Electrohydraulic Rock Fracturing by Pulsed Power Generated Focused Shocks[1]

Kenell J. Touryan, William M. Moeny,
Catherine T. Aimone, and Jay W. Benze

Abstract

The electrohydraulic effect for rock breaking and drilling was investigated using focused shocks. The multikilobar shocks were generated in the test chamber of an 80 kJ pulsed power facility. The latter consisted of an 80 kJ Marx bank connected to a water-filled chamber through four 1 MV pulse-forming lines (PFL). The PFLs were 3.35 Ω, coaxial, deioinized water lines, 3.66 m long. The pulse length was 0.2 - 1 μs. The electrohydrodynamics of the arc discharge in water, the physics of the resulting shock waves and the rock fracture were analyzed theoretically and experimentally using one of the four PFLs. We were able to discharge 8 - 10 kJ energies in an arc, generated in tap water, in 100 ns. A series of such discharges has produced erosion rates of 0.25 cm/sec, in 6 cm holes in limestone and sandstone samples. At a repetition rate of one discharge per second, this rate is equivalent to 7 - 10 m/hour for an 8-inch hole.

Introduction

There has been a surge of interest in recent years in the use of pulsed power technology for rock breaking, spark drilling and seismic sounding. The electrocrushing of rocks and the electrohydraulic (EH) rock fracture technologies using high voltage pulses, are not new.[1-4] However recent developments in pulsed power technologies for generating terawatt level power have made electrocrushing and the EH effect more practical for commercial applications such as disintegration of rocks, ore comminution, mining and spark drilling.

In the EH effect, the high energy impulse that is delivered to the rock is created by means of an electric discharge between two electrodes immersed in a fluid medium. Under a sufficiently intense electric field E at the electrodes, i.e., E > 100 kV/cm, a narrow, conductive plasma channel forms between the electrodes. The sudden expansion of the plasma channel, with T > 10,000 K, creates pressure pulses that can exceed 1 GPa (10 kbars). The ensuing supersonic shock waves impinge on the rock surface placed in the immediate vicinity of the arc (within a few cms) and fracture the rock. A bubble collapse, which follows the reflected shock can contribute to the fracture and/or material removal (cavitation).

Experimental Set-up

1. Pulsed Power System. The electrohydraulic effect for rock breaking and drilling was investigated using focused shocks. The multikilobar shocks were generated in the test chamber of a 80 kJ pulsed power facility. The latter consisted of a 80 kJ Marx bank connected to a water-filled steel chamber through four, 1 MV, pulse-forming lines (PFL). The PFLs were 3.35 Ω, coaxial, deionized water lines, 3.66 m long. Figure 1 is a schematic of the pulsed power facility.

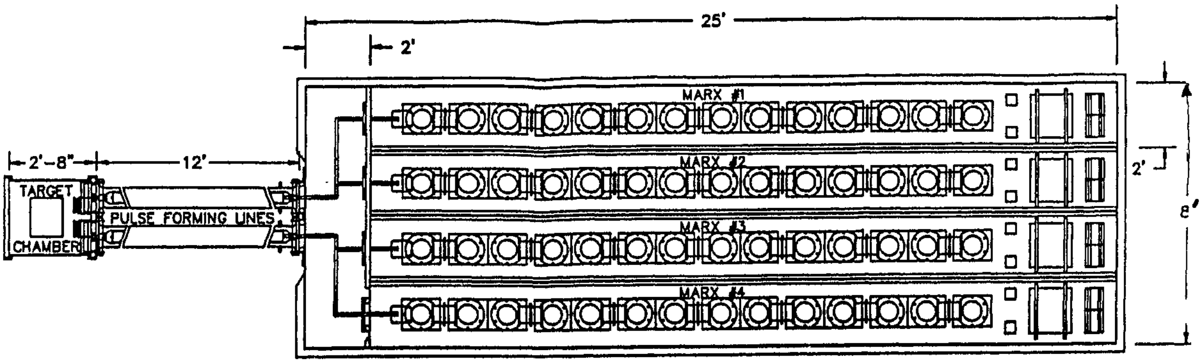

Figure 1. Schematic of Eoin Gray, 80 kJ Pulsed Power Facility for Short Pulse Operation (top view).

2. Electrodes. Three types of electrodes were used throughout the various experiments conducted. The first type was a tapered, stainless steel electrode pair, without insulators, designed to withstand 10 to 20 kJ discharges, with minimum interference from the cylindrical/spherical shock waves propagating outward from the gap. The very short pulse lengths obviated the use of insulators. The other two types of electrodes were of much simpler design. Tests with 40 to 50 arc discharges with a single electrode pair of this simpler design, even at 10 kJ energies showed erosion rates comparable to the much larger and more complex designs of type one, above. A Star design, shown in Figure 2 was used to provide a substantially reduced circuit inductance to improve energy-loading in the resistive phase of spark formation. In

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14. ABSTRACT

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addition, the parallel connected, five electrode pair (Star design) provided a simple way for evaluating pressure enhancement effects caused by shock focusing.

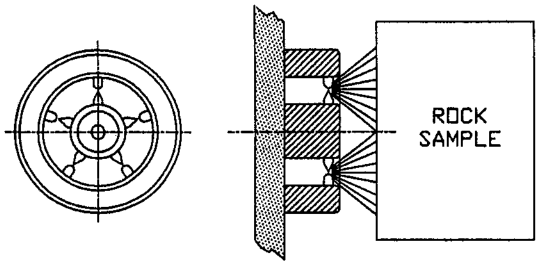

Figure 2. Star Electrode Array with Five Stainless Steel Electrodes.

3. Instrumentation. In order to determine the amount of energy transferred to the arc key parameters were monitored. These were: input voltage to the Marx bank during discharge; V(t), I(t) near the electrodes; the input pulse length (and shape), and the magnitude and shape of the pressure pulse in the water as a function of distance from the arc center. Digital and analog voltage monitors were used as standard equipment in the pulsed power supply and the Marx bank, together with pressure monitors for the spark gaps connecting the 14 capacitors in each bay. Current and voltage rise times at the electrode were monitored via B-dot and V-dot probes located on the PFL 20 cm from the electrodes. Nanosecond response quartz gauges mounted on probe supports, inside the test chamber, measured the magnitude and shape of the pressure pulse at various distances from the spark gap. The resistivity of the water in the tank (tap) was monitored through digital ohm meters. Figure 3 and 4 exhibit typical arc discharge characteristics and pressure data recorded by the various gauges.

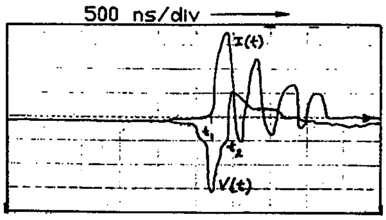

Figure 3. Typical Arc Discharge Voltage and Current Measured by V-dot and B-dot gauges. (Note half cycle t_2-t_1) V_{max} = 344 kV, I_{max} = 75 kA).

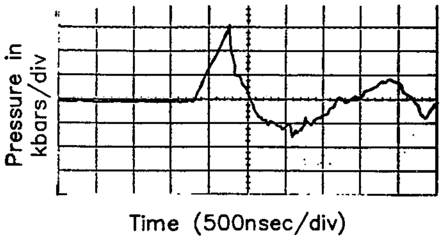

Figure 4. Typical Oscilloscope Output for Quartz Gauge Pressure Data.

Phenomenology Investigation

The electrohydraulic effect arises from the complex interaction of several electrohydrodynamic processes. The phenomenon actually occurs in three phases: 1) arc discharge phase; 2) the shock wave generated in water; and 3) the mechanics of rock fracture when the shock impinges on the surface. The arc discharge phase itself represents the interaction of three distinct but coupled processes: the pre-breakdown buildup of the electric field at the electrodes; the water breakdown phase which leads to the formation of the plasma column; and, the rapid plasma column expansion phase that transmits a pressure pulse to the surrounding water. The total sequence takes between 0.2 to 2 μs, and the resulting steep shock front (1 to 10 GPa) expands first as a cylindrical and subsequently as a spherical supersonic wave through the liquid until it impacts on the rock surface. Of the three phases identified above, the shock formation and propagation is understood best. Much work has been done on the arc phase and rock mechanics phase of the EHE, but because of the very complex nature of the phenomena, most of the analysis is semi-empirical. Space does not permit us to treat the above three phases exhaustively. Detailed discussions and results are given in Chapter IV of Reference 5. Below we touch upon some highlights of our experimental results and semi-empirical analysis.

1. Arc discharge and shock physics. Table 1 summarizes the measured and calculated values of the energy input to the arc, energy in the shock wave (Eq. 2) for several typical runs.

Table 1. Thumper II Discharge Characteristics: Energy at Electrode and in Pressure Pulse.

W(kJ) Marx	V(kV) V-dot	I(kA) B-dot	t_2 -t_1 (ns)	W_{dis}(kJ) Eq. 1	W_{shock}(kJ) Eq. 2
12	130	55	200	6	2-2.5
12	190	65	250	7	2.5-3
12	340	75	300	8	3.5
16	390	85	350	9	4
18	450	96	400	12	5

The 2 to 5 kJ energies in the pressure pulse listed in Table 1 are best estimates from the quartz pressure data extrapolated to the discharge arc boundary.

Based on the V-dot and B-dot measurement, the energy into the electrode can be estimated from the V(T) and I(t) curves, then,

$$W_{discharge} = \int_{t_1}^{t_2} V(t)\ I(t)\ dt \qquad (1)$$

Where t_2-t_1, is the interval during the first half-cycle of the discharge (see Figure 3).

The energy transmitted to the pressure pulse in the water can be determine approximately from

$$W_p \simeq \int r^2 \, d\Omega \int_0^t \frac{p^2}{\rho U} \, dt \qquad (2)$$

In Equation 2, the pressure p was determined from the quartz gauge measurements and the shock velocity U was calculated using a one-dimensional hydrodynamic code,and checked against Schlieren data from Reference 2 for energy inputs that were comparable to the present experiments. Figure 5 gives typical peak pressure data as a function of distance r from the arc center. Single spark pressure amplitudes varied from 0.1 kbars at 10 cm from the gap to kbars at 1 cm distance. Shock widths varied from 0.75 μs at 2 cm from the arc center to 1.10 μs at 5 cm shock velocities ranged from a high of 5,000 m/s at the arc to 1,700 m/s (acoustic speeds) at distances greater than 5 cm.

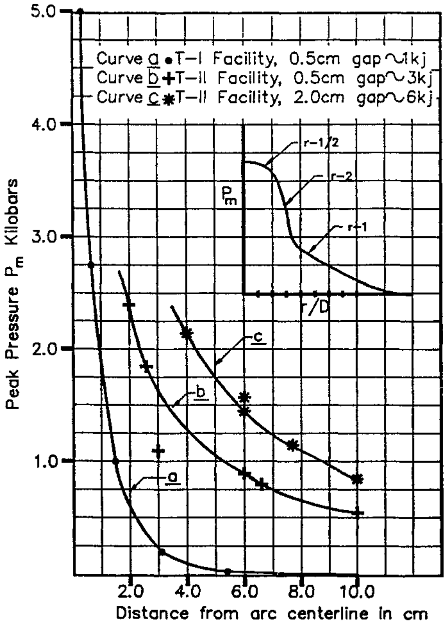

Figure 5. **Peak Pressure P_m as a Function of Distance r from the Arc Center. Inset Depicts Behavior of Typical P_m versus r/D curve.**

The discharge voltage, current and peak pressure were also measured as a function of gap size. Table 2 lists some of these values.

Table 2. **Variation of Discharge Voltage, Current and Peak Pressure with Gap Size.**

Gap Size D, cm	V (kV)	I (kA)	P (kbars)
0.5	100	55	0.8
1.0	190	65	1.0
1.5	250	75	1.2
2.0	340	80	1.6

A series of tests were conducted comparing a single gap electrode system (D = 0.5 cm) with a multiple gap system with four floating electrodes separated by 1.5 mm each. It was found that energy input into the arc for a given discharge condition is higher for the multiple gap system than for the single gap system.

Finally, theoretical analyses with shock focusing and steering demonstrated amplification of shock waves from arc discharges generated by arrays of electrodes (ring or star formation). Because of time constraints, only limited series of experiments were conducted to validate the analytic efforts. These experiments demonstrated factors of two or more pressure enhancement, using the Star array, shown in Figure 2.

2. Mechanics of Rock Fracture. The rock fracture mechanics were investigated using finite difference fracture models couple to the one-dimensional hydrocode followed by a series of controlled experiments. These were conducted with cylindrical core and rectangular block Leuders limestone and Berea sandstone samples. Three stages in rock fracturing were identified, as the impact pressure on the samples was raised from 0.8 kbars to 10 kbars. These were spalling, ring damage and surface gouging (or cratering, see Figure 6). The optimum gouging or rock erosion rates observed were 0.25 cm per second for a 6 cm hole (Figure 7) both in sandstone and limestone samples at energy levels in the arc ranging from 6 to 8 kJ. The above three stages can be used to indicate the energy levels in the shock wave impinging on the rock surface (see Table 1 data).

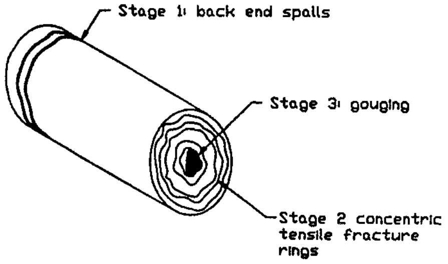

Figure 6. **Three Stages of Fracture Patterns in Cylindrical Rock Samples (Leuders limestone and Berea sandstone).**

Figure 7. **Berea Sandstone Block Sample S-3 Showing Erosion Characteristics.**

Conclusions

Using a single pulse every few minutes, we have been able to discharge 8 to 10 kJ energies in an arc, generated in tap water, in 100 ns. A series of such discharges has produced erosion rates of 0.25 cm/sec, in 6 cm holes in limestone and sandstone samples. At a repetition rate of one discharge per second this yields an advance rate of 7 to 10 m/hr. for an 8-inch hole.

It is within the state-of-the-art to generate 25 kJ energies at the rate of one pulse per second, per electrode pair. Increasing the pulse rate (10 pps) and number of electrode pairs, (4 to 5) it is possible to provide upwards of 100 kW power to the rock surface and obtain penetration rates of 50 m/hr. Our own studies and those obtained at Sandia indicate that the successful development of a spark drill would require a 4- to 5-year development program before a prototype unit can be successfully tested under realistic field conditions. A conceptual design was therefore completed of a downhole focused shock drill bit. The system is designed to deliver a total of 8.4 kJ to the spark array at a repetition rate of 50 Hz, for an average power of 430 kW. The system will utilize three pulse-forming lines for providing power to the spark array. The power conditioning unit, the capacitor bank and the pulse-forming lines will be operating downhole, in a 12-inch diameter borehole. Power will be transmitted downhole from a three-phase generator at 400 Hz, 5 kV, and 50 A.

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