

UNCLASSIFIED

D _ 406 718 _

DEFENSE DOCUMENTATION CENTER

FOR

SCIENTIFIC AND TECHNICAL INFORMATION

CAMERON STATION, ALEXANDRIA, VIRGINIA



UNCLASSIFIED

NOTICE: When government or other drawings, specifications or other data are used for any purpose other than in connection with a definitely related government procurement operation, the U. S. Government thereby incurs no responsibility, nor any obligation whatsoever; and the fact that the Government may have formulated, furnished, or in any way supplied the said drawings, specifications, or other data is not to be regarded by implication or otherwise as in any manner licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture, use or sell any patented invention that may in any way be related thereto.

Final Technical Report
A STUDY OF UNDERWATER PROPAGATION
FROM A HIGH-POWER
ELECTRICAL DISCHARGE

By

M. J. Larsen
M. M. Newman
O. R. Gano

Department of the Navy
Office of Naval Research
Contract No. Nonr 580(10)
NR 371-340

June 1963

Reproduction in whole or in part is permitted
for any purpose of the United States Government

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS	iii
ABSTRACT	iv
REPORT	
Review of Contract Work	1
Introduction to the Acoustical Study	4
The Electrical Discharge as a Sound Source	6
Reception of Signals from Underwater Discharge	11
Underwater Reception of Surface Discharges	15

LIST OF ILLUSTRATIONS

Figure		Page
1a	Top view of discharge electrode and hydrophone positions	17
1b	Side view of discharge electrode and hydrophone positions	17
2	Schematic of energy source	18
3a	Typical oscillogram of discharge current	19
3b	Typical hydrophone waveform	19
3c	Delayed and expanded hydrophone waveform	19
4	Hydrophone output from two simultaneous but space separated discharges	20
5	Night view of underwater discharge	20
6a	High voltage air-to-water discharge - hydrophone in air	21
6b	High voltage air-to-water discharge - hydrophone in water	21

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 discharge electrode design. Measurements made of air-to-water electrical discharges, as for example, a simulated lightning discharge 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 recorder 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 approximate 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 output 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 discharge 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 electrode and receiving probe relatively close, say from 10 to 20 feet. Following this procedure the direct wave clearly would be delineated 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.

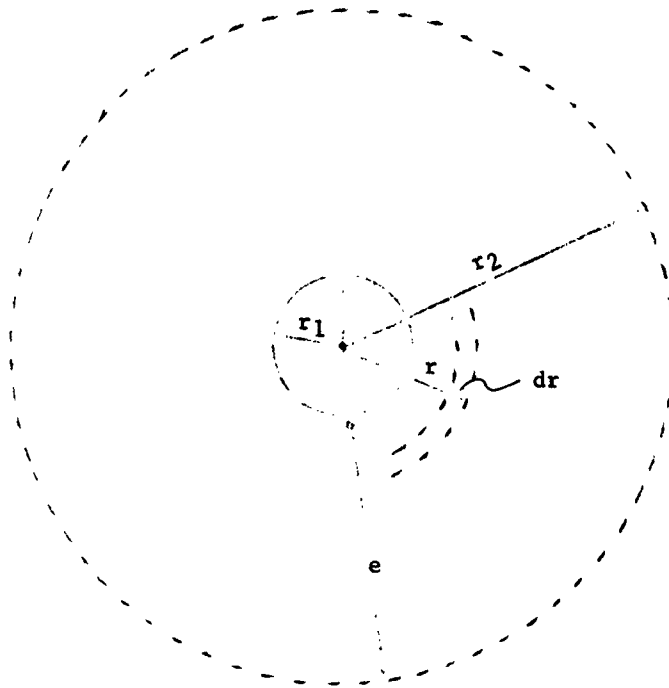
¹"Propagation of Sound in the Ocean," Ewing, Worzel and Pekeris. The Geological Society of America, Memoir 27, October 1948 (Contribution No. 415 from Woods Hole Oceanographic Institution.)

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

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

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

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

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

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

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

$$R_{1,2} = \frac{\rho}{4\pi r_1} \quad (3)$$

$$\text{and} \quad i = \frac{4\pi e r_1}{\rho} \quad (4)$$

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

$$P_V = \frac{i^2 dR}{dV} \quad (5)$$

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

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

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

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

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

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)

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

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)

$$W_V \geq 2570$$

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

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

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

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

$$\text{or } r_1 \leq 0.43 \text{ cm}$$

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

$$w_V = \frac{E_{\text{eff}}^2}{\rho r_1^2} \Delta T \quad (9)$$

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 liquids² 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.

²See, 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 μ f, the sensitivity may be expressed as follows:

$$\begin{aligned} \text{pounds/in}^2 &= 4.5 \times \text{volts, also,} \\ \text{dynes/cm}^2 &= \text{volts} \times 3.16 \times 10^7 \end{aligned}$$

where -110 db reference 1V/dyne/cm².

The intensity of the sound wave is expressed as $(p^2/\rho c) \times 10^{-7}$ watts/cm² where p is in dynes/cm² 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

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

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 transmitted 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 discharge voltages on the order of one million volts with peak discharge currents up to approximately 6000 amperes. The oscillogram 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/millisecond. 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/millisecond. 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 discharge 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 unable to note even the firing time of similar discharges at distances 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 considerably above the surface with insulation below the surface down to a point where the electrode would be exposed.

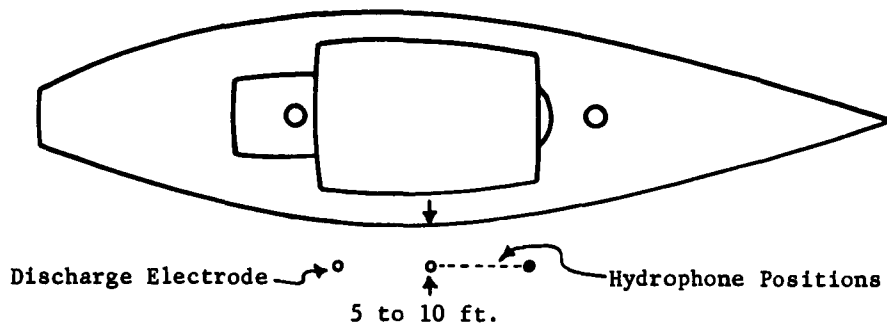


Fig. 1a—Top View of Discharge Electrode and Hydrophone Positions

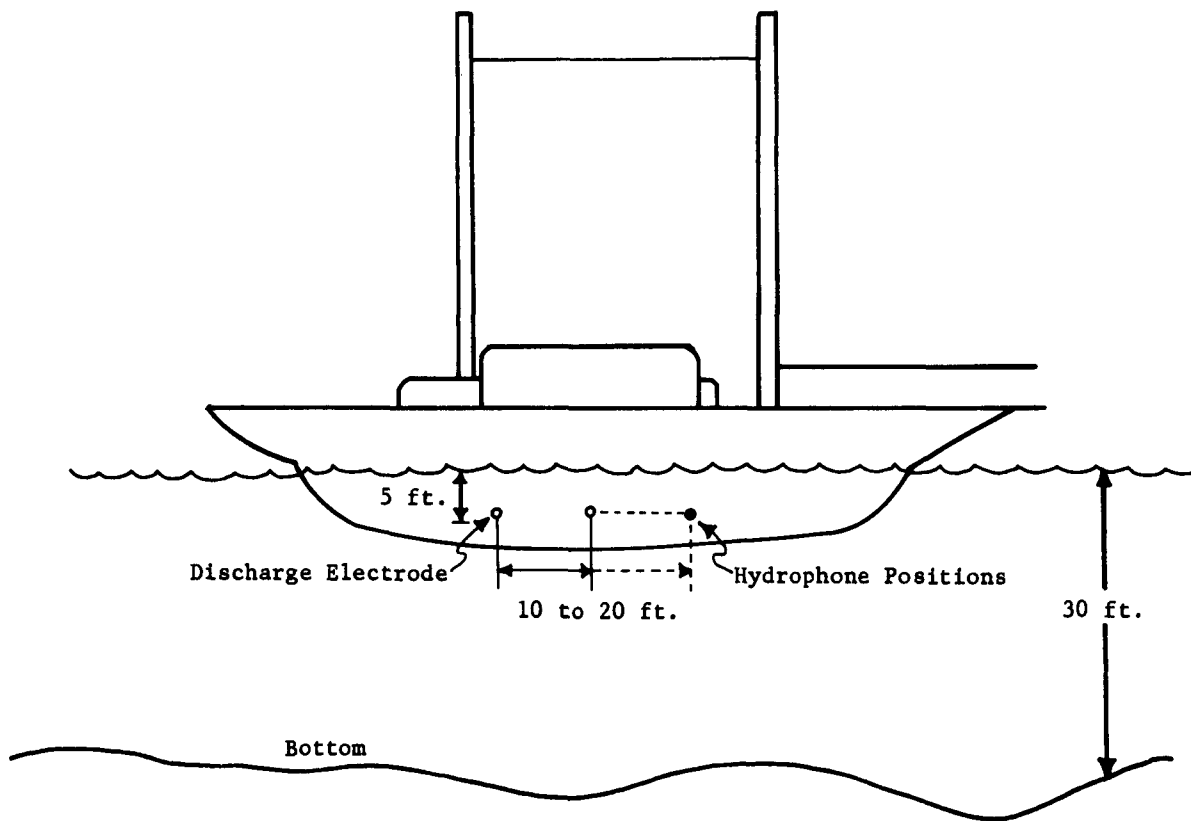


Fig. 1b—Side View of Discharge Electrode and Hydrophone Positions

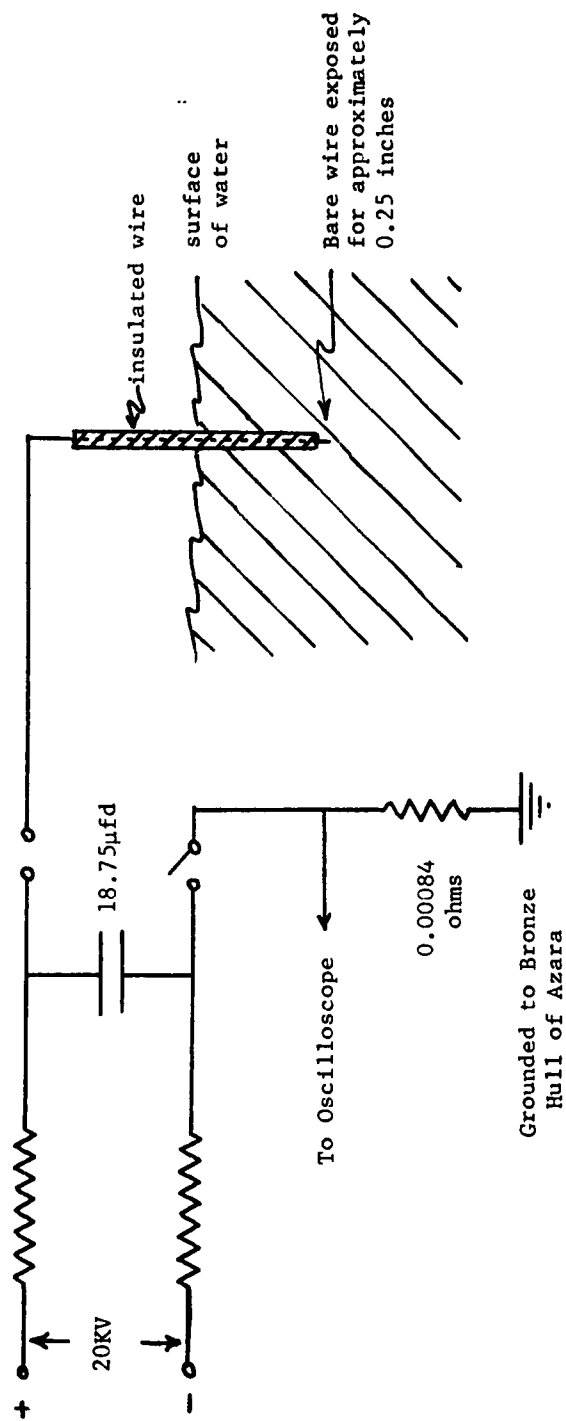


Fig. 2. Schematic of Energy Source

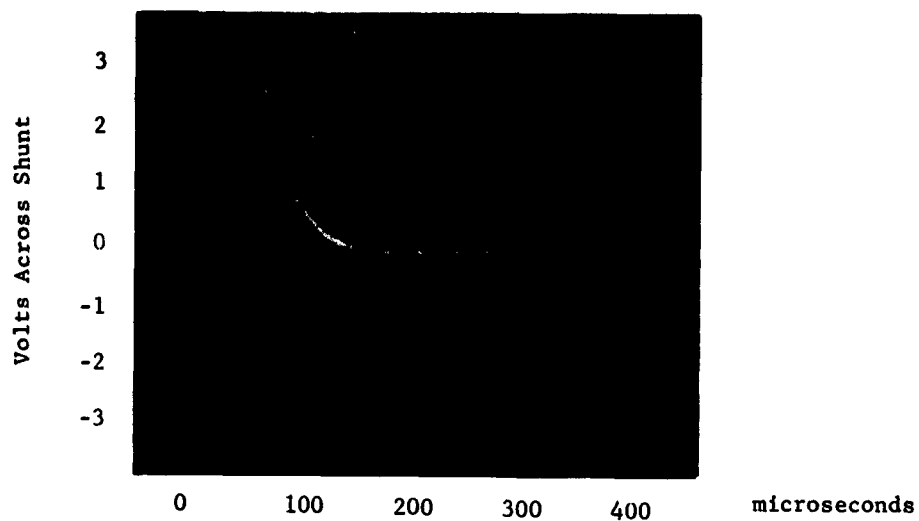


Fig. 3a. Typical Oscillogram of Discharge Current (1V = 1190 Amps.)

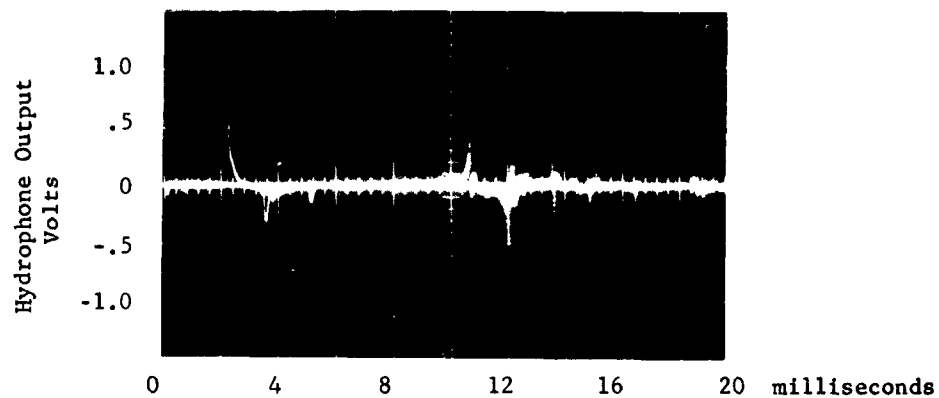


Fig. 3b. Typical Hydrophone Waveform

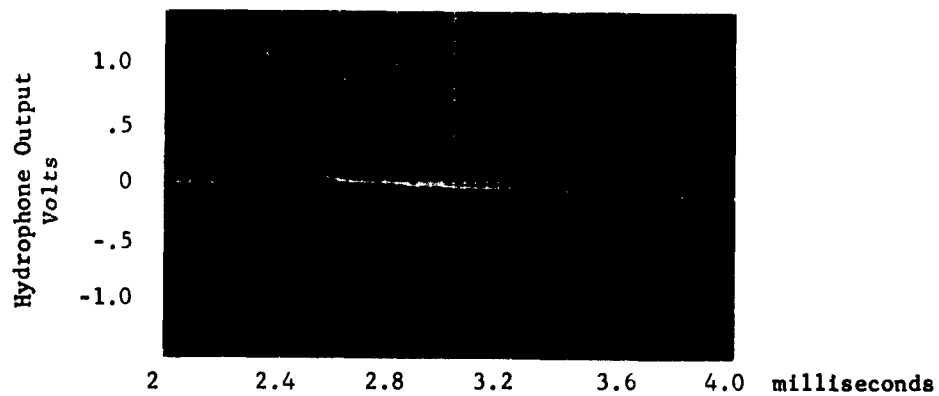


Fig. 3c. Delayed and Expanded Hydrophone Waveform

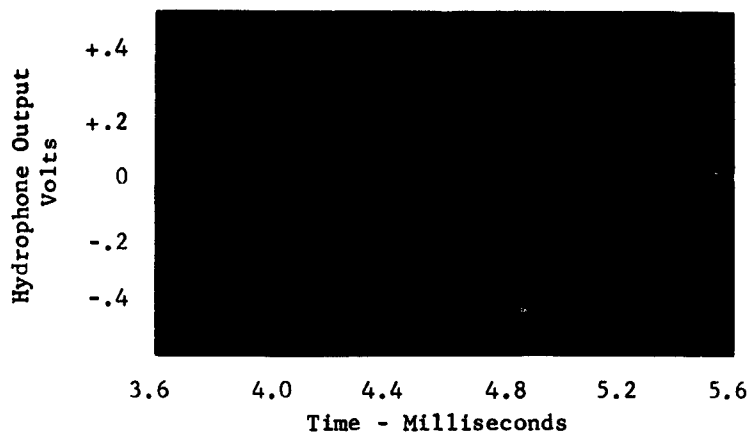


Fig. 4. Hydrophone Output From Two Simultaneous But Space Separated Discharges

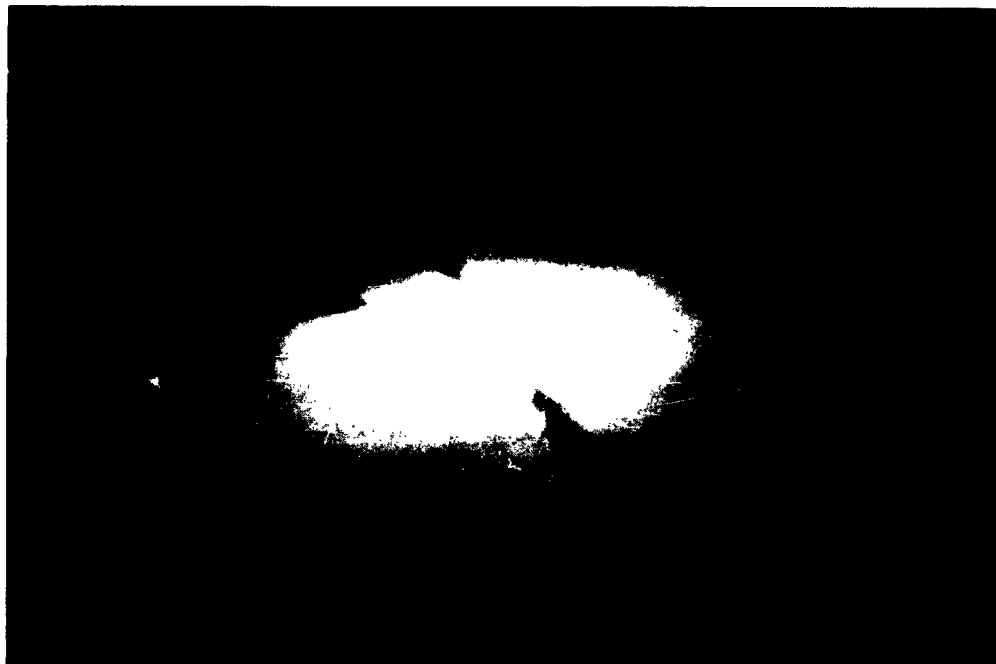


Fig. 5. Night View of Underwater Discharge
Ship Railing in Foreground

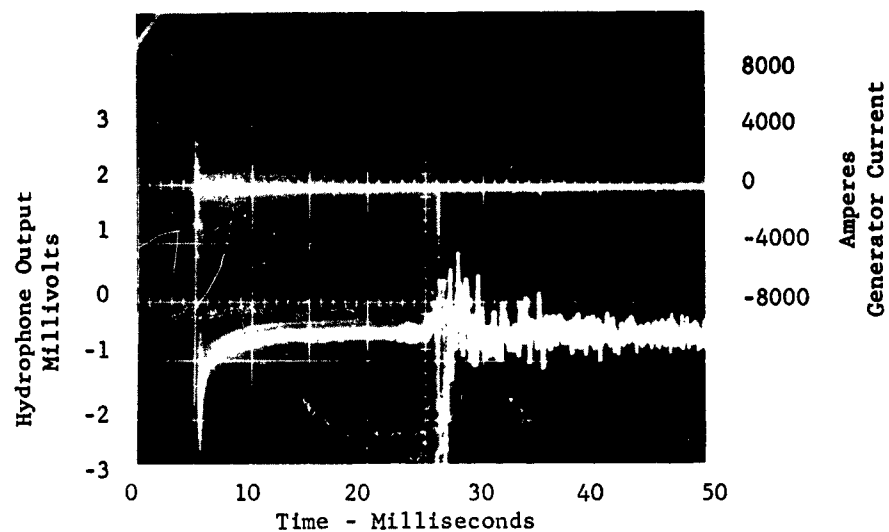


Fig. 6a. High Voltage Air to Water Discharge - Hydrophone in Air
Upper Trace Generator Current
Lower Trace Hydrophone Output

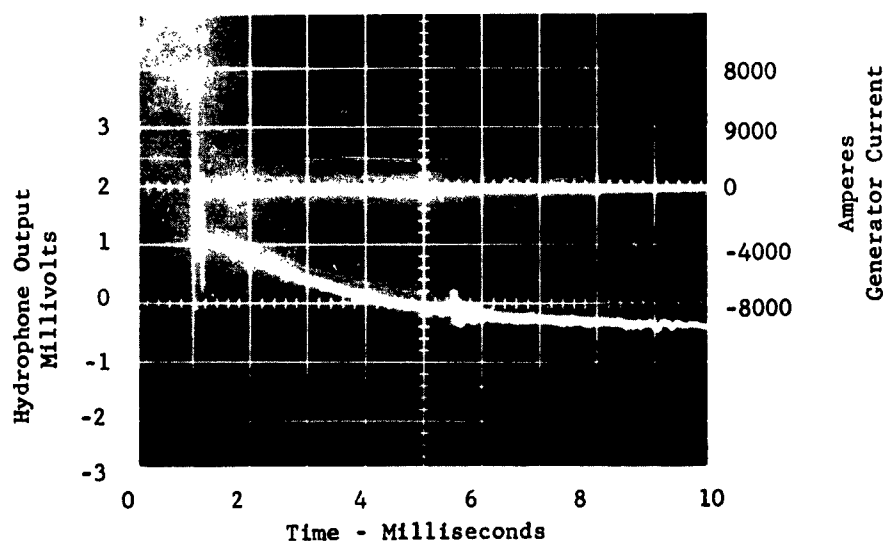


Fig. 6b. High Voltage Air to Water Discharge - Hydrophone in Water
Upper Trace Generator Current
Lower Trace Hydrophone Output

Distribution List for Contract Nonr 580(10)

Addressee	No. of Copies
Asst. Sec. of Defense for Research and Development Information Office Library Branch Pentagon Building Washington 25, D. C.	2
Armed Services Technical Information Agency Documents Service Center Arlington Hall Station Arlington 12, Virginia	10
Chief of Naval Research Electronics Branch (Code 427) Department of the Navy Washington 25, D. C.	2
Director, Naval Research Laboratory Technical Information Officer (Code 2000) Washington 25, D. C.	6
Commanding Officer ONR Branch Office 346 Broadway New York 13, New York	1
Commanding Officer ONR Branch Office The John Crerar Library Building 86 E. Randolph Street Chicago 1, Illinois	1
Commanding Officer ONR Branch Office 1030 East Green Street Pasadena 1, California	1
Commanding Officer Office of Naval Research Navy No. 100, Fleet Post Office New York, New York	2
Office of Technical Services Technical Reports Sections Department of Commerce Washington 25, D. C.	1

Continued Distribution List for Contract Nonr 580(10)

Chief, Bureau of Ordnance (Code Re P) Department of the Navy Washington 25, D. C.	1
Chief, Bureau of Ordnance (Code Re 9)	1
Librarian, National Bureau of Standards Department of Commerce Washington 25, D. C.	2
Applied Physics Laboratory Johns Hopkins University Silver Springs, Maryland	1
Commanding Officer Wright Air Development Center Wright-Paterson Air Force Base, Ohio	1
Solid State Group Hughes Aircraft Co. Research and Development Laboratories Culver City, California	1
Solid State Development Branch Evans Signal Laboratories Belmar, New Jersey	1
Advisory Group on Electron Tubes Secretary, Working Group on Semiconductor Devices 346 Broadway New York 13, New York	1
Research Laboratory for Electronics Massachusetts Institute of Technology Cambridge, Massachusetts	1
Navy Representative, Project Lincoln Massachusetts Institute of Technology Building B, Lincoln Laboratory P. O. Box 73 Lexington 73, Massachusetts	1
Library U. S. Naval Ordnance Plant Indianapolis, Indiana	1

Continued Distribution List for Contract Nonr 580(10)

Commander Air Force Office of Scientific Research Washington 25, D. C. Attn: SRY	1
Electronics Research Directorate Library Air Force Cambridge Research Center Laurence G. Hanscom Field Bedford, Massachusetts	1
Office of Ordnance Research Box CM, Duke Station Durham, North Carolina	1
Technical Information Officer Signal Corps Engineering Laboratory Fort Monmouth, New Jersey	1
Director National Science Foundation Washington 25, D. C.	1
Director, Naval Research Laboratory (Code 6430) Washington 25, D. C.	1
Director, Naval Research Laboratory (Code 5220) Washington 25, D. C.	1
Librarian U. S. Naval Ordnance Laboratory White Oak, Maryland	1
Chief, Bureau of Ships (Code 816c) Department of the Navy Washington 25, D. C.	2
Chief, Bureau of Ships (Code 327) Department of the Navy Washington 25, D. C.	1
Chief, Bureau of Aeronautics (Code EL-412.1) Department of the Navy Washington 25, D. C.	1
Director U. S. Naval Electronics Laboratory San Diego 52, California	1