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Novel Sound Sources

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A Bureau of Ships Laboratory

THE PROBLEM

Design and develop novel low-frequency sound sources.

RESULTS

Two different types of high-intensity sound sources have been developed which have both military and commercial potentialities:

1. The underwater spark sound source is suitable for explosive echo ranging, particularly from a submarine, and shows promise as a source for long-range, active detection and for long-range underwater signaling. The underwater spark is safer than chemical explosives and, unlike them, is repetitive. It is simple, reliable, and easily adapted to working at great depths. Its short-duration pulse allows discrimination against reverberation and is too short to "home on," particularly if single-pinging or staggered repetition rates are used.

This source has been tested at a depth of 300 feet below the surface and generated peak pressures corresponding to an acoustic level in excess of 3 million watts for a broad-band nondirectional condition. In the 1000-4000-c/s frequency band, a corresponding acoustic level in excess of 300, 000 watts was developed for a nondirectional condition.

2. The pneumatic sound source, operating models of which were built and tested extensively, is probably the simplest generator of underwater sound yet discovered (in its lightest form it weighs less than 1 pound). This source has generated a peak acoustic level of over 4000 watts for a nondirectional condition, in the frequency range between 5 and 300 c/s.

The pneumatic sound source is suitable for ASW operation; conversion of coastal defense passive systems into active systems; explosive echo ranging; mine countermeasures; anti-limpeteer operations; and coded signaling. Typical commercial applications could be geophysical prospecting and explosive metal forming.

RECOMMENDATIONS

1. Conduct operational research to determine the usefulness and limitations of both sound sources in the tactical applications suggested above.
2. Continue the study and experiments described here, with a view to extending the potentialities of the two sound sources, and improving the materials and techniques involved in manufacturing and operating them.
3. Consider the feasibility of resuming study of the other sound sources partially explored and briefly reported here.

ADMINISTRATIVE INFORMATION

Work was performed under AS 02101, S-F001 03 04, Task 8050 (NEL L3-3) by members of the Acoustics Division. The report covers work from June 1956 to September 1960 and was approved for publication 17 October 1960.

The author appreciates the assistance of F. D. Parker, Group Leader, and of M. R. Markland, C. C. Dietrich, J. Lyons, and P. Olszanecky. The work of John Pflaum in obtaining the high-speed underwater photographs; of E. Rolle, who developed many combinations of compounds for trial as dielectric material; and of R. J. Bolam, who assisted in the interpretation of the data, is also gratefully acknowledged.

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INTRODUCTION

The advent of deep-running nuclear submarines has brought about an urgent need for greater detection ranges and, consequently, a requirement for new and improved means of generating sound underwater, at increasingly lower frequencies. This requirement has increased the size and cost of sonar equipment, and sonar advances to date have been considerably dependent upon transducer construction. As the number of transducer engineers is somewhat limited, it has been necessary to concentrate most of their efforts on established techniques. However, it has been recognized that some investigation should be directed toward unconventional methods of generating sound, particularly in the low-frequency region. Accordingly, the Bureau of Ships established a problem to investigate novel sound sources. The personnel at NEL assigned to this problem were all experienced in the field of generating high-power signals, and had previously conducted intermittent studies of the underwater spark as a sound source. Thus it was logical to use this technique as a point of departure in undertaking the new assignment. Although other government laboratories no longer were exploring this approach, a study was made of previous work by others before the study was resumed at NEL.

Work with the underwater spark at this laboratory prior to May 1956 has already been reported.[1] The early work had clearly indicated that much of the success of the spark source was directly related to the electrodes and the geometry of the gap. It was therefore decided that this particular phase would be studied thoroughly, leaving major power increases to later.

A number of other techniques, such as exciting metals into vibration by contact with solid carbon dioxide, or vibrating wires, reeds, plates, etc., have been given limited trials, but have not been explored sufficiently to warrant reporting at this time. The work on novel sound sources is continuing.

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[1] "Underwater-Spark Sound Source," by L. R. Padberg, Jr. (Article 32 in NEL Report 698, Lorad Summary Report, CONFIDENTIAL, 22 June 1956)

I. THE UNDERWATER SPARK SOUND SOURCE

The theory of the underwater spark as a sound source has been considered for some time without conclusive findings as to its value and limitations, or the optimum design of the equipments involved. The principle of this sound source may be stated briefly as follows: an underwater electrical discharge causes a sharp increase in temperature of the water between the electrodes. The water vaporizes and forms a gas bubble which expands and collapses, and radiates acoustic waves. The nature of the radiation is dependent upon a number of factors. The following sections discuss some of the major theoretical and mechanical considerations involved, and the development and testing of a workable model of the underwater spark sound source.

DESIGN CONSIDERATIONS

Several years of experiment made it apparent that much had to be learned about the development and construction of suitable electrodes and gaps before a satisfactory underwater spark sound source, producing high acoustic levels in the lower frequency region, could be achieved. Experience at NEL and other laboratories showed that there was considerable variability from one spark discharge to another.

Construction of the Gap

A basic fact about spark gaps, operated underwater, is that the power into the load is equal to the current squared times the resistance, or

$$P = I^2 R$$

Therefore, it is necessary to make the resistance of the gap as large as possible. When two electrodes are short-circuited by water the resistance is low rather than high as is desired. It is apparent that the gap should be as wide as possible to raise this value. A method for getting high power that at first seems effective is to use a wide gap and very high voltages to cause the gap to break down. Another way is to raise the gap resistance by using the best dielectric material obtainable between the electrodes, slightly imbedding them in it. When very high electrical energy is discharged across the gap, the water is vaporized almost instantaneously and the gap resistance is raised.

In studying the literature and noting the size of the conductors used in some tests it is apparent that few experimenters have realized the magnitude of the first surge of current. For example, in discharging 3000 watt-seconds of energy across the electrodes, the current has been measured in excess of 220,000 amperes for brief periods. (Short, heavy leads are essential for such an operation.) Very high temperatures at the gap were also reported and, on one occasion, electrodes made of titanium showed considerable melting. (Titanium melts at 1800°C.)

Since it is desired to have the electrical discharge appear only at the exposed electrode surface, NEL underwater spark gaps have all been based upon the principle of the "horn gap." The basic design of this gap is shown in figure 1. While the optimum electrode material is tungsten, it is difficult to machine and, for experimental purposes, too expensive. Most of the NEL electrodes were machined from either brass or copper. Some of the NEL gaps have been fired thousands of times.

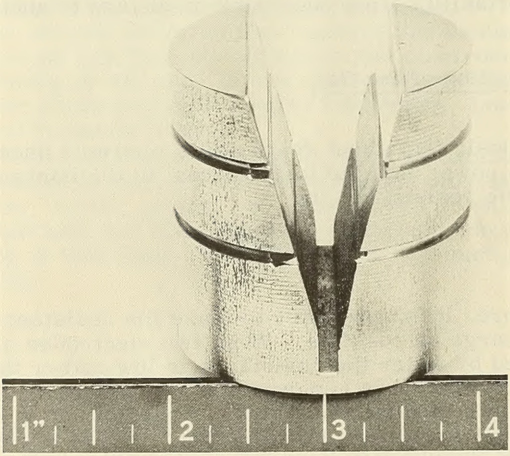


Figure 1. Basic design of horn gap (before encapsulating).

The narrow slot shown in figure 1 will eventually be the front of the gap. Note how the gap space widens toward the rear. Although the picture shows one continuous piece of brass, the metal will eventually be machined, after encapsulating in a suitable dielectric material, into two separate halves. This is an original technique, which insures a constant gap spacing. Many configurations have been tried and all incorporate the principle of having the narrowest part of the gap at the front to prevent the discharge from occurring inside the material where it will not only be ineffective but will explode the gap. Figure 2 shows several types of underwater spark gaps investigated.

Figure 2. Variety of underwater spark gaps investigated.

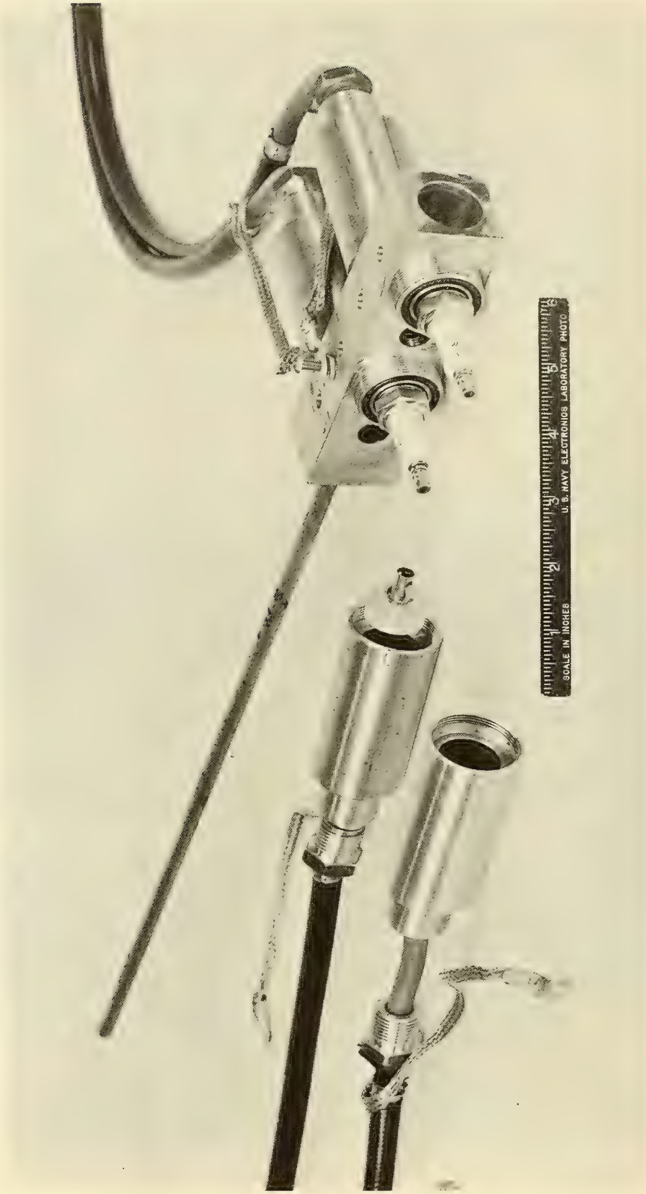


Figure 2. (Continued)

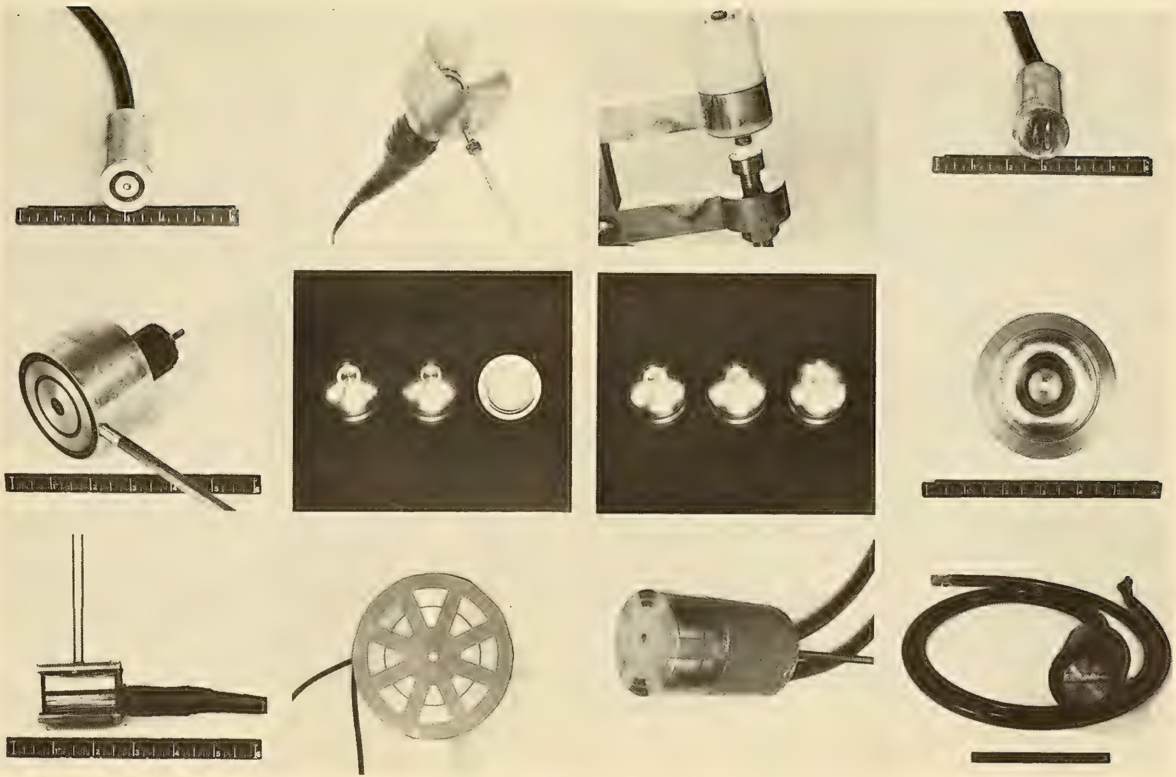


Figure 2. (Continued)

Early Types of Underwater Spark Gaps

The first experiments with underwater sparks as a source of sound utilized special types of automotive and aircraft spark plugs. Since spark plugs were not designed for use underwater, in general they were unplated and rusted very quickly. Several better types were found that were either chromium or cadmium plated. The types with multiple discharge points, such as the aircraft variety designed for igniting jet fuel, proved most satisfactory. In general it was found that the porcelain insulation near the firing points blew off on the first firing but the plugs continued to function.

It was concluded very early in the experimental program that special spark gaps would have to be designed to handle any substantial power level. For energy levels below about 100 watt-seconds, several types of plugs proved satisfactory. To obtain greater power, attempts were made to operate plugs in various series and parallel combinations. Such arrangements usually proved unsatisfactory since the plugs would seldom fire simultaneously. Firing would be random and almost unpredictable due to non-uniform point burning. Various modes of insulating and encapsulating the plugs were tried. A few of the combinations are shown in figure 3.

Energy Transfer

The sudden discharge of a large amount of stored energy into a virtual short circuit is a great strain on any type of electrical switch. A literature search revealed that many experimenters are still using a three-ball open air gap for the energy transfer. This method may result in extremely low efficiency. Hydrogen thyratrons are fairly effective but are short-lived and have associated "flash-back" troubles.

From the beginning of the underwater spark studies at NEL, specially designed high-vacuum switches have been used for the energy transfer function. Switching the high voltages and current in a vacuum solves many problems and is probably the most practical way of accomplishing the transfer. Thus all the energy is directed into the gap in water, where it can be utilized, rather than into the air where its effectiveness is lost and where it is hazardous to the eardrums of the personnel in the area. The vacuum switch used (fig. 4) has a rating of 30 kv at 600 amperes rms, and has been used successfully to carry peak pulse currents of 220,000 amperes.

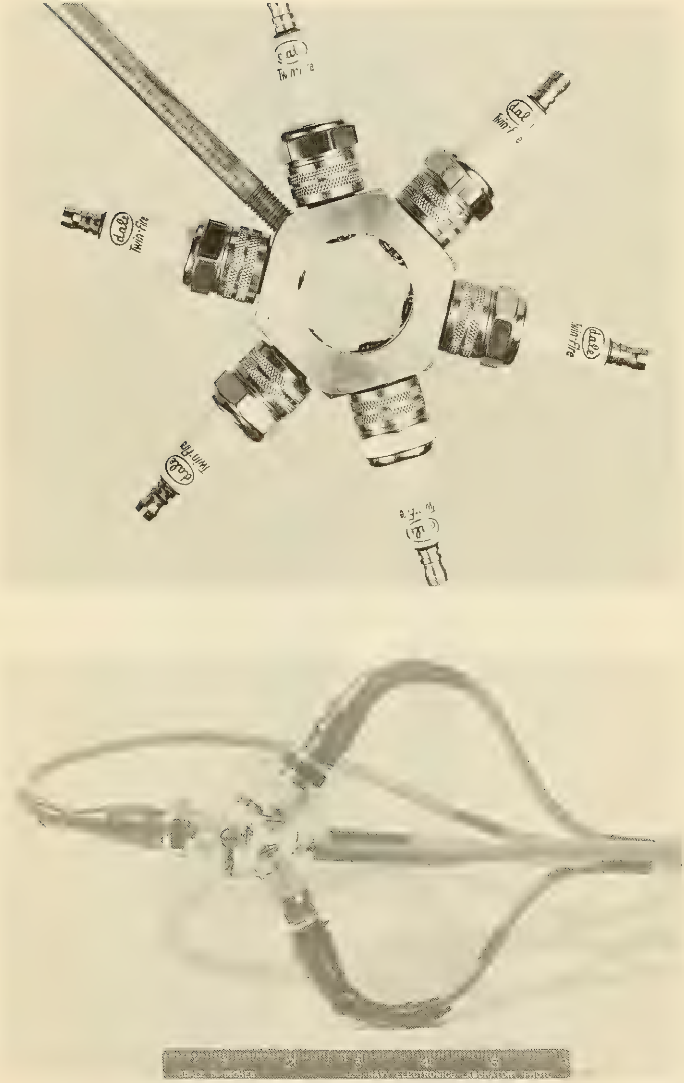


Figure 3. Examples of methods used to insulate and encapsulate spark plugs.

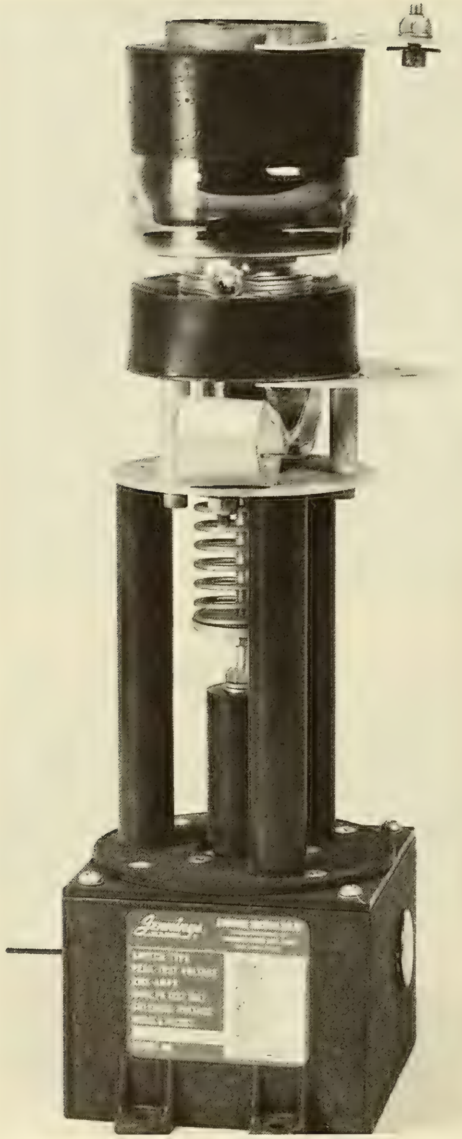


Figure 4. High-vacuum switch for energy transfer.

Energy Storage

Although the principle of energy storage is as old as the electrical industry, great advances have recently been made in the construction of energy storage capacitors, largely as a result of atomic power developments. The type of job to be done will dictate whether to use very low capacity at high voltage, or very large capacity at lower voltage. The basic formula for energy storage is:

$$E = \frac{CV^2}{2}$$

In most of the experiments reported here, very large capacitors were used at moderately high voltages, for example 60 microfarads at a working voltage of 15, 000. Most early work used 100 or more microfarads at 4000 working volts. Corona discharge causes little trouble at these voltages but can be severe at higher voltages, particularly in the damp atmosphere at sea.

Few experimenters have made any mention of the inductance of energy storage capacitors. It is important to keep this value low for efficient operation. Only recent designs have this feature. It is equally important to keep all the "tank circuit" leads of heavy copper bus, since the discharge currents run into many thousands of amperes.

Dielectric Material for the Gap

For many years there has been a continuing search for a suitable dielectric material that could withstand the explosive forces at the point of discharge. A number of materials have been found that are fairly satisfactory for energy levels up to about 1000 watt-seconds, at 1 atmosphere of pressure. Pressure increased beyond that level resulted in water getting inside the gap and causing internal explosion. Many materials were found that could withstand severe beating with a hammer without breaking or chipping but fractured when used in the gap. A certain amount of pliability seems desirable and also reduces the problem of recoil which is very great in the underwater spark explosion. Additional evidence of the tremendous forces at the gap is that the shock wave generated can be used to form metals such as stainless steel, titanium, etc. Numerous combinations of unsaturated compounds of high molecular weight were tried for the dielectric material. Some have proved far superior to commercial epoxy resins. One of the latter, known by the trade name of "Scotchcast No. 2" has been satisfactory up to levels of around 3000 watt-seconds.

In recent experiments using an energy level of 6000 watt-seconds, it was found necessary to abandon the dielectric material and simply fire a well insulated brass rod against a heavy bronze ground plate. This may be one of the practical solutions to the problem.

Geometry of the Gap

Since one of the basic aims of the work was to obtain significant output levels in the low-frequency region below 5000 c/s, many configurations of electrodes were tried. The importance of the gap geometry became evident early. This factor can be made to focus sound, can affect the size and shape of the bubble, and it controls the duration of the pulse. The many bubble photographs included in the report illustrate its significance; note the strange, almost "square" shapes of bubbles produced under some conditions. The phenomena associated with the geometry of the gap are not fully understood, and should be studied.

THEORETICAL DISCUSSION

Frequencies Generated by an Underwater Spark Discharge

The underwater spark discharge is essentially broadband in character and similar to the discharge of a chemical explosive except that it is more susceptible to energy peaking at certain frequency bands. From an echo-ranging standpoint, high acoustic energy in the region between 1000 and 3000 c/s is desirable. Through the use of techniques reported here, peak acoustic powers greater than those obtained from large costly sound projectors have already been achieved. Since we are not interested in wasting large amounts of power in the region above 15 kc/s, we have designed underwater spark gaps that generate large, low-frequency bubbles. The bubble pulse from an underwater spark can be quite useful, although previous experimenters have given little attention to this fact. The frequency of the bubble pulse is directly proportional to the depth at which it is generated. In the region of 1000 to 3000 c/s for a nondirectional condition, peak acoustic pressure levels of about 125 db/dyne/cm^2 at 1 meter have been measured. This would correspond to 300 kw of acoustic power (fig. 5).

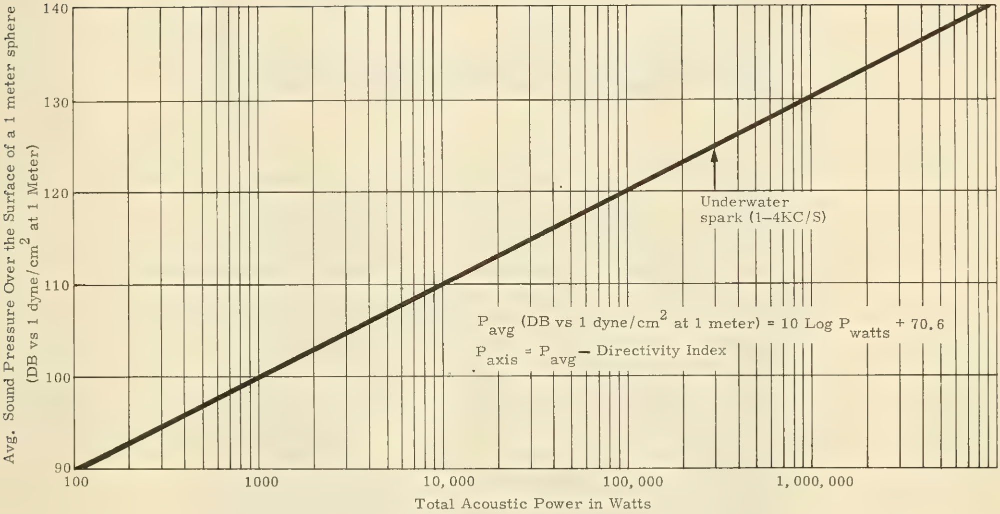


Figure 5. Plot of acoustic power vs. sound pressure.

Add to this the 10 db or more that can be gained by a reflector of reasonable size, and the result is a megawatt of acoustic power in a beam that can be directed wherever desired.

By combining such features as resonant discharge loops, exciting resonant cavities, and operating the spark source, if possible, at a depth where the bubble pulse is at the same frequency as the resonators, substantial acoustic levels could be obtained in the low-frequency region required for long-distance echo-ranging. The underwater spark is simplicity itself when compared with complex sophisticated sonars.

Effect of Pressure on Electrodes

Insufficient evidence has been obtained to form any positive conclusions on the effect of pressure on electrodes. However, several findings can be reported.

In deep-water tests at Lake Pend Oreille it was found that electrodes that performed very well in many firings at near atmospheric pressure blew to pieces when used at a depth of 300 feet below the surface. An example of this is shown in figure 6. Evidence of many firings can be seen by examining the electrode surfaces. Experience has shown that if water gets inside the electrode it will cause it to explode from within. In the case shown, apparently water penetrated the dielectric material via a small crack when subjected to pressure at this depth.

In one test, using a gap separation of 1/2 inch, the gap which fired well at atmospheric pressure would not fire when the pressure was increased to 200 psi for the same impressed potential. Decreasing the gap solved the problem. This result would indicate that there is probably a critical gap spacing versus depth, at least in fresh water. This should not be a problem in sea water.

All the problems of deep submergence appear to be ultimately surmountable, and the underwater spark sound source appears to be well adapted for use in the deep ocean.

TESTS AND MEASUREMENTS

Test Procedure

Tank Observations

Pressure and frequency measurements of underwater sound usually have to be made in an open body of water or in specially constructed acoustic tanks. For visual and aural observations, however, a small tank is useful. Two tanks were used in most of the laboratory experiments reported here. The smaller of the two was a modified ammunition box measuring approximately 48 by 40 by 30 inches (fig. 7); the larger tank was a modified barge pontoon measuring approximately 5 by 7 by 5 feet. Both tanks were painted white on the inside to provide contrast for photography.

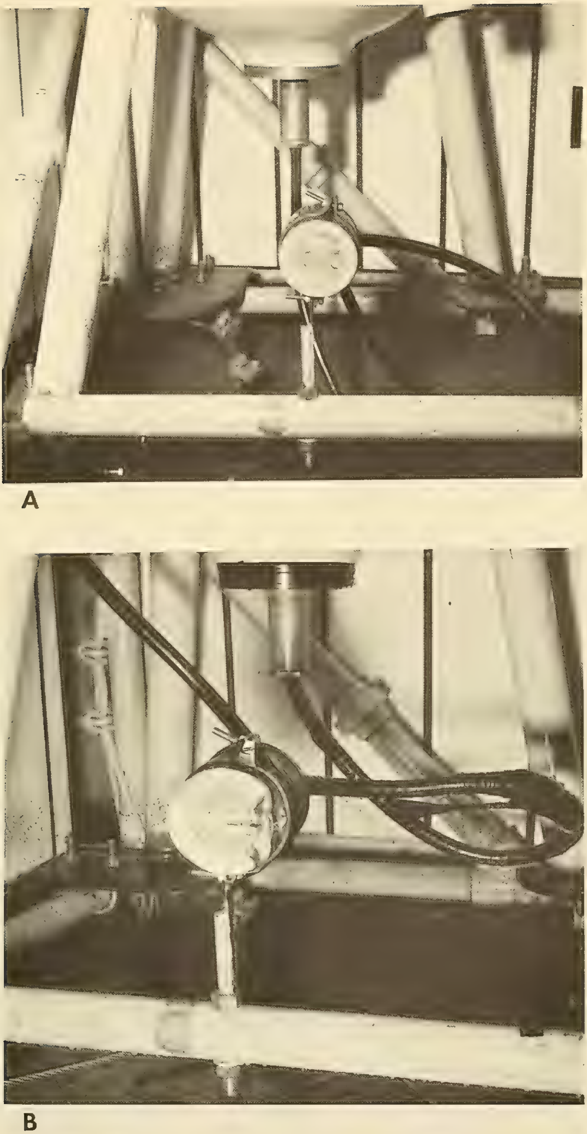


Figure 6. Spark gap (A) before and (B) after firing at 300-foot depth.

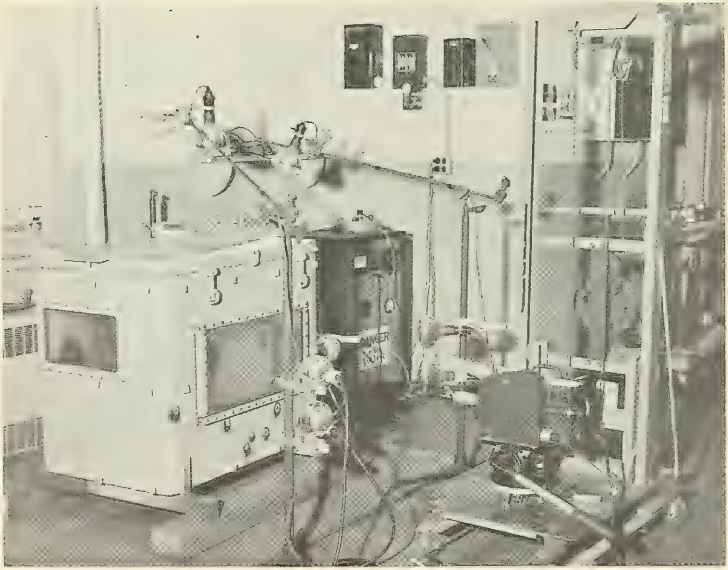


Figure 7. Laboratory tank and camera installation. The second camera has been removed to show end window and tank construction.

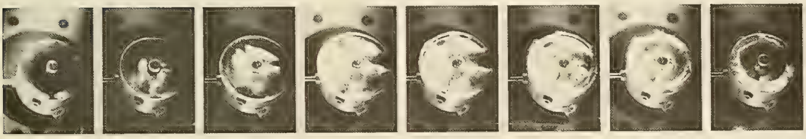
Salt Water vs. Fresh Water

Almost all the underwater spark experiments to date have been made with fresh water. On occasion salt water was substituted with no apparent difference except in gap spacing. Distilled water was also tried and the gaps would not fire. In most areas, fresh water contains many impurities and therefore has a sufficiently low resistance. In one experiment the gap was opened to a point at which there was not sufficient potential to cause the gap to fire. Increasing the salinity of the solution caused the gap to fire as before.

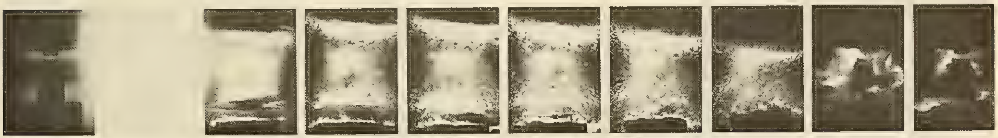
High-Speed Photography

High-speed photography was used to study the phenomena of the underwater spark and pneumatic sound sources. For nearly all this work two Eastman Type 3 high-speed cameras were used, photographing the action from two angles. Picture rates for the underwater spark shots averaged about 2800 per second and for the pneumatic explosions about 2000 per second. Thousands of feet of 16-mm motion pictures were made, and stills from many of the sequences are shown in this report. Figures 8A-B are pictures of bubble development in the laboratory tank under various conditions. The deep-water photographs appear in subsequent sections.

(A) From reflector gap.



Gap which produced the "square" bubbles.



(B) "Square" bubbles illustrating effects of geometry of gap on size and shape of bubbles.

Figure 8. Sequences from high-speed motion pictures of bubble development produced in laboratory tank under various conditions.

Figure 8. (Continued) (C) From plated underwater spark plug.

Figure 8. (Continued) (D) From parallel electrodes imbedded in high dielectric material.

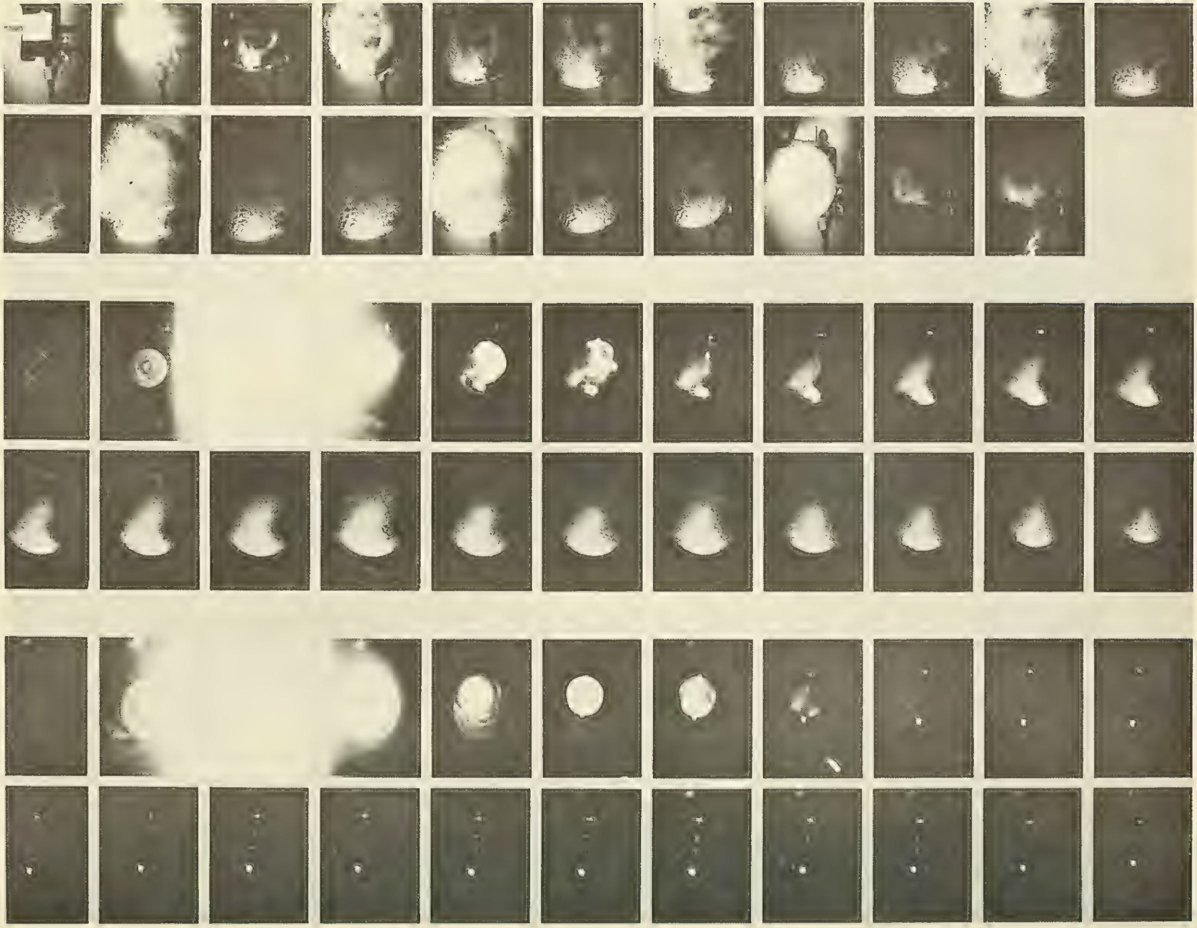


Figure 8. (Continued) (E) From spherical electrodes of different diameters.

Deep-Water Tests at Lake Pend Oreille, Idaho

As the limitations of the small tank precluded meaningful measurements in the low-frequency region, arrangements were made for calibration measurements at the NEL Pend Oreille Calibration Station in Idaho (fig. 9). Months of preparation were necessary to obtain high-speed underwater photographs of the bubble development down to a depth of 300 feet below the surface, simultaneously with sound-pressure and frequency measurements. The problems of adequate lighting and synchronizing were sizable.

Figure 9. Installation at Lake Pend Oreille for deep-water tests, showing extension dock used to lower power and control cables into water. Small float in foreground holds transformers for boosting shore power to barge.

A large framework was constructed on which the necessary equipment was mounted (fig. 10). The equipment included two Eastman Type 3 high-speed cameras mounted to photograph the bubbles from two different angles, eight 1000-watt lamps, the underwater spark capsule, and pneumatic source. To accomodate the heavy currents required for the lights, welding cables were used for conductors. All the components were enclosed in watertight housings.

Spark Capsule

Since it is impractical to run very heavy currents, such as those generated in the underwater spark, down long cables, the entire spark sound source was built into a discarded air flask from a torpedo (fig. 11). The flask was cut in half and a flange welded at the center. It contained a 3000-watt-second energy storage system and 15,000-volt dc power supply. Vacuum relays, such as previously described, were used for keying and safety discharge. Figure 12 is an inside view of the capsule. Note that the spark gaps were mounted directly at the bottom of the capsule to keep the lead length to a minimum. A small, multiple conductor cable connected the capsule with the surface and supplied 110-volt, 60-c/s, ac to the unit. A single pair of wires triggered the source from the surface. This arrangement worked well and would be suitable for lowering the equipment from a ship or helicopter. A switch inside the camera would automatically synchronize the firing with the camera. The spark capsule demonstrated that an intense sound source can be made into a small unit. For use aboard a submarine, the capsule could be attached on the deck, outside the hull, and thus conserve space inside.

Analysis of the Underwater Spark Signals

In the tests reported here, the underwater spark discharge data were obtained by means of three separate methods for later analysis in the laboratory. One was high-speed photography of the bubble formation. Speeds of approximately 2800 frames per second were used. In addition, the signal, received on a calibrated hydrophone separated 20 meters from the source, was recorded on a Magnecord Model PT6J tape recorder. Tape speeds of

15 inches per second were used. In a third method this same signal was fed to the vertical deflection amplifier of a Tektronix Model 512 oscilloscope. This display was photographed using a 35-mm Fairchild oscillograph camera. The horizontal sweep or time base was achieved by the movement of the film past the vertically deflected spot on the scope face. The film was set to run by the deflected spot at 25 inches per second; to insure accuracy of final reading, timing marks were placed on the film at 100-msec intervals.

During the laboratory analysis of the data it was found that the tape recordings were of limited value. This was because the data were amplified and put on the tape as amplitude changes. The low-frequency response of an AM recording distorts and loses much of the detail in this type of complex signal. A frequency-modulated type of recording and playback would have corrected this deficiency; however it was not possible to conduct further experiments after this shortcoming was noted. Fortunately the two types of photographically recorded data appear to contain the necessary detail. Figure 13, with its associated description, provides pertinent information on a typical underwater spark signal. It should be noted that the signal from the underwater spark is very similar to the signal received from underwater explosions of TNT.

The signal in figure 13 covers a period of slightly more than 13 milliseconds with the source at 100-foot depth. During the first 2 msec the shock wave amplitude was so high that the signal was off the film and cannot be seen. At about 3.8 msec the bubble has expanded to its greatest diameter and the pressure is falling. At about 7.6 msec from the start the pressure rises sharply as predicted,[2] corresponding in time with the near maximum contraction of the bubble. The bubble then expands to a second maximum at about 9.2 msec and the pressure falls until it reaches a point at about 10.8 msec, where again the pressure rises sharply, corresponding to another maximum in the contraction of the bubble. The bubble then tries to expand again but begins to disperse.

In addition to the oscillograph trace of figure 13, pertinent frames from the high-speed record are shown with identification of their time-position relative to the oscillograph trace.

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[2] Cole, R. H., Underwater Explosions, Princeton University Press, 1948

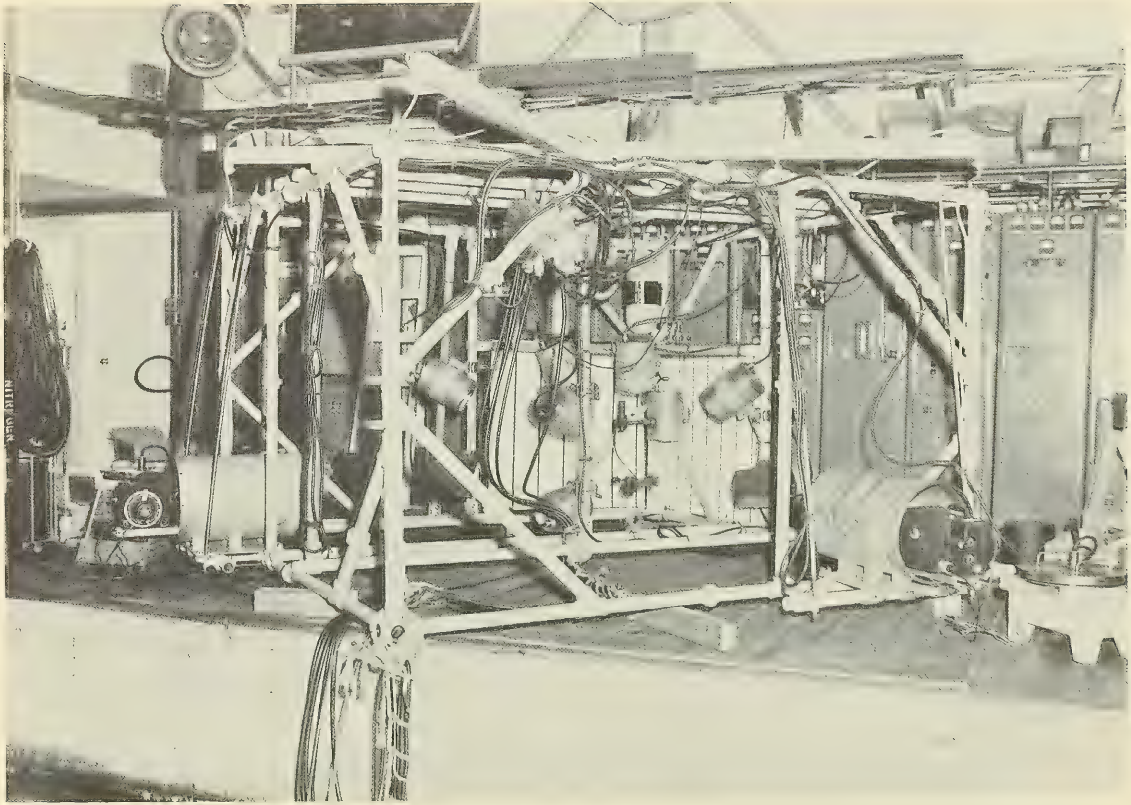


Figure 10. Assembly for underwater high-speed photography, showing frame, cameras and cases; lights and cables are attached to frame.

Figure 11. Circular spark gap with cluster of underwater lights to provide illumination for photography. Nose of camera case in foreground; visual calibration grids in background.

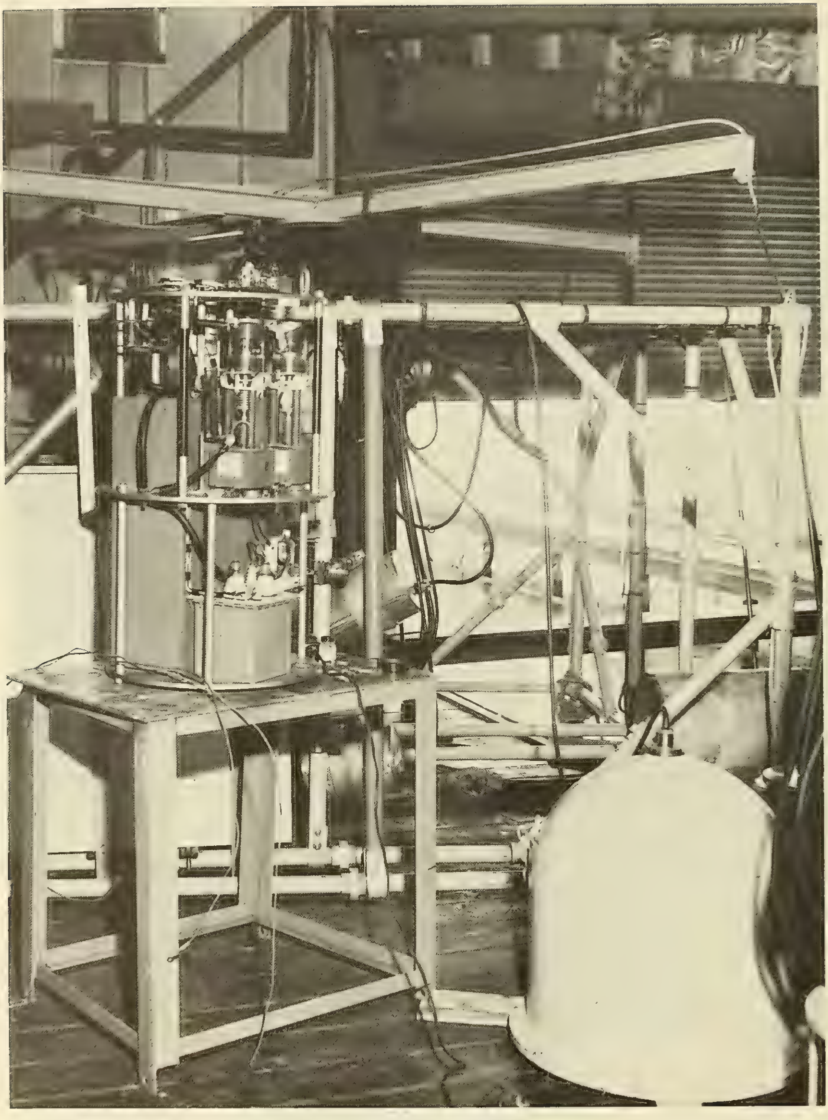


Figure 12. Inside view of spark capsule.

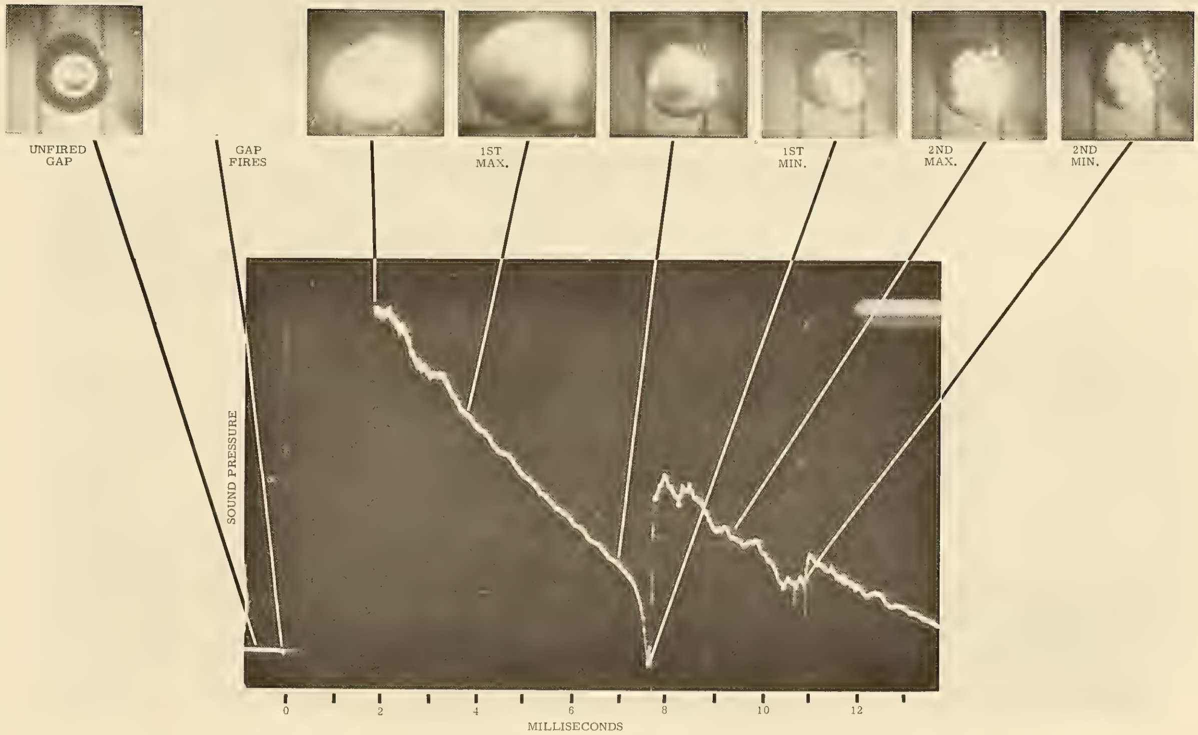


Figure 13. Oscillograph traces and selected high-speed photographs of a typical underwater spark signal.

Sound-Pressure Measurements

The sound-pressure levels listed below were measured at the NEL Pend Oreille Calibration Station in Idaho in July 1959. The lake is 750 feet deep at this point. (Photographs of bubble development at NEL POCS appear in figure 14.)

Using an energy source of 3000 watt-seconds, a peak, broadband sound-pressure level of 135.2 db/dyne/cm^2 referred to 1 meter was measured with the underwater spark source 100 feet below the surface. This was for a nondirectional condition and corresponds to a peak acoustic power in the water of about 3 million watts.

Additional omnidirectional measurements, made at a depth of 300 feet and using low-pass filtering, show the following results:

Low-pass Cut-off (c/s)	Acoustic Pressure Level (db/dyne/cm^2 ref. 1 meter)	Approximate Acoustic Level (kw)
200	114.0	25
1000	122.0	150
4000	122.0	150
5000	122.5	160

As can be seen, a substantial amount of energy appeared in the region between 1000 and 4000 c/s. Reference to the graph in figure 5 will show that the acoustic level in the 1000 to 4000 c/s region is 300,000 watts. There are few, if any, existing sound sources generating powers of this magnitude. Since the source levels were for the nondirectional case, it appears that additional gains can be made by operating the spark source at the focus of a reflector. The dimension of such a reflector at this frequency is practical for many applications where directivity is desired.

Since these measurements were made, the electrical storage-transmitter power has been doubled. However, no sound-level measurements have been made using the new storage unit.

EXPERIMENTS WITH A MAGNETIC GAP

A few experiments were conducted to determine the effects of a magnetic field on the spark gap. The first simple measurements used a spark plug inserted between the poles of a large magnetron magnet (fig. 15). Later experiments employed

Figure 14. High-speed photographs of bubble development at Lake Pend Oreille. (A) Bubbles from spherical gap 300 feet below surface.

Figure 14. (Continued) (B) From needle-point electrodes 200 feet below surface.

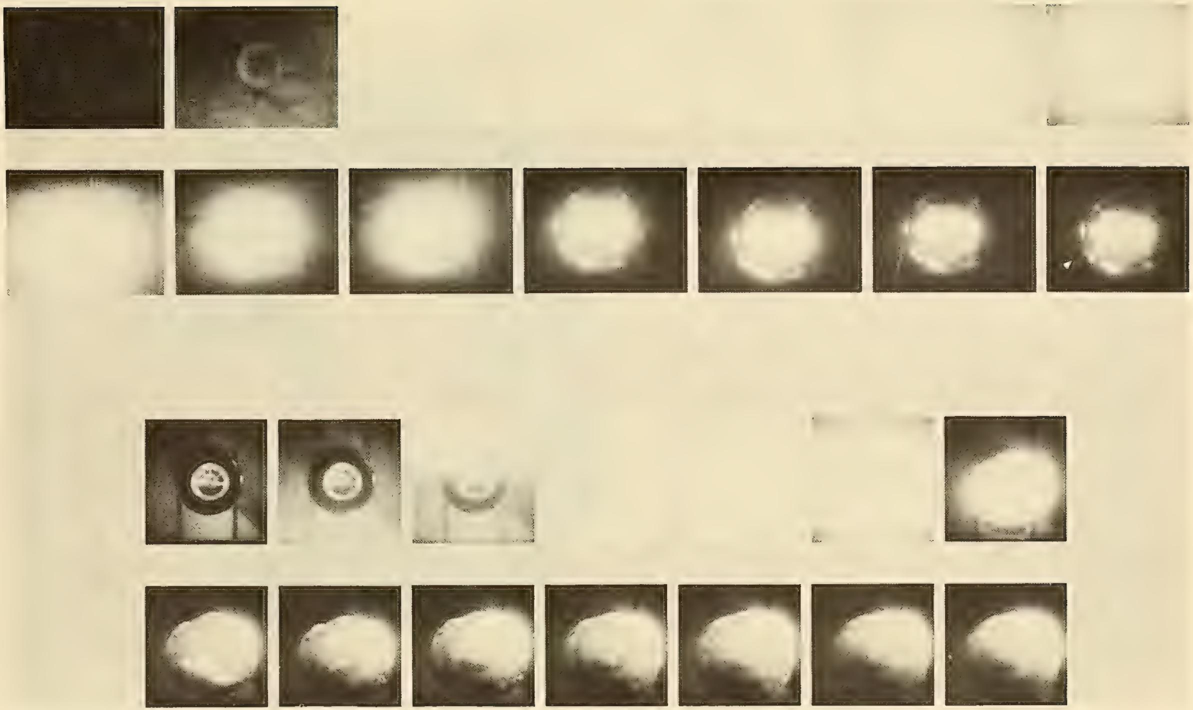


Figure 14. (Continued) (C) Partial sequence produced by spark gap (two types) 200 feet below surface.

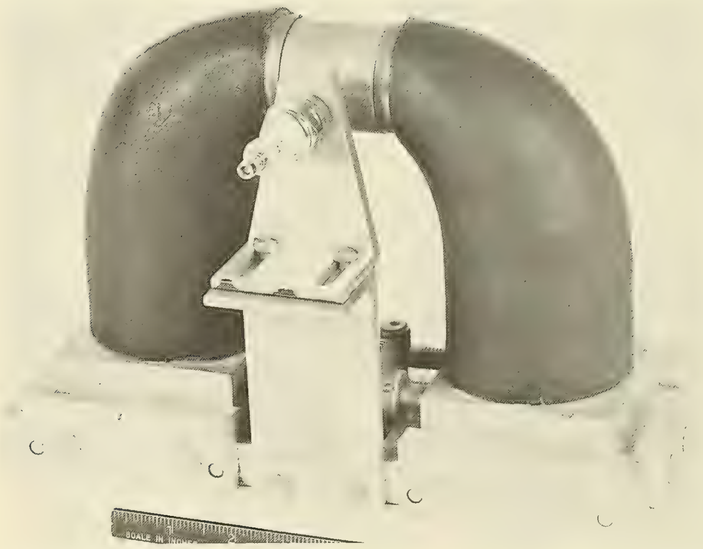


Figure 15. Arrangement for studying effect of magnetic field upon spark gap (keeper in place).

ceramic magnets, "Mobilarc Gaps," manufactured by the Westinghouse Electric Corporation for protecting high-tension power lines from lightning discharges. These magnets spun the arc and thus avoided burning a gap at one spot. The underwater spark gap which was designed around the ceramic magnet is shown in figures 16A-B. While the gap performed well, its over-all improvement over other designs was questionable. In using the large circular gaps it was difficult to produce a true "ring fire," as the spark tended to rotate around the gap in a random manner.

EXPERIMENTS WITH RESONATORS

A limited amount of work at obtaining spectral emphasis in the 1000-c/s region by the use of water-filled resonant chambers was described in reference 1. Several chambers were designed and tested using these techniques. A typical chamber is shown in figures 17A-B. The resonant frequency was first calculated as previously described and checked in water using Lissajous patterns. The agreement with original calculations was very close (fig. 18). The chamber was then shock excited into vibration by the underwater spark, using electrical resonance in the charging circuit (fig. 19). This combination worked very well.

Dr. William Toulis, while at NEL, constructed a compliant-tube type of resonant chamber (fig. 20) for use with underwater spark gaps. Data from tests using this device are shown in figure 21.

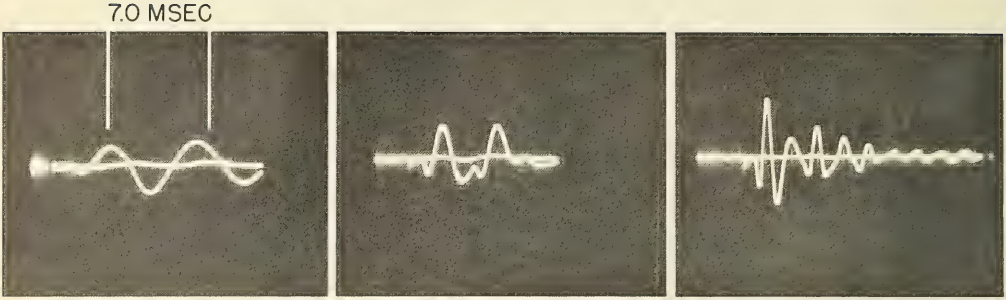
II. THE PNEUMATIC SOUND SOURCE

BACKGROUND

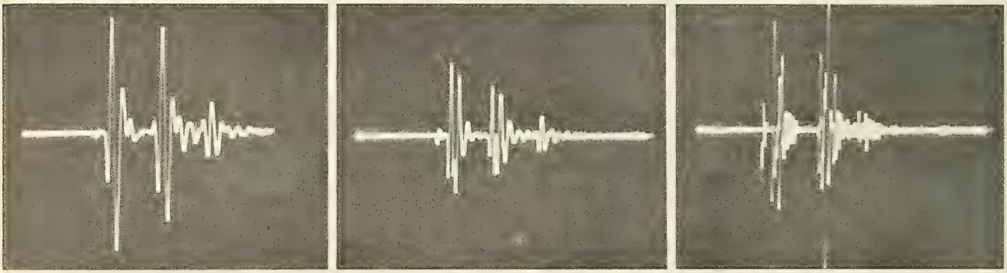
In a further attempt to generate high-intensity sound underwater, several simple experiments were performed with the pneumatic sound source. Its principle of operation is as follows: An elastic sphere is inflated underwater until its expansion limit is exceeded and it ruptures. Upon being

Figure 16. Experimental magnetic spark gap, (A) assembled and (B) disassembled.

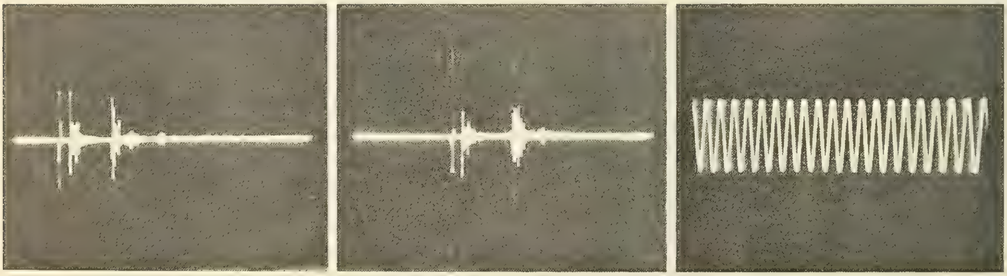
Figure 17. Typical resonant chamber (A) assembled and (B) disassembled.



100-200 CYCLES 200-400 CYCLES 400-800 CYCLES



800-1600 CYCLES 1600-3200 CYCLES 3200-6400 CYCLES



6400-12,800 CYCLES 12,800-25,600 CYCLES CALIBRATE = 1000 CYCLES

Figure 18. Waveforms produced by resonant spark sound source.

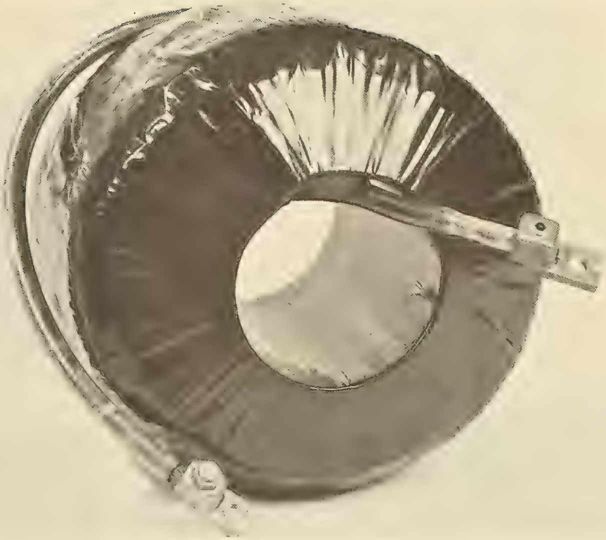


Figure 19. Resonating coil for underwater spark.

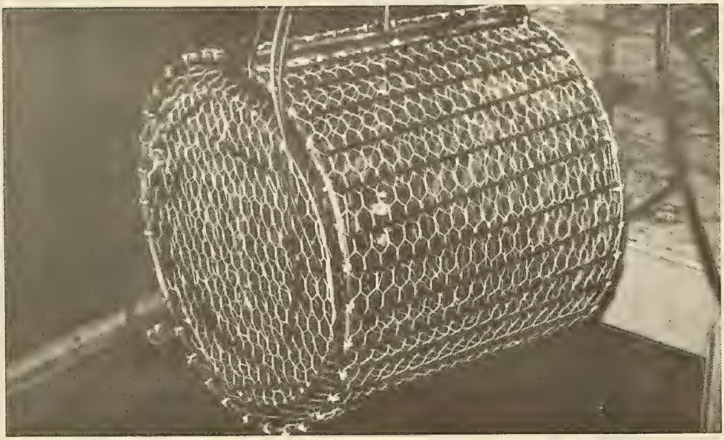


Figure 20. Spark gap in compliant resonant chamber.

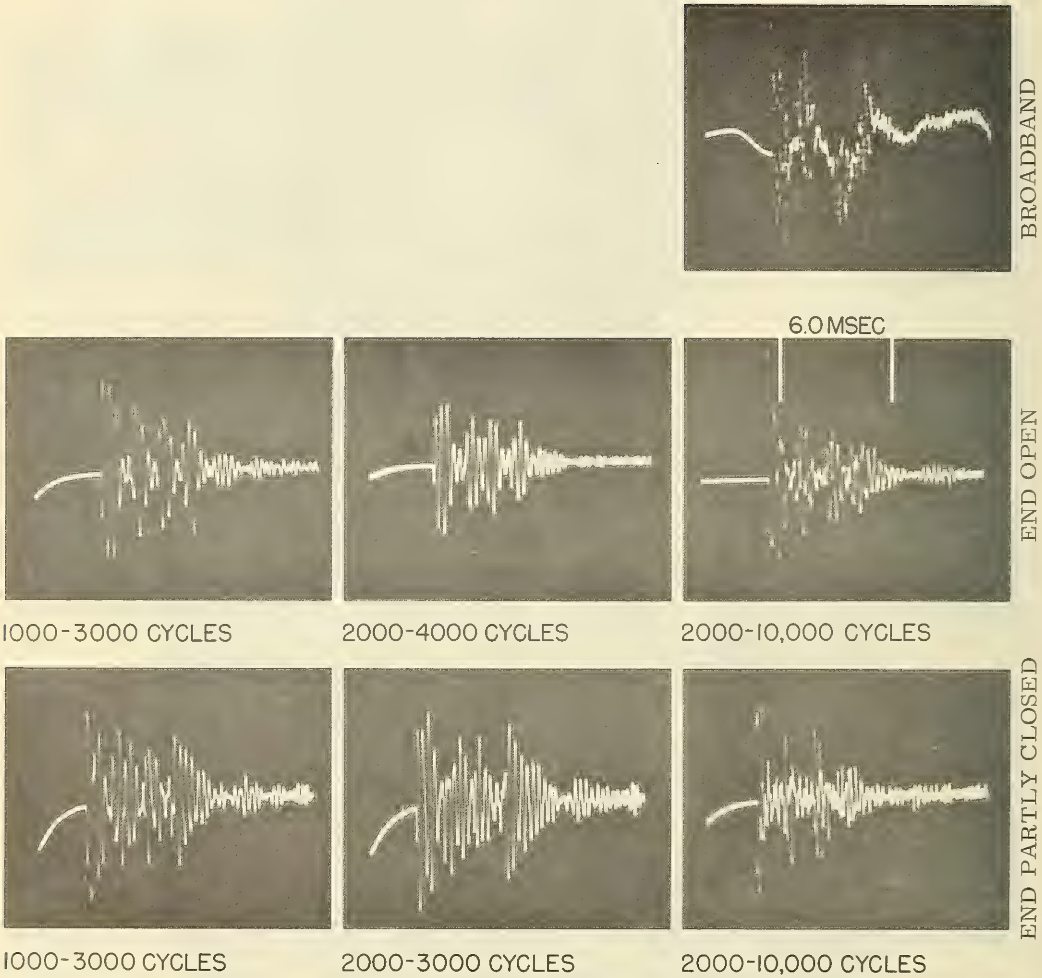


Figure 21. Waveforms produced by spark source in compliant resonant chamber.

released, the air bubble alternately expands and contracts, providing a wave train at the resonant frequency of the bubble. The frequency of a given bubble size is controlled by the stiffness of the medium, which is proportional to depth. Thus, the frequency of oscillation can be controlled. Preliminary tests with this source were encouraging.[3] Work has continued, and thousands of pneumatic explosions have been made with uniform results. Frequencies between 5 and 300 c/s have been generated in this fashion.

EARLY EXPERIMENTS

The early trials consisted of inflating many types and shapes of elastic material underwater. Surgical rubber tubing was tried in many lengths and wall thicknesses. Rubber bulbs, plastic bottles, and glass beakers were also tested and were blown to destruction. Best results were obtained with surgical rubber because of its uniformity. For inflation, both compressed air and carbon dioxide were used--the latter in the form of carbon dioxide cylinders, with their triggering mechanisms, from standard Navy life jackets. Figure 22 shows one of the early designs.

Figure 22. Pneumatic high-power/lf sound source, with 6-8 gram CO_2 cartridge.

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[3] Novel Low Frequency Sound Sources, by L. R. Padberg, Jr., NEL Letter Report 38, CONFIDENTIAL, 14 October 1957

DESIGN CONSIDERATIONS

Early measurements made at the Sweetwater Calibration Station showed that pressure was dependent upon the wall thickness of the rubber. It was also observed that the best waveform was obtained from spherical sources. A local rubber manufacturer was therefore contacted to discuss the problem of fabricating special rubber spheres. The manufacturer agreed to develop special formulas, attempting to find one that would give results equal or superior to those obtained with surgical rubber. NEL designed and built molds for the job (fig. 23). In order to obtain a maximum of data in a short time, it was decided to concentrate on a sphere approximately 1 inch in diameter, varying the wall thickness from one model to another to compare results (fig. 24). High-speed photographs (approximately 2500 frames per second) were made of the bubbles produced by these spheres; figure 25 is a typical sequence. Later, spheres of other outside diameters and various wall thicknesses were made by the manufacturer for testing (fig. 26).

Following are the major characteristics of rubber mixtures used in the NEL tests:

	Surgical Rubber	Reeves Mix 3011.1	Reeves Mix 3015.5*	Reeves Mix 416
Durometer Hardness	42	47	50	60
Specific Gravity	?	1.02	1.02	1.11
Tensile Strength (psi)	3400	3310	4500	3400
Elongation (%)	600	690	775	480

---

*The greatest number of tests at NEL have used Reeves Mix 3015.5

Directionality at Low Frequency

The problem of obtaining high directivity at frequencies below 1000 c/s has been a major difficulty for many years because the necessary reflector, to be effective, must be of such large physical dimensions.

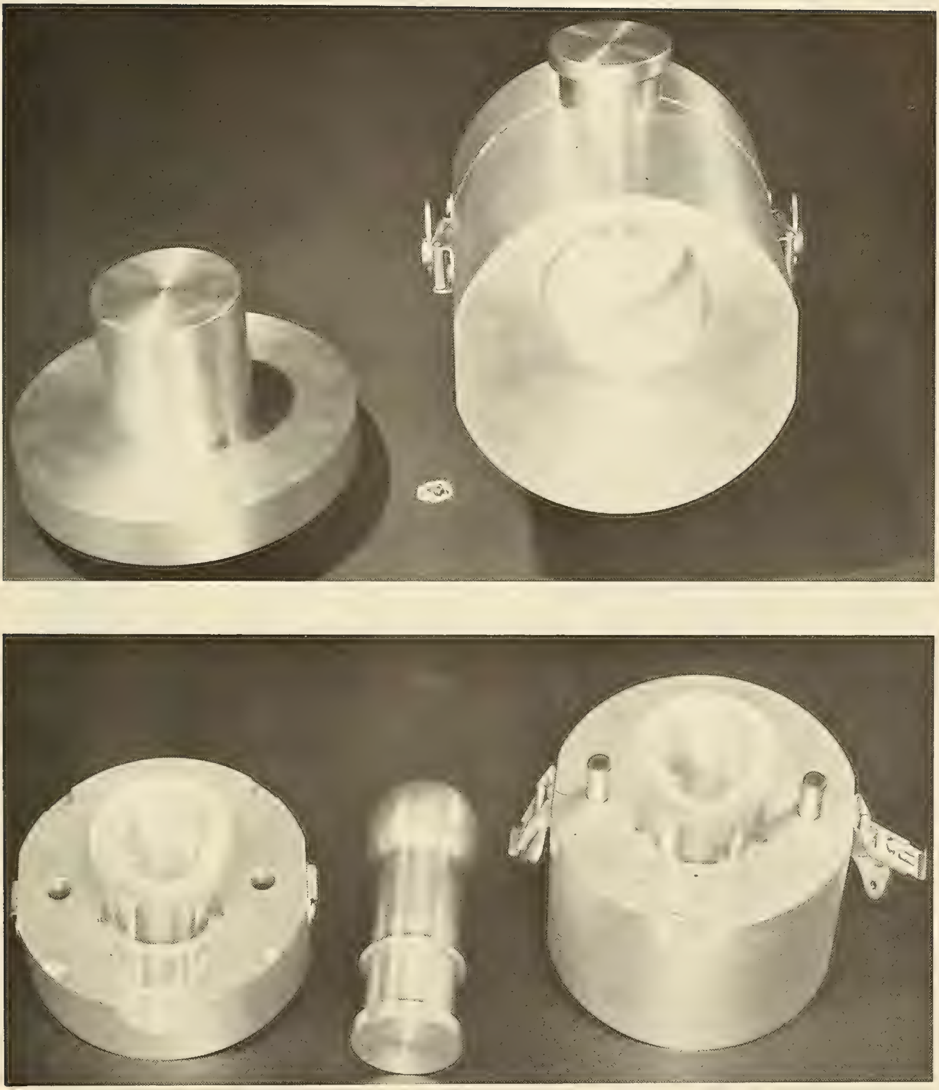

Figure 23. NEL designs of molds for rubber spheres.

Figure 24. Pneumatic spheres of various wall thicknesses.

Figure 25. Sequence of bubble development from a 2-inch OD sphere. Duration of this phase, approximately 100 μsec.

Figure 25. (Continued) Duration of this phase, approximately 100 μsec.

For years, the explosives industry has sought a directive explosive charge, with only minor success. The pneumatic sound source would provide an intense low-frequency point source for use with large parabolic reflectors. At frequencies in the order of 300 c/s the size of a suitable reflector might not be compatible with a shipboard installation, although it might be quite suitable for an ocean-floor installation. As an example, at 300 c/s, if the parabolic reflector were 200 feet in diameter, then a 5° beam would be obtained. The directivity index of such an assembly would be approximately 32 db and it is possible that a source level of as much as 138 db above 1 dyne/cm^2 at 1 meter would be obtainable. This would be a very usable source level at this low frequency.

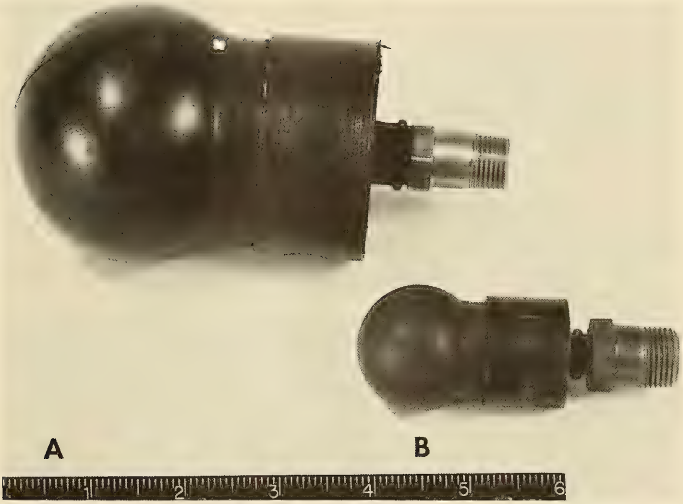

Figure 26. Examples of rubber spheres designed by manufacturer for testing: (A) 3-inch OD with 0.75-inch wall; (B) 1.375-inch OD with 0.25-inch wall.

Inflation of the Sphere

The kind of gas used for inflation will be dictated somewhat by where and how the pneumatic source is used. In shallow-water applications, most of the experiments were conducted using conventional Navy issue carbon dioxide cylinders of different sizes. For deep submersion work the problem is more involved, since carbon dioxide is very temperature-sensitive. In these applications compressed air at around 2000 psi was used. In order to obtain rupture a certain differential pressure must be achieved depending upon the elastic material used.

Inflation of pneumatic spheres or tubes might also be accomplished by an explosive gas, with the rupture induced by application of a spark. Since there is a marked difference between the broad-band sound produced by a chemical explosive alone and the almost monofrequency effect of the pneumatic source, it would appear that a combination of the two might well produce a substantial low-frequency output. However, this possibility has not been explored at NEL, as considerable study of chemical explosives as sound sources has already been performed elsewhere.

THEORETICAL DISCUSSION

Frequency Control

The frequency of the pneumatic sound source can be closely controlled. Although it is dependent to some degree on characteristics of the basic sphere, it is more conveniently dependent on the hydrostatic pressure to which it is subjected at the time of bursting. The composite effect of diameter and wall thickness is evident by comparing the data on figures 27, 28, and 29, which are plots of frequency vs. depth for three different sizes of spheres, all made of Reeves Rubber Company Mix No. 3015.5. It has been found that other rubber mixes influence the frequency characteristic of a given sized sphere, probably because of differences in elasticity.

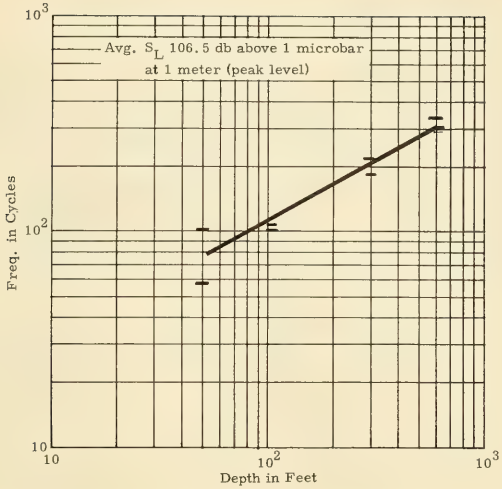

Figure 27. Plot of frequency vs. depth for pneumatic sound source (1-inch OD sphere inflated with compressed air). Wall thickness 0.3125 inch.

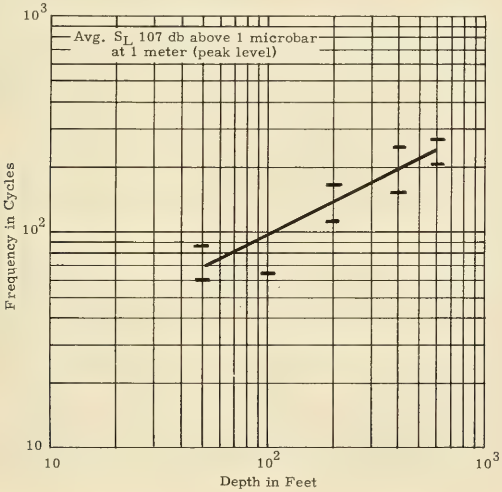

Figure 28. Plot of frequency vs. depth for pneumatic sound source (1.375-inch OD sphere inflated with compressed air). Wall thickness 0.25 inch.

Sound-Pressure Level

The behavior of the bubble produced by the pneumatic source varies significantly from that produced by the underwater spark. After rupture of the sphere, the resulting bubble oscillates without complete collapse, until it finally disintegrates. The pulse so generated remains at a single frequency and does not contain the high frequencies that are produced by chemical explosives or the underwater spark; their bubbles collapse completely and re-expand during their oscillation period, thus producing a broad band of sound frequencies.

In hundreds of measurements involving the 1-inch sphere with 3/8-inch walls, the average peak sound-pressure level for an omnidirectional condition was found to be 107 db/dyne/cm^2 at 1 meter, at selectable frequencies within the band 25-250 c/s. This corresponds to an acoustic level of about 4000 watts, which is impressive at low frequencies. Much higher levels appear obtainable in the near future.

Waveform

A typical waveform from a 1.3-inch pneumatic sphere is shown in figure 30. This form is obtained without any filtering using an amplifier and hydrophone with a flat response between 20 c/s and 10 kc/s. The sine wave at the bottom of the figure is that of a 50-c/s calibrate signal. It will be noted that the waveform has a very steep front, probably indicating the presence of many frequencies, and immediately goes into the low-frequency oscillation which in this case is approximately 30 c/s. An unusual effect is shown in figures 31 and 32. Here the rubber material has ruptured in the form of a decayed sine wave similar to the actual waveform (fig. 30).

Pulse Length

The acoustic signal generated by the bursting of the pneumatic source is a damped wave of approximately 100 milliseconds of usable duration. This lends itself to narrower band filtering in the receiver than can be used with the much shorter pulse lengths generated by the underwater spark source.

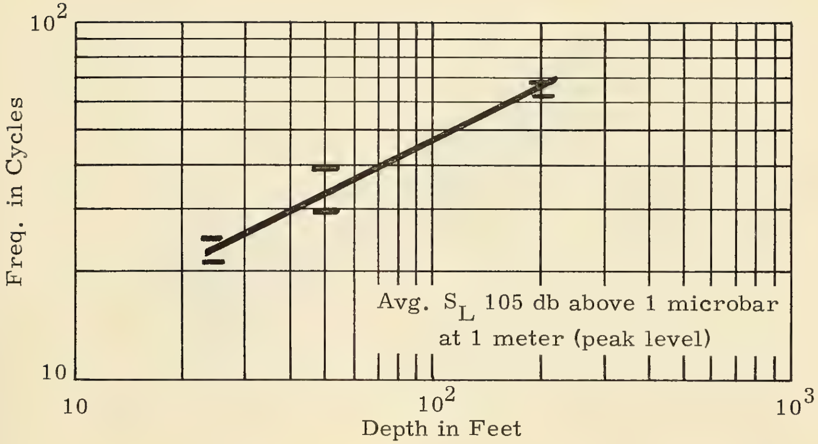

Figure 29. Plot of frequency vs. depth for pneumatic sound source (3-inch OD sphere inflated with compressed air). Heavy wall thickness.

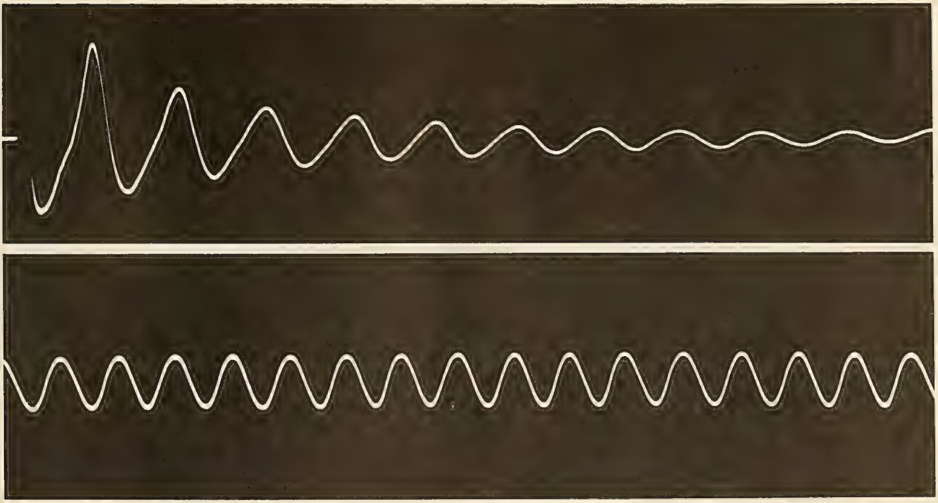

Figure 30. Typical waveform produced by 1.3-inch OD pneumatic sphere; no filtering used. The sine wave at the bottom is that of a 50-c/s calibrate signal.

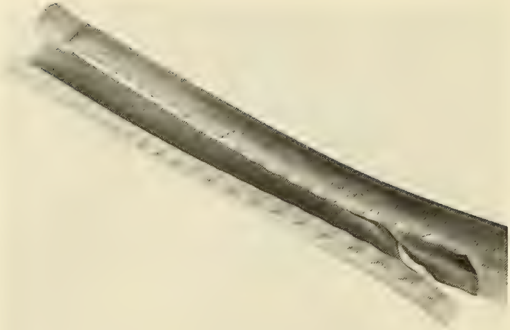

Figure 31. Close-up view of 3/4-inch surgical rubber tube after rupture.

Figure 32. Close-up view of 3-inch OD rubber sphere with 0.25-inch wall after rupture.

TESTS AND MEASUREMENTS

Shallow Water Tests

All initial tests of the pneumatic sound source were conducted in shallow water at the Navy Sweetwater Calibration Station. These tests can be summarized by stating that the average peak sound level was around 100 db/dyne/cm^2 at 1 meter for the early thin-walled spheres and surgical rubber tubing used. Hundreds of combinations were tried. Since the resulting frequencies were all around 100 c/s or below, it was apparent that, to obtain a true picture, much deeper water would be necessary to study the device. For this reason all the later measurements were made in deep water at the NEL Pend Oreille Calibration Station in Idaho.

Deep-Water Measurements

As mentioned earlier, elaborate preparations were made to measure both the underwater spark source and the pneumatic device at various depths and to obtain as much high-speed photographic data as possible. The large rigging to accomplish this was shown in figures 9 and 10. Photographs of the phenomena connected with the oscillating bubble are shown in figure 33 which was taken 200 feet below the surface, and in figure 34 which was taken at a depth of 300 feet. These are thought to be the first pictures of such phenomena taken at such great depth. It will be noted that the sphere reaches the same external dimension regardless of the depth. This is because for a given initial diameter, wall thickness, and type of material, the spheres rupture at a nearly constant differential pressure. To date, the maximum depth at which measurements have been made is 600 feet.

One important finding at the greater depths was that the air initially entrapped in the sphere and inflating line was compressed allowing the sphere to be forced into the inflating fitting, thus weakening a small area of the rubber wall prior to normal inflation. This problem was eliminated by making the ball on the end of the molding mandrel removable and allowing it to remain in the sphere. This provided several advantages since it eliminated the entrapped air and provided support to the inside of the sphere when it was under compression from the outside. The ball has not interfered with the inflation process.

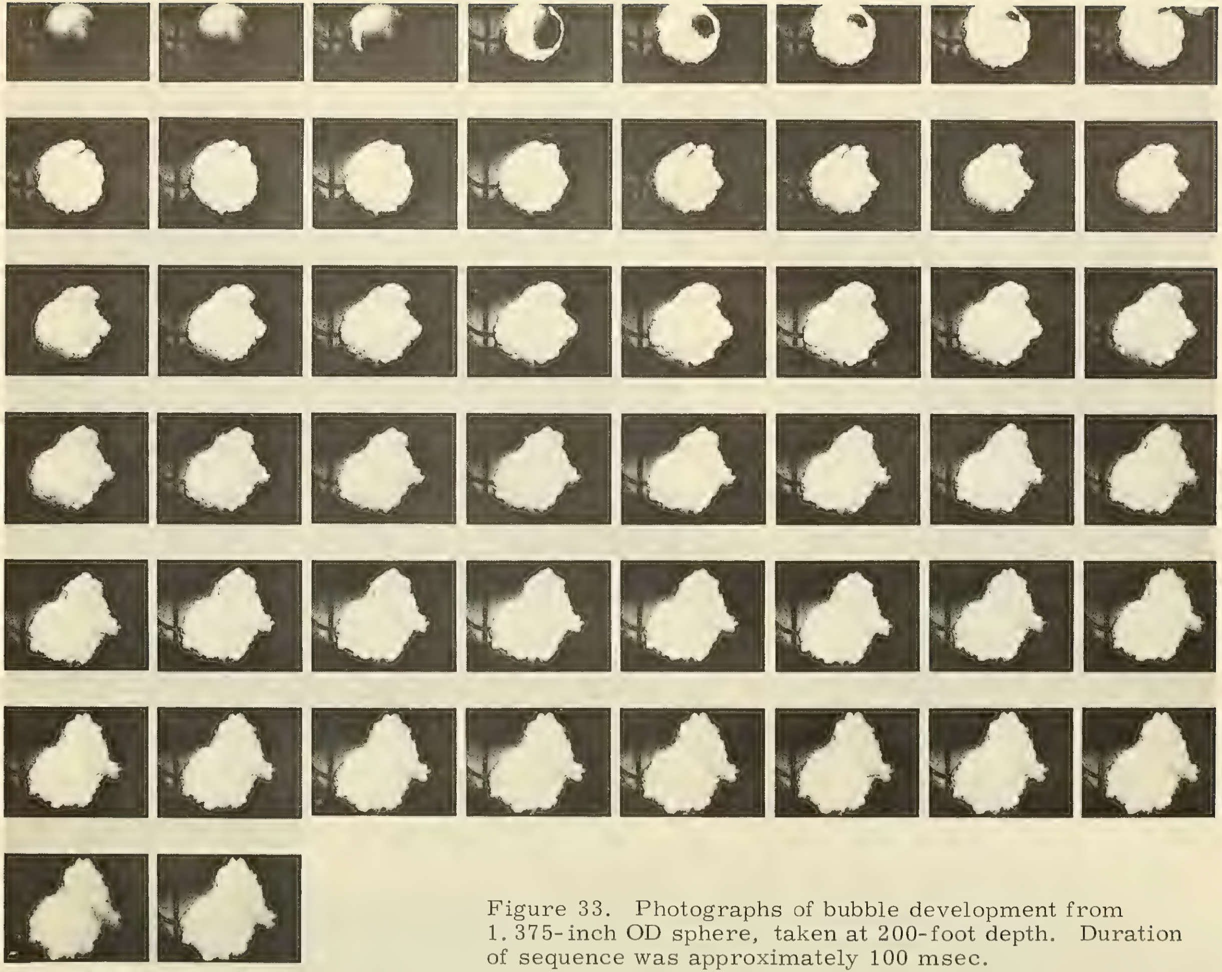

Figure 33. Photographs of bubble development from 1.375-inch OD sphere, taken at 200-foot depth. Duration of sequence was approximately 100 msec.

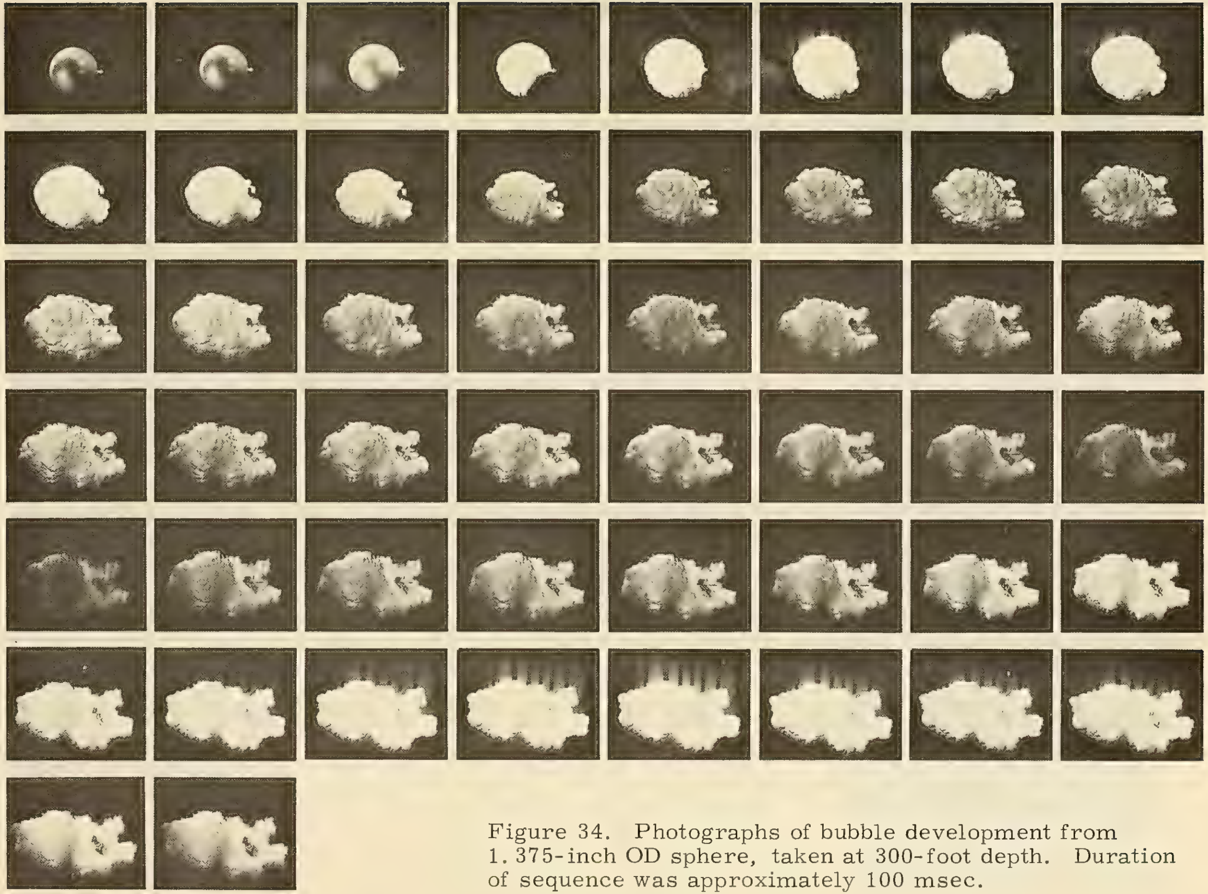

Figure 34. Photographs of bubble development from 1.375-inch OD sphere, taken at 300-foot depth. Duration of sequence was approximately 100 msec.

THE ACOUSTIC BOMB

It is frequently desired to make sound transmission studies in the deep ocean. Because there are few sources that can generate substantial power, particularly in the very low frequency region below 1000 c/s, chemical explosives of various sizes are used for the study. This is not only a costly process, but involves considerable hazards.

The pneumatic sound source is ideal for use as a sound bomb. It is safe, cheap to produce, and creates a substantial sound level at essentially a single low frequency which can be controlled. The sound pressure generated is a function of wall material and thickness. The frequency generated is a function of the depth at which the source is operated and of its initial physical dimension.

The first model of the acoustic bomb consisted of a very simple pressure mechanism, a small cartridge of carbon dioxide, and a small length of surgical rubber tubing sealed off at the end (fig. 35). This mechanism worked satisfactorily to a depth of about 150 feet.

Later versions of the acoustic bomb consist of Mark 15 Mod 0, practice depth charge pressure mechanisms attached to flasks of compressed air or carbon dioxide, combined with specially designed elastic spheres of various sizes. Figure 36 shows one type used.

OTHER NOVEL SOUND SOURCES

CONVERSION OF HEAT TO SOUND

With the advent of nuclear submarines there is an abundance of heat available which might be utilized in the generation of sound. A few simple experiments involving the principle of converting heat to sound were conducted as part of the Novel Sound Sources program and are reported briefly as a possible impetus to others to continue this approach.

Carbon dioxide, or dry ice, at a critical point about -110°F, changes state from a solid to a gas. This phenomenon is known as "subliming." If a metal object which is at or near room temperature is brought into

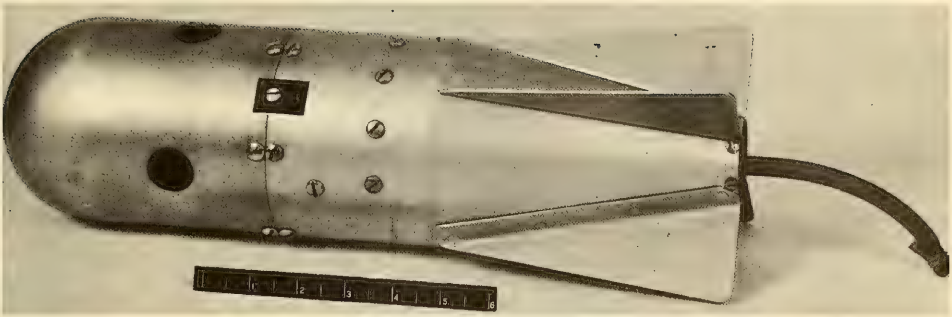
Figure 35. Original model of acoustic bomb.


Figure 36. Acoustic bomb using Mark 15 Mod 0 pressure mechanism.

momentary contact with dry ice, it imparts considerable heat to it. This causes release of gas and considerable pressure at the point of contact, and the metal object will be set into vibration. Depending upon the shape and size of the vibrating object, sounds of various frequencies and surprisingly high levels are thus produced. Many variations of this method of generating sound are possible. (This is a crude but effective method of testing vibrations in metals at very low temperatures.) The frequencies can be measured with a calibrated oscillator by means of Lissajous patterns.

THE "WOLF WHISTLE"

In this sound source a condition which is normally avoided as undesirable is intentionally put to use. It is well known to players of string instruments that under certain conditions beyond their control, a sympathetic resonance can occur between the vibrating string and the sound box. This undesired tone is call a "wolf-tone."

In the "wolf whistle" sound source, the vibrating string is replaced by a more rugged vibrating body such as a small metal saw blade, steel clock-spring, reeds, rods, or bars. The vibration is started by placing the body in front of a jet of air or water. Varying the tension adjusts the frequency. The vibrator is in turn placed at the open end of a resonant chamber which is sympathetically excited by the vibrating element. When the two frequencies are identical, the resulting sound is loud. The adjustable deflection plate can be used to control the intensity of the sound generated. The two variations of the "wolf whistle" shown in figure 37 have been operated in air but no underwater measurements have been made of their performance.

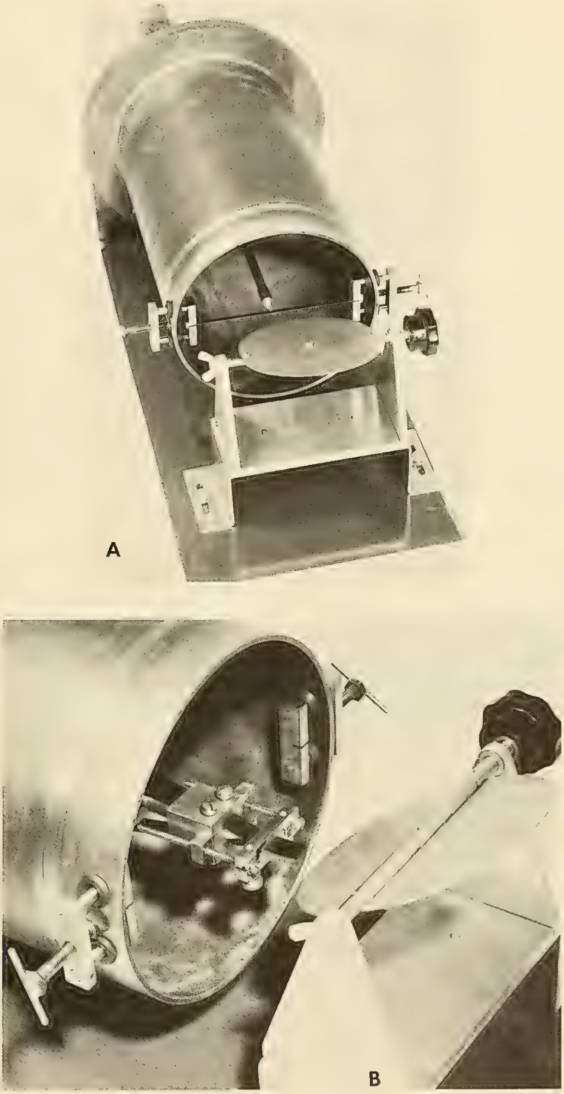

Figure 37. The "Wolf Whistle," (A) with vibrating blade in position; (B) with adjustable reeds in position.

CONCLUSIONS

I. THE UNDERWATER SPARK SOUND SOURCE

1. An underwater spark is capable of providing very high intensity, broadband, nondirectional short pulses of acoustic energy.
2. Resonators excited by an underwater spark are capable of providing selected frequencies or bands of frequencies of acoustic energy.
3. The apparatus required for a high-powered underwater spark is suitable for assembly in a capsule for deep submergence.
4. An underwater spark is useful in explosive metal forming.

II. THE PNEUMATIC SOUND SOURCE

1. Small rubber spheres are capable of providing acoustic source levels of at least 107 db above 1 dyne/cm^2 at selected frequencies within the band 10 - 300 c/s.
2. The frequency of a given pneumatic source can be controlled by selection of its depth at the time of rupture.
3. The nature of the simple pneumatic source makes it appear useful in a variety of applications requiring a single pulse of selected frequency within its operating band.

RECOMMENDATIONS

I. THE UNDERWATER SPARK SOUND SOURCE

1. Conduct tests with the underwater spark to determine its suitability for converting existing passive coastal defense systems into active systems.
2. Conduct tests with the underwater spark to determine its suitability for converting existing submarine passive equipment into active echo-ranging equipment.
3. Conduct tests with the underwater spark to determine the feasibility of obtaining desired directivity by use of suitable reflectors.
4. Continue effort to determine the utility of the underwater spark in fields of oceanography, hydrography, and seismology.
5. Continue effort to obtain improved materials for electrodes and gaps, as well as to determine possible upper power limits, utility of resonators, etc.

II. THE PNEUMATIC SOUND SOURCE

1. Conduct tests to determine the usefulness of the pneumatic source in converting passive coastal arrays into active ones.
2. Conduct tests to determine the usefulness of the pneumatic source in low-frequency echo-ranging operations from submarines, helicopters, etc.
3. Conduct tests to determine the usefulness of the pneumatic source in other military applications, such as:
    a. Pre-cursor acoustic sweep in mine countermeasures
    b. Location of missile nose-cone water entry position
    c. Anti-limpeteer operations
    d. Submarine signalling
    e. Oceanography, seismology, etc.
4. Continue effort to obtain improved materials and to determine upper power and frequency limits.

Navy Electronics Laboratory
Report 990

NOVEL SOUND SOURCES, by L. R. Padberg, Jr.
63 p., 17 October 1960.
UNCLASSIFIED

Two high-intensity underwater sound sources have been developed and tested extensively for use in the low-frequency region: (1) the underwater spark, which at 300-foot depths has generated peak pressures corresponding to an acoustic level in excess of 3 million watts for a broadband nondirectional condition; and (2) the pneumatic sound source, which has generated a peak acoustic level of over 4000 watts for a nondirectional condition, in the frequency range of 5 to 300 c/s. Both devices are small, easily handled, and suitable for numerous tactical applications. Other novel sound sources are explored and reported briefly.

1. Underwater sound - Sources - Research
2. Underwater sparks - Research

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