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HYDRA PROGRAM
THE NRDL LOW-YIELD UNDERWATER EXPLOSION TANK AND
ASSOCIATED INSTRUMENTATION

by
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**U.S. NAVAL RADIOLOGICAL
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ADMINISTRATIVE INFORMATION

The work reported is part of a project sponsored by the Defense Atomic Support Agency, under NWER A-7, No. 10.001. The project is described in USNRDL Technical Program Summary For Fiscal Years 1963, 1964, and 1965, 1 November 1962, where it is designated Program A-1, Problem 2. Progress in the project is reported in Nuclear Weapons Effects Research Semiannual Progress Summary, Headquarters, DASA, Symbol DASA-78.

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ABSTRACT

A facility was designed and constructed to simulate underwater nuclear explosions on a very small scale by employing a submerged exploding wire in a contained environment. This facility is a laboratory complement to the NRDL HYDRA Program.

The variable pressure explosion tank and related mechanical features are described. Development of the energy storage system, trigger, and discharge circuit for the submerged exploding wire are discussed. The instrumentation needed to determine the explosion yield and the results for a 25 KV discharge are given.

SUMMARY

The Problem:

It is difficult, if not impossible to determine needed underwater histories of various aspects of large yield underwater explosions. A facility was required to investigate this problem on a very small scale in the Laboratory.

Findings:

A variable pressure explosion tank was constructed that includes controllable environmental conditions. A system was devised to produce known yield underwater explosions by means of an electrical discharge through a submerged exploding wire.

INTRODUCTION

The underwater history of the fission products from a deep nuclear explosion relates directly to their eventual atmospheric distribution; this relationship is part of the problem being studied at the USNRDL under the HYDRA Program. In order to study this phenomena, a small scale laboratory facility was constructed in which experiments can be carried out to simulate nuclear phenomena. This facility, a variable pressure explosion tank, exploding wire energy source and associated instrumentation was constructed and the various components are described in this report.

Major considerations around which the system was designed were the energy release required, the environmental conditions necessary to allow simulation to larger yields and the employment of the required instrumentation.¹

The tank can be used to study underwater phenomena resulting from either chemical explosions or from the rapid release of electrical energy. The submerged electrical discharge was chosen for initial work. This method has the advantage of accurate determination of energy release. It differs from the chemical explosion in that (1) much higher initial temperatures are produced, (2) the underwater explosion bubble formed consists of steam rather than noncondensable gases (3) no opaque carbon particles are formed, and (4) the explosion yield and detonation rate are easily controlled.

The first planned employment of this facility is to study the loss of explosion products from a deep migrating bubble to the surrounding water by means of suitable tracers and measuring techniques.

DESCRIPTION OF EXPLOSION TANK FACILITY

Figure 1 shows the tank and associated equipment. It was designed to withstand an underwater detonation having an energy release equivalent to one gram of TNT. To meet scaling requirements² the air pressure above the water surface and the water temperature in the tank can be controlled. Further, oil can be used as a working medium should this be required.

The height of the explosion tank is 12 ft, allowing a wide variation in water depth and in height above the water surface. These features were incorporated so that both above and below surface effects from an underwater explosion could be studied. The radius of the tank is 2.5 ft.

When the explosion tank is one-half full of water its total weight is approximately 15,000 lbs. The tank has, therefore, been placed on an 8 X 8 foot square steel pad directly above one of the building support beams to distribute the load over the floor. The bottom of the tank is a hemispheroid which rests in a 2.5-ft radius steel cylinder. The cylinder is the only connection the tank has to the floor pad which reduces the shock loading transmitted to the floor during an explosion.

A one-gram TNT equivalent underwater explosion will result in a maximum hydrostatic shock pressure of 760 psi at a distance of 2.5 ft. Since the shock wave is reflected from the rigid wall, the sides of the tank will experience 1520 psi shock pressure. The wall thickness is $3/8$ in., which results in a maximum hoop stress of 122,000 psi. High-strength carbon steel plate is used with a proportional limit of approximately 82,000 psi. The maximum stress experienced by the tank walls actually exceeds the proportional limit of the steel. However, the shock pressure exists for an extremely short time and energy calculations show the walls to be sufficiently strong for energy releases up to one-gram TNT equivalent.

The viewing windows, 18 in. wide and 60 in. high, are of 1-in. thick tempered glass. They are mounted on the tank in heavy steel frames which allow them to experience bending stresses only and are capable of withstanding 36,000 psi in compression and 30,000 psi in tension.

Beside the tank are located the condenser bank, charging section and firing control instruments for the submerged electrical discharge. The filtering system and water heating elements are on the other side of the tank, and the vacuum system and photo lights are behind. Above is a $3/4$ -ton electrically operated hoist, with which the top of the tank can be removed for access to the interior from above. The vacuum inside the tank is maintained by an O-ring seal at the flanged joint.

Frontal access to the inside of the explosion tank is through the front viewing window (Fig. 1). It is necessary to lower the water level inside the explosion tank between each firing in order to replace the exploding wire. Instruments are admitted to the tank interior through seven, 4-in. diameter ports. Two ports, one on each side of the tank, are for the electrodes forming the underwater gap (Fig. 2). The tank also has a $1/4$ -in. pipe outlet in the top for the pressure measuring instruments.



Fig. 1 General View of Test Facility



Fig. 2 Inside of Explosion Tank Showing Support Electrodes for Exploding Wire and Ports for Instrumentation

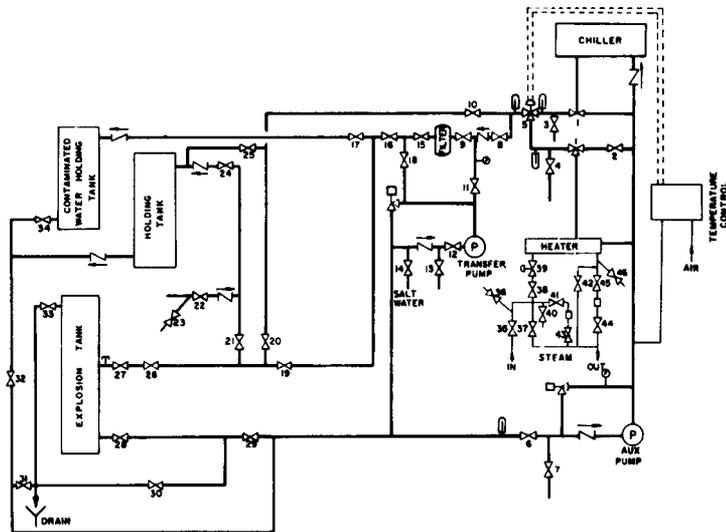


Fig. 3 Water Conditioning Flow Diagram

The vacuum system consists of a high-vacuum pump*, which is capable of evacuating the tank in 15 min. The minimum pressure obtainable is the vapor pressure of the fluid medium employed at its working temperature. The pressure is measured with a manometer** which incorporates a mercury barometer to determine the ambient pressure. Both gauges have a vernier to read the pressure to the nearest 0.01 in. of mercury, which is comparable to the accuracy in the measurement of the depth beneath the surface at which the explosion takes place.

The water conditioning component is diagrammed in Fig. 3. The water is transferred through a 5-10 μ filter to the explosion tank from outside holding tanks by a Weinman pump***. A steam water heater**** and a water chiller***** give a working temperature between 35 and 170^oF.

A suction "T" inside the explosion tank assures complete mixing of the incoming water. The water is put into vertical and horizontal rotation to prevent formation of isothermal layers during heating.

The main transfer pump allows only rough adjustment of the water level inside the explosion tank. In order to control the depth of the explosion to the nearest 1/16-in., such that accurate depth scaling can be accomplished, a small external water tank and auxiliary pump was added. The auxiliary pump can be operated with a control at the viewing window so that water level measurements can be conveniently made.

Two auxiliary tanks are located outside the building. One tank is the holding tank, used to store the water when the level in the explosion tank is to be lowered. Also, a supply of filtered and heated water can be stored at all times. The other is a waste tank for storing water for any length of time, such as when decay of radioactive tracers used in the explosion tank is necessary before disposal.

To keep the heat losses at a minimum the explosion tank, outside holding tank, and connecting plumbing, were lagged with 2 in. of insulation. The cavity between the explosion tank and the base was also filled with rock wool.

* Model KDH-65, Kinney Vacuum Div., The New York Air Brake Co., Boston, Mass.

** Model No. 1464, Wallace and Tiernan, Inc., Belleville, N. J.

*** Type "K"-2-4, The Weinman Pump Mfg. Co., Columbus, Ohio.

**** Model SU 42-2, Bell and Gossett Co., Morton Grove, Ill.

***** Model WCA-30, Acme Industries, Inc., Jackson, Michigan.

EXPLOSION PRODUCTION BY ELECTRICAL DISCHARGE

Exploding Wire

The reproducibility of underwater explosions with an electrical discharge through large gaps between the firing electrodes is unreliable,³ even under otherwise identical conditions. This can be corrected with a fine wire placed between the submerged electrodes. During the initial stages of discharge, the wire is vaporized by a small fraction of the total energy transferred to the gap from the condenser bank. The remaining energy transferred to the gap is stored there in the form of dissociation, excitation, ionization, and kinetic energy of the vaporized water particles.⁴ The energy is then slowly released during the spark channel expansion to form the shock wave and underwater bubble.

Energy Storage System

The recent interest in the control of thermonuclear reactions has led to the development of low-inductance, high-capacitance discharge condensers. The energy storage bank used to produce the underwater explosion consists of six clam-shell capacitors* arranged coaxially in parallel (Fig. 4). Each one is rated at 1.0 μf and 50,000 v, with an inductance of 0.01 μh . They are rated as being capable of 4200 discharges with a 70% voltage reversal at a 100 kc ringing frequency. The total measured capacitance using a General Radio Company Type 650-A capacitance bridge is 5.76 μf (0.96 μf each), giving a maximum stored energy of 7200 joules.

The condenser bank is charged with a high-voltage DC power supply** rated at 50 ma at 60,000 v, which allows a charging-time of less than 40 sec. The charging unit is in two sections: the control panel, and the high voltage tank which is oil-insulated. The control section contains a precise high-voltage adjustment and various overload safety features. The high voltage can be held before discharging to permit the adjustment of other instruments before firing. An insulated cable (RG 17/u) connects the high-voltage tank with the condenser bank.

* Type 14F756, General Electric Company, Hudson Falls, New York.

** Model 2060-50, Sorensen and Company, Stanford, Conn.

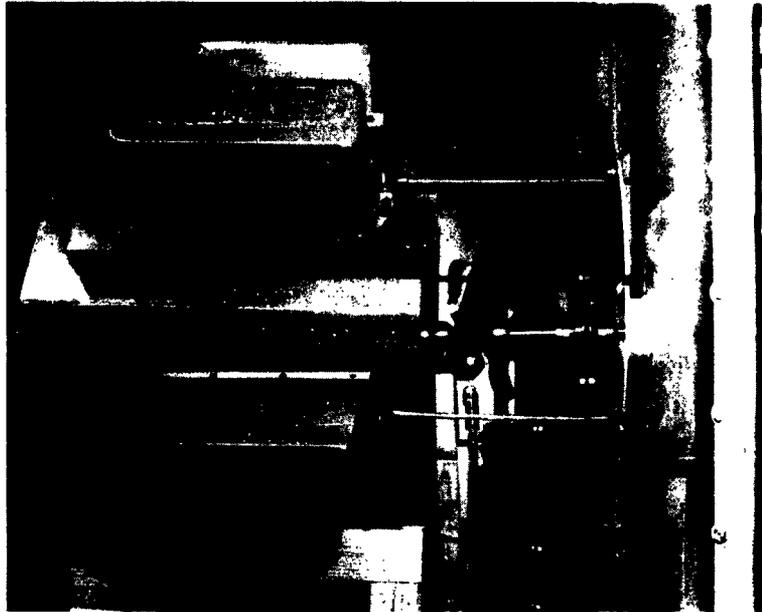


Fig. 4 Condenser Bank and Trigger

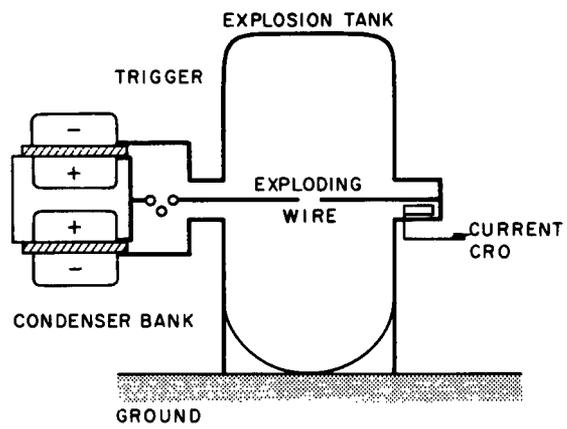


Fig. 5 Section View of Exploding Wire Circuit

Discharge Circuit

The exploding wire circuit should be as short as possible to minimize resistance losses and allow a rapid discharge of the energy stored in the condenser bank. The underwater explosion, however, must take place at the center of a 5-ft diameter tank in which there can be no obstructions to perturbate the bubble. This requirement imposes the necessity of an extremely long discharge circuit. To shorten the circuit, the explosion tank is incorporated as a current ground return to the condenser bank (Fig. 5). The circuit is, in effect, a large diameter coaxial cable surrounding the trigger and exploding wire. This minimizes the circuit inductance (L) and average effective resistance (R).

Since R is small the discharge frequency (ω) is dependent on L and the circuit capacitance (C), according to Eq. 1.

$$\omega = \sqrt{\frac{1}{LC}} \quad (1)$$

Any combination of the six condensers can be used by disconnecting the ground cable and shorting those not participating in the discharge. This allows a maximum variation in the discharge frequency by a factor of $\sqrt{6}$.

The exploding wire is placed between 3/16-in. diameter brass electrodes, 2.5 ft long (Fig. 2). The rods are small enough that bubble disturbances can be neglected except at small maximum bubble radii. These rods are in turn supported by 3/4-in. diameter insulated brass rods leading through the tank walls.

Trigger

Some type of switching is needed to transfer the energy stored in the condenser bank into the exploding wire. A thyatron was used in the initial stages of development. As the amount of energy to be transferred increased, thyatrons were no longer suitable because of electrode erosion due to large currents. Therefore, the convenient and reliable three-ball air gap was adopted. Two, 2-in. diameter brass spheres are separated by a distance of 2 in. and hold off the high-voltage discharge. To fire the trigger, another 2-in. diameter brass sphere is moved between them by a pneumatically operated cylinder (Fig. 4).

ENERGY YIELD

The discharge circuit containing the exploding wire can be represented by the equivalent circuit in Fig. 6. When discharged, the energy stored in the condenser bank is absorbed by the circuit through resistive heating. Losses from the circuit such as electromagnetic radiation can be neglected. The total average effective resistance of the circuit (R) is the sum of the effective resistance of the trigger (R_T), the underwater discharge (R_W), and the remaining length of circuit (R_C). Thus

$$R = R_T + R_W + R_C \quad (2)$$

The stored energy (E_S) is divided among the various parts of the circuit according to their effective resistances. Therefore, the energy absorbed by the underwater discharge (E_W) is given by

$$E_W = \frac{R_W}{R} E_S \quad (3)$$

The circuit's average effective resistance (R) can be found from the behavior of the current (I) during discharge. This behavior is governed by a differential equation (Eq. 4) which has the solution given in Eq. 5.

$$\frac{Ld^2I}{dt^2} + \frac{I}{C} \frac{dI}{dt} + \frac{RI}{I} = 0 \quad (4)$$

$$I = I_0 e^{-\frac{Rt}{2L}} \sin \omega t \quad (5)$$

Equation 5 shows that the current has the form of a decaying sine wave, the rate of decay being determined by the average effective resistance. The value of R can be found from the logarithmic decrement of successive current maximums (I_m, I_{m+1}) according to Eq. 6.

$$R = \frac{1}{\pi} \sqrt{\frac{L}{C}} \ln \frac{I_m}{I_{m+1}} \quad (6)$$

Current Measurement

At first the discharge current was found by measuring the voltage drop across a known series resistance in the circuit. This method was plagued with induced signals due to induction coupling between the

discharge circuit and measuring circuit. Spurious signals from ground currents also led to unreliable results. A different method of determining the current was examined, in which there is no direct connection between the discharge circuit and the measuring circuit.

The basis of this method is that when a wire carries an alternating current, a varying magnetic field is produced coaxially. A section of the coaxial discharge circuit is of sufficient radius to place a coil in the region where the field is predictable. The voltage (ϵ) induced in the coil indicates the rate of change of current (Eq. 7).

$$\epsilon = L \frac{dI}{dt} \quad (7)$$

The mutual inductance (L_m) of a rectangular coil placed inside a coaxial conductor is given by

$$L_m = \frac{\mu h}{2\pi} \ln \frac{r_2}{r_1} \quad (8)$$

The inside and outside radii of the coil are r_1 and r_2 respectively. The length of the coil is h , its number of turns is n ; and μ is the magnetic permeability of the medium. Combining Eqs. 7 and 8 give the discharge current

$$I = \frac{2\pi}{\mu h \ln(r_2/r_1)} \int_0^t \epsilon dt \quad (9)$$

Integration of the induced voltage over the time of discharge is performed by a simple rc network (Fig. 7) at the recording oscilloscope. The product rc of the integrating network is several times as long as the time of interest so that ϵ is independent of the current magnitude.⁵ The discharge current (Eq. 9) can then be written as a constant (γ) times the induced voltage

$$I = \gamma \epsilon$$

where
$$\gamma = \frac{2\pi rc}{\mu h \ln(r_2/r_1)} \quad (10)$$

The current measuring coil used has a γ value of 1.04×10^4 amps/volt. Figure 8 shows a close-up of the part of the circuit containing the coil. The voltage is then displayed on a Tektronix No. 551 dual beam oscilloscope with a rise time of 0.012μ sec. The current oscillogram for a 25 KV discharge is shown in Fig. 9. The first current peak has a value of 37,440 amps.

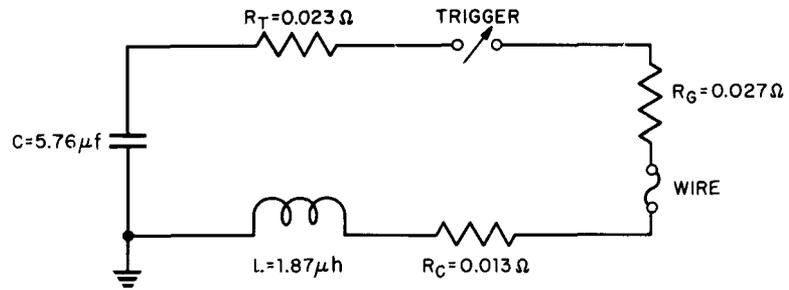


Fig. 6 Equivalent Circuit of Exploding Wire Circuit

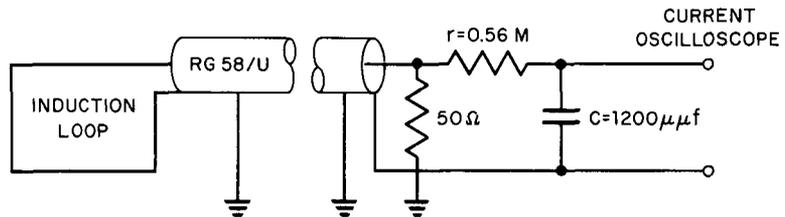


Fig. 7 Diagram of Current Integrating Network

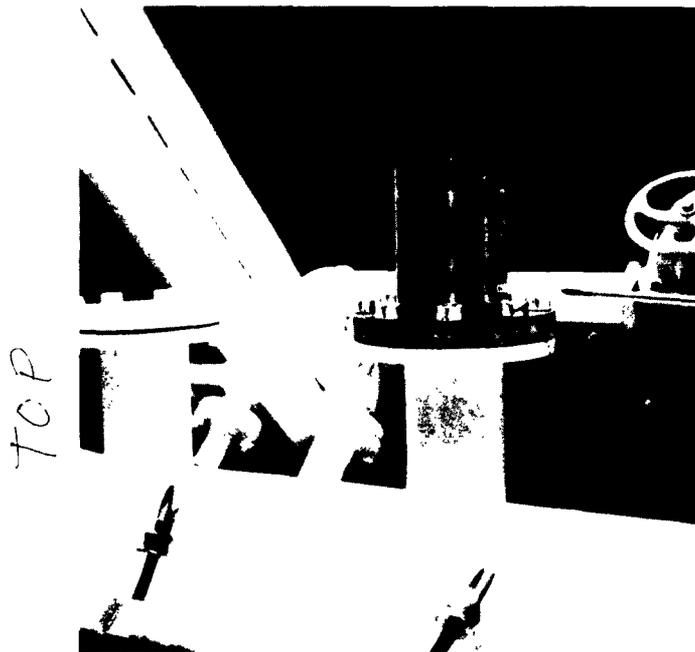


Fig. 8 Current Measuring Device

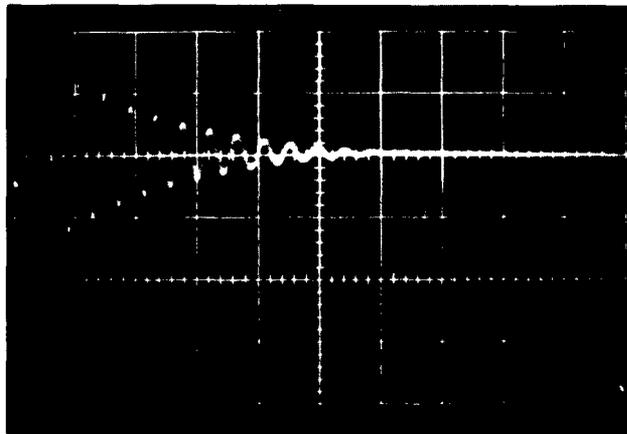


Fig. 9 Discharge Current Oscillogram:
Scale: Vertical - 2 V/cm
Horizontal 50 μ s/cm

Resistance of the Trigger

The average effective resistance of the trigger (R_T) was determined by the rate of current decay (Eq. 9) when a short is placed across section AB of the circuit in Fig. 6. The internal resistance of the condenser bank is negligible compared to that of the trigger. Shorting the discharge circuit decreases its length and hence its inductance. This results in a much higher current than when the full length of circuit is used. An 8.5 KV, 5.76- μ f discharge was found to give a current peak which was approximately that of a 25-KV, 5.76- μ f discharge through the full circuit. The average effective resistance of the trigger was found to be 0.023 ohms. The discharge frequency was 143.0 KC, giving a short circuit inductance of 0.214 μ h (Eq. 1).

Resistance of the Underwater Gap

A 1-in. long, 5-mil copper wire was placed between the underwater electrodes. The total average effective resistance (R) for a 25-KV, 5.76- μ f discharge was found to be 0.063 ohms. The discharge frequency was 48.5 KC and the circuit inductance 1.87 μ h.

Next the underwater gap was shorted. The average effective resistance ($R_T + R_C$) of the resulting circuit was 0.036 ohms, while the discharge frequency remained at 48.5 KC. Through Eq. 2, the average effective resistance of the underwater gap was found to be 0.027 ohms. Likewise, the average effective resistance, R_C , was found to be 0.013 ohms.

Energy Partition

Equation 3 was used to determine the fraction of stored energy absorbed in each part of the discharge circuit. In a 25-KV, 5.76- μ f, discharge (1800 joules stored energy) using a 1-in. long underwater gap, the trigger absorbs 658 joules, the underwater gap 771 joules, and the remaining length of circuit 371 joules. For each change in voltage, circuit configuration, or exploding wire length, the energy partition and circuit parameters will change. The breakdown distance for the trigger increases with higher voltages, increasing its resistance. Likewise, a greater percentage of the stored energy can be transferred to a longer underwater gap in a given voltage.

CONCLUSION

The explosion test facility lends itself to the study of many problems concerning underwater explosion phenomena. The tank's

auxiliary equipment permits a wide range of physical conditions to be employed, which is necessary when scaling explosion phenomena to higher yields.

A major feature of the system is the use of a calibrated electrical discharge energy source, which is of great value in obtaining and controlling the energy yield and detonation rate of the explosion.

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1 Moran, Proctor, Mueser and Rutledge
1 Mound Laboratory
2 NASA, Scientific and Technical Information Facility
2 Nevada Operations Office
1 Office of Assistant General Counsel for Patents
1 Phillips Petroleum Company
1 Power Reactor Development Company
1 Public Health Service, Washington
1 Reynolds Electrical and Engineering Company, Inc.
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1 State of California, Department of Fish and Game (Bissell)

1 Tennessee Valley Authority
1 Tracerlab, Inc., Richmond
1 Union Carbide Nuclear Company (ORGDP)
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1 University of Washington (Donaldson)
1 University of Washington (Flemming)
1 Woods Hole Oceanographic Institute
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25 Technical Information Extension, Oak Ridge

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Naval Radiological Defense Laboratory
USNRDL-TR-623

HYDRA PROGRAM THE NRDL LOW-YIELD
UNDERWATER EXPLOSION TANK AND ASSOCIATED
INSTRUMENTATION by R. R. Buntzen 18 February
1963 25 p. illus. 5 refs. UNCLASSIFIED

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underwater nuclear explosions on a very
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Program. (over)

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2. Exploding wire phenomena.
3. Electric discharges.
4. Tanks (Containers)

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