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INVESTIGATIONS INTO THE EFFECTS OF AN ARC DISCHARGE ON A HIGH VELOCITY LIQUID JET

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ABSTRACT

High velocity liquid jets have been shown to be effective in removing rock in drilling and mining. The high pressures needed to accelerate the fluid to the required velocities are difficult to sustain at reasonable costs. The effect of an arc discharge on the stream of liquid is investigated to determine the value of the spark as an enhancement device. The primary effects investigated are the enhancement of the initial shock wave by the stream velocity, the water hammer from the interrupted stream, the possibility of disruption of the arc by the jet, and the jetting into a collapsing cavitation bubble. All of the experiments are conducted at atmospheric conditions with an analysis of the effects of hydrostatic pressure on the system. The experimental apparatus is a 25 kV capacitive discharge system to develop the arc in a liquid with a jet passing between the electrodes. Pressures up to 20 MP_a (3 kpsi) that give velocities of 200 m/s (650 fps) are used in the experiments. The primary diagnostic techniques are piezoelectric pressure transducers, framing and streak cameras, and rock specimen damage observations.

A definite enhancement in the rock removing capabilities is observed. Steady jets that will not erode a specimen become effective in rock erosion when disrupted by an arc discharge. The energy required by the arc discharge is much less than the amount required to comminute rock with the spark alone. Problems in operating an impulse type jet cutter at atmospheric pressure when the working fluid is not degassed are discussed.

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Introduction

One of the most effective drilling techniques is jet (or erosion) drilling. Experiments with jet drilling have shown the technique to be effective with pressures up to 100 MPa (14,500 psi) in most sedimentary rocks (1-5). Considering the difficulty in pumping large volumes of fluid at high pressure, the technique would be much more valuable if it could be made effective at pressures commonly used in drilling (normally below 24 MPa - 3,500 psi). For this, an enhancement technique is required. A study of the physics of the problem leads to the conclusion that there is a distinct possibility of enhancing the effectiveness of a lower pressure stream by disrupting the jet. Pulsed jets have been reported to be more effective than steady jets because of the water hammer pressures created (6-9).

In an attempt to determine an enhancement technique, the effects of an arc discharge on a jet are investigated. The primary effects considered are the enhancement of the initial shock wave by the stream velocity, the water hammer caused by the interrupted stream and the jetting into a collapsing cavitation bubble. Although the experiments were conducted at atmospheric pressure conditions, effects of hydrostatic pressure on the system are considered. The experimental apparatus consisted of a capacitive discharge system to develop an arc through the jet passing between the electrodes. The primary diagnostic tools are piezoelectric pressure transducers, framing and stream cameras and physical damage observations.

It is possible that an arc discharge can be used to significantly enhance the rock removing capabilities of a high velocity liquid jet. Any of the several effects may independently prove beneficial to the jet drilling technique. These phenomena, along with possible areas are discussed below.

Analysis

The effectiveness of a water jet as a drilling or rock removal technique has been demonstrated in field tests (1,2). In order to remove harder rock, pressures must be raised to high levels. Some experiments have been conducted using pressures in excess of 100,000 psi. This is technically effective but rather difficult to achieve practically since the cost of producing the high pressures generally renders the system uneconomical.

When a steady jet is used, the maximum pressure exerted on the rock is the stagnation pressure ($P = 1/2\ \rho U_{st}^2$), where U_{st} is the stream velocity. If the jet is pulsed, the maximum pressure obtained is the impact (water hammer) pressure ($P = \rho U_s U_{st}$ where $U_s \cong 1500 + 1.9\ U_{st}$, U_s is the shock velocity in m/s). Although the duration of the impact pressure is very short, a pulsed jet is more effective at rock removal than a steady jet (7). Thus, an enhancement technique that will in effect interrupt the jet would be valuable. An arc discharge through or near the stream can disrupt the jet. Besides the impact pressure created by the interrupted jet, there are two additional effects that can enhance the drilling capabilities of a jet. These three effects are discussed below in the order in which they occur in the experiment.

The arc discharge creates a plasma channel in the liquid, which expands rapidly with time. Expansion of the arc channel formed in the liquid rapidly drives the surrounding liquid out from the arc thereby creating a shock wave. The strength of the shock wave is a function of the particle velocity caused by the channel expansion. If the discharge occurs in a moving stream, the particle velocity relative to a fixed reference frame in the direction of the stream flow, will be the sum of the stream velocity and the particle velocity due to channel expansion. The resulting shock wave velocity will be enhanced by this effect.

The enhanced shock wave will occur only if the arc discharge goes through the stream. This shock wave will be more effective than one created by an arc discharge or other explosive of the same shock strength alone because of the non-uniformity of the stress state created on the rock surface. Anytime a stress discontinuity is created the conditions for rock removal are enhanced. (This situation is what makes roller cone bits so effective.) The shock stress is applied only over the area of the jet creating the desired discontinuity.

This effect is even more pronounced in the stress created by the water hammer which occurs after the original shock wave has dissipated.

Probably the most effective enhancement technique is created by the disruption of the jet by growth of the arc channel into a bubble. This bubble growth effectively interrupts the jet, which as pointed out above, creates the impact or water hammer pressure condition when the jet re-enters and impacts the lower side of the bubble. This creates pressures much greater, by a factor $2U_s/U_{st}$, than a steady stream. The extremely high pressures generated coupled with the stress discontinuity makes this a very effective rock removal technique.

The final effect to be considered is the cavitation bubble jetting that will occur when the spark generated bubble collapses. Cavitation bubble collapse has been studied extensively by Ellis (10) and others. Their results show that when a bubble collapses near a surface, a small extremely high velocity jet is formed which is an effective damage mechanism. There is a possibility that the caviation bubble collapse can act synergistically with the interrupted jet to enhance the impact even further if the timing is proper.

The primary concern with the technique is the effect of hydrostatic pressure on the shock wave and bubble dynamics. The effect of the stream on the arc discharge would be minimal since the relative motion of even a high velocity stream is small in the time required to generate the arc discharge (usually less than 1 μs). The effect of hydrostatic pressure on whock wave generation has been shown to be small in unpublished experiments at Sandia Laboratories. The effect of pressure on bubble dynamics is significant though, because the potential energy of a bubble is PV. The energy stored in bubbles of the same volume, V, is directly proportional to the pressure, P. Although bubbles are more difficult to create at depth, the greater stored energy increases the potential for rock removal.

The hydrostatic pressure that occurs at depth increases the probability that the bubble collapse can enhance the impact velocity of the interrupted jet. As the bubble starts to collapse the pressure inside the bubble drops low enough for the jet to reenter and traverse through the bubble. For the bubble collapse to enhance the jet velocity, the bubble collapse velocity must be equal or greater than the jet velocity. This occurs when the system is under the hydrostatic pressure found in well bores.

The exact hydrostatic pressure required is a function of the bubble size, jet velocity and other system parameters, but the system can be sized so that normal bottomhole pressures in typical wells will be adequate.

Theoretically, this system should significantly enhance the jet drilling technique. The equipment required will be complex, but not outside present state-of-the-art technology. Preliminary experiments conducted to initiate verification of the theory are discussed below.

Experimental Apparatus

Three different systems were used to create the water jet in these experiments. The systems and their pressures were: water main -- 0.34 to 0.55 MPa (50 to 80 psi), Hypro pump -- 2.69 MPa (390 psi), and Partek Liquiblaster -- 3.45 to 13.79 MPa (500 to 2000 psi). The pressures yielded velocities ranging from 20 m/s to 164 m/s when passed through a converging nozzle with exit diameter of 0.0027 m (0.1 in). This nozzle is made of stainless steel and is threaded into an insulating plastic housing (see Figure 1). During the experimental runs the test pressure was monitored with a standard Bourdon pressure gauge.

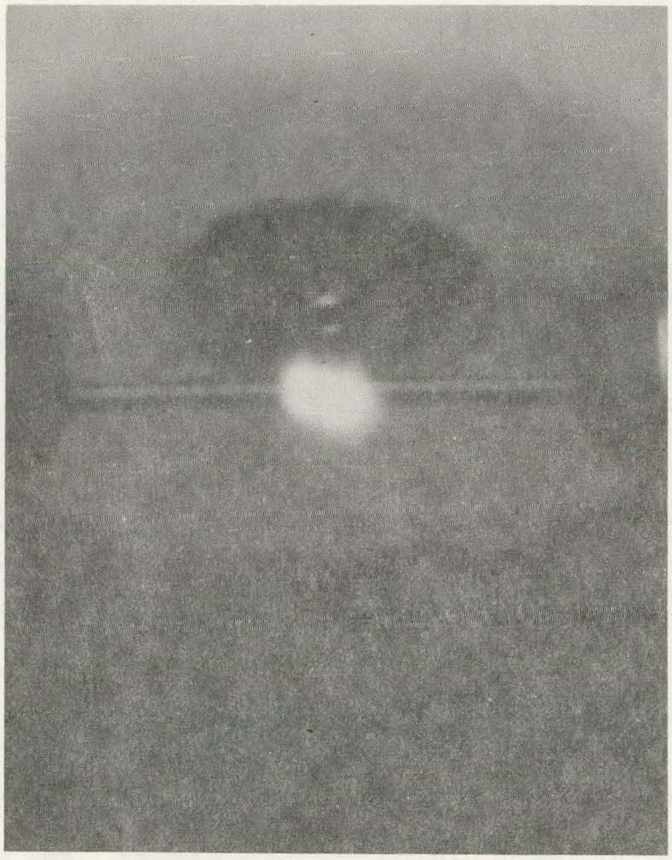

Figure 1. Jet nozzle and discharge electrodes

The arc was created by discharging a 1.86 μF (or 0.35 μF) capacitor through a cable line, switch and electrode pair with a total inductance of about 1.65 μH. Charging voltages were in the 15-25 kV range. Again, Figure 1 shows the electrodes and their positional relationship to the nozzle. The short gap (3 mm, 0.120 in) and high inductance of the system made conversion of energy into channel growth very inefficient, but the system was adequate for the purpose of this experiment. Both single and rapid fire discharges were available. The voltage across the electrodes and the current through the arc was monitored by oscilloscope.

High speed photographic equipment was used to gather data. Frame rates of 7500 to 850,000 fr/sec were available, along with streak records to record shock wave velocities. The streak records have a velocity resolution capability of less than 100 m/s. In addition, twelve frames at spacings of 10 to 100 μsec could be recorded on Polaroid film. The first frame could be delayed for as long as 8 ms and an electronic flash could be programmed to operate at any time desired.

The basic element of the pressure sensing transducer is a Z-cut lithium-niobate piezoelectric crystal which is nominally 6.4 mm in diameter and 0.64 mm thick. The dimensions of the transducer were so selected that equilibrium is established within the gauge in times which are short compared to the risetime of the pressure pulse. The transducer was operated in the voltage mode by making the RC time constant of the circuit long compared to the pressure pulse duration and the gauge output was recorded with a camera coupled oscilloscope. For both shock wave and bubble collapse pressure measurements the transducers were mounted near the surface in an RTV matrix and located from 10 to 30 mm below the electrodes.

Experimental Results and Discussion

Initial results indicated that the jet stream had no detrimental effects on the arcing phenomena. As discussed earlier, this is a reasonable finding due to the short time necessary to establish the arc (about 1 μs). In fact, the arc appeared as if no stream were present.

The next major question to be resolved was that concerning the ability of the pressure field generated by the arc to stop the water jet. At stagnation pressures up to 2.7 MPa (390 psi) this ability was clearly demonstrated, however, above this level small air bubbles obscured most of the action and the determination could not be made. Figure 2 shows the jet moving downward during the time period in which the arc is being formed; while Figure 3 shows a later time period where the existing pressure field has disrupted the stream. The jet will be interrupted only as long as the bubble pressure is greater than the stream pressure; as the bubble pressure drops the jet will pierce the bubble, pass through the low density region and impact the surface (the bottom of the hole in drilling operations).

Figure 2. Discharge established through jet

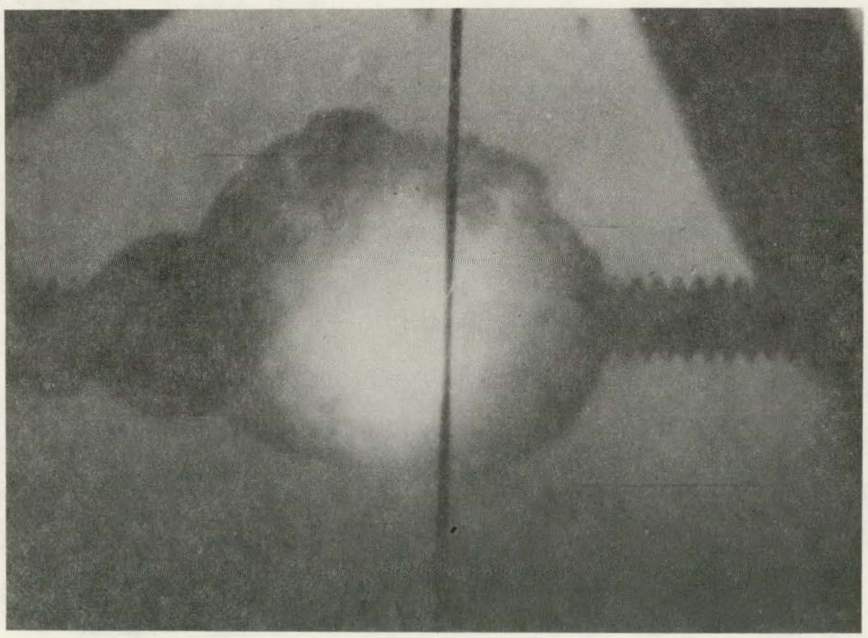

Figure 3. Interruption of the jet-stream by the bubble

The problems with operating the system at atmospheric pressure are caused by dissolved air in the liquid (water) and by bubble size (length of time to collapse). The first problem occurs when the high pressure water is accelerated through a nozzle. Any dissolved gases are forced out because of the pressure drop in the nozzle. The small bubbles of air obscure the action that is occurring and weaken the shock wave created by the discharge.

Figure 4 shows a streak record of the arc with the accompanying shock wave. This shock wave is attenuated both in velocity and in magnitude by air bubbles in the water. This was easily evidenced by the difference in the transit times of the shock wave from the arc to the transducer when the jet was on compared to when it was off. The magnitude of the shock wave (seen as a voltage peak on the oscilloscope traces) was not consistently reduced when the jet was on. The reason for this is thought to be that in some instances a

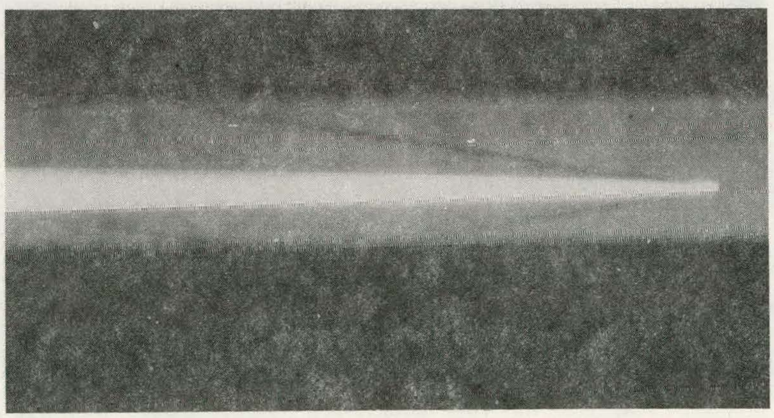

Figure 4. Arc streak record with shock wave

shock wave is formed outside the stream thus lessening the magnitude and velocity attenuation whereas in other instances the shock wave is formed in the stream and the air represents a severe impedance to the shock wave and substantially attenuates it. Shock wave velocities as low as 200 m/s were observed (compared with minimum shock velocities of 1500 m/s in water without gas bubbles). The effect of finely dispersed gas bubbles on shock wave properties has been observed before (12). This situation represents a severe problem to tests at atmospheric conditions but the problem will not exist at bottomhole pressures.

Another difficulty is actually a timing problem in the experiment. For the cavitation bubble collapse to be effectively influenced by the jet, the bubble diameter must be of same order as the jet diameter, and the average bubble collapse velocity and jet velocity must be similar. At atmospheric pressure the bubbles grow to a large size and collapse slowly. The obvious solution to both of these experimental problems is to conduct the tests under hydrostatic pressures similar to borehole conditions, where bubble sizes will be small and collapse velocities high.

There is enhancement of the shock particle velocity by the stream velocity but this is somewhat more difficult to observe. Because of gas bubbles, sharply defined shock waves were observed in the streak records only at the lower stagnation pressures. Although at these pressures, the variation in shock particle velocity is often as great as the stream velocity, indications are that the stream velocity augments the shock particle velocity as predicted.

Figure 5 shows a typical pressure vs time trace as received from the mounted transducer. The two small negative pulses at the beginning are associated with voltage application and current conduction at the electrodes. The shock wave generated by the arc discharge travels through the water at the shock velocity, U_s, and activates the transducer. This is the first pulse seen in Figure 5 and is typical of blast wave pressure pulses. The second pressure pulse is the dynamic pressure, $1/2\ \rho v^2$, of the fluid flow caused by the bubble expansion. If the transducer is free in the water, this pulse is not seen. Superimposed on the pressure from bubble expansion is another pulse of unknown origin. The time of occurrence is in the range of time when the interrupted jet strikes the bottom of the bubble. Because of the repeatability problems, it was not possible to confirm that this pulse was in fact impact pressure in this experiment.

In these experiments, the effect of the jet on cavitation bubble collapse was not satisfactorily quantified. As stated above, at atmospheric pressure, the bubble size is too large and the collapse velocity is too slow for the jet to control the bubble collapse. The high speed photographs show that the stream has an influence on the bubble collapse but the usefulness of the stream in controlling collapse will have to be proven in subsequent experiments. Figure 6 shows a pressure response curve that results from bubble collapse.

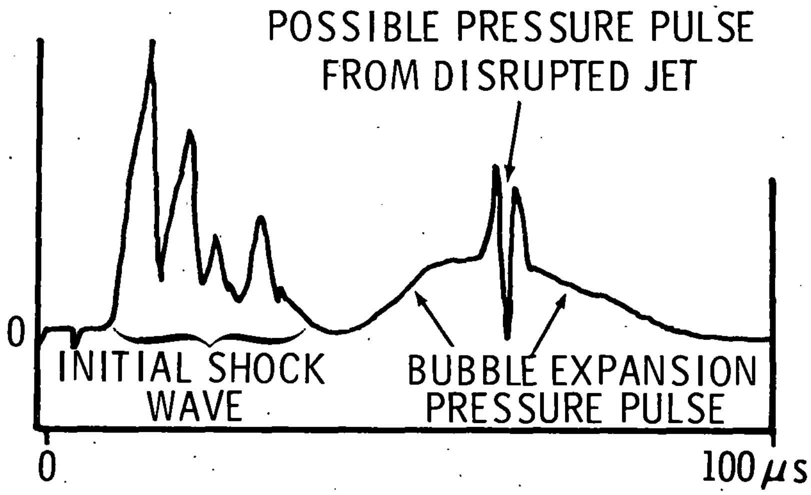

Figure 5. Early time pressure pulses measured by a pressure transducer embedded in rubber

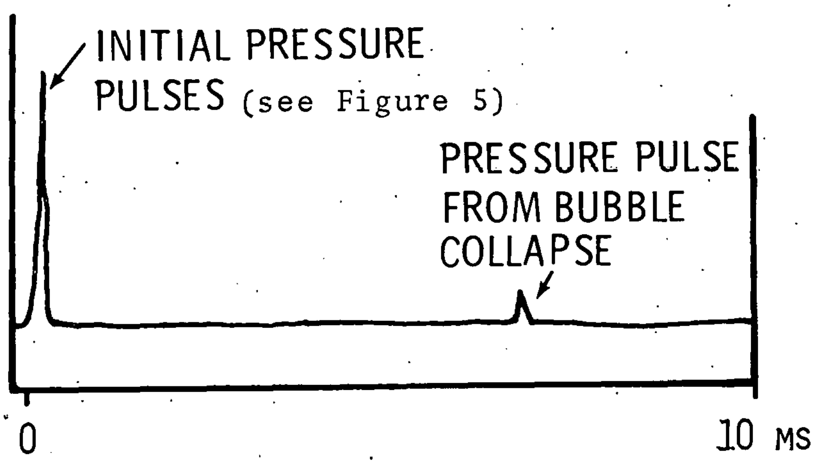

Figure 6. Full pressure trace from arc discharge

Collapse times varied from 4 to 6 ms depending on the amount of energy transferred from the discharge to the bubble. The variation in energy transfer and other factors created such a large variation in the pressure pulse generated that any differences in the pulses caused by the jet were indistinguishable from bubble collapse without a jet.

The most significant information gained was from a qualitative rock-breaking experiment using the 2.69 MPa (390 psi) HYPRO pump system. In this experiment, three conditions -- a jet alone, arc discharges alone and arc discharges through a jet alone -- were used in an attempt to damage Berea Sandstone, Indiana Limestone and granite. The exact energy input and shock pressure were not determined for this experiment.

The 2.69 MPa (390 psi) stream was directed against the sandstone (Figure 7) for 30 seconds and the limestone for 60 seconds. The slight dimple seen in Figure 7 may have been made in the sandstone by the jet but no damage was done to the limestone (Figure 8). The arc was discharged near the sandstone five times, and near the limestone six times. No damage was visible in either case. In the final portion of the experiment, the jet was turned on and an arc passed through it three times for the sandstone and six times for the limestone with a jet flow of about five seconds per pulse. A significant depression was made in both cases (Figures 7 and 8). Another run was made with 12 discharges and flow against granite. This marred the surface of granite in an area about

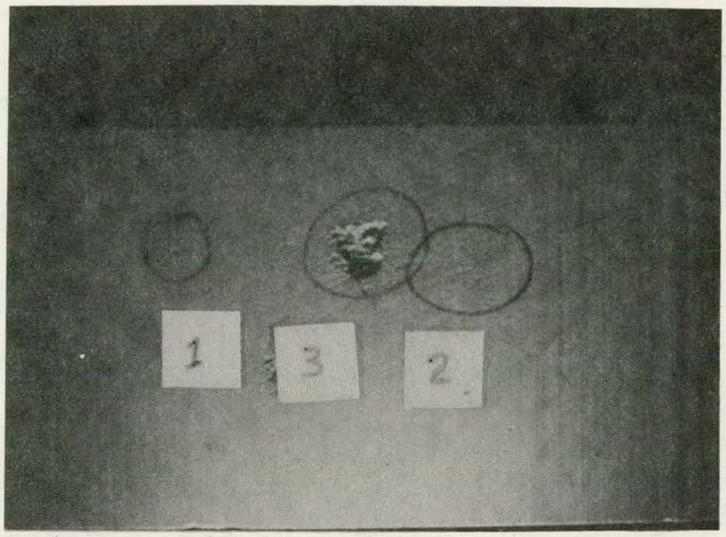

Figure 7. Berea Sandstone -- 1) 30 seconds water jet, P_s = 390 psi, 2) 5 arc discharges only, 3) 3 arcs with water jet < 15 seconds.

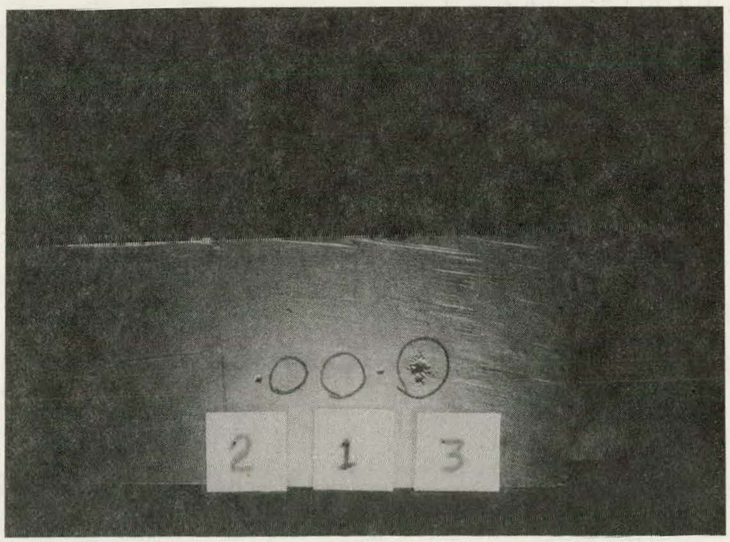

Figure 8. Indiana Limestone -- 1) 60 seconds water jet, 2) 6 arc discharges only, 3) 6 arc discharges with water jet < 30 seconds (extra holes not from this experiment).

30 mm in diameter. In a final run, the jet flow was discharged against the sandstone six times, resulting in a hole 1.3 cc in volume.

The impact pressure in this case was only about 23 MPa (3260 psi) because of the air bubbles in the water. With degassed water, the pressure would be about 123 MPa (17860 psi). The pressure exerted here is about the threshold pressure for Indiana limestone reported in the literature for a traversing jet (12).

These experiments show that there is a beneficial effect in arcing through a high velocity stream. It should be noted that no positive determination was made as to which possible effect was responsible for the rock-removal capability although impact seems most likely to be responsible for the damage. The significance of the experiment is that rock was removed by a combination of two systems, neither of which was powerful enough alone to do any significant damage. Individually, the arc and the jet systems represent something far below the capabilities required of either system alone, but in a synergistic combination they were successful in removing rock.

Conclusions and Recommendations

To date, the analysis and experiments have revealed the following:

1) The arc passes through a liquid jet. No evidence has been found that the arc would have a tendency to go around a stream.

2) The arc discharge effectively interrupts the jet stream flow creating water hammer (impact) conditions.

3) The shock particle velocity is probably enhanced by the jet stream velocity.

4) The jet stream has some effect on the cavitation bubble collapse although the magnitude of this effect was not determined.

5) Rock removal is significantly increased by combination of the two techniques.

Further experiments must be carried out to quantify Items 3 and 4. Experiments under bottomhole simulated hydrostatic pressures should be conducted to evaluate the system under realistic conditions.

A jet stream passing through the area between the electrodes in an arc discharge (spark) drilling system appears to have definite advantages. No problems were observed that would exist under the hydrostatic pressure in a well bore. The use of a relatively high velocity jet in combination with the spark drilling technique warrants intensified investigation.

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