2015 WJTA-IMCA Conference and Expo
November 2-4 • New Orleans, Louisiana

Paper

CUTTING AND DRILLING WITH SUPERCRITICAL FLUID SLURRY JETTING

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ABSTRACT

Use of solids-entrained-in-polymer water slurries (ASJ) pressurized through a 'pump' have been limited to offshore surface casing and pylon cutting and for downhole cutting of casing, tubing and other 'junk' in the borehole. Such high pressure (69-104 MPa) slurries are currently generated in batch mixed tubes or in large bore hydraulic or triplex pumps, accepting the inherent abrasive wear. New slurry pumps equipped with low wear patented HPSP technology have been utilized by Impact. New cutting and drilling techniques using the patented FLASH ASJ™ system, that uses supercritical gases, have been demonstrated for cutting steel, granite and sandstone and for drilling through sandstone. New patented nozzles have been designed for optimum expansion of the supercritical fluid slurries to obtain the desired cutting dimensions (width and depth). Low specific energies were found required to cut even the hardest material using CO_2, even with pressures below 5000 psig. Other supercritical gases (including nitrogen, air, propane, methane and even compressed air) are to be tested in the future. Targeted applications include mining, tunneling, trenching, excavation, fabrication material cutting and wellbore drilling in hard rocks.

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1. INTRODUCTION

1.1 Water Jet Cutting Development

The ability of water to erode materials has been known since ancient times by observing running water cutting wider flow channels in soils and rocks. In current times we have enhanced that natural capability of water by pressurizing and controlling fluid systems at increasing pressures and rates. Later it evolved into utilizing additives to enhance the eroding power of the jet. The methods now available for a broad range of applications are: High Pressure Water Jetting (WJ), Abrasive Water Jetting (AWJ) and Abrasive Slurry Jetting (ASJ).

1.1.1 High Pressure Water Jetting

This method utilizes only pressurized water through a single nozzle focused onto a target to cut holes, slots and other penetrations into that target material. WJs can cut materials without heat treating or heat affecting the material, which is not possible with lasers or EDM [1].

Polymers are added to the water to keep the jet coherent for longer distances. Pressures and rates of such systems have increased as pump capability has allowed. Pressures in excess of 4400 bars (65,000 psi) are now routinely used in machine and job shops internationally. Nozzle materials and smoothness have improved for longer useful and economic life. The limitation of WJ is that water only jets cannot efficiently cut harder materials. WJ systems typically make very narrow cuts, which is not adaptable for drilling systems, except for kerfing to aid mechanical rotary bits [2].

1.1.2 Abrasive Water Jetting (AWJ)

In 1980 a method for injecting abrasive into the fluid jet stream was developed that made it possible to cut a much greater range of material at lower, though still considerable pressures. That development has led to abrasive waterjet cutting for precision cutting in a wide range of materials that includes metals, glass and rocks. AWJ technology adds the abrasives via a dry feed to the water stream at an induction nozzle, using air as the carrier fluid of the abrasive. The pressurized water, abrasives and air then passes through a mixing chamber / second focusing nozzle to the target material. As with WJ, considerable pressure is required for both the efficient induction of the abrasives and for cutting. This method has some performance issues since the air used as the solids carrier fluid must also be accelerated in passing through the mixing chamber. This required configuration also imposes some design problems in developing an AWJ drill capable of drilling in the Earth. AWJ systems also typically make very narrow cuts, which is not adaptable for earth drilling applications. AWJ has limitations of slow cutting rates (compared to lasers or EDM, but that gap is narrowing with the higher pressure pumps now available), thin kerf and small fillet radii (below 025mm), and not efficient for cutting carbides, ceramics and other hard materials [1].

1.1.3 Abrasive Slurry/ Suspension Jetting (ASJ)

To overcome the efficiency problems of AWJ and to provide a simpler nozzle system the direct use of abrasive slurries was developed, ASJ. Although the initial design for the abrasive slurry jet has been assigned to Fairhurst [3, 4] in 1982, there was significant reported research available prior to that time [1]. In 1981, Fair may have made the first large scale attempt to directly use pumped abrasive slurries for oil well drilling [1]. Hashish [5] reviewed the possible ways of making abrasive suspension jets and described a concept to directly pump abrasive slurries. Leach and Walker [6] worked on nozzle design including the need for high levels of surface finish and smoothness of flow in the nozzle construction. Selberg and Barker [7, 8] confirmed these conclusions and added consideration of the entrance flow path. Hollinger et.al. [10, 11], Hashish [12] and Resnick [13] further developed ASJ systems. Their studies 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 and cutting distance. However, it was later found that the use of long nozzle designs had little benefit when the nozzle was very close to the target.

Summers, et. al. [14] showed that a properly designed ASJ system at 700 bar will give as much energy to the abrasives as a 2,800 bar AWJ system, or a 4x improvement of ASJ over AWJ. The removal of the air carrier fluid from the system, and the concurrent acceleration of the water and abrasive through the cutting nozzle, and only one nozzle, gave the system much more efficient 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 only 5,000 psi and up to 12 inches of depth. It also has advantages in submerged water applications.

The limitations of ASJ are the narrow jet (typically less than 0.1-inch in diameter), which is too small for the nozzle to advance into the cut hole to advance the cutting depth, such as required in drilling. One disadvantage in both AWJ and ASJ is the amount of abrasive required per volume or mass of material cut, although used abrasive recycling systems are available. The next limitation of both methods comes from the difficulty in creating the pressurized slurry, specifically the wear on valve and seats in pumps. Lastly is the concern for continuous operation and smaller equipment for mobilization.

1.2 ASJ Slurry Pumps

In 1981 Fair probably demonstrated the first large scale attempt to directly pump ASJ slurries for oil well drilling. Hashish [5] reviewed the possible ways of making abrasive suspension jets and described a concept to directly pump abrasive slurries. The first development of the ASJ system occurred in 1984, when Fairhurst [4] 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. From that he developed a low pressure (69 MPa) batch pumping system based on a fluidized bed concept.

Oilfield service companies have utilized low pressure, high rate abrasive slurry systems for downhole cutting of casings and tubings for many decades. In these applications they often utilize large triplex pumps to pressurize the low concentration slurries. Others have utilized modified versions of the Fairhurst system. Surface cutting of casings and wellheads for well control have also utilized low pressure abrasive slurry systems since there is inherent spark control.

1.3 Erosion Mechanics for ASJ Systems

Erosion mechanisms are governed by many different parameters which need to be studied individually. Meng and Ludema [15] undertook a comprehensive study of many previous researches done in the area of erosion modeling up to that time and came to the conclusion that so far no unifying erosion model had been proposed that could predict erosion for all materials and flow conditions. Due to this, there are many publications in literature which look at different parameters that affect erosion. Various people have looked at mechanisms of erosion and the effects of particle size, velocity, material hardness, and fluid viscosities. Finnie [16] concluded that ductile and brittle materials exhibit different mechanisms of erosion. Ductile erosion is described as resulting from plastic deformation of material. Finnie [17] reported that the plastic deformation is due to multiplication of a surface dislocation caused by impacts. According to Levy [18] erosion takes place due to the shear deformation that occurs at the point of impact of abrasive particles and metals. Due to repeated impacts the material is heated close to its annealing temperature. Small distressed platelets are formed in this softened layer. The metal layer under this softened layer remains hard and gets cold worked by plastic deformation. The erosion efficiency actually is increased due to this hard layer. Consecutive impacts remove the platelets formed by the initial impacts.

One of the major factors affecting erosion is particle impact velocity. Equation 1 describes the empirical power law relation between the erosion ratio and the velocity of the impacting particle.

$$ER \propto V^n \qquad \text{(Equation 1)}$$

where ER is the erosion rate, V is the velocity of the particles and n is an empirical constant. Finnie [19] explained that the exponent 'n' discussed should increase with impact angle for a range of velocities and ranges from 2.05 to 2.44. Lindsley and Marder [20] studied the empirical power law relation described in Equation 1 and showed that the value of 'n' was 2.9 for two different erosion mechanisms namely brittle cracking and plastic deformation mechanisms.

Another factor affecting erosion rate is the impact angle of the particles. Finnie [21] derived an angle function for rigid particles impacting ductile materials. The model shows that maximum erosion for aluminum alloys is at 13 degrees and becomes nonexistent at zero and ninety degrees. The discrepancy between measurement and model is explained by the existence of different mechanisms for erosion at high and low angles. At low angles the erosion is due to cutting mechanisms while at high angles it is due to surface roughening and low cycle fatigue fracture. Winter and Hutchings [22] studied another factor that affects erosion rate, the particle orientation before impact. They studied the rake angle of the particles when they impacted the surface. They found that when the impacting particles had positive or small negative rake angles the erosion occurred via a cutting mechanism. However, at large negative rake angle values, the erosion was due to a ploughing mechanism. Palasamudram and Bahadur [24] furthered this work and proposed another parameter called the angularity parameter 'An'. This parameter is calculated using geometrical parameters of abrasives such as shape, size, sharpness, etc. Erosion rates of 1020 Steel were measured and it was found that the erosion rate increased with an increase in n when particle size was maintained at a constant value. It was also observed that the erosion increased with particle size if n was kept constant.

An Erosion Model was developed at the Erosion/Corrosion Research Center of The University of Tulsa [25]. Since erosion is dependent, among other things, on the target material, the equations developed are different for different materials. Even though this equation was developed for a specific material, it can be used for other materials if the constants C, n, and the angle function are determined by erosion testing of that material. In general, the erosion equation can be expressed as follows:

$$ER\ (kg/kg) = Fs \cdot C \cdot V^n \cdot F(\theta) \qquad \text{(Equation 2)}$$

where ER is the erosion ratio (material mass loss/mass of impacting particles), C and n are empirical constants, V is the particle impact velocity in m/s, F_S is particle shape factor (0.2 for fully rounded, 1.0 for highly angular), and $F(\theta)$ is a function of the impingement angle where the angle, θ is measured in degrees. This full model development will be reported separately [25].

1.4 Drilling Boreholes with Abrasive Fluids

Gulf Oil Company and others successfully tested abrasive cutting combined with rotary drilling in the field to depths of 15,000 ft. High rates-of-penetration (ROP) were achieved, but problems with high wear on the pumps, pipes and connections leading to higher costs outweighed the benefits of the higher ROP [2]. There is a push in the oilfield and geothermal industries to go to smaller bores, which pushes the limits to what can be done only mechanically. Typical oilfield industry wells use standard 6-1/4" to 24" OD drilling bits. Geothermal wells target bore sizes ending at depth with 8-1/2" and up to 36" at the surface. Those sizes require a lot of rock to be removed taking a lot of energy and very large equipment. The next step down in borehole size is called 'Slimhole Drilling' with bit sizes from 4" to 6-1/4", with 4-3/4" as standard. Slimholes have found acceptance in selected industry applications, primarily in oil and gas directional and horizontal drilling using conventional rotary bit drilling systems [27].

Microbores are bores of less than 4" in diameter. This is a new technology frontier where the conventional rotary bit drilling systems that require torque and weight on bit cannot perform satisfactorily. The potential benefits of microbores are:

1. Less rock removed, thus faster drilling;
2. Less fluids, muds and chemicals required and less volume for disposal;
3. Smaller tubing and casing required for reduced cost;
4. Smaller operational environmental footprint;
5. Smaller (hence less expensive) tubulars and rigs, even allowing for coiled tubing systems.

But microbores are hard to achieve with conventional drilling due to the limited weight-on-bit and torque that is possible with small diameter pipe. This is where ASJ can provide significant benefits due to its low reactive force, no torque and small tool sizes. However full bore cutting or rotation of the nozzle is required, but not possible with the narrow cut of conventional ASJ.

2. DISCUSSION

2.1 Impact HPSP Slurry Pumps

The wear on the ball and seat of all type pumps has been the concern for ASJ systems in reaching the desired pressures. A valve closing on hard, dense, angular abrasive particles can cause rapid wear of the valve and seat faces, as well as on any non-metallic seals. High pressure slurry pump (HPSP) systems were developed to flush abrasive from the valves just prior to closing to minimize wear. HPSP pumps are patented under US11/033,615 for piston and US11/705,222 for plunger versions, as well as internationally [28, 29, 30]. Some examples of HPSPs with clean fluid valving are given in Figures 1, 2 and 5.

Figure 1. HPSP1 Piston Pump, hydraulically driven

Figure 2. HPSP2 Plunger Triplex Pump, hydraulically driven

Such pumps have been used for a variety of applications, including for abrasive cutting up to 15,000 psi, 5000 psi FLASH ASJ^{TM} abrasive cutting using supercritical fluids, and abrasive bio-pulp processing. The limitations of HPSPs are that a relatively long stroke, meaning a larger pump size, is required. In addition, a viscous clean flush fluid and more viscous carrier fluid are required for high concentration abrasive systems to carry and control abrasive particles when required. This requires a pressurized suction system.

2.2 Advancements beyond ASJ

The need for a wide cut from the jet nozzle has not been a big concern or need in job shop machining or demolition. However, it is needed for full bore microhole drilling systems or for trenching to install utility cables or small pipes. For drilling, a bore that is wide enough for the nozzle to advance and to allow unimpeded return flow to the surface is required. Lower pressure systems would also be advantageous to reduce the cost of tubulars and pumps. To that end FLASH ASJ^{TM} technology systems were developed and tested by Missouri University of Science and Technology, Impact Technologies LLC and Oak Resources Inc.[27]. Such systems utilize a slurry jet created with supercritical fluids, including carbon dioxide (CO_2), nitrogen (N_2), propane, methane and steam. Only one simple nozzle is required. The process relies on the pressure reduction to drive jet, plus expansion of the supercritical fluid through the nozzle. In addition to the higher particle velocities delivered to the target, a wider pattern is developed, the standoff distance (nozzle to target) now has a gas phase for improved particle-target interactions, and a lighter gas phase exists for aiding and clearing the wellbore of solids. FLASH ASJ systems are trademarked and patented under US12/400,507 for method and fluids and US13/589,626 for nozzle and methods [32, 33]. The new process has been tested at MS&T in 2002-2008 [30] and at Impact Technologies LLC in 2005-2013, both reported now.

Potential applications of this new technology are: oilfield enhanced oil recovery and tight unconventional resources that require small drainholes; shallow (60 meter depth) geothermal heat pump heat exchange bores; shallow instrumented wells; trenching in hard rocks (granites, basalts, limestones, etc.) for utilities, cables and pipes; and tunneling, especially the cut along the finish wall. Related technology developments are- Inverted Motors for downhole rotation of the nozzle using pressurized abrasive fluids, Inverted Drainholes for low pressure recovery of oil or environmental pollution, and TOP Plate for multiple bores from one surface site.

Impact and Missouri University of Science and Technology (MS&T) initially developed the supercritical gas jet system under a Department of Energy (DOE) project, DE-FC26-04NT15476 [27], for very fast full-bore drilling without rotation, no torque, no weight on bit, and low (less than 5000) standpipe pressures. The system consists of abrasives, supercritical fluids, chemical additives, a specialized and patented nozzle [33] and modified patented HPSP pumps [29, 30]. Examples of the desired supercritical fluids include water as steam, carbon dioxide, methane, propane, butane and nitrogen. The supercritical fluid must be in its liquid or near liquid state inside the drill string and into the nozzle to suspend carry the abrasive particles. It then transitions to a low-density gas or fluid across the nozzle, expanding in volume by 5 to 12 times and further accelerating the abrasive particles and carrier fluid, in addition to the normal flow area restriction of the nozzle. With proper nozzle design, expansion of the gas phase propels the abrasive into a wider diameter pattern creating a wider cut bore.

2.3 Bench Testing at Missouri University of Science and Technology

Using a modified DiaJet pump system to create the supercritical CO_2 abrasive fluids, MS&T tested the new abrasive cutting system on a variety of rocks and materials, including limestone, sandstone, basalt, cement and steel. This work was performed in 2004 to 2008. The results of those tests can be seen in Figures 3-4 and Table 1 [27].

Figure 3. Drilling sandstone using 4,000 psi CO_2 at MS&T

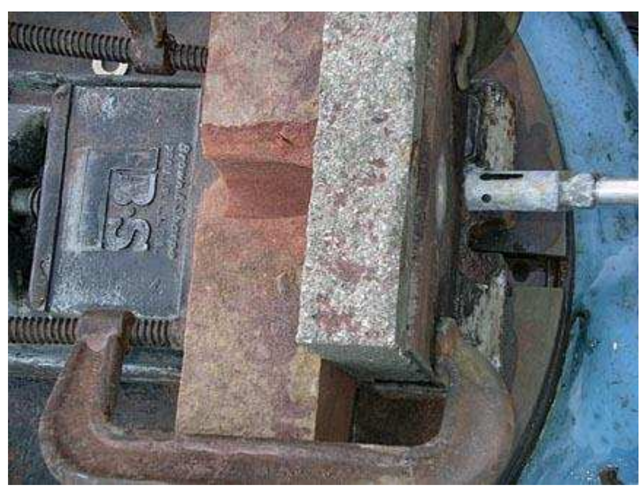

Figure 4. MS&T Hole through steel, concrete and rock using CO_2 abrasive system

The rate in these tests was highly variable due to the dry ice CO_2 source, but the success in drilling full bores in a variety of rocks, including basalt was considered significant. In addition, extremely low cutting specific energies (SE) were found.

Table 1. Cutting Performance of a CO_2 Abrasive System at MS&T.

Rock	Jet Pressure (MPa)	Nozzle Dia. (cm)	ROP Max (m/min)	ROP Min (m/min)	Specific Min (J/mm^3)	Energy Max (J/mm^3)	Hole Dia. (cm)
Roubideaux	24.15	0.111	4.85	1.07	0.133	0.560	2.54
Roubideaux	24.15	0.111	3.41	0.64	0.150	0.810	2.22
Joachim lls	27.8	0.099	4.21	1.19	0.410	1.443	1.52
Joachim lls	27.8	0.099	2.71	2.71	0.360	0.360	2.03
Joachim lls	27.8	0.099	3.60	0.76	0.334	1.560	1.80
Joachim lls	27.8	0.099	4.85	0.61	0.560	4.510	1.25
Indiana lls	27.8	0.099	3.0	1.19	0.207	0.519	2.54
Missouri do	27.8	0.099	4.51	0.64	0.216	1.488	2.03
Missouri do	27.8	0.099	4.51	0.98	0.216	0.992	2.03
Missouri do	27.8	0.099	2.71	0.61	0.736	2.210	1.40
Basalt	**27.8**	**0.099**	**0.91**	**-**	**3.00**	**-**	**1.25**

2.4 Full Scale FLASH ASJ Testing at Impact

Impact Technologies' facility was designed to provide material removal information for various rock targets at a variety of rates and slurry/gas ratios. Figure 5 shows the experimental facility which consisted of two separate pumping systems- a high pressure gas pump to raise the CO_2 pressure and a high pressure slurry pump with HPSP clean fluid valving to deliver the high concentration abrasive slurry to the desired operating pressure. The slurry pump was driven by a high pressure water triplex pump. The water – polymer – abrasive slurry mixture was created in a storage tank prior to the test to control quality. The gas was pumped through a 2-in insulated stainless steel pipe to the mixer. A concurrent flow water jacket was placed around the pressurized gas pipe to raise the temperature of the gas to ensure that the gas stays in the super critical region. The super-critical gas and slurry mixture was delivered to the nozzle from the mixer via a 2-in stainless steel pipe. All water and gas rates were metered

The target rock was positioned on a moveable table at a fixed distance from the nozzle. All tests had a 2" standoff, except for tests 39 and 40 which had 6" standoffs. The table allowed the rock to be positioned at various standoff distances to the nozzle and also to allow transverse or movement of the target toward the nozzle (simulating drilling). The table transverse speed was adjustable, but was fixed during all tests at 0.1 meters/ minute. For transverse tests, the target rock was cycled across the nozzle on a continuous loop and on the same line until the test ended.

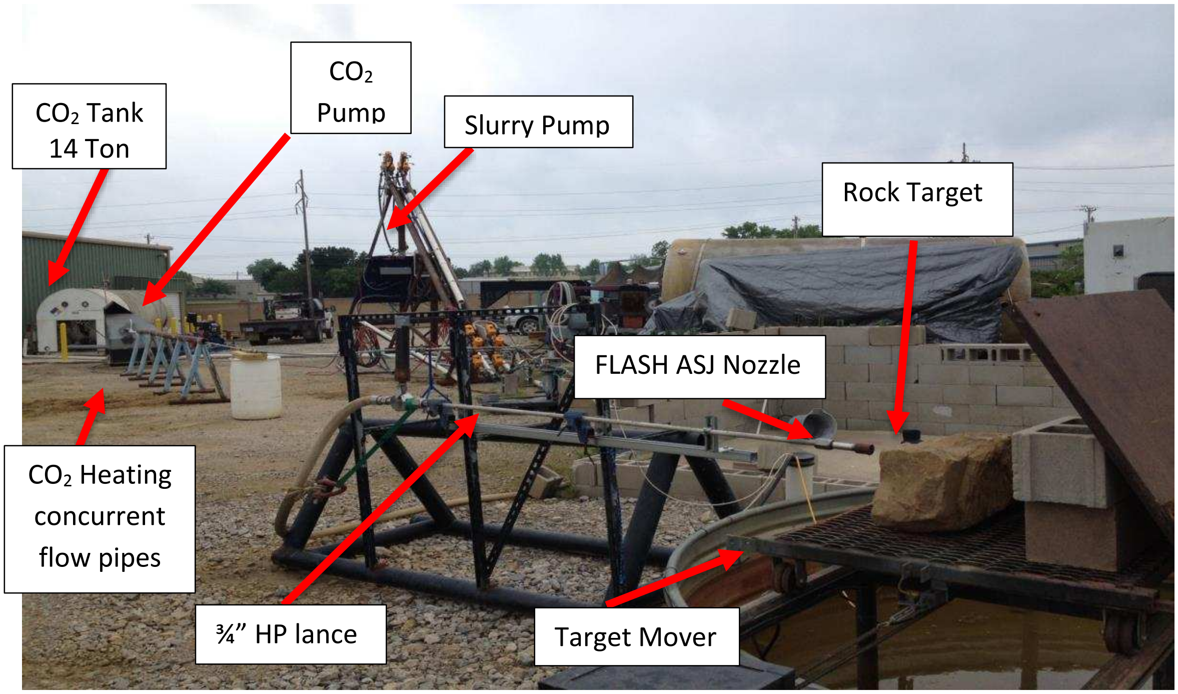

Figure 5. Impact Full Scale Test Facility

Figure 6, a, b, c. Rock Target Test Results

Both red and gray granites were tested with approximate properties of:

Density -	2700	kg/m^3
Young's Modulus (E)-	10-70	GPa
Modulus of Rigidity-	24	GPa
Unconfined Compressive Strength-	100-250	MPa
Shear strength-	14-50	MPa
Tensile strength-	7-25	MPa

Also, a local Oklahoma medium strength Red Sandstone was used in a few tests. Garnet abrasive sizes used were 40& 60 mesh, with the 60 mesh the most commonly used. Except for the tri-nozzle, all nozzle holders had outer diameters of about 3.2 cm (1.25 inches). A variety of nozzle designs were used, which contributed to the spread in the test data. A summary of these tests are given in Table 2 and Figures 7-10 in the evaluation section. A "B" on test number indicates it was a bore/ drilling test. Prior to CO_2 slurry cutting tests, steam tests were conducted with pressurized water heated to about 204°C (400°F), but these steam tests are not included in this report as different nozzle designs were utilized.

2.5 Evaluation of Bench Test Results

Figures 7-10 and Tables 1 and 2 were utilized to evaluate the bench test data. The first goal of these tests was to obtain operating proficiency of the combined supercritical abrasive system. The next goal was to obtain as wide a cut as possible with the small fixed nozzle. In this regard 20-107 mm widths were obtained, mostly on the first pass of the nozzle. Secondary passes only increased depth of cut. This is 6 to 33 times the diameter of the nozzle holder and would allow easy passage of the nozzle through the cut hole and allow sufficient return flow.

The next goal was to compare efficiency standards of this new system to other established abrasive cutting systems and to optimize the system's parameters. To do this two metrics were utilized-specific energy (SE) defined as the power required for a material removal rate (MRR) and an abrasive utilization efficiency term defined as mass of material removed per mass of abrasive utilized. Even though the abrasive and material debris can be processed and reused, this has a cost and was considered important to optimize the system.

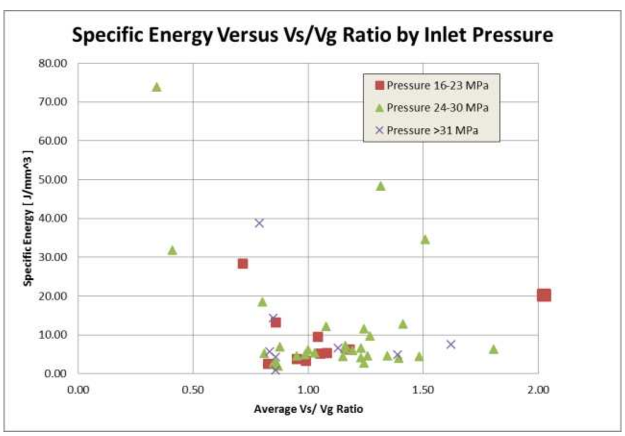

Figure 7. Specific Energy (J/mm^3) versus Slurry/Gas Volume Ratio Sorted by Inlet Pressure (MPa)

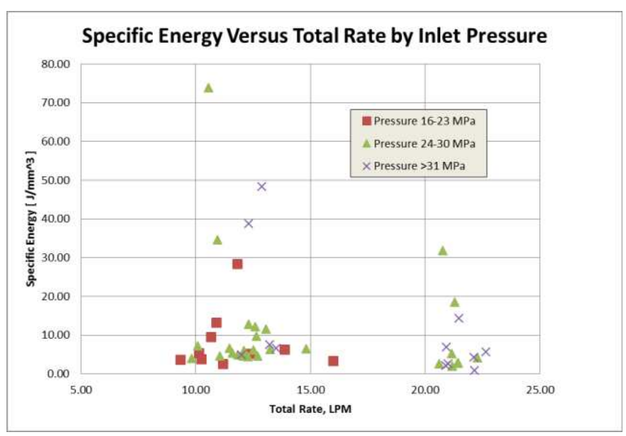

Figure 8. Specific Energy (J/mm^3) versus Total Rate (LPM), Sorted by Inlet Pressure (MPa)

Table 2. Impact Test Data using Carbon Dioxide on Rock Targets

Test No.	Nozzle	Rock Cut (mm) Type	Width	Depth	Volume	40-60 mesh Abrasive Used (kg)	Cutting Time min	CO2 Temp °C	Inlet Pressure Mpa	Slurry Vol: Gas Vol Ratio	Total Rate LPM	Abrasive Efficiency R-kg/A-kg	Specific Energy J/mm^3
12	500S-2	Grey Granite	30.70	22.64	169,688	23.90	12.0	25.5	29.68	1.81	13.23	0.029	6.30
13	500S-2	Grey Granite	25.34	40.68	248,395	52.80	26.3	26.4	37.96	1.13	13.49	0.042	6.68
14	500S-2	Grey Granite	24.57	58.62	339,687	34.84	14.5	29.4	32.96	1.62	13.22	0.028	7.52
15	500S-2	Grey Granite	26.91	57.77	338,442	25.99	18.3	27.7	27.79	1.16	10.07	0.028	7.32
16	500S-2	Grey Granite	32.61	71.60	516,520	20.37	12.8	23.9	24.86	1.39	9.82	0.042	3.96
17	500S-2	Grey Granite	19.78	16.07	72,988	19.96	20.3	32.8	28.75	0.34	10.54	0.006	73.98
18	500S-2	Grey Granite	19.59	55.43	246,183	10.75	14.0	32.8	19.17	10.00	9.31	0.020	3.73
19	500S-1	Grey Granite	20.25	11.79	48,194	46.67	24.3	33.6	30.06	1.51	10.95	0.003	34.60
20	500S-1	Grey Granite	28.31	8.27	65,368	33.25	8.8	36.3	33.44	0.79	12.29	0.004	38.77
21	500S-1	Grey Granite	24.39	30.76	151,203	30.39	9.7	5.2	28.89	1.24	13.05	0.009	11.51
22	500S-2	Grey Granite	22.95	46.97	238,618	39.75	9.5	30.9	23.52	1.19	12.10	0.015	6.05
23	500S-2	Grey Granite	23.89	47.42	261,497	33.03	18.2	34.2	24.34	1.00	12.51	0.016	6.22
24	500S-2	Grey Granite	23.82	10.12	65,327	27.82	8.7	37.8	23.23	0.71	11.80	0.004	28.49
28	500S-2	Grey Granite	24.78	41.40	240,432	57.66	15.8	43.5	24.95	1.16	14.81	0.028	6.45
29	500S-2	Grey Granite	23.59	33.70	196,940	139.22	32.5	40.3	20.25	1.18	13.86	0.023	6.34
30	500S-2	Grey Granite	25.27	36.71	211,375	89.67	28.5	45.1	16.82	1.05	12.34	0.025	5.18
31	500S-1	Grey Granite	23.27	59.59	325,129	20.48	15.5	24.5	25.59	1.48	12.28	0.038	4.40
32	500S-1	Grey Granite	28.68	51.49	366,989	30.15	12.5	4.4	31.67	1.39	12.00	0.043	4.95
33	500S-1	Grey Granite	27.68	28.78	201,910	28.78	14.5	45.0	17.02	1.08	10.12	0.024	5.41
34	500S-1	Grey Granite	28.36	34.04	240,059	19.68	5.2	41.0	23.67	0.95	11.06	0.040	4.69
35	R100-3"	Grey Granite	19.02	39.02	172,812	13.37	8.0	37.4	27.36	1.23	11.47	0.029	6.66
36	500S-1	Grey Granite	25.50	41.80	257,067	13.39	8.2	34.1	28.95	1.26	12.70	0.043	4.68
37	500S-1	Grey Granite	29.37	33.43	255,662	17.16	9.5	29.8	26.66	0.99	11.82	0.043	4.87
38	500S-1	Grey Granite	24.82	39.55	230,315	15.11	7.8	10.0	26.94	1.03	11.60	0.039	5.35
39	500S-1	Grey Granite	58.12	73.74	87,039	14.00	7.7	-7.3	28.07	1.41	12.29	0.015	12.77
40	500S-1	Grey Granite	60.45	242.09	231,612	168.62	64.2	36.6	31.21	1.32	12.86	0.004	48.36
41	500S-1	Grey Granite	21.96	26.65	126,254	5.54	9.3	48.0	29.87	1.27	12.64	0.060	9.80
42	500S-1	Grey Granite	23.51	16.24	83,111	6.96	9.8	50.2	17.42	1.04	10.65	0.040	9.53
43	500S-1	Grey Granite	21.67	24.22	109,461	4.88	6.8	46.0	29.85	1.08	12.60	0.052	12.18
44	500S-1	Grey Granite	22.06	14.75	69,639	6.28	7.2	49.9	18.38	0.86	10.90	0.033	13.24
45B	500S-1	Grey Granite	36.47	163.45	85,392	129.21	62.3	47.8	25.83	1.04	11.77	0.007	30.21
46	500S-1	G Granite-500oF	25.85	59.11	243,976	13.89	4.5	43.6	27.45	1.34	12.08	0.041	4.55
47	500S-1	G Granite-500oF	29.92	64.51	289,142	16.04	5.7	44.9	30.16	1.15	12.24	0.049	4.52
48	500S-1	G Granite-500oF	31.44	41.97	235,258	20.47	6.8	43.0	19.00	0.95	10.24	0.040	3.85
49	500S-1	Grey Granite	30.93	94.27	434,915	22.03	7.3	45.0	21.90	0.83	11.17	0.073	2.58
50B	500S-1	Sandstone	39.42	200.20	162,899	131.75	50.8	35.7	24.92	1.29	12.34	0.003	55.37
51	500S-1a	Grey Granite	42.55	57.26	661,517	28.74	7.0	46.0	30.11	1.23	22.27	0.051	4.21
52	500S-1a	Grey Granite	45.75	35.33	451,703	35.41	8.3	58.9	15.02	0.99	15.99	0.035	3.41
53	500S-1a	Grey Granite	41.98	58.38	619,287	26.51	6.8	40.4	31.81	0.83	22.63	0.047	5.77
54	500S-1a	Grey Granite	30.26	16.97	144,491	65.61	13.2	38.2	28.82	0.41	20.77	0.006	31.85
55A	500S-1a	Grey Granite	52.43	63.97	1,265,576	58.05	8.5	36.2	30.82	0.86	21.01	0.056	2.61
56	500S-1a	Grey Granite	47.01	60.25	840,429	54.57	7.2	2.0	26.69	1.24	21.43	0.037	2.84
57	500S-1a	Grey Granite	49.57	35.00	610,439	63.42	9.2	48.1	29.30	0.81	21.15	0.027	5.30
58	500S-1a	Grey Granite	48.59	10.07	180,910	61.40	8.0	53.0	30.07	0.80	21.27	0.008	18.47
59	500S-1a	Grey Granite	75.37	59.18	1,056,521	61.51	8.0	33.6	29.07	0.85	21.42	0.047	2.96
60	500S-1a	Grey Granite	47.35	25.40	1,506,725	0.00	0.0	31.4	30.58	0.87	20.88	0.066	2.16
61	500S-1a	Grey Granite	43.69	-	1,190,913	0.00	0.0	14.2	29.17	0.86	20.61	0.052	2.62
62	500S-1a	Grey Granite	46.25	-	469,096	2.72	0.0	33.9	30.72	0.88	20.91	0.020	6.93
63	500S-1a	Red Granite	50.11	30.39	1,097,425	0.00	2.0	29.9	28.38	0.87	21.18	0.047	2.06
64B	500S-1a	Red Granite	35.36	59.18	173,867	61.51	8.0	31.6	27.30	0.84	20.79	0.007	68.22
T65-68B	500S-1a	Sandstone	107.95	-	3,408,509	0.86	1.7	31.7	29.82	0.91	21.10	0.147	0.00
T69-70B	500S-1a	Sandstone	84.33	-	3,052,910	1.11	2.5	31.8	30.52	0.89	21.28	0.132	0.00
71	500S-1a	Red Granite	50.52	-	296,884	0.45	0.5	32.9	31.53	0.85	21.46	0.013	14.31
72	500S-1a	Red Granite	49.61	-	526,041	0.91	2.0	30.1	34.01	0.86	22.12	0.023	4.32
73	TriNozzle	Sandstone	64.16	-	5,000,021	0.00	0.0	34.5	32.11	0.86	22.15	0.214	0.86
74B	TriNozzle	Sandstone	42.19	-	849,997	0.00	0.0	33.0	29.57	0.83	20.82	0.036	4.73

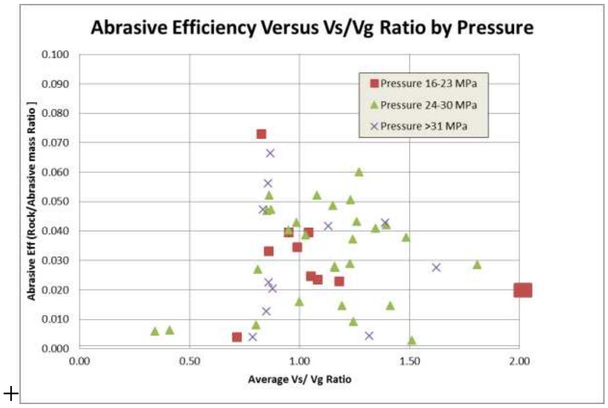

Figure 9. Abrasive Efficiency (Rock Removed/Abrasive Used, kg) versus Slurry/Gas Ratio, Log Scale on Efficiency axis

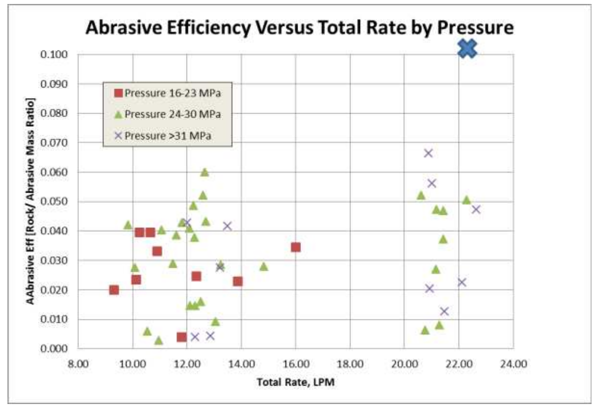

Figure 10. Abrasive Efficiency (Rock Removed/abrasive Used, kg) versus Total Rate (LPM), Sorted by Inlet Pressure (MPa)

The variability of the data was considered a function of the size of the system, the number of different nozzles tested and the limitations on the accuracy of controlling the various parameters during the tests. It can be seen from the data that SE is not a function of total flow rate. Gas volumetric content greater than the slurry volume provides the best SE values. Surprisingly, no strong influence of inlet pressure was found on SE values. Abrasive efficiency was relatively low across all conditions tested, ranging from 0.5 to 7% and averaged about 4%.

2.6 Evaluations at The University of Tulsa

Computer simulations of the supercritical gas abrasive cutting process were made and a model was developed for predicting performance [25]. Fluent™ was used to make a discrete phase simulation of the flow of particles through the nozzle. The particles of the discrete phase were assumed to be spherical in shape with a diameter of 300 µm and a density of 4100 kg/m3 (corresponding to garnet particle) and were injected from the inlet face. Figure 11 shows the results of the simulations, the plot shows the velocity of the particles, which are colored according to their velocity magnitude at that location. It can be observed that like the carrier fluid, the particles are accelerated through the nozzle. It is apparent that the velocity of the particles is also conserved similar to the fluid. It was observed that the particle velocity near the wall is significantly higher with this nozzle design. In particular, the velocity of the particles in the region away from the centerline is also high implying that this higher velocity will contribute towards more efficient material removal along the outer diameter of the wellbore.

2.7 Comparison of Specific Energies (SE) in the Literature

SE is not the only factor to compare in evaluating various cutting systems, but it provides a relative comparison of the efficiency of various processes and for optimization within a given process. From Tables 1 and 2 for the MS&T and Impact FLASH tests, the SE for cutting ranged from 0.133 to 74 J/mm^3 and averaged 10.5 J/mm^3. Ucun et. al. reported 4.5-10 J/mm^3 for a diamond circular saw [34]. Summers in Waterjetting Technology [1] reported water jetting (WJ) SEs at 5,000-25,000 J/mm^3. Darling [35], from data sourced by Rostamie et. al. 1994 [36], reported SEs based on mean particle size of the detrital – Bit Drilling averaged 0.21 J/mm^3 (50-70 Hp*hr/yd^3) and Tunnel boring averaged 0.035 J/mm^3 (10 Hp*hr/yd^3). Kolle [37] reported - Ultra-high pressure waterjetting (WJ) at 5-100 J/mm^3, abrasive water jetting (AWJ) at 3-100 J/mm^3, abrasive slurry water jetting (ASJ) at 70-500 J/mm^3, and Diamond rotary bit at 1-10 J/mm^3. Yao reported 10-80 J/mm^3 for a mechanical bit [38].

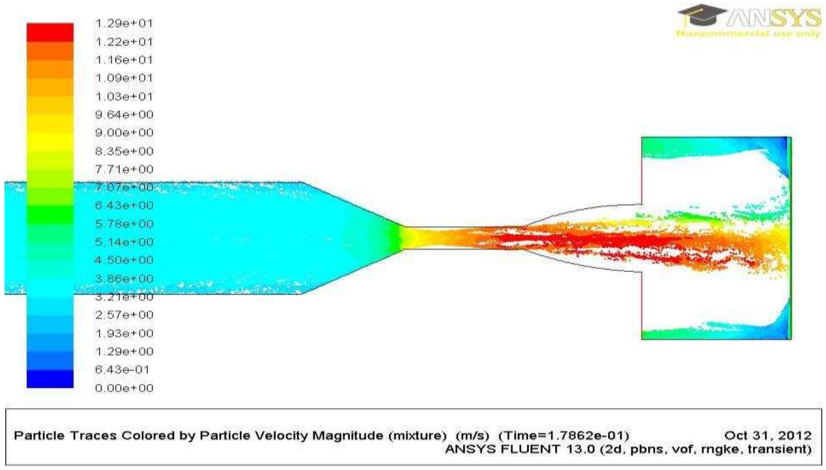

Figure 11. Particle Velocity Magnitude Plot

From this comparison of SE values in the literature, FLASH processes are not as low as mining or tunneling values, but are significantly lower or on the lower end of the range reported for waterjetting (WJ), abrasive waterjetting (AWJ) and even standard abrasive slurry jetting (ASJ) SE values. They are within the range of diamond saws and lower than mechanical rotary bits.

3. CONCLUSIONS

1. High Pressure Slurry Pumps (HPSP) are effective for pumping abrasive slurries to high pressures, but such pumps must have larger bores and slower stroke speed, due to the inertia of suspended dense solids. Otherwise, a viscous carrier and clean fluid must be used that require a pressurized suction. HPSPs may be used to directly pump the supercritical abrasive systems, but this was not directly tested.
2. Supercritical abrasive systems are very efficient, based on SE values, when compared to all water jet and water abrasive systems, and even some diamond cutting systems, but it is not as efficient as reported for mining and tunneling processes, including explosives.
3. Supercritical abrasive systems can cut wide bores sufficient for nozzle entry and drilling of microbores. Rotation of the nozzle can provide even wider created bores.
4. Optimal conditions for the supercritical abrasive system were found to be broad and stable, with only a Vs/Vg ratio above about 1.0 found to be important.
5. Such supercritical systems can be applied in utility trenching, tunneling (finished wall cut), shallow drilling for geothermal heat sink bores and instrumented bores.

4. ACKNOWLEDGMENTS

Stripper Well Consortium at Penn State University; Oklahoma Center for the Advancement of Science and Technology (OCAST); Department of Energy- Fossil Fuels and Geothermal Energy programs; The University of Tulsa - Dr. Ovadia Shoham, Missouri University of Science and Technology- Dr. D. Summers, Dr. G. Galecki, Dr. P. Nambiath; Lawrence Berkeley National Laboratory- Dr. S. Finsterle, Dr. Y. Zhang, Dr. L. Pan, Dr. P. Dobson; Dr. B. Felber; Dr. D. Rychel; and Impact Technologies LLC- B. McCollam, B. Oglesby, T. Luscoito, and N. Novak.

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6. NOMENCLATURE

A = Area [m2]
An = Angularity Parameter
At = Area of Throat of the Nozzle [m^2]
CS = Slurry Concentration
CT = Target Concentration
CV = Volume Fraction
ER = Erosion Rate
Fs = Shape Factor
m_a = Total Mass of Abrasive Particles Used [kg]
n = Velocity Exponent