Jefferson dolomite, and basalt. The basalt (Figure 13) was drilled to a depth of 0.5 inches in 24 frames of video, giving a penetration rate of just under 3 ft/min.

Figure 13. Drilling basalt at 4,000 psi COOAC

A measure of the performance of the system can be seen by reference to Table 1.

Rock	Jet Pressure (psi)	Nozzle Dia. (in)	ROP Max (ft/min)	ROP Min (ft/min)	Specific Minimum (j/cc)	Energy Max (j/cc)	Hole Dia. (in)
Roubideaux	3,000	0.044	11.2	2.1	150	810	0.875
Roubideaux	2,500	0.044	17		75		1.00
Roubideaux	3,500	0.044	15.9	3.8	133	560	1.00
Jouchim lls	4,500	0.044	8.9	4.4	350	701	1.00
Joachim lls	4,000	0.039	8.9	8.9	360	360	0.80
Joachim lls	4,000	0.039	11.8	2.5	334	1560	0.71
Joachim lls	4,000	0.039	8.9	1.4	641	4090	0.60
Indiana lls	4,000	0.039	8.9	1.7	360	1890	0.80
Indiana lls	4,000	0.039	9.8	3.9	207	519	1.00
Indiana lls	4,000	0.039	8.9	0.9	230	2,250	1.00
Missouri do	4,000	0.039	14.8	2.1	216	1,488	0.80
Missouri do	4,000	0.039	14.8	3.2	216	992	0.80
Joachim lls	4,000	0.039	3.0	3.0	4,329	4,329	0.40
Joachim lls	4,000	0.039	15.7	2.0	560	4,510	0.50
Missouri do	4,000	0.039	8.9	2.0	736	2,210	0.55
Missouri do	4,000	0.039	7.4	3.0	277	692	1.00
Joachim lls	4,000	0.039	5.9	3.0	6,010	12,030	0.25
Joachim lls	4,000	0.039	13.8	3.9	410	1,443	0.6
Missouri do	4,000	0.039	17.7	2.0	721	6,490	0.40
Missouri do	4,000	0.039	9.8	5.9	320	540	0.80
Basalt	4,000	0.039	3	-	3,000	-	0.5

Table 1. Performance of a conventional abrasive COOAC in various rocks. Roubideaux is Roubideaux sandstone, a local rock, with a reported unconfined compressive strength of 3,700 psi. Joachim limestone is from the St Louis region, and has a UCS of 2,000 psi.

Indiana limestone (Bedford limestone) has a UCS in the range from 8-10,000 psi. Missouri dolomite is local and quite variable in strength but runs around 17,000 to 19,000 psi UCS. The basalt strength is unknown, but values above 30,000 psi are reported.

Ideal flow rates (gpm) for the nozzle can be calculated, with a 0.85 discharge coefficient:

Nozzle Dia		Jet Pressure	(psi)		
(ins)	2,500	3,000	3,500	4,000	4,500
0.039	1.98	2.17	2.34	2.50	2.65
0.044	2.52	2.76	2.98	3.18	3.38

Table 2. Calculation of jet flow rates, based on the diameters in table 1.

The above tests varied in the test condition (nozzle designs were changed in some, as was the internal feed design for the abrasive). The test results were taken by reading the relative position of the bottom of the hole being drilled from the video record, and finding the increase in depth for a given number of video frames (at 30 frames/sec). Because of the uneven, and only partial abrasive feed to the stream, the numbers varied during a test.

1.4 Changing hole geometry with COOAC

The original holes that were drilled, while significantly larger than the orifice of the nozzle, were not large enough for the ultimate purpose – which is to create a hole that is 2.0 inches in diameter. However the work to date has shown, based on the use of water as the cutting fluid, that drilling a 2 inch hole is quite feasible (Figure 8). There are several steps that can be taken, and although the current configuration for the test apparatus precludes complete testing of this configuration, nevertheless some validation experiments were carried out to illustrate the viability of the different parts of the approach.

The first step was to determine if adding a cone to the outside of the jet would work to widen the jet, as had occurred with the use of water. When tests of a diverging cone on the outside of the throat were tried in cutting dolomite, then it again proved possible to generate a wider cavity (Figure 14).

Figure 14. Holes drilled in dolomite with a diverging cone at the front of the 0.039 inch nozzle, jet pressure 4,000 psi.

The second test was to evaluate if placing turning vanes into the feed line to the jet would produce the same type of dispersed jet as occurred with the high pressure water system as shown in Figure 7. A set of turning vanes was therefore placed upstream of the throat section of a nozzle, and a test carried out. As can be seen (Figure 15), the same form of dispersed jet can be created using carbon dioxide as the liquid as was provided by the water.

Figure 15 The use of turning vanes in a carbon dioxide feed to generate the COOAC jet.

1.5 Recommended Components and Technology

The evolution of a drill that creates a hole, large enough for the following drill assembly to feed into it, without the need for rotation, has been documented in the above section.

The limited amount of flow available with the carbon dioxide system means that it is necessary to assume that some of the results obtained with continuous flow from a water driven dispersed jet can be repeated with carbon dioxide as the cutting fluid. The data presented, however, shows that the carbon dioxide system is much superior in cutting ability to the water-based system, and thus the performance parameters that are designated in recommending the design should be more than ample for the need.

In order to achieve a 2-inch diameter bore the turning vanes that spin the fluid going into the nozzle should be set at an angle to the flow path of at least 60^o (Figure 16). Jet pressure does not have much influence on hole diameter, which can be set by the size of the controlling diameter of the leading edge of the dispersal cone (Figure 10), but pressure rather controls the rate of penetration of the drill, and to this end, since ROP is linearly related to depth of cut, and concurrently therefore to pressure, the higher the pressure the faster the drill will operate. However, it will perform at pressures as low as 3,000 psi, (Figure 9) although higher pressures are recommended.

Figure 16. Two-inch diameter holes drilled in Joachim limestone with 60^o turning vanes behind the nozzle, at 5,000 psi jet pressure.

Flow rate should be as high as the system can provide, since this will increase the amount of abrasive (in a mix of some 8% by weight) that will impact a given surface in a given time, and thereby increase the ROP. Flow rates in the tests shown have been on the order of 3 gpm to achieve the results shown with carbon dioxide drilling.

The cone angle of convergence of the focusing nozzle should be at least 90^o, while the throat section should be kept short, in order to improve abrasive dispersal. (Note that the length of this section will be a balance between higher performance and operational life).

The system will perform to provide a hole of the required dimension if a dispersing cone is attached to the distal end of the throat of the nozzle.