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THE FEASIBILITY OF
DEVELOPING A
BOREHOLE SPARKER
FOR GEOTHERMAL WELLS

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SECTION 1.

SYNOPSIS

A feasibility study was undertaken to determine the practicality of designing a borehole sparker (underwater electric discharge) seismic source for use in an extremely harsh environment (69MPa @ 275°C = 10,000 psi @ 527°F). Important electrical and hydrodynamic parameters of underwater spark discharges, component availability, and past accomplishments of others in the field of borehole-to-borehole sparker surveying are discussed.

It is concluded that this instrument could be economically developed.

SECTION 2.

INTRODUCTION

In November 1976, EG&G/LAO was requested by the Q-Division of the Los Alamos Scientific Laboratory (LASL) to perform a study to determine the feasibility of designing a borehole sparker seismic source.

The design of this instrument is to be based on the principle of quickly discharging a high voltage, high energy, capacitor bank across electrodes immersed in a liquid; thus, creating a high-pressure wave that can be detected by acoustic sensors in a remote borehole. This technique would offer several important advantages over the present method of discharging high-explosives to produce seismic waves. Among the more significant are: (1) at least an order of magnitude greater firing rate, (2) the ability to recharge the seismic source without bringing the instrument to the surface, and (3) the ability to easily tailor the seismic source magnitude (within limits) by altering the capacitor bank charging voltage.

SECTION 3.

GENERAL SPECIFICATIONS

This instrument is to be initially employed by LASL at their Fenton Hill Geothermal Research Site in the Jemez Mountains. Hence, it is required to withstand the downhole environment, be compatible with existing physical constraints (e.g., casing I.D.), and be capable of operating in the hostile environment for the duration of one of their experiments.

In consideration thereof, design criteria are as follows:

- 1) Maximum continuous time of instrument in the hostile environment is 12 hours.
- 2) Minimum time between instrument immersions in the hostile environment is 24 hours; during this time the instrument will be placed in an air ambience at -30°C to $+30^{\circ}\text{C}$ temperature.
- 3) Maximum hostile environment pressure is 69MPa (10,000 psi); including static and pump heads.
- 4) Maximum hostile environmental temperature is 275°C (527°F).
- 5) Instrument is to be lowered to a maximum depth of 4.57Km (15,000 ft).
- 6) Maximum O.D. of instrument enclosure is 15.24cm (6.000 in.).
- 7) There will be no significant mechanical dynamic loads applied to the instrument (e.g., shock due to "bottoming-out" in the hole).
- 8) The instrument shall be suspended from an existing high-temperature logging cable. Electrically, this cable consists of six twisted/shielded pairs of AWG No. 20 and one AWG No. 22 coax (with estimated characteristic impedance of 48 ohms). A cable-head will be provided.
- 9) Upon firing the instrument, the resulting pressure-wave strength should be essentially omnidirectional unless a means of orienting the instrument in relation to magnetic north is provided.
- 10) The instrument shall be capable of being "fired" continuously at a rate of at least once each 30 seconds while immersed in the hostile

environment; a repetition rate of up to once each 5 seconds is highly desirable. Additionally, the repetition rate and capacitor bank charging voltage should be programmable over a wide range.

SECTION 4.

DISCUSSION

4.1 GENERAL

The idea of using electrical pulse discharges in a liquid to obtain a great concentration of energy is not a new one. Their possible use in machining metal was mentioned in 1944 (BR6*, Page 3). Martin (BR 2), in his experiments, punched slugs from sheet metal to obtain a relative value of transient pressure created by an underwater electrical discharge (established by calculating the static pressure required for shearing the slugs). In fact, according to him, their use for subaqueous sound sources were suggested in 1953; during this period the first patent for the marine profiling technique using a spark source was issued to Dr. Hersey of Columbia University's Lamont Geophysical Laboratory (BR 11).

For any seismic source to be effective, there are several essential criteria to be met: 1) the device must impart a high rate of acceleration to the surrounding medium, 2) provide sufficient energy to allow seismic events to be seen above the background noise level, and 3) the pressure wave characteristics must be repeatable within reasonable limits or vary in a predictable manner (e.g., variance of bubble collapse time with depth).

In the past, the primary energy source has been high-explosives. More recently, the marine sparkers (e.g., EG&G's "Sparkarray") have revolutionized seismic profiling at sea; continuous profiling techniques are possible due to their rapid-firing capability. However, these marine sparkers are too large to be lowered into boreholes. Realizing this problem and the potential value of a borehole sparker, others have designed same and employed it with excellent results (BR 3). Although their tool is not directly applicable due to our present environment, it is of great interest and will be discussed in Section 4.4

Basically there are two types of underwater spark discharge systems; the electrode and the electrodeless. The following discussion holds true for both with the exception that bubble suppression techniques are readily

* "BR" refers to a bibliographical reference in Section 6.

Figure 1. Simplified circuit diagram of a typical underwater electrical discharge system.

adaptable to the latter and not to the former; a more specific discussion for the electrodeless type is reserved for Section 4.3.

4.2 ELECTRICAL AND HYDRODYNAMIC DISCHARGE CHARACTERISTICS VS. PHYSICAL PARAMETERS

4.2.1 General Considerations

A simplified circuit diagram of a typical underwater electrical discharge system is depicted in Figure 1. The discharge characteristics are primarily determined by the: 1) initial storage capacitor voltage, 2) capacity of the storage capacitor, 3) magnitude of the inductance of the circuit, and 4) discharge channel length.

Other parameters that can have considerable influence include the:

- 1) Intrinsic discharge circuit resistance (energy loss in bussbars, capacitors, etc.).
- 2) Shape and size of electrodes (via its control over the field strength).
- 3) Conductance of the medium shunting the discharge channel (e.g., tap water, salt water, drilling mud, etc.).
- 4) Discharge being aperiodic (BR 6, BR 7).

The interrelation of the above parameters are complex. In this report they will be discussed only in a topical sense; detailed equations for numerical analysis (similarity and dimensionality methods) of pulse discharges exist in BR 1 and BR 7. Additionally, related experimental data are presented in these and, particularly, in BR 5.

For all practical purposes, the means of initiating discharges between electrodes immersed in a liquid can be divided into two categories: 1) streamer breakdown and 2) initiating-wire breakdown.

4.2.2 Streamer Breakdown

When electrical field strengths between electrodes become great enough, streamers (leaders) form in the surrounding medium. If the strength is increased, one of the streamers will complete the path between electrodes to establish a conduction channel; the unsuccessful streamers become dormant.

The breakdown process typically takes only a few microseconds to form a high-pressure and high-temperature (20,000 - 40,000° K) plasma. The magnitude of the spark channel pressure is very dependent upon the initial rate of current rise (BR 2).

Naugolnykh and Roii (BR 6) have analyzed the streamer breakdown process by considering the magnitude of the initial storage voltage and the conductivity of the medium:

1) For the case of a high-voltage (several tens of kV) applied across electrodes immersed in tap water (conductivity = 10^{-4} /ohm-cm), they concluded that the discharge takes place with stability and over a few microseconds.

2) For the case of a high-voltage applied to electrodes immersed in sea-water (conductivity = 10^{-2} /ohm-cm); they found a reduction in streamer length, accompanied by prolonged pre-breakdown currents. These currents caused large energy losses to heat, sapping away the amount of energy available to create pressure waves.

3) For the case of low voltage breakdown in a liquid, the parasitic effects were even worse.

Of course, the above conclusions were drawn based upon the fact that the other complex interrelating parameters were optimized. Optimization of one of these parameters, electrode shape, is of immediate interest.

They present equations for determining the electric field strength for:

1) The case of a point-to-plane electrode pair

$$E \approx \frac{2u}{r \ln \frac{4l}{r}} .$$

2) The case of point-to-point electrodes

$$E \approx \frac{u}{r \ln \frac{2l}{r}} .$$

where, E = electric field strength

u = voltage applied across electrodes

r = radius of curvature of the electrode tip

l = electrode gap length

Obviously, the point-to-plane arrangement results in a higher field strength if the point electrodes and applied voltages are the same. A factor not obvious is that it makes a very substantial difference that the pointed electrode is the more positive electrode (plane negative); experience has shown that a field strength of approximately 36kV/cm is required for a good (fast) breakdown.

Graphic data, helpful in the optimization of various parameters, can be found in BR 5.

4.2.3 Initiating-Wire Breakdown

Initiating-wire breakdown has been used by many experimenters with success. This technique makes use of a feeder-wire to provide an initial conduction path between electrodes in place of a streamer.

The random duration of the prebreakdown period and the irregular, unpredictable path of the spark made correlation of data taken on different sparks very difficult.... These difficulties were all circumvented by initiating the spark with a fine wire between the electrodes.... In addition, the sparks became quite reproducible from one to the next. Excellent consistency of the data justified the use of instantaneous measurements on successive sparks at increasingly later delay times as a means of obtaining the spark behavior as a function of time....

It was established that the metal of the initiating wire played no significant part in the plasma phenomena of the spark channel....

Photographs of underwater sparks initiated by a relatively large diameter wire showed transverse striations during the early stages of spark development.... The spacing

was a function of the initiating wire diameter but was relatively unaffected by changes in wire material.

- Martin (BR 2)

Okun' (BR 7) suggests that "... the complicating circumstances (discharge instability) are easily eliminated by the use of a fine wire jumper between electrodes."; employing this method, he proceeds to derive underwater pulse discharge similarity criteria and demonstrates their usefulness via experiments.

A detailed treatment of the subject can be found in BR 6; the authors disagree with Martin's findings that the wire material makes no difference:

... thin tungsten wires are more suited for initiating discharges in water. With the aid of tungsten wires it is possible to initiate discharges with a working voltage of several kilovolts....

4.2.4 Bubble Phenomena

Upon initiation of a conduction channel, the electrical energy is released to form a rapidly expanding gas plasma which, in turn:

- 1) creates a high pressure shock wave,
- 2) stores kinetic energy into potential energy by forming a bubble, and
- 3) loses some of the energy to heat transfer.

The remote borehole sensor (geophone or hydrophone) will first detect acoustic energy as a result of the initial pressure wave. Subsequent pressure waves will be sensed due to the implosion of the bubble. The bubble, depending upon its energy, the medium ambient pressure, and other factors may actually form again and result in a damped oscillating pressure wave being received in the remote borehole.

Bubble formation in close proximity to a surface (within a few bubble diameters) can cause cavitation damage to that surface upon collapse due to the formation of water jets (BR 8). This phenomena has been used to advantage by some researchers (BR 1, BR 10) but would be detrimental in our case --- if surfaces were placed in close proximity. Surface proximity to a bubble varies

with depth since the bubble radius and collapse time are a function of the discharge depth (ambient hydrostatic pressure). For example: for 100 joules released into water near the surface, BR 1 gives a maximum bubble radius of 48mm and a collapse time of 9ms; at a depth of 10,000 ft., these values have reduced to 7mm and 75 μ s.

4.3 ELECTRODELESS UNDERWATER SPARK DISCHARGE

The outstanding feature of interest of the electrodeless sparker is the ability to use a hydromechanical means of suppressing bubble formation. One of its greatest drawbacks is its low electro-acoustic efficiency.

The abstract from BR 9 follows:

ABSTRACT

The electrodeless spark sound source is an impulsive electro-acoustic transducer. It generates a broadband impulse which is typically several tens of microseconds in duration. The electrodeless spark principle is described, and the results of parametric studies presented. It is found that the device is long lived, its emitted pressure waveform can be readily controlled, the emitted waveform is extremely reproducible, and the bubble pulse emission can be virtually eliminated.

The peak pressure developed at one yard is typically a few tenths of a bar to several bars. The electro-acoustic efficiency is modest, usually being no more than a few percent.

A discussion of several specific device configurations shows that the wave form of the emitted pressure is strongly dependent upon both the electric and, particularly, the geometric parameters used.

4.4 EXISTING BOREHOLE SPARKER SYSTEM USED FOR SURVEYING.

McCann et al., in their interest in obtaining accurate data for use in Civil Engineering projects via borehole-to-borehole logging, have developed two instruments; one having a storage capacity of up to 10 joules and

the other up to 1000 joules. While the small sparker is used in one case to determine an attenuation coefficient by releasing 2 joules of stored energy and monitoring the high frequency energy up to 10kHz, the paper concentrates on use of the large sparker.

"The electronic circuitry developed to drive...the high power probe is based on the standard EG&G marine sparker equipment.... The acoustic signal is detected by a spherical 80kHz radial resonance hydrophone...." (BR 3). The authors provide a simplified drawing of the sparker, it being manufactured from 7.5cm I.D. Duralumin tubing of 75cm length. It employs one high-voltage (positive) electrode along the tubing axis; the tubing acting as the other electrode (negative). The storage capacitors are "... charged to 3-4kV." This is a surprisingly low voltage for streamer breakdown; their success in using this voltage is obviously coupled to the fact that the discharge takes place in a captivated electrolyte (calcium chloride solution).

In-depth case studies of a wide range of propagation media are given, including methods of interpreting the data.

4.5 EXISTING BOREHOLE SPARKER SYSTEM USED FOR DESCALING OF TUBING

A Dallas firm (Sonics International, Inc.) has developed a sparker tool for use in removing mineral deposits from borehole casing. These residues often interfere with oil well productivity.

This tool is 10.16cm (4.0 in.) DIA X 5.12m (16.79 ft.) long, employs an initiating-wire (feeder-wire) between electrodes, and is capable of storing almost 400 joules (14 μ f at 7.5kV). They have repeatedly operated the device at 27.6MPa (4000 psi) pressure and 100°C temperature. According to their personnel, the present capacitors (rated at 100°C) could be replaced with capacitors rated at 350°C for approximately \$4000; however at this time it is not known if they could withstand 69MPa pressure. Additionally, the downhole electronic components are rated at 125°C and would require protection from the Fenton Hill downhole environment.

SECTION 5.

CONCLUSIONS

In conclusion, a project to develop a borehole sparker for downhole use at the Fenton Hill Geothermal Research Site seems a practical undertaking; offering a high potential for success. The investment required to accomplish the task could vary considerably, according to the adaptability and availability of existing hardware. However it appears economically feasible even if existing hardware is not available (based on a comparison with other instruments being developed at present).

While the purpose of this research was to study the feasibility of design and not to write a design specification, a few design recommendations seem to be in order:

1) Early in my investigation, in consultation with Mr. Lee Aamodt of LASL, it was decided that a 100-joule output at the electrodes would yield satisfactory results. An electro-acoustic efficiency of 10 percent seems to be realizable without excessive design effort; hence, I would recommend a design goal of 1000 joules stored energy at the capacitor bank. This feeling is reinforced by the success of McCann et al. (BR 3) in using an instrument of this size.

2) Some of the electrical components will probably need protection from the environment; I would suggest using the instrumentation enclosure now being fabricated to the specifications of BR 4.

3) The capacitor storage voltage should be kept as low as practical since:

a) the existing cable will be limited to a maximum of 500 volts between conductors.

b) the component size and cost increase with an increased voltage rating.

4) It is recommended that the designer visit McCann et al., EG&G/Mass. Division (where the marine sparkers are designed), and Sonics International, Inc. to discuss their equipment. While visiting these facilities,

it could be determined if any of the aforementioned would be interested in participating in the project.

5) Some comments about adapting the McCann et al. tool (streamer breakdown):

a) To accomplish a brisk discharge at such a relatively low voltage for streamer breakdown, even in a known electrolyte, requires optimization of electrode spacing and design --- one should be careful to pay particular attention to these parameters.

b) Although streamer breakdown is not too dependent upon the ambient pressure through 1000 atmospheres (BR 6), the storage voltage should be increased slightly (5-6kV).

c) A piston or bellows, restrained to move along the tube axis, might be used as the bottom of the closed electrolyte container; thus, eliminating the differential pressure problems.

6) Some comments about adapting the Sonics International, Inc. tool (initiating-wire breakdown):

a) A capacitor storage voltage of 4kV should be more than adequate for breakdown with an initiating-wire technique; they presently employ 75kV, but with less energy than we would require.

b) Their present feeder-wire mechanism stores "motor-energy" in a torsion spring; this spring would probably have to be replaced due to the higher temperatures.

c) Although their tool does not employ a captivated electrolyte, its shock wave repeatability should still be excellent within most any liquid.

SECTION 6.

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