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Final Technical Report

A STUDY OF UNDERWATER PROPAGATION
FROM A HIGH-POWER
ELECTRICAL DISCHARGE

by

M. J. Larsen
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ABSTRACT

This constitutes the final technical report of a series
of three technical reports submitted under the present contract.
Included is a brief chapter summarizing the work covered over the
contract period. The previous reports treated with certain
electromagnetic observations on the propagation of a transient
signal through sea water. This report considers some acoustical
observations resulting from a high-power electrical discharge.

One of the main objectives in making acoustical tests was
to obtain some kind of measure of the ratio of the radiated
acoustical energy to that of the electrical energy of the discharge.
For the tests made under sea water this ratio was observed to be
on the order of 1 to 1000, while using a simple non-optimized dis-
charge electrode design. Measurements made of air-to-water
electrical discharges, as for example, a simulated lightning dis-
charge to the surface, revealed substantially negligible underwater
acoustical response.

REVIEW OF CONTRACT WORK

The period of the present contract started March 1, 1960, and with subsequent renewals and extensions is scheduled to terminate June 30, 1963. The work was conducted by several staff members of the Electrical Engineering Department working through the Engineering and Industrial Experiment Station of the University of Florida's College of Engineering. Collaborating were personnel of The Lightning and Transient Research Institute of Minneapolis, Minnesota. The Institute's research schooner, the Azara, was the main laboratory as it housed the capacitor bank used for the energy source throughout the several testing periods in various ocean areas.

The first major test period took place in Nassau Harbor and also in deep water just north of New Providence Island, during May 1960. In these tests the capacitor bank energy was discharged into a large square loop (11 x 11 feet) which was in the air for some tests and submerged just below the surface for others. The extending signals (mainly induction field) were received by a 1-meter diameter loop at relatively close distances, usually not exceeding 300 meters and to depths down to approximately 26 meters. The frequencies involved were low with the frequency spectrum of the transmitting pulse centering near 500 cps. The pulse energy released by the charged capacitor bank was on the order of 1100 watt-seconds (joules). There were no particular anomalies as the

test results were consistent with theoretical calculations within probable experimental tolerances.

The results of this first test period are reported in Technical Report No. 1, "Study of Electro-Magnetic Propagation of a Transient Signal Through Sea Water," by M. J. Larsen, M. H. Latour, and M. M. Newman (April 1961).

The second major series of tests was conducted in South Bight, Andros Island, of the Bahama Islands during April 1962. The objective of these tests was to transmit a higher frequency pulse than that from the loop of the previous set of tests so that the radiated field could be investigated, both at the surface and underwater. (In the tests reported in Report No. 1 the field extending from the transmitting loop was considered to be largely induction and not radiating.)

The energy source again was the capacitor bank of the schooner, Azara, and the radiating antenna was a kite-supported wire of lengths up to 3,000 feet. Considerable effort and expense were made to prepare an aluminum sphere which was submergible and which housed, isolated from the surface, tape recording equipment for receiving signals from crossed loops which surrounded the shell. This portion of the work was unsuccessful because the winds were not quite strong enough to give the kite sufficient supporting strength for the desired length of antenna wire. It would be necessary to have an antenna nearly one and one-half miles in length in order to transmit the peak energy of the pulse at a

frequency below the frequency limit of the recorder which was
about 30,000 cps.

Satisfactory results were obtained, however, by substituting
another loop which could be oriented in desired planes but which
was connected by cable to oscilloscopes on the receiving boat.
This equipment did not have the frequency limitations of the re-
corder and was able to receive adequately the signals from a
3000-foot antenna. Although data were taken at distances as far
as four nautical miles from the source, the data subject to analysis
were taken at a distance of approximately one nautical mile with
the receiving loop above the surface and at depths of five feet and
ten feet. Included in the report of this work are a comparison of
experimental results with theoretical, a derivation of an approxi-
mate expression for optimum propagation frequency as a function of
ocean depth for loop reception, and comments on certain interface
measurement problems.

The story and results of the second test period are reported
in Technical Report No. 2, "Study of Electro-Magnetic Propagation
of a Transient Signal Through Sea Water," by M. J. Larsen, O. R. Gano,
and M. M. Newman (December 1962).

The third and final major test period was conducted in the
St. John's River in an isolated bend a few miles up from Mayport,
Florida, during July 1962. This work explored the acoustical out-
put of an electrical pulse discharge and is the subject of the
remaining portion of this report.

INTRODUCTION TO THE ACOUSTICAL STUDY

In June 1962 an extension of the contract was requested
and granted so that work could proceed on the study of some
acoustical properties associated with a relatively high-power
electrical discharge. It was thought that it would be of basic
interest to obtain a measure of the total acoustical power
radiated from an electrical discharge source so that a figure
of the acoustic-electric efficiency could be obtained.

The plan of the experimental procedure was to discharge the
stored energy from a capacitor bank through a suitable electrode
immersed in the ocean. The acoustic wave produced by the dis-
charge was intercepted by a small hydrophone probe and recorded
off the face of an oscilloscope. As the objective was to measure
energy relations and not propagation characteristics, it was
thought that measurements could be made best with transmitting elec-
trode and receiving probe relatively close, say from 10 to 20 feet.
Following this procedure the direct wave clearly would be de-
lineated from reflected waves and the observable signal probably
could be considered as measuring a spherical wave front.

The positions of the discharge electrode and the hydrophone
relative to the boat are shown in Fig. 1. While testing, the research
schooner, the Azara, was anchored off the regular traffic channel
in a secondary channel of the St. Johns River a few miles up stream

from Mayport, Florida, where the water was tidal and averaged approximately 30 feet deep. Electrode and probe clearances from the boat varied between 5 and 10 feet but always were sufficient so that reflections were discernible from the main pulse.

Extensive work on sound propagation of a transient signal in the ocean has been reported by Ewing, Worzel and Pekeris.[1] In the reference cited the sources of the signals were explosive shots with resultant propagation extending over very large distances, in some cases several thousand miles. In the case of an electrical source, however, the energy is very much less. The mechanism by which the sound is produced, nonetheless, might perhaps be considered analogous to a minor explosion.
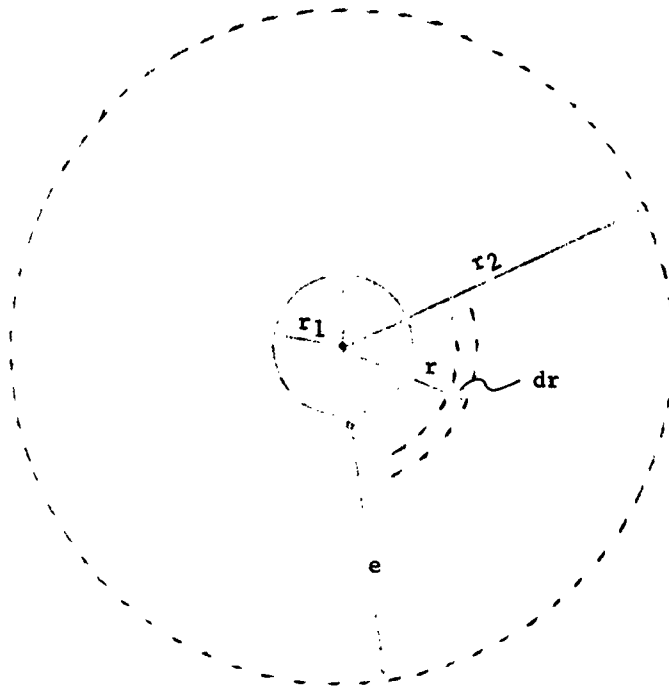
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[1]"Propagation of Sound in the Ocean," Ewing, Worzel and Pekeris. The Geological Society of America, Memoir 27, October 1948 (Contribution No. 415 from Woods Hole Oceanographic Institution.)

THE ELECTRICAL DISCHARGE AS A SOUND SOURCE

A schematic of the energy source is shown in Fig. 2. When the capacitor is fully charged the discharge cycle is effected by shorting one of the two spark gaps, the voltage being sufficient to cause a discharge through the remaining gap and the immersed electrode. The waveform of the discharge current is observed from the voltage drop across the very low resistance shunt. An oscillogram of the current of a typical discharge is shown in Fig. 3a.

During some preliminary tests the discharge electrode was a small brass sphere of approximately 1 cm in radius. While using this electrode no appreciable acoustical output was observable. When the brass sphere was removed, however, leaving a short portion of a threaded shank, then considerable acoustical energy was produced. In fact, any small-radius source seemed to be effective; even a break in the insulation which would leave a minimum of wire exposed produced considerable acoustical output. Although this admittedly is a highly empirical approach, it leads to suggesting the following analysis of a possible mechanism for producing electroacoustic explosions.

Consider, for example, a metallic sphere of radius r_1, immersed in sea water of resistivity ρ and at e volts relative to ground, or a grounded sphere of radius r_2.

The current i flowing between the smaller sphere and the ground sphere is

$$i = e/R_{1,2} \qquad\qquad (1)$$

where $R_{1,2}$ is the resistance between these two spheres. Neglecting contact resistance, this resistance is derived readily as follows:

$$dR = \rho dr/4\pi r^2 \qquad\qquad (2)$$

$$R_{1,2} = \frac{\rho}{4\pi} \int_{r_1}^{r_2} \frac{dr}{r^2}$$

$$= \frac{\rho}{4\pi} \left[\frac{1}{r_1} - \frac{1}{r_2} \right]$$

In most cases the radius of the outer sphere (effectively the ground plane) is much larger than the electrode radius, that is $r_2 \gg r_1$. Then for all practical purposes

$$R_{1,2} = \frac{\rho}{4\pi r_1} \tag{3}$$

and

$$i = \frac{4\pi e r_1}{\rho} \tag{4}$$

The next thing to consider is the power density, particularly near the electrode. The power volume density P_V in a thin spherical shell at radius r (volume dV) is evidently

$$P_V = \frac{i^2 dR}{dV} \tag{5}$$

From (2) and as $dV = 4\pi r^2 dr$, (5) becomes

$$P_V = \frac{i^2 \rho}{(4\pi r^2)^2} \quad \text{watts/cm}^3 \tag{6}$$

If the effective current (rms value) of the pulse is used, then the average power volume density for the duration of the pulse is

$$P_V = \frac{\rho i_{eff}^2}{(4\pi r^2)^2} \quad \text{watts/cm}^3 \tag{7}$$

where ρ and r have centimeter dimensions.

It will be assumed, or conjectured, that the acoustical pulse is initiated by conversion of the water into steam at the electrode surface. To see if this is a plausible assumption the energy in gram-calories to convert water to steam must be compared with the energy density of the volume concerned. To convert water

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at 25° C to steam requires (100 - 25) + 539 or 614 gram-calories per cm³ of water. This is equivalent to (4.186)(614) or approximately 2570 watt-sec of electrical energy.

The electrical energy volume density W_V in the vicinity of the spherical electrode is $P_V \Delta T$, or from (7)

$$W_V = \frac{\rho I^2_{eff} \Delta T}{(4 \pi r_1^2)^2} \text{ watt-sec/cm}^3 \tag{8}$$

where ΔT is the duration of the pulse over which the power is averaged. Hence to cause vaporization it is necessary to equate the two energies, thus, (neglecting heat losses)

$$W_V \gtrless 2570$$

for the temperature indicated. Using the effective value of the current of the pulse illustrated, see Fig. 3a,

$$I_{eff} \cong 2350 \text{ amperes.}$$

Also using a typical sea-water value for ρ of 25 ohms across a cm³, and a value of 100×10^{-6} sec for ΔT, then (8) becomes

$$\frac{(25)(2350)^2(100 \times 10^{-6})}{(4 \pi r_1^2)^2} \gtrless 2570$$

or $\quad r_1 \lesssim 0.43$ cm

It would follow from this analysis that with a discharge current as illustrated that no steam would be produced at the electrode unless the radius was under 0.43 cm. There is support for this theory when it is realized that no acoustical output was noted from a spherical electrode tried in the beginning which was on the order of 1 cm in radius.

An alternative form for equation (8) is

$$W_V = \frac{E^2_{eff}}{\rho r_1^2} \Delta T \tag{9}$$

where E_{eff} is the rms value of the voltage between the discharge electrode and the ground plane (or sphere). It is evident at once that for non-salt water where ρ is high that the electrode would need to be very small to produce an acoustical effect for the same period ΔT. If the period ΔT over which the power density is averaged is too long, the heat losses to the cooler outer surfaces will become excessive and a balance will be reached below the temperature of vaporization.

There has been a great deal of study and experimental work relating to spark discharges in liquids[2] as well as in gases. The above simplified analysis was made to determine a boundary condition. What goes on after steam is formed is subject to a further analysis which would seem to involve a rapidly enlarging cavity and a resulting arc condition between the electrode and the inner wall of the cavity.

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[2]See, for example, the unclassified ASTIA Technical Document AD No. 267722, "Electrohydraulic Effect," by L. A. Yutkin. (A translation dated October 1961)

RECEPTION OF SIGNALS FROM UNDERWATER DISCHARGE

An oscillogram of a typical signal received by the hydrophone is shown in Fig. 3b with the expanded scale shown in Fig. 3c. With the velocity of sound in sea water being on the order of 5000 feet/sec, one millisecond on the scale represents 5 feet of transmission. The oscilloscope sweep was triggered by the discharge, so the distances of the signals indicated are measured in terms of distances of travel from the source, whether direct paths or reflected paths. In Fig. 3b, for example, the first positive pip was the direct signal, the negative pip following was the reflection from the surface (a rarefaction), while the third probably was a reflection from the boat. Those signals occurring beyond 10 milliseconds evidently were scattered reflections from the river bed with accompanying surface and boat reflections. The expanded scale of Fig. 3c reveals, of course, only the direct signal and surface reflection.

The Table following gives values for the hydrophone peak output signal for nominal distances of 10 feet and 20 feet from the discharge electrode. The discharge currents were of the form shown in Fig. 3a. The hydrophone calibration data are given in the Table.

TABLE OF MEASUREMENTS
FOR POWER CALCULATIONS

Peak Discharge Current	Approximate Separation Distance	Hydrophone Output	Peak Power at Source (Watts)	
			Electrical	Acoustical
3460 amps	10 feet	0.72 volts	55×10^6	41×10^3
3460 amps	20 feet	0.38 volts	55×10^6	43×10^3

Hydrophone Calibration, ARC-LC10M1

    Average sensitivity:

        888 micro-micro coulombs/psi

        With the combined hydrophone and cable capacitance of 0.0040 µf, the sensitivity may be expressed as follows:

$$pounds/in^2 = 4.5 \times volts, \quad also$$
$$dynes/cm^2 = volts \times 3.16 \times 10^5$$

        where -110 db reference $1V/dyne/cm^2$.

The intensity of the sound wave is expressed as $(p^2/\rho c) \times 10^{-7}$ watts/cm^2 where p is in dynes/cm^2 and ρc is the acoustical resistance which is approximately 15×10^4 in gram-centimeter dimensions. Assuming this expression is valid for defining peak acoustic power, then from the Table for the 10-foot separation distance:

$$I = [(0.72)(3.16 \times 10^5)]^2 \times \frac{10^{-7}}{15 \times 10^4}$$

$$= 0.035 \text{ watts/cm}^2$$

Assuming uniform spherical radiation from the source, then the peak power (neglecting dissipation which would be small) from the source would be

$$P_{\text{acoustic}} = (0.035)(4\pi r^2)$$

$$= 41,000 \text{ watts}$$

and similarly the peak power from the source for the 20-foot separation calculates to be 43,500 watts.

The peak electrical power output can be calculated by multiplying the capacitor discharge voltage times the current. This peak occurs near the peak of the current wave (see Fig. 3a and the schematic of Fig. 2) at which time the capacitor voltage would be

$$20,000 - \frac{1}{C} \int_0^{25 \times 10^{-6}} i\,dt$$

or approximately 16,000 volts. At the time of the current peak any inductive drop is zero (L di/dt = 0) so all of the drop must be resistive and between the probe and the return ground. (This is the bronze hull of the schooner which because of its size

relative to the small source can be considered as an equivalent

grounded surface surrounding the source, that is, making

$r_2 \gg r_1$ as in equation (3).) Thus with the peak currents indicated

in the Table, the peak electrical power into the probe is

$$P_{electric} = (16,000)(3,460)$$
$$= 55 \times 10^6 \text{ watts}$$

The results show that the power efficiency, or the ratio of

acoustic to electric power, is on the order of 1 to 1000. Because

of the similarity of the current waveform (Compare oscillogram of

Fig. 3a with that of Fig. 3c.) it is apparent that energy ratios

are on the same order of magnitude as the power ratios. The bulk

of the energy evidently is lost in heat, and some light. A night

view of the flash or glow which accompanies the discharge is shown

in Fig. 5.

Of special interest is the phenomenon of two or more

simultaneous discharges as shown in Fig. 4. The oscillogram was

obtained when the insulation of the cable leading to the underwater

probe was punctured about a foot below the surface, thus emitting

two discharges. Here the bottom probe was about 5 feet down and

the break occurred, as mentioned, about a foot below the surface.

The wire was not quite vertically placed in the water so the

separation distances are somewhere between 18 and 20 feet. It

would seem feasible that identifying coded signals could be trans-

mitted by utilizing multiple discharges with time, space, and

amplitude patterns or arrays. Undoubtedly directional emission

also could be worked out.

UNDERWATER RECEPTION OF SURFACE DISCHARGES

A few experiments were conducted to measure the magnitude
of the underwater acoustical signal caused by an air-to-surface
discharge. For purposes of the tests the capacitor bank after being
charged in parallel was discharged in a series array, yielding dis-
charge voltages on the order of one million volts with peak dis-
charge currents up to approximately 6000 amperes. The oscillo-
gram of Fig. 6a was taken with the hydrophone in air at about
20 feet from the discharge. The scale shows that the distance
corresponds with the velocity of sound in air, approximately
1 foot/millisec. Fig. 6b is with the hydrophone submerged in water to
a depth of 5 feet and separated about 20 feet from the discharge.
Again, from the change in scale, the correspondence with the velocity
of sound in water is observable as approximately 5 feet/millisec.
The peak amplitude under water is very small relative to that in air.
The scales are difficult to read accurately but an estimate of the
ratio indicates the pressure level in water to be approximately 30 db
below the level in air.

In other words, the so-called impinging effect of the dis-
charge on the surface seems to contribute nothing to the sound
level underwater as the above-surface sound would in itself be
transmitted with very nearly the same attenuation through the
air-water interface as indicated by the oscillograms. Further
evidence of the absence of any appreciable acoustical effect caused

by the contact of the discharge with the surface was borne out
in some tests made during the test periods at South Bight, Andros
Island, in April 1962. An observer listening underwater was un-
able to note even the firing time of similar discharges at dis-
tances of about 100 feet.

It would be expected that the acoustical effect of a
lightning discharge would follow the same pattern and yield
negligible underwater sound levels. It would seem possible,
however, to produce by lightning a strong underwater acoustical
transient signal by floating a vertical conductor extending con-
siderably above the surface with insulation below the surface
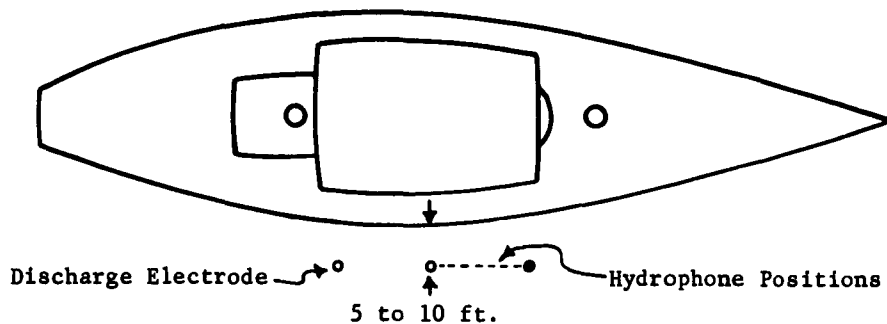down to a point where the electrode would be exposed.

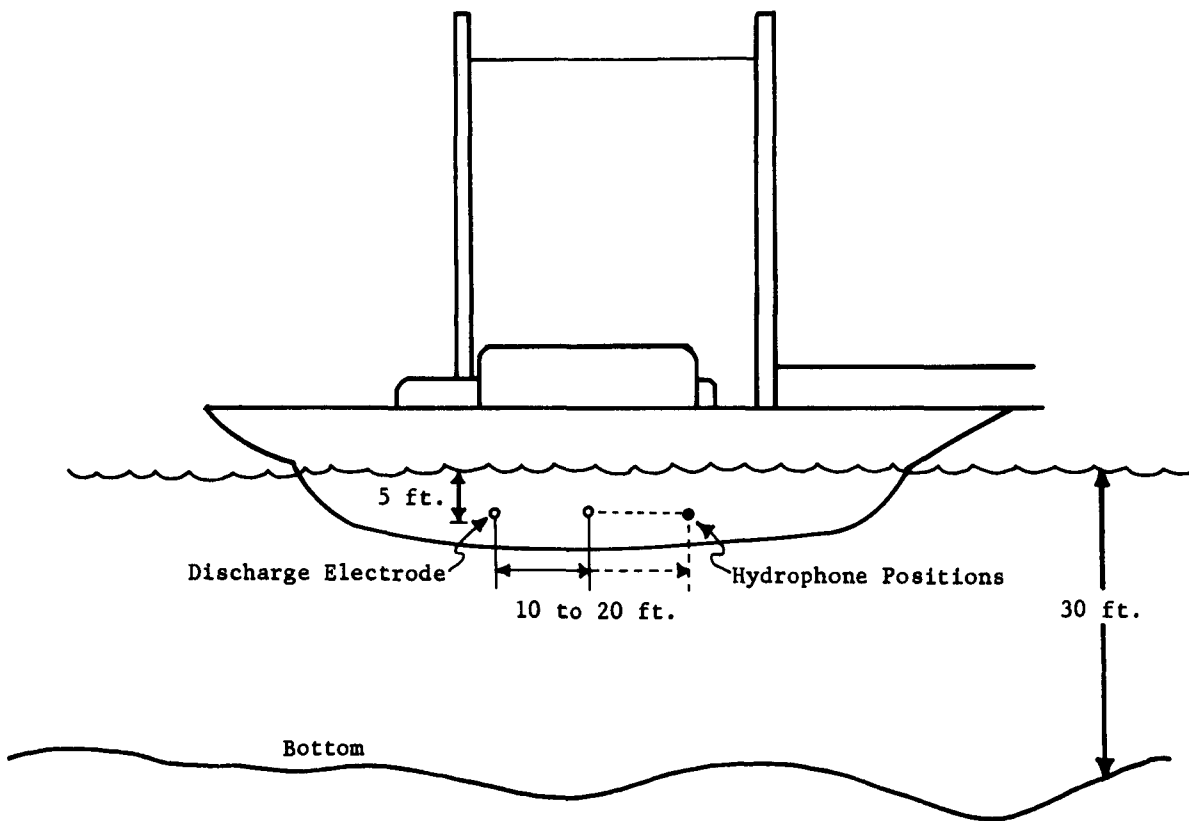Fig. la—Top View of Discharge Electrode and Hydrophone Positions

Fig. lb—Side View of Discharge Electrode and Hydrophone Positions

insulated wire

surface
of water

Bare wire exposed
for approximately
0.25 inches

18.75μfd

20KV

+

−

To Oscilloscope
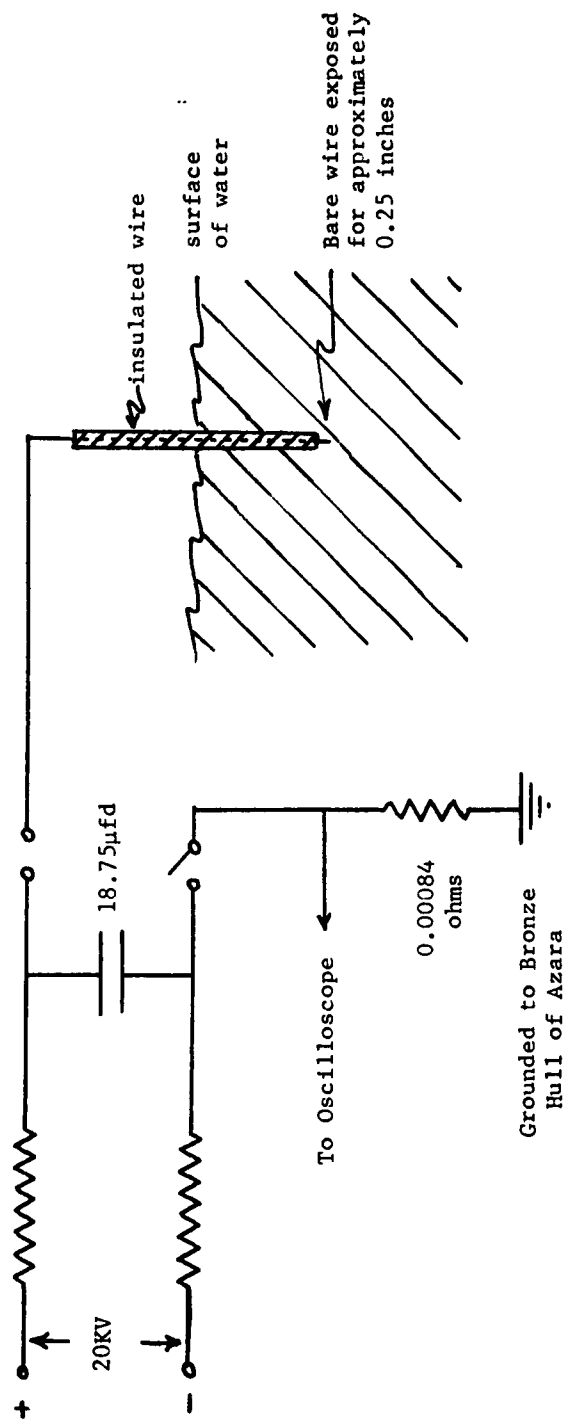
0.00084
ohms

Grounded to Bronze
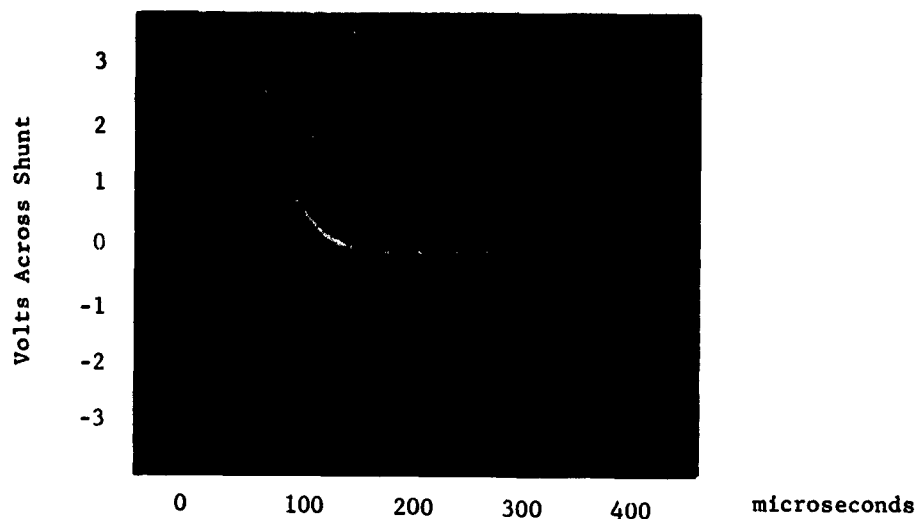Hull of Azara

Fig. 2. Schematic of Energy Source

Fig. 3a. Typical Oscillogram of Discharge Current (1V = 1190 Amps.)
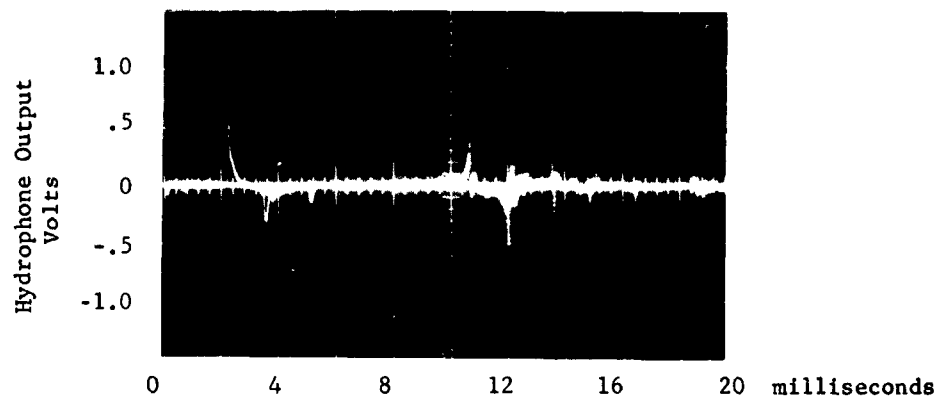

Fig. 3b. Typical Hydrophone Waveform
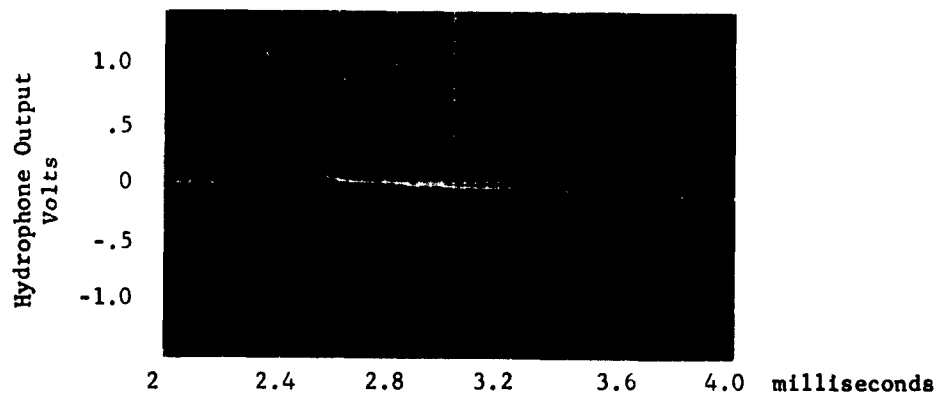

Fig. 3c. Delayed and Expanded Hydrophone Waveform
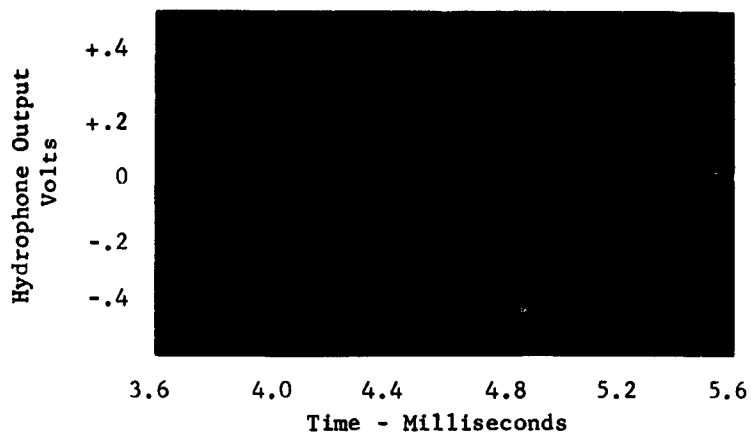
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Fig. 4.   Hydrophone Output From Two Simultaneous
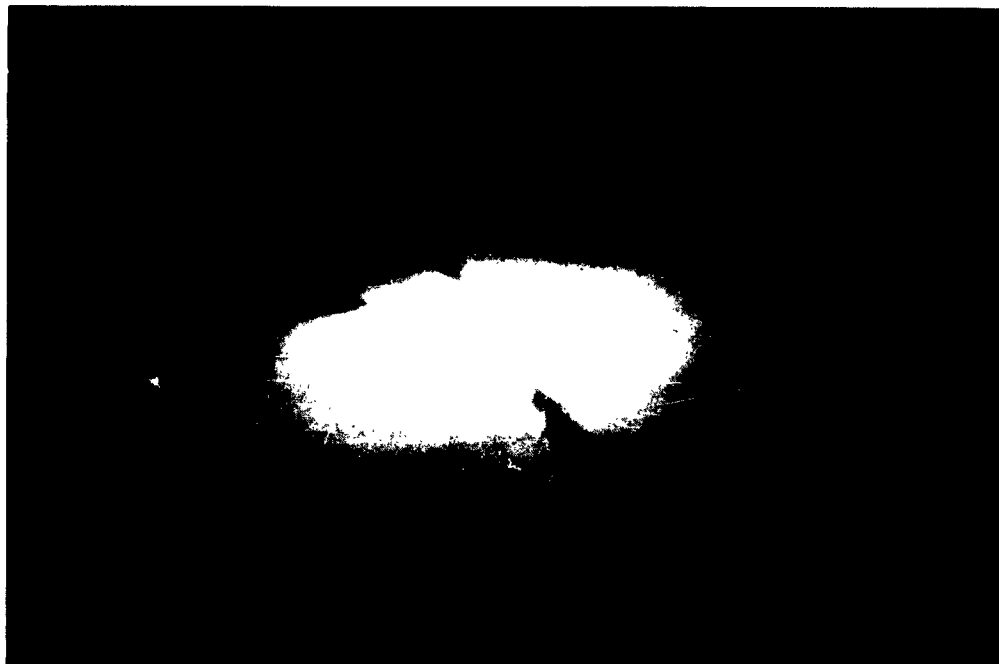   But Space Separated Discharges

Fig. 5.   Night View of Underwater Discharge
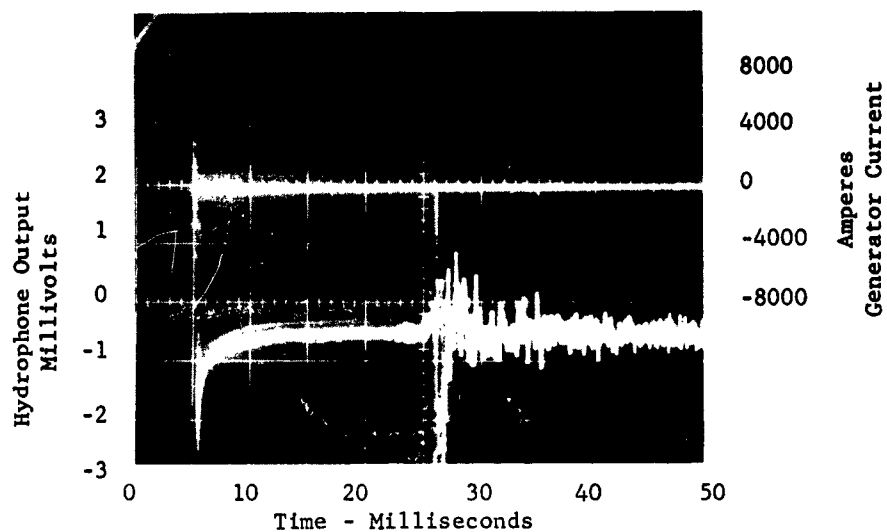   Ship Railing in Foreground

Fig. 6a. High Voltage Air to Water Discharge - Hydrophone in Air
Upper Trace Generator Current
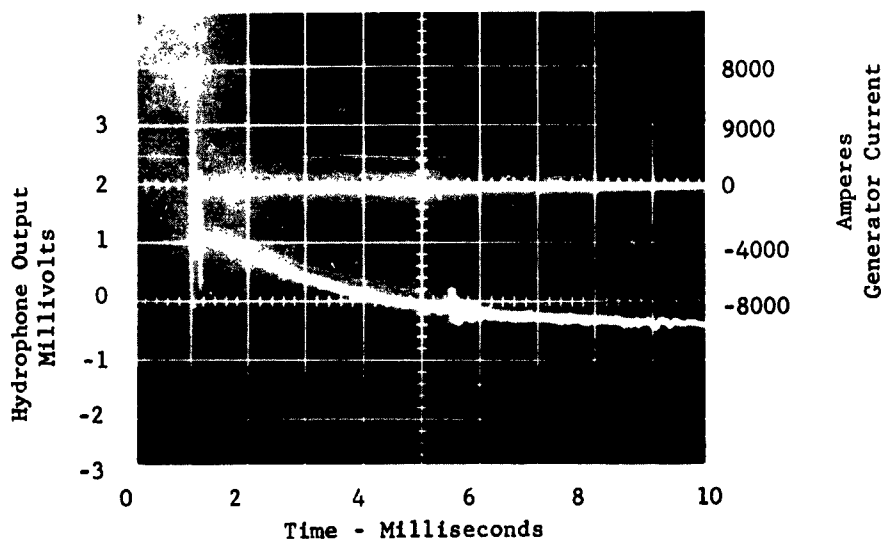Lower Trace Hydrophone Output

Fig. 6b. High Voltage Air to Water Discharge - Hydrophone in Water
Upper Trace Generator Current
Lower Trace Hydrophone Output

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