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The Design of Deep-Submergence Hydrophones

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13. ABSTRACT

The goals and achievements in the development of a long-life, deep-submergence, wide-frequency-range hydrophone based on tried and proved designs and materials are summarized. The hydrophone has been divided into sensor, preamplifier, and cable assembly compartments to minimize failure and to facilitate construction and repair. All joints have double O-ring seals. The piezoelectric element is double-booted with butyl rubber as the water barrier. Each boot is filled with degassed, low-water-vapor castor oil. All of the exterior metal parts are covered with an elastomer to minimize corrosion and to reduce the possibility of electrical crosstalk. Fourteen different sensor elements were constructed and evaluated, and four hydrophones of one design have been constructed to give "in-service" evaluation. The report includes a discussion of the sensor element, charts of sensitivity and directional characteristics, photographs of hydrophones and subassemblies, an assembly drawing, and a set of specifications. Data are included on elastomers and metals suitable for use at depths as great as 9000 meters.

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Illustrations

Tables

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Abstract

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THE DESIGN OF DEEP-SUBMERGENCE HYDROPHONES

Introduction

One of the chief concerns in the design of a piezoelectric hydrophone is the stability of the sound-sensitive element. The sensitivity of this element may vary with temperature, hydrostatic pressure, and time, and because it is the nature of piezoelectric ceramic materials to exhibit such variations, it is important to choose the best material and the best configuration for a given requirement.

Other concerns are the ability of the assembly to resist leakage or collapse at pressures to which it will be subjected at deep submergence, and to resist the corrosive effects of sea water and sea life. Cables and electrical connections also must withstand the rigors of deep-submergence pressure and the deleterious effects of sea water and marine life.

The various components of the hydrophone will be discussed separately in what follows.

PART I. Design Considerations

Sound-Sensitive Element

The element that responds to sound pressure by generating a voltage will be called a sensor in this discussion, which will be restricted to piezoelectric sensors.

The three piezoelectric materials that have been studied and used the most in transducers designed at the Underwater Sound Reference Division (USRD) are lead zirconate-titanate, lead metaniobate, and lithium sulfate. Each material and each configuration has its own characteristics that make a particular one the most suitable for a given requirement. Cost and availability also are important considerations that can narrow the selection. The configurations that have been studied under a pressure of 110.3 MPa (16,000 psi, approximately equivalent to the depth 11,000 m) are flat plates, capped tubes, free-flooding tubes, and hollow spheres [1].

Although stress alone cannot polarize a ceramic, properly oriented stress applied during polarization can aid or impede the process and at other times can cause partial or complete depolarization [2]. It is

Table 1

PROPERTIES OF THREE PIEZOELECTRIC CERAMIC MATERIALS AT HIGH PRESSURE

Material	Max rated hydrostatic pressure	Compressive strength	Max rated static compressive stress (25°C)		
			(maintained) parallel to polar axis	(cycled) parallel to polar axis	(maintained) perpendicular to polar axis
PZT-4	344.7 MPa 50000 psi	517.1 MPa 75000 psi	82.74 MPa 12000 psi	82.74 MPa 12000 psi	55.2 MPa 8000 psi
PZT-5A	137.9 MPa 20000 psi	517.1 MPa 75000 psi	34.5 MPa 5000 psi	20.7 MPa 3000 psi	13.8 MPa 2000 psi
PZT-5H	137.9 MPa 20000 psi	517.1 MPa 75000 psi	13.8 MPa 2000 psi	17.2 MPa 2500 psi	10.3 MPa 1500 psi

Table 2

COEFFICIENT OF LINEAR THERMAL EXPANSION (0-50°C), TWO PIEZOELECTRIC CERAMIC MATERIALS

(Ratio of change in length per °C to length at 0°C)

Material	α_1*	α_3**
PZT-4	$+3.8\times10^{-6}$	$+1.7\times10^{-6}$
PZT-5	$+1.4\times10^{-6}$	$+4.0\times10^{-6}$

*Perpendicular to polar axis
**Parallel to polar axis

Source of data: D. Berlincourt and H. H. A. Krueger, "Properties of Clevite Ceramics," Clevite Technical Paper TP-226 Engineering Memorandum 64-1 necessary, therefore, to know the effect of stress on the properties of piezoelectric ceramics and to design the sensor element to minimize the effect of the high static stress that will be encountered in deep-water operation. It has been found that transducers containing free-flooding ceramic elements undergo little change in performance characteristics with depth or time [3,4].

Tables 1 and 2 give some properties of commonly used lead zirconate-titanate formulations.

Lead metaniobate and lithium sulfate are volume expanders used almost without exception in the shape of a disk or a plate in an oil-filled boot, the entire sensor element being exposed to the sound field. The sensitivity of such a configuration is slightly less than that of a disk or plate acoustically masked so that the sound pressure is admitted only to the major faces. The increased stability gained by eliminating all acoustic pressure-release material, however, greatly outweighs the increased sensitivity that results from masking these materials.

Lead zirconate-titanate is used in the form of tubes, disks, hollow spheres, and hemispheres, as illustrated in Fig. 1a-d. For greatest stability at high hydrostatic pressure, the sensor made of this material should be designed for three-dimensional stress rather than for high one- or two-dimensional stress, which degrades performance. Small capped tubes (Fig. 1e) can be used at pressure as high as 6.89 MPa (1000 psi, or 689 m depth) with no more than 0.1 to 0.2 dB change in sensitivity [5]. Radially polarized capped tubes 1.27 cm diam by 1.27 cm long by 3.18 mm wall thickness have been calibrated at pressure to 58.6 MPa (8500 psi, or 5860 m depth). A change of only 1 dB was measured at pressure to 17.24 MPa (2500 psi). Liquid-filled end-capped ceramic tubes (Fig. 1f) can be used at high pressure with some loss in sensitivity, but with good stability [6]. The sensitivity of a 5-cm-o.d. by 5-cm-long by 3.18-mm-wall capped PZT-5H tube, constructed as in Fig. 1h, changed from -190 dB re 1 V/μPa to -193.5 dB when it was oil filled. The sensitivity of the oil-filled element did not change when it was calibrated at pressure to 55.15 MPa (8000 psi).

Table 3 provides data on materials suitable for use as end caps. In addition to considerations of strength and weight, it frequently is desirable to select for the end caps a material whose coefficient of thermal expansion approximates that of the piezoelectric material with which it is being used. This precaution can prevent failure of the cement bond between the end caps and the ceramic element at extremes of temperature. The temperature at great depth in the oceans is 1 or 2°C.

Hollow ceramic spheres (Fig. 1c) have been calibrated at pressure to 110.3 MPa (16,000 psi). There is a limit to the size of a gas-filled sphere that can be used to a given pressure. A standard hydrophone whose sensitive element is a 2.54-cm-diam gas-filled sphere suitable for use to 68.94 MPa (10,000 psi) has been described by Henriquez and Ivey [7].

Table 3

CHARACTERISTICS OF MATERIALS SUITABLE FOR END CAPS ON PIEZOELECTRIC CERAMIC TUBES

Material	Density ρ (kg/m^3) ($\times 10^3$)	Young's modulus Y (N/m^2) ($\times 10^{10}$)	Poisson's ratio (σ)	Sound speed (m/sec)			Coefficient of linear thermal expansion (0°C) ($\times 10^{-6}$)
				Long. plate c_p	Long. rod c_r	Shear plate c_s	
Alumina (Al_2O_3)	3.96	34.5	0.22		9405		6.5
Aluminum	2.7	7.0	0.355	6420	5000	3040	23.8
Beryllia (BeO)	2.88	30.9	0.21				4.0
Beryllium	1.87	30.8	0.05	12890	12870	8880	12.3
Glass (Pyrex)	2.23	6.2	0.24	5640	5170	3280	3.2
Magnesium	1.74	4.24	0.306	5770	4940	3050	27.0
Quartz (fused)	2.23	7.17	0.16	5900	5760	3750	0.55
Stainless steel (347)	7.91	19.6	0.30	5790	5000	3100	14.0

If pressure higher than the sphere can withstand without mechanical failure or changes in its electroacoustic characteristics is to be encountered, it is necessary to allow the sphere to free-flood in the liquid medium [8]. The free-field voltage sensitivity can be maintained constant down to low frequencies by providing a small orifice (Fig. 1g) that serves as a low-pass acoustic filter or offers high acoustic impedance but permits the hydrostatic pressure to equalize with the pressure at the depth of operation. The sensitivity at the lower frequencies can be enhanced, even, by choosing orifice size and cavity volume to utilize the Helmholtz resonator effect. Sensitivity may be a function of temperature in the region of resonance because of a change in characteristics of the liquid. When a sphere is liquid filled and used as a driven transducer, cavitation can occur within the sphere; however, this is of little concern at great depth and need not be considered in hydrophone applications.

Two methods for equalizing the pressure on cylindrical piezoelectric elements in hydrophones for deep submergence have been described by O'Neill [9,10]. Either method--the capillary orifice or tube, or opposed relief valves (Fig. 1h)--can be applied to the design of low-frequency hydrophones by using sensor elements of 2.54 to 5.0 cm diameter; the free-field voltage sensitivity remains constant down to 1 Hz. When requirements call for higher frequencies, however, smaller elements must be used to minimize the diffraction effects [11] and to keep the resonance frequencies of the component parts well above the operational range of the hydrophone.

As the component parts become smaller, it is difficult to use either relief valves or capillary tubes; however, if the lower frequencies (below 100 Hz) are not of great interest, or can be attenuated, a small slot or orifice in the end cap can provide the necessary equalization passage. Thus, the low-frequency rolloff in the sensitivity of the sensor element can be designed to meet many requirements without resorting to a valve or a tube. Usually, the greatest assembly problems are completely removing the air and filling the sphere with a suitable fluid.

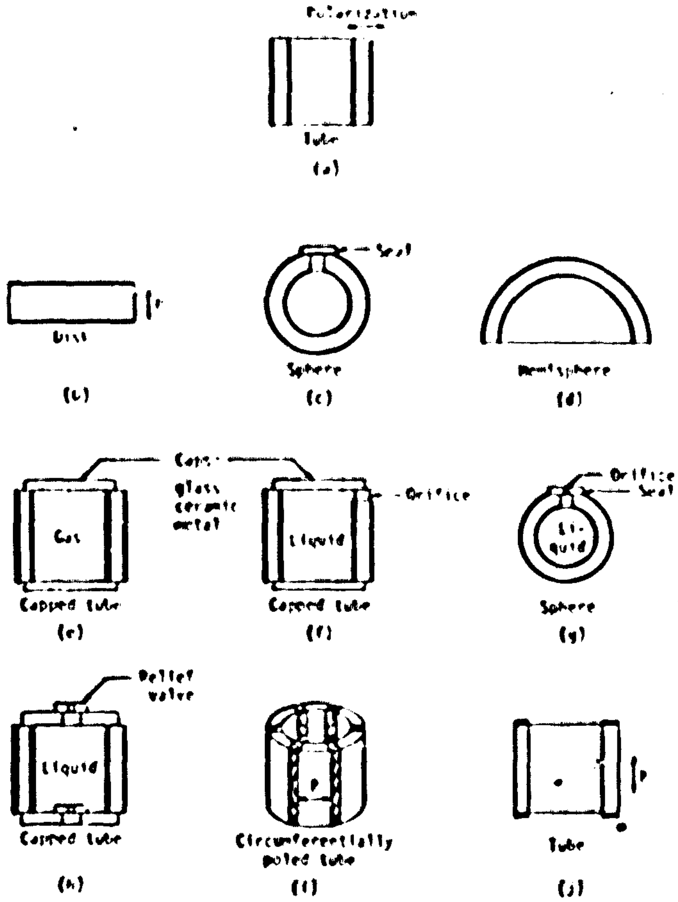

Fig. 1. Configurations of piezoelectric ceramic sensor elements.

Lead zirconate-titanate disks (Fig. 1b) and plates usually are not exposed to acoustic pressure on all surfaces of the element because such a configuration results in a lower sensitivity. If stability is a paramount consideration, however, and the high sensitivity is not required, there are some applications in which the simplicity of design and reduced cost of this approach can be used.

The sensitivity of cylindrical ceramic tubes (Fig. 1a,i,j) has been analyzed by Langevin [12] by considering three sets of boundary conditions for each of three types of polarization. Experience has shown that sensitivity change is greatest when the ends are shielded. These sensitivity changes are due to changes in the characteristics of the material used to shield the ends acoustically. Both temperature and hydrostatic pressure and, to a lesser extent, time cause the acoustical and mechanical characteristics of the acoustically soft materials to change, which, in turn, changes the boundary conditions for the ends of the ceramic tube and results in a condition somewhere between shielded and exposed. Consequently, the sensitivity of a sensor element with shielded ends is susceptible to change.

Design Limitations and Trade-Offs

The optimum sensor design for a given application usually is reached only after considering a number of choices: (1) material (*e.g.*, lead zirconate-titanate, lead metaniobate, lithium sulfate), (2) configuration (disk, tube, sphere), (3) dimensions of the sensor element, (4) compensated or uncompensated element, and (5) polarization (thickness, circumferential, radial). The choices can be made only after a thorough analysis of the requirements, which include (1) sensitivity, (2) directional response patterns (vertical and horizontal), (3) impedance (self-noise), (4) frequency range and response characteristics, (5) maximum operating depth, (6) stability (temperature, time, pressure), and (7) cost.

Usually the choices that confront the designer are concerned with sensitivity, frequency range, and directional characteristics. If the sensor element must be made larger to increase sensitivity, then the upper frequency to which the element will be omnidirectional will be reduced. Moreover, doubling the diameter of a sensor element such as a tube reduces the radial-mode resonance to half its former value. On the other hand, if the sensor element is to operate at higher frequencies, it must be made smaller to minimize diffraction effects and self resonance. As the size of the element is reduced, the capacitance (and usually the sensitivity) decreases, and can reach the point at which self-noise is too high.

Watertight Integrity

Water and water vapor are responsible for most failures in underwater transducers. Designers long have sought materials that have low water-vapor permeability and metals that will not corrode. The water barriers and acoustic windows of most early sonar transducers and hydrophones were boots of natural rubber. Failure rates were high as the result of the high water-vapor permeability of natural rubber and the water solubility of Rochelle salt and ammonium dihydrogen phosphate (ADP). Even a minute amount of water vapor caused surface electrical leakage and low electrical resistance. Larger amounts of water dissolved the crystals.

Later, neoprene was substituted for natural rubber in many applications. Its superior resistance to oil and its weatherability were great advantages, of course, but it provided only slight reduction in water permeability.

Butyl rubber was the material in the acoustic boot of the Brush Development Company's type BM101 hydrophone, which dates from early 1948 at least, as shown by USRL calibration data of June of that year.

The water permeability of most butyl rubber compounds is one twentieth to one fortieth that of natural rubber, neoprene, polyurethane, Hypalon, GR-S (government rubber, styrene type), PVC (polyvinyl chloride), or Hycar elastomers. Representative values for some materials are shown in Table 4.

Butyl rubber is not difficult to mold or to bond to metal parts when the mold is properly designed and the correct primer method is used on the metal. Transducer coverings and acoustic windows have been molded from butyl at the USRD since 1954 on a small Carver press with electrically heated platens. A typical split mold used for making a hydrophone boot is shown in Fig. 2. Perhaps the most serious drawback to using butyl for acoustic windows is the change in sound speed with temperature, which increases the mismatch in acoustic impedance as the water becomes colder. The sound speed in butyl gum changes from 1630 m/sec at 25°C to 1985 m/sec at 5°C, whereas that in natural rubber changes from 1518 m/sec to 1578 m/sec for the same temperature change. The sound speed in sea water changes in the opposite direction as temperature decreases, going from 1570 to 1510 m/sec.

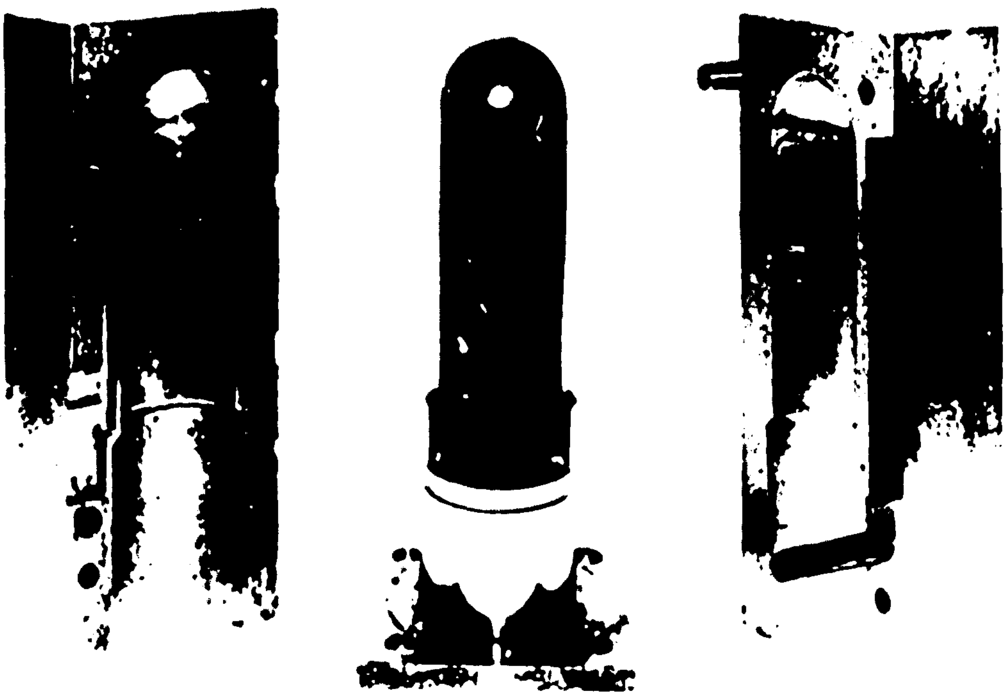

Fig. 2. Typical split mold and molded hydrophone boot.

The acoustic impedance mismatch is not as serious as these figures might imply, because at audio and low ultrasonic frequencies the elastomer thickness is small in comparison with a wavelength, and "thin membrane" theory applies. It has been found that when the geometry is symmetrical with respect to the sensor element and the acoustic window, butyl boots with a wall thickness of 6.35 mm do not affect seriously the response or directional characteristics at low temperature, as long as the acoustic window is of uniform cross section and the upper frequency is not higher than 40 kHz. A thinner wall will permit operation to higher frequencies (200 kHz), but usually with some change in response characteristics as a function of temperature.

Table 4

SOME PROPERTIES OF RUBBER AND SYNTHETIC COMPOUNDS

Property	Polyethylene Low density	Polyethylene High density	Neoprene	Butyl	Natural rubber
Physical					
Max operating temp	75°C	75°C	90°C	100°C	75°C
Elongation (%)	600	500	750	400	500
Tensile strength					
(MN/m^2)	16.55	22.06	19.31	11.03	27.58
(psi)	2400	3200	2800	1600	4000
Low-temp flexibility					
(brittle temp)	-60°C	-60°C	-30°C	-55°C	-55°C
Abrasion resistance	Good	Excellent	Good	Fair	Fair
Ozone resistance	Excellent	Excellent	Good	Very good	Poor
Tear resistance	Very good	Good	Fair	Fair	Fair
Flammability	Burns	Burns	Nonflam	Burns	Burns
Density ρ (g/cm^3)[a]	0.92	0.95	1.32	1.04	1.10
Sound speed c at 25°C					
(m/sec)	1950	2000	1525	1700	1525
Electrical					
D-c volume resistivity at 25°C (ohm-cm)	10^{17}	10^{17}	8×10^{12}[c]	1.5×10^{13}[c]	1.9×10^{13}[c]
Dielectric strength					
(volts/mil at 25°C)	1000	1000	400	530	425
Power factor at 1 kHz	0.0002	0.0002	0.07	0.009	0.08
Dielectric constant					
at 1 kHz	2.34	2.26	6.7	3.1	5.4
Chemical Resistance					
Strong bases	Very good	Very good	Good	Good	Fair
Strong acids	Very good	Very good	Good	Very good	Fair
Oil and gasoline	Very good	Very good	Good	Fair	Poor
Castor oil	Very good	Very good	Very good	Very good	Very good
Water Permeability[b]	47×10^{-10}	-	379×10^{-10}	8×10^{-10}	413×10^{-10}

[a] Density of sea water is 1.03 g/cm^3; sound speed is 1570 m/sec.

[b] Grams water/cm^2/cm/hr/mm Hg water vapor pressure differential. The water permeability of polyurethane (ether-based PR-1538) is 3000×10^{-10}.

[c] Volume resistivity will vary according to compound ingredients.

When an elastomer is to serve as an electrical insulator as well as a mounting material for a sensor element, the volume resistivity of the elastomer must be high. An elastomer with low volume resistivity may be satisfactory as an acoustical boot, yet may not be acceptable if it must contact the electroded surface of the sensor element. Three butyl compounds that have low water permeability and have been used successfully in underwater sound transducers are given in Appendix A.

Corrosion Resistance

Much is available in the literature about the selection and the performance of materials in the marine environment [13,14]. Many designers have underestimated the extent and the intensity of corrosion processes manifested as galvanic corrosion, pitting, crevice corrosion, uniform removal of material, and velocity effects.

Perhaps the pitting and crevice corrosion create the greatest problems. Frequently, an O-ring seal provides a man-made crevice and accelerates the failure of the seal. Cupro-nickel (70-30) and red brass (85 Cu) provide good resistance to pitting and have a low uniform corrosion rate that is between 0.25 and 7.6 mm per year. Fouling is very low because of the toxic nature of the copper.

Stainless steels, including types 316 and 304, pit badly. A new stainless steel, Armco 22-13-5, is reported to show virtually no pitting after 9 months exposure in quiet sea water. At this time, however, this steel has not been fully evaluated.

Some aluminums have good corrosion resistance in sea water. Two of the better alloys are 5086-H34 and 5083-0, as shown in Table 5. Table 6 gives a comparison of some of the physical properties. If strength-to-weight ratio is an important consideration, alloys 7075-T6 and 6061-T6 provide higher strength at the sacrifice of corrosion resistance. Alloy 7075-T6 always needs protection, whereas 6061-T6 may get by without it.

The best corrosion protection is provided by a coating or covering over the metal. All metal parts of the USRD type H54 hydrophone are completely covered with an elastomer such as butyl. The metals for the housing can be selected to provide the best strength-to-weight ratio for the application. It must be emphasized that when long life is required, the proper sealing of the entire hydrophone is very important.

Cable Requirements

The design of electrical cable is beyond the scope of this report; however, some recommendations can be made regarding insulation and jacket materials, and general construction.

When cables hang vertically in water, there is a tendency for them to stretch, even when strength members are included. If the insulation or jacket contains an elastomer, the material will stretch, but will

Table 5

TYPICAL CORROSION RATES AND PITTING CHARACTERISTICS OF VARIOUS METALS AND ALLOYS IN SEA WATER

Material	Corrosion rate (mean range)	Resistance to pitting	Typical rate of penetration in pits
70-30 Cu-Ni[a]	$0.2\text{-}3.8\times10^{-2}$ mm/yr 0.1-1.5 mils/yr	Good	$2.5\text{-}13\times10^{-2}$ mm/yr 1-5 mils/yr
Copper[a]	$1.2\text{-}7.6\times10^{-2}$ mm/yr 0.5-3.0 mils/yr	Good	$15\text{-}30\times10^{-2}$ mm/yr 6-12 mils/yr
Ni-Al Bronze[a]	$2.5\text{-}30\times10^{-2}$ mm/yr 1.0-12 mils/yr	Good	$5\text{-}23\times10^{-2}$ mm/yr 2-9 mils/yr
Monel 400[a]	b	Fair	$13\text{-}38\times10^{-2}$ mm/yr 5-15 mils/yr
316 Stainless[a]	b	Fair	178×10^{-2} mm/yr 70 mils/yr
Armco 22-13-5 Stainless[c]	Not available	Good	Unaffected after 9 mo in quiet sea water
Berylco 717C[d]	Reported by manufacturer to have virtually the same corrosion characteristics as Std 70-30 Cu-Ni alloy		
7075-T6 Aluminum[e]	b	Fair	$28\text{-}51\times10^{-2}$ mm/yr 11-20 mils/yr Always needs protection
6061-T6 Aluminum[e]	b	Moderate	$13\text{-}25\times10^{-2}$ mm/yr 5-10 mils/yr May need protection
5086-H34 Aluminum[c]	b	Excellent	$<2.5\times10^{-2}$ mm/yr <1 mils/yr Usually unprotected
5083-0 Aluminum[c]	b	Excellent	$<2.5\times10^{-2}$ mm/yr <1 mils/yr Usually unprotected

[a] H. H. Uhlig, *Corrosion Handbook* (John Wiley & Sons, New York, 1948).

[b] Characteristic form of corrosion makes over-all weight loss data meaningless, since failure occurs by pitting.

[c] Armco Product Data S-45 (June 1970).

[d] The Beryllium Corporation, Bulletin No. 4100 (1966).

[e] R. E. Groover, T. J. Lennox, Jr., and M. H. Peterson, "Characterization—of the Corrosion Behavior and Response to Cathodic Protection of Nineteen Aluminum Alloys in Sea Water," NRL Memorandum Report 1961, Jan 1969.

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Table 6

SOME MECHANICAL AND PHYSICAL PROPERTIES OF VARIOUS ALLOYS

Alloy	Ultimate tensile strength MN/m^2 / ksi	0.2% Yield MN/m^2 / ksi	Elongation in 5 cm (2 in.) (%)	Modulus of elasticity $10^3 MN/m^2$ / 10^3 ksi	Density $10^3 kg/m^3$ / lb/in^3	Strength/wt (yield/dens) 10^2 m / 10^3 in.
Berylco 717C (aged)	758.4 110	517.1 75	7	152 22	8.91 0.322	59.2 233
Std 70-30 Cu-Ni MIL-C-20159-1	413.7 60	220.6 32	20	152 22	8.91 0.322	25.3 99
5% Ni-Al Bronze MIL-B-16033-1(4) (heat treated)	758.4 110	413.7 60	5	131 19	7.72 0.279	54.7 215
316 Stainless MIL-S-18262-3	482.6 70	206.8 30	30	200 29	8.02 0.290	26.3 103
Ni-Al Bronze MIL-B-21230-1	586.1 85	241.3 35	15	131 19	7.53 0.272	32.7 129
Mn-Ni-Al Bronze MIL-B-21230-2	620.6 90	275.8 40	20	124 18	7.53 0.272	37.4 147
Armco 22-13-5 Stainless[a]	827.4 120	448.2 65	45	200 29	7.89 0.285	57.9 228
7075-T6 Aluminum	572.3 83	503.3 73	11	71.7 10.4	2.80 0.101	183.4 722
6061-T6 Aluminum	310.3 45	275.8 40	12	68.9 10.0	2.71 0.098	103.8 408
5086-H34 Aluminum	324.1 47	255.1 37	10	71.0 10.3	2.66 0.096	97.8 385
5083-O Aluminum	289.6 42	144.8 21	22	71.0 10.3	2.66 0.096	55.5 218

[a]Annealed at 2050°F (1121°C) and water quenched.

recover when the cable is withdrawn from the water and rolled up. On the other hand, the copper conductors stretch, but do not recover, and so cause the cable to buckle--principally at the connector or terminal. One solution is to use a cold-flowing plastic that will stretch but will not recover; then, if the cable stretches, the plastic will not recover enough to cause serious damage to the cable.

Even the filler material or sealant used in "blocked" cables to keep the cable from acting like a water hose can cause trouble. Fillers within the jacket can cause movement and ultimate failure of the cable. When possible, it is best to fill all of the space around the insulated conductors by extruding the jacket over the cable and by filling interstices completely.

Neoprene is the outer jacket on many cables. It is tough, flexible, and abrasion resistant. It is considered to be an elastomer. Polyethylene, also, has many superior qualities as an insulating material and as jacketing on underwater cables. It stands up well in the sea environment. The electrical resistance is high and the water permeability is low [15]. Usually, polyethylene jackets are color pigmented to protect them from ultraviolet radiation. Bell Telephone Laboratories (BTL) has used polyethylene-insulated and jacketed cables in transocean telephone cables and in underwater transducer construction for many years. The British have encapsulated a number of their transducers in polyethylene.

Development by BTL of repeater station pressure housings and cable glands of polyethylene for deep-submergence use has been described in the *Bell System Technical Journal* [16].

Butyl rubber is an excellent insulating material with low water-vapor permeability. Butyl has good weathering properties and heat resistance, but it does not perform well when exposed to mineral oil or some silicone fluids.

Underwater Electrical Connectors

Three types of underwater electrical connectors are in general use today. These are typified by the Marsh & Marine molded rubber connector (Figs. 3 and 4), the Electro-Oceanic rubber molded connector (Fig. 5), and the Cannon metal housing, O-ring seal connector illustrated in Fig. 6. Each connector has certain advantages. The Marsh & Marine type probably is the least expensive and the metal Cannon type, the most

Fig. 3. Marsh & Marine connectors.

Fig. 4. Marsh & Marine bulkhead and cable connectors.

Fig. 5. Electro-Oceanic connectors.

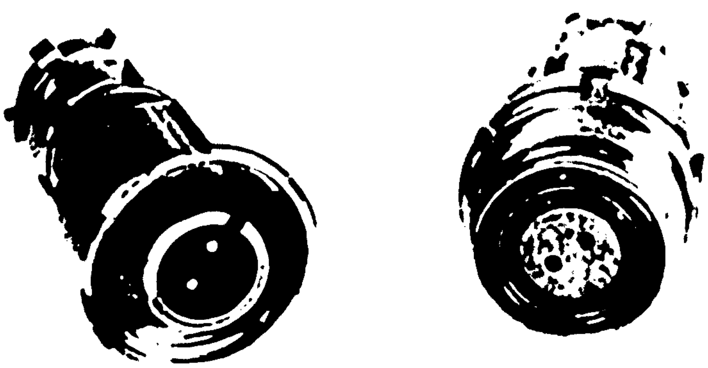


Fig. 6. Cannon connectors.

expensive. The Electro-Oceanic design is suitable for mating cables under water and is less likely to leak when subjected to partial vacuum, as sometimes occurs when air is removed from the water of a tank in which transducers are calibrated. From an operational point of view, however, the Marsh & Marine and the Cannon types probably provide the best electrical contact area and for that reason are most suitable for high electrical currents.

In an attempt to reduce corrosion, some manufacturers have substituted plastic components for metal ones. Although plastic is suitable when there is protection from physical abuse, it frequently breaks if struck or unduly stressed, so metal such as silicon bronze or cupronickel generally is preferred under such conditions. In other respects, the plastic materials perform very well.

Fig. 7. Capped tubes in hairpin support frame.

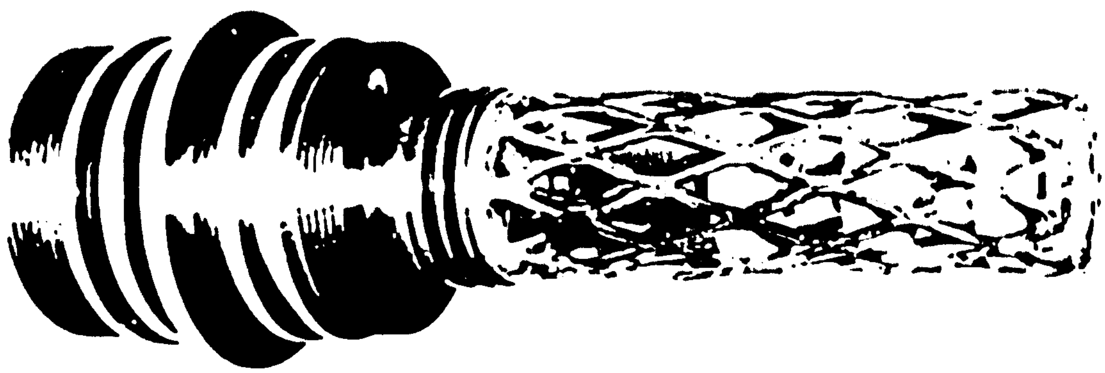


Fig. 8. Expanded-metal support frame.

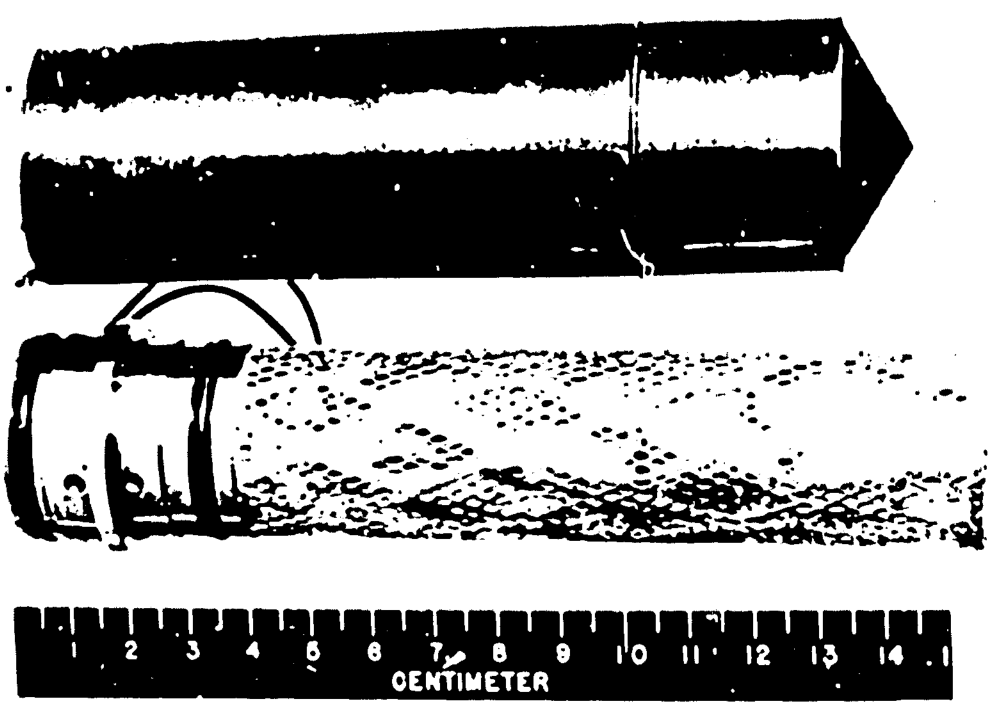


Fig. 9. Fine-mesh expanded-metal shield.

PART II. A Deep-Submergence Hydrophone Designed According to the Preceding Considerations

The USRD type H54 represents one design for a deep-submergence hydrophone. It incorporates many features that have proved successful in USRD-designed standard reference hydrophones. Several sensor configurations have been evaluated. Three of these now will be described and illustrated.

Sensor Elements

Figure 7 shows three 1.27×1.27×0.327-cm-wall capped ceramic tubes mounted on natural rubber disks bonded to two hairpin-shaped wire frames. The elements can be used in series or in parallel. The series configuration provides a 9.5-dB increase in sensitivity over that of the parallel configuration at the expense of higher electrical impedance. The capacitance of the elements in parallel is 3600 pF; that of the series connection is only 400 pF. In most instances, however, this higher impedance does not cause a problem when adequate electrical shielding is provided around the elements and a relatively high-impedance preamplifier is used near the sensor element. Generally, the shielding afforded by the expanded-metal support frame shown in Fig. 8 is adequate. Nevertheless, additional shielding can be provided without introducing acoustical problems by using a flattened expanded metal, as shown in Fig. 9.

Figure 10 shows a sensor consisting of six ceramic lead-metaniobate disks. Because this ceramic material is a volume expander, as explained earlier, there is no need to shield the sides of the disk with acoustic pressure-release materials such as Corprene (a cork-neoprene composition). Lithium sulfate crystals can be mounted in a similar manner to achieve the same acoustical characteristics. For a given volume of material in disk form, lithium sulfate will have the greater sensitivity for a given impedance. This type of construction can be used at depths to 9000 m.

Figure 11 is representative of a design embodying a capped ceramic tube and two relief valves. The cylinder is oil filled and can be used at any depth with very little change (0.5 dB) in sensitivity. The single rubber mount at the center of the element helps to minimize its sensitivity to acceleration along the length of the tube.

Appendix B provides some practical equations and examples of the computation of free-field voltage sensitivity of a capped tube, a disk or plate, and a hollow sphere.

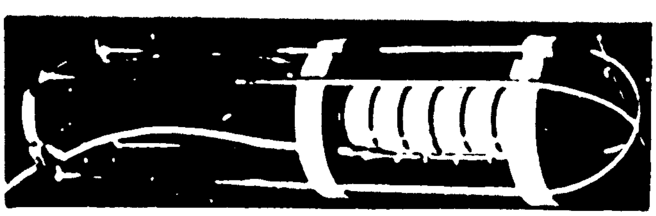


Fig. 10. Lead metaniobate ceramic disks.

Fig. 11. Capped ceramic tube with relief valve.

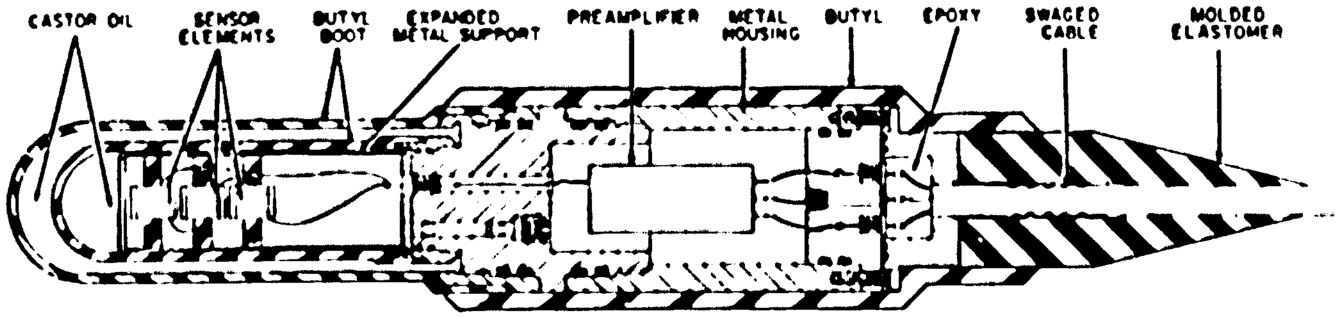


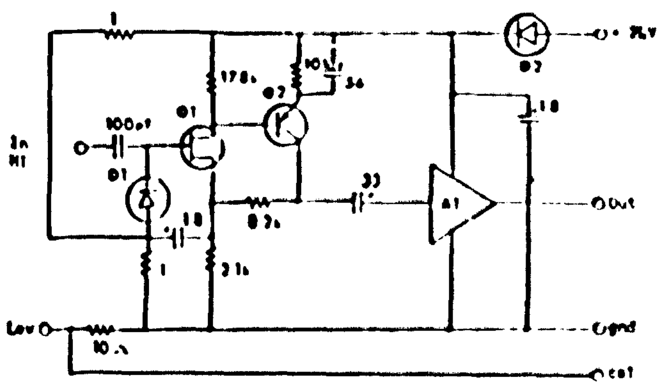
Fig. 12. Section, type H54 deep-submergence hydrophone.

General Construction Details

Figure 12 shows the assembly details for the USRD type H54 hydrophone. All mating metal parts have two O-ring seals for redundant protection and low water permeability. The user has the option of specifying cupro-nickel (70-30), bronze, stainless steel (22-13-5), or aluminum (7075-T6 for greatest strength) for the housing. A butyl boot over all of the metal parts will add considerable protection from corrosion; therefore, weight, strength (depending upon operating depth), and cost can be considered in the selection. To assure longest life with the least amount of corrosion and the least possibility of ultimate entry of water, cupro-nickel is the best choice.

The double butyl boot over the sensor element, with castor oil as the acoustic coupling medium, offers low water permeability and added physical protection. The inner boot can provide years of service even if the outer boot deteriorates or is damaged.

Small solid-state amplifiers are readily available and can be mounted within the preamplifier pressure housing. An example of one USRD design is shown in Fig. 13. If more space is required for special amplifiers, such as auto-ranging, the housing can be lengthened easily.



A1 Beckman 866 or 822
Q1 2N4867
Q2 2N2906
D1 2N929 (emitter not used)
D2 1N4001

Unless otherwise specified, resistance is in megohms; capacitance is in microfarads.

Specifications

Voltage gain:	12 ± 1 dB	*Power supply:*	+24 V at 140 mA
Frequency range:	5 Hz to 100 kHz	*Output impedance:*	50 Ω -10%
Input impedance:	1000 MΩ	*Maximum output:*	0.8 V (rms) for 1% distortion
Input shunt capacitance:	10 pF (max)	*Noise:*	5 μV broadband with 100-pF source

Fig. 13. Low-noise preamplifier with line driver.

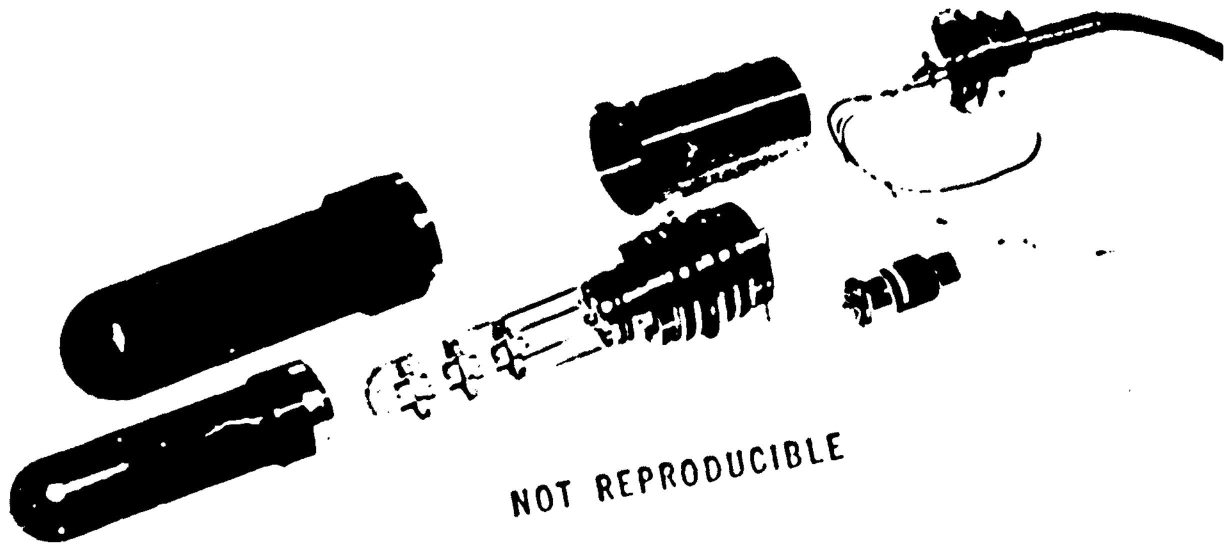


Fig. 14. Exploded view, type H54 hydrophone.

The cable enters through high-pressure glass-to-metal seals. The cavity immediately above the seals is filled with an epoxy after the cable gland has been assembled and the wires soldered to the high-pressure feed-through insulators. Filling this cavity keeps hydrostatic pressure from forcing the cable inward, with the possibility of gland failure. The cable is secured to the metal gland by a swaged copper fitting. A tapered rubber sleeve is molded and vulcanized over the metal and the cable to keep the cable's outer sheath from being bent too sharply and damaged.

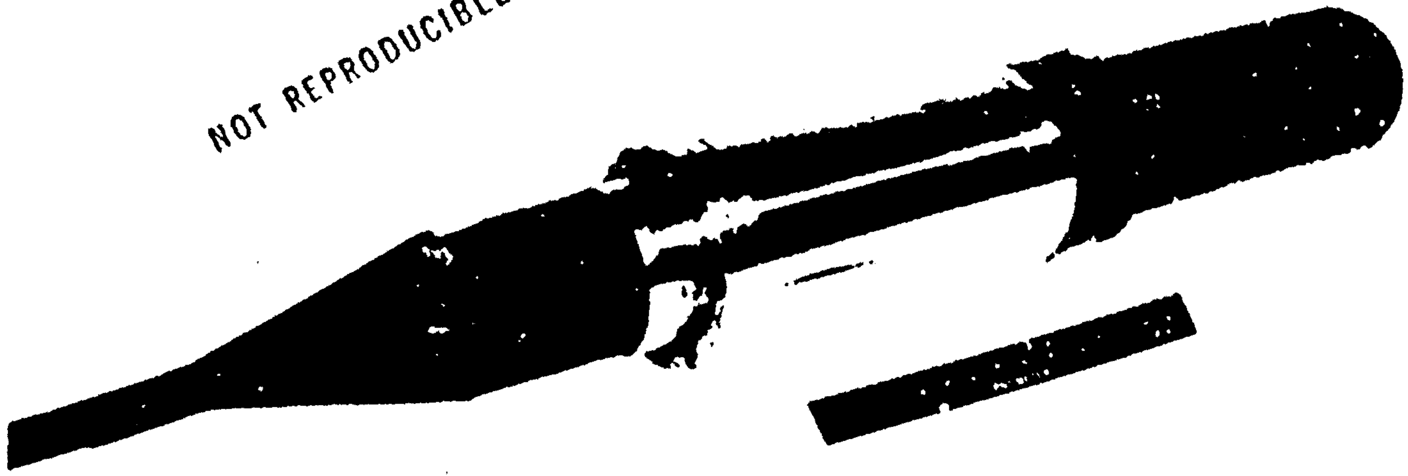


Fig. 15. Type H54 hydrophone without external elastomer cover.

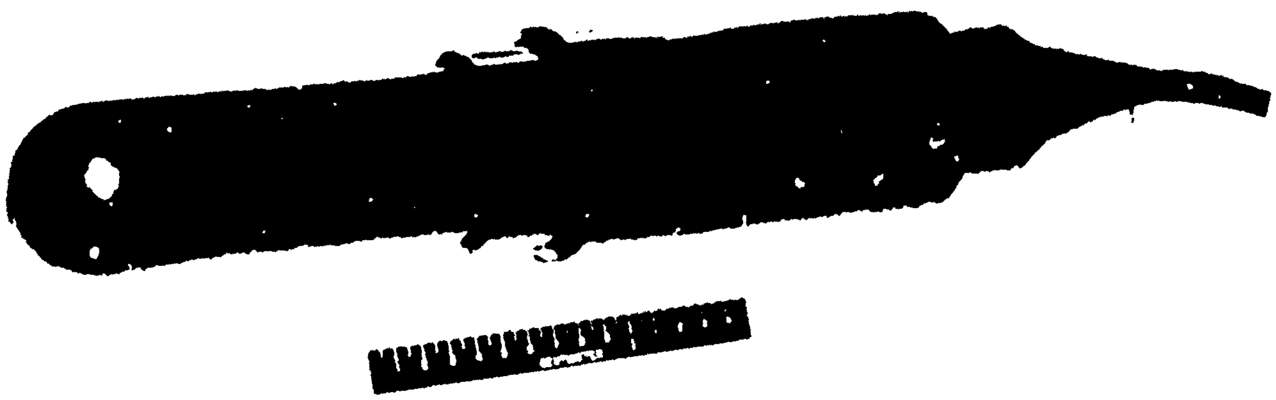


Fig. 16. Type H54 hydrophone completely assembled.

Figure 14 is an exploded view of the H54 hydrophone. The outer elastomer cover for the preamplifier pressure housing, and the molded cable gland are not shown. Figure 15 shows the assembled hydrophone without the elastomer cover. The completely assembled hydrophone is shown in Fig. 16. All metal parts are covered with an elastomer.

Specifications for the USRD type H54 hydrophone are given in Appendix C. A procurement for this specific hydrophone would require that all of the NRL-USRD drawings listed be furnished in the procurement document.

Acoustic performance data for four H54 hydrophones using 1.27×1.27×0.317-cm wall capped PZT-4 ceramic tubes is given in Appendix D. For greatest stability with hydrostatic pressure, a hydrophone of this design should not be used at pressure greater than 20.68 MPa (3000 psi, or 2068 m depth), although this capped tube will withstand more than 58.6 MPa (8500 psi, or 5860 m equivalent depth).

Appendix E provides additional information as to how the permeability of elastomers and plastics is affected by hydrostatic pressure.

Conclusion

The state of the art in hydrophone design is such that a deep-submergence hydrophone can be designed to operate satisfactorily at

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depths as great as 9144 m (30,000 ft) and have a life expectancy of five years. Elastomers are available with low water-vapor permeability to maintain the watertight integrity and provide adequate protection for both ceramic and water-soluble sensor elements. Sensor-element configurations using piezoelectric ceramic or lithium sulfate crystals can be designed to produce very little change in sensitivity with depth or temperature variation.

Acknowledgments

The author thanks R. J. Kieser for preparing the H54 specifications in Appendix B and for his contributions to the mechanical design of the hydrophone. Thanks are due also to Lloyd Hill for his fine workmanship in assembling the developmental models.

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Appendix A

Ingredients and Characteristics of Some Butyl Rubber Compounds

Enjay Compound No. 70821

Ingredient	*phr*
Enjay butyl 217	100
Stearic acid	0.5
Calcined clay	85
Whiting	40
Zinc oxide	6
Polyethylene	6
Paraffin wax	4
EPC black	10
Dibenzo GMF	6
Red lead (Pb_3O_4)	9
Sulfur	0.8
Polyac	0.15

To minimize free-sulfur content, Enjay Compound No. 70821 must be fully cured at 307°F for 1 hour. When cured for 16 minutes at 320°F, however, it has the following characteristics:

Tensile	700 psi
Elongation	500%
Modulus	300%
D-c resistivity	4.3×10^{14} ohm-cm
Power factor	0.37%
Dielectric constant	3.59

Butyl Rubber Compound B-252

Ingredient	*phr*
Butyl 150	100
Pelletex (SRF)	50
Zinc oxide	5
Red lead (Pb_3O_4)	10
Circo light process oil	5
Dibenzo GMF	3
AA-1177-20	6

Cure 1 hour at 307°F. The volume resistivity of this compound may be too low for some applications.

Butyl Rubber Compound NASL-H862A

Ingredient	*phr*
Chlorobutyl HT-1066	100
Sterling V black	50
Litharge	10
Stearic acid	1
AC polyethylene 617A	3
DPG	2
Maglite M	1
Zinc oxide	5
NA-22	1.5

Cure 1 hour at 310°F. Characteristics are as follows:

Tensile	1625 psi
Elongation	375%
Modulus at 300%	1500 psi
Hardness (Shore "A")	55-60

Appendix B

Practical Equations for Calculating Sensitivity of Various Piezoelectric Ceramic Sensor Configurations

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Capped Tube

The free-field voltage sensitivity for the capped piezoelectric ceramic tube can be computed from the equation

$$\frac{V}{p_0} = b\left(g_{33}\frac{1-\rho}{1+\rho} + g_{31}\frac{2+\rho}{1+\rho}\right), \qquad (1)$$

adapted from Eq. 12, reference [12], where V is the open-circuit output voltage developed by the element; a and b in meters are the inner and the outer radii, respectively, of the ceramic tube; g_{33} and g_{31} are the electromechanical voltage constants of the ceramic material; $\rho = a/b$ is the ratio of the inner to the outer radius; and p_0 is the external pressure in newtons per square meter (pascals).

Nominal values for the electromechanical voltage constants of PZT-4 are $g_{33} = 24.9\times10^{-3}$ V·m/N and $g_{31} = -10.6\times10^{-3}$ V·m/N. Let the dimensions of the element be: outer radius $b = 9.52\times10^{-3}$ m (0.375 in.), and inner radius $a = 7.95\times10^{-3}$ m (0.313 in.). So, $\rho = 0.835$.

Then, substituting $p_0 = 1$ dyne/cm² (1 μbar, or 10^{-1} Pa) in Eq. (1) yields

$$V = 13.2\times10^{-6} \text{ V/μbar}.$$

If $p_0 = 1$ μPa (10^{-6} N/m²), then

$$V = 13.2\times10^{-11} \text{ V/μPa},$$

which is the free-field voltage sensitivity M_0 of the element when the dimensions are small in comparison with the wavelength. Expressed in decibels,

$$M_0 = 20 \log 13.2\times10^{-6} = -97.6 \text{ dB re 1 V/μbar, or}$$

$$M_0 = 20 \log 13.2\times10^{-11} = -197.6 \text{ dB re 1 V/μPa}.$$

Disk or Plate

For the sensitivity of a disk or plate, when the sound pressure is impinging on the major surfaces and the size of the element is small in comparison with a wavelength,

$$V/p_0 = g_{33}t, \qquad (2)$$

where g_{33} is the electromechanical voltage constant of the piezoelectric material, t is the thickness in meters, and p_0 is the pressure in newtons per square meter (pascals).

A nominal value for the electromechanical voltage constant for lithium sulfate as a thickness expander is $g_{33} = 175\times10^{-3}$ V·m/N. When the plate is used as a volume expander, the value $g_{33} = 148\times10^{-3}$ V·m/N should be used.

Let the thickness $t = 1.524\times10^{-3}$ m (0.060 in.). Then, substituting $p_0 = 1$ dyne/cm^2 (10^{-1} Pa) in Eq. (2) yields

$$V = 26.67\times10^{-6} \text{ V/}\mu\text{bar} = 26.67\times10^{-11} \text{ V/}\mu\text{Pa},$$

which is the free-field voltage sensitivity M_0 of the element. Expressed in decibels,

$$M_0 = 20 \log 26.67\times10^{-6} = -91.48 \text{ dB re 1 V/}\mu\text{bar, or}$$

$$M_0 = 20 \log 26.67\times10^{-11} = -191.48 \text{ dB re 1 V/}\mu\text{Pa}.$$

Hollow Sphere

The free-field voltage sensitivity of a piezoelectric ceramic hollow sphere can be computed from the relation

$$\frac{V}{p_0} = \frac{b}{(\rho^2 + \rho - 1)}\left[g_{33}\frac{(\rho^2 + \rho - 2)}{2} - g_{31}\frac{(\rho^2 + \rho - 4)}{2}\right], \qquad (3)$$

where $\rho = a/b$ and a and b in meters are the inner and the outer radii, respectively, of the sphere.

For a thin-walled sphere where $a \to b$, a close approximation to the free-field voltage sensitivity is given by

$$V/p_0 = -bg_{31}. \qquad (4)$$

Let the dimensions be: $a = 2.22\times10^{-2}$ m (0.875 in.) and $b = 2.54\times10^{-2}$ m (1.0 in.); $a/b = 0.875$. For PZT-5, $g_{33} = 24.8\times10^{-3}$ V·m/N and $g_{31} = -11.4\times10^{-3}$ V·m/N. Substituting the appropriate values in Eq. (3) yields

$$V/p_0 = 26.647\times10^{-5} \text{ V/Pa}.$$

If the reference pressure is 1 μPa = 10^{-6} Pa, then

$$M_0 = 20 \log 26.647\times10^{-11} = -191.5 \text{ dB re 1 V/}\mu\text{Pa}.$$

The value obtained by using the approximation, Eq. (4), is $V/p_0 = (-2.54\times10^{-2})(-11.4\times10^{-3}) = 28.95\times10^{-5}$ V/Pa, or

$$M_0 = 20 \log 28.95\times10^{-11} = -190.8 \text{ dB re 1 V/}\mu\text{Pa},$$

which is in close agreement with the value -191.5 dB obtained by using Eq. (3).

Appendix C

USRD Specification for

HYDROPHONE, PIEZOELECTRIC, BROADBAND (20 Hz to 60 kHz)

DEEP-SUBMERGENCE

NRL-USRD TYPE H54

1. SCOPE

1.1 This specification covers the requirements, design, and construction of an electroacoustic, piezoelectric, high-pressure (68.9 MPa or 10,000 psi) transducer designated type H54; preamplifier; and cable.

1.2 Classification - The transducer is in Group 3 as defined in American Standard Procedures for Calibration of Electroacoustic Transducers, Particularly Those for Use in Water, Z24.24-1957.

2. APPLICABLE SPECIFICATIONS AND OTHER PUBLICATIONS

2.1 The following specifications, drawings, and publications of the issue in effect on date of invitation for bids form a part of this specification to the extent specified herein:

SPECIFICATIONS

MILITARY

MIL-C-915(SHIPS)	- Cable, Cord, and Wire; Electrical (Shipboard Use)
MIL-C-3432A	- Cable, Flexible and Extra Flexible 300 and 600 Volts
MIL-C-5015	- Connectors, Electrical, "AN" Type
MIL-Q-9858	- Quality Control System Requirements
MIL-E-16400	- Electronic Equipment, Naval Ship and Shore; General Specification
MIL-E-17555E	- Electronic and Electrical Equipment and Associated Repair Parts, Preparation for Delivery of
MIL-C-20159B	- Copper-Nickel Alloy (70-30 and 90-10); Castings

STANDARDS

FEDERAL

601, Test Method Standards; Adhesion of Rubber to Metal, Method 8031

MILITARY

MIL-STD-129 - Military Standard Markings for Shipment and Storage

MIL-STD-202B - Test Methods for Electronic and Electrical Component Parts, Methods 301, 302, 303

MIL-STD-417(ORD) - Rubber Compositions, Vulcanized, General Purpose, Solid (Symbols and Tests)

MIL-STD-177 - Rubber Products, Terms for Visible Defects of

DRAWINGS

NAVAL RESEARCH LABORATORY, UNDERWATER SOUND REFERENCE DIVISION

DM 2430 - Assembly
BM 2431 - Cable Gland Assembly
BM 2432 - Cable Header
AM 2433 - Terminal Block
BM 2434 - Housing
BM 2435 - Adaptor
AM 2436 - Oil Seal Plug
AM 2451 - Crystal Motor Spacing Assembly
AM 2437 - Crystal Motor Assembly
AM 2438 - End Cap
AM 2439 - Piezoelectric Element
AM 2440 - Rubber Mount
AM 2441 - Crystal Support Frame Assembly
AM 2442 - Expanded Metal Tube
AM 2443 - Crystal Support Frame Ring
AM 2444 - Crystal Support Frame Plate
BM 2445 - Outer Boot
AM 2446 - Outer Boot Ring
BM 2447 - Inner Boot
AM 2448 - Inner Boot Ring
BM 2449 - Outer Jacket
AM 2450 - Modified Hermetic Seal
AM 2155 - Butyl Rubber Specification
AM 2057 - Electro-mechanical Specification of Ceramic Element
AM 2186 - Test for Rubber

3. REQUIREMENTS

3.1 Preproduction model - A preproduction model shall be furnished for the preproduction inspection of 4.2. The model shall be suitable for complete evaluation of mechanical and electrical form, design, and performance. It shall be of final mechanical and electrical form, employ approved parts, and be completely representative of final equipment. Subsequent units shall conform to the acoustical performance of the approved, preproduction model within plus or minus 1 decibel (dB).

3.2 General requirements - The hydrophone shall conform to the drawings referenced in section 2 and the requirements specified hereinafter.

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3.2.1 Material - Unless otherwise specified herein, material shall be in accordance with MIL-E-16400.

3.2.2 Piezoelectric crystal element - Depending on requirements, several options are available as to the type of piezoelectric element to be used. Drawings are shown for one option, which shall consist of three lead zirconate-titanate elements as shown on AM 2437. The procuring activity will specify the sensor element configuration to be used.

3.2.3 Preamplifier housing - The preamplifier housing shall be corrosion-resistant metal free of defects and capable of withstanding 68.9 MPa (10,000 psig) hydrostatic water pressure without mechanical failure and without leaking. The housing shall be machined as shown on BM 2434.

3.2.4 Sensor element support - The sensor elements shall be supported by three sulfur-free natural rubber mounts.

3.2.5 Acoustic window - The acoustic window shall be butyl rubber containing no free sulfur or any other substance that will contaminate the electrodes on the sensor elements. It shall be firmly bonded to AM 2446 and AM 2448 to form a watertight seal. The adhesion of the rubber to metal shall be greater than 30 lbs per inch of width (peel strength per Federal 601 Test Method Standards, Method 8031). The rubber shall be completely free of air, imperfections, blemishes, and visible defects as defined in MIL-STD-177.

3.2.6 Oil - The rubber boots shall be completely filled with filtered Baker's DB grade castor oil, or approved equal, in accordance with Oil Filling Instructions No. 102-70. All air, gas, and water vapor shall be removed from the transducer and the oil.

3.2.7 Preamplifier - A transistor preamplifier with the following characteristics shall be provided unless otherwise specified by the procuring activity.

VOLTAGE GAIN	20.0 ± 0.2 dB at midband
GAIN STABILITY	±0.1 dB long term
FREQUENCY RESPONSE	-3 dB maximum at 20 Hz and 100 kHz
INPUT IMPEDANCE	1000 meg shunted by 15 pF maximum
MAXIMUM INPUT	±75 volts peak without damage

MAXIMUM NOISE (dB re 1 volt rms) — Measured at 25°C, referred to input

	BROADBAND	SPECTRAL DENSITY	
	200-kHz BW	1-Hz BW @ 100 Hz	1-Hz BW @ 10 kHz
Shorted Input	-112 dB	-150 dB	-164 dB
1000 pF Input	-112 dB	-147 dB	-164 dB
100 pF Input	-102 dB	-136 dB	-161 dB

DYNAMIC OUTPUT IMPEDANCE	50 ohms
TEMPERATURE RANGE	-25°C to +55°C operating; -55°C to +85°C storage
CONSTRUCTION	Hermetically sealed, encapsulated, electrostatically shielded
POWER SUPPLY RANGE (volts)	+12 to +25
Supply Current (mA)	4 to 8
Max Output (volts pk-pk)	6 to 11
Short Ckt Output (mA-pk)	0.75 to 1.5
Output DC Level (volts)	4 to 8
OUTPUT CAPACITOR	Director coupled
CAN SIZE	2.86 cm (1-1/8") dia, 3.97 cm (1-9/16") long
MAXIMUM DISTORTION AT MIDBAND (1 V rms into 1K ohm load)	0.5% to 0.25%

3.2.8 Cable and gland - The hydrophone shall be furnished with 23 meters of 5-conductor shielded cable with an impervious polychloreprene outside sheath. The cable shall conform to MIL-C-3432A and shall be prepared as shown on BM 2431. The cable gland at the hydrophone shall be molded, vulcanized, and securely bonded to the metal end cap as shown on BM 2432. The adhesion of the rubber to the metal and to the cable sheath shall be greater than 30 lbs per inch of width.

3.3 Interchangeability - All machined parts, preamplifiers, crystal assemblies, and cable assemblies shall be interchangeable with the same component in all hydrophones supplied under this contract.

3.4 Temperature - The hydrophones shall not be damaged by storage at temperatures from minus 20° to plus 45°C (ambient) and shall be capable of normal operation at temperatures minus 1° to plus 38°C.

3.5 Performance

3.5.1 Resistance, capacitance, and dissipation factor - The direct current (d-c) resistance, capacitance, and dissipation factor shall meet the requirements of Table 1.

3.5.2 Resistance between leads of the assembled cable and connector - The direct current (d-c) resistance values when measured between any pair of leads or from any lead and shield, after the cable has been completely assembled shall be greater than 1×10^9 ohms.

3.5.3 Watertight integrity - Each hydrophone shall be capable of withstanding a continuous hydrostatic pressure of 68.9 MPa (10,000 pounds per square inch) without physical or electrical damage.

3.6 Identification and serial markings - The hydrophone housing shall be engraved as shown on BM 2434. Outer jacket BM 2449 shall have H54 and the serial number molded on the outside by placing a 0.127 mm embossed strip of stainless steel in the mold as the part is molded.

Serial and identification numbers will be furnished by the contracting agency upon request by the contractor.

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Table 1

CRYSTAL ELEMENT ASSEMBLY

All measurements made at 24 to 26°C (76 to 78°F) with relative humidity 40 to 50%. Capacitance and dissipation factor measurements made at 1000 Hz.

Measurement Conditions	Resistance* (ohms) (greater than)	Capacitance* (pF)	Dissipation* Factor (%) (less than)	Measured between
12 hrs after assembly of 8 crystals with foils and lead wires	5×10^{10}	400 pF ± 10 pF	0.5	high and low leads
After mounting crystal element and attaching leads to glass-to-metal seals	5×10^{10}	400 pF ± 10 pF	0.5	high and low leads
24 hrs after oil filling boot	5×10^{10}	400 pF ± 10 pF	0.5	high and low leads
	5×10^{10}	42 pF ± 3 pF	0.5	high lead and case
	5×10^{10}	42 pF ± 3 pF	0.5	low lead and case

*The actual value to be used depends upon the sensor configuration chosen.

3.7 Workmanship - The workmanship and finish of each hydrophone shall be in accordance with the highest quality practice in manufacturing for precision, scientific equipment and shall conform to the requirements of MIL-E-16400.

4. QUALITY ASSURANCE PROVISIONS

4.1 Responsibility for inspection - Unless otherwise specified in the contract or purchase order, the supplier is responsible for the performance of all inspection requirements as specified herein. Except as otherwise specified, the supplier may utilize his own facilities or any commercial laboratory acceptable to the Government. The Government reserves the right to perform any of the inspections set forth in the specifications where such inspections are deemed necessary to assure supplies and services conform to prescribed requirements.

4.1.1 Contractor's quality assurance system - The contractor shall provide and maintain an effective inspection and quality assurance system acceptable to the Government covering the supplies under the contract. A current written description of the system shall be submitted to the cognizant Government inspector for system approval prior to preproduction inspection. Any changes to the approved quality assurance system that might affect the degree of assurance required by this specification or other applicable documents shall be submitted to the cognizant inspector and approved in writing prior to use. The quality control system shall meet the requirements of MIL-Q-9858.

4.1.2 Government verification - All quality assurance operations performed by the contractor will be subject to Government verification at any time. Verification will consist of (a) surveillance of the operations to determine that practices, methods, and procedures of the written system description are being properly applied, and (b) Government product inspection to measure quality of product to be offered for delivery. Failure of the contractor to promptly correct deficiencies discovered by him or of which he is notified shall be cause for suspension of acceptance until corrective action has been made or until conformance of product to prescribed criteria has been demonstrated.

4.2 Preproduction inspection - The contractor shall submit one or more hydrophones as necessary for inspection to determine that the preproduction model will meet the requirements of this specification. These tests will be made at the NRL Underwater Sound Reference Division, P. O. Box 8337, Orlando, Florida. The contractor will be notified of the results of these tests within 30 days after the equipment is received for testing.

4.2.1 Modifications - The preproduction model or models tested shall be subject to return to the contractor's plant for such modifications and corrections as may be required due to failure to meet the requirements of this specification. All costs thereby incurred shall be borne by the contractor.

4.3 [illegible]ts and inspection by manufacturer - Each hydrophone shall pass the [illegible] and inspections before delivery to the designated agency.

4.3.1 Each hydrophone shall be inspected and measured with calipers, micrometer, and other necessary gages at the contractor's plant to determine conformance with dimensional, material, and finish requirements of this specification.

4.3.2 The resistance, capacitance, and dissipation factor measurements specified in 3.5.1 and Table 1 shall be made on each hydrophone and recorded on Test Data Sheet No. 102-70.

4.3.3 Test for leaks - Each hydrophone acoustic boot shall be tested for leaks prior to oil filling. The boots shall be individually installed on part BM 2435 and inflated with air to a pressure of 34.47 kPa (5 psi) and then submerged in water while so inflated. If there is any evidence of leakage of the rubber boot, O-ring, glass-to-metal seals, or any other place, the cause shall be determined and repairs made. A mass spectrometer-type helium leak detector shall be used when operational life of 3 years or more is required.

4.3.4 Water and oil leakage - Each completed hydrophone and cable assembly shall be tested for watertight integrity at a pressure of 68.9 MPa (10,000 psig). The test shall consist of subjecting the hydrophone and attached cable to 4 cycles of pressure at 68.9 MPa (10,000 psig). The first cycle shall be of 15 minutes duration. Cycles 2, 3, and 4 shall each be of 30 seconds duration. Any hydrophone or cable assembly indicating water or oil leakage shall be repaired and shall pass this test before delivery.

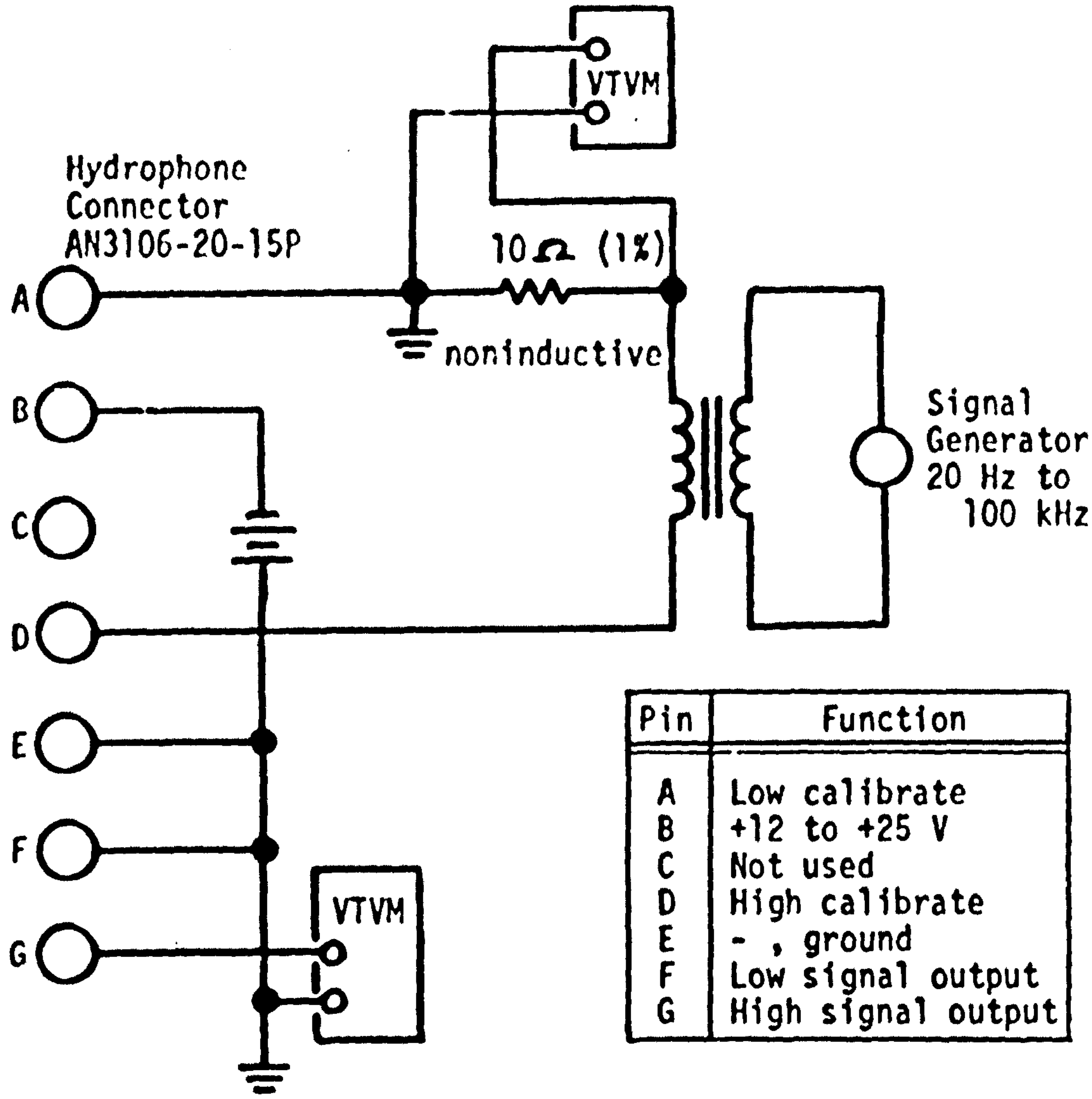
4.3.5 Coupling measurements - Coupling measurements shall be made according to Instruction 103-70 and Fig. 1. The measured values shall be within plus 2.0 or minus 0.5 decibel (dB) of the values recorded in Table 2.

4.3.6 Test Data Sheets - The completed Test Data Sheet No. 102-70 shall be furnished with each hydrophone at time of delivery.

4.4 Inspection at the NRL Underwater Sound Reference Division

4.4.1 Final inspection of the hydrophones supplied under this specification will be made at NRL Underwater Sound Reference Division, Orlando, Florida or as directed by the procuring activity. Each hydrophone will be calibrated as received from the manufacturer over the frequency range 20 Hz to 100 kHz. Other tests will be made as deemed necessary to determine that the hydrophones meet the requirements of this specification.

4.5 Failure to meet specifications - Any hydrophone failing to meet the requirements of this specification will be rejected and will be returned to the contractor for repair or replacement at no expense to the government. The manufacturer when resubmitting a rejected hydrophone, shall furnish in writing a description of changes made to correct the cause of failure.



Pin	Function
A	Low calibrate
B	+12 to +25 V
C	Not used
D	High calibrate
E	- , ground
F	Low signal output
G	High signal output

Figure 1

Table 2

	100 Hz	1 kHz	10 kHz	25 kHz	50 kHz	75 kHz	..00 kHz
Gain in dB at end of 23-m cable	19.2	19.2	19.2	19.0	18.7	17.0	15.0

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5. PACKAGING AND PREPARATION FOR SHIPMENT

5.1 Packaging instructions - Unless otherwise specified, the transducer shall be preserved, packaged, and packed in accordance with the requirements of Electronic and Electrical Equipment and Associated Repair Parts, Preparation for Delivery, MIL-E-17555E, for domestic shipment. Suitable interior packing shall be used to prevent shifting in the exterior shipping containers, and to absorb the shock of impact encountered in handling and transit.

5.2 Markings - In addition to any special markings required by the contract or order, marking of interior packages and shipping container shall be in accordance with the requirements of the Military Standard Marking for Shipment and Storage, MIL-STD-129.

6. NOTES

6.1 The USRD Type H54 hydrophone is designed for a deep submergence, long life hydrophone with a frequency range of 20 hertz to 60 kHz. It can operate at pressures up to 68.9 MPa (10,000 psig) and the metal housing is completely rubber covered. The piezoelectric elements are supported on rubber mounts in a cylindrical expanded metal frame. To ensure long life, double O-rings have been used throughout and two oil-filled butyl boots are used over the piezoelectric elements.

6.2 Failure to perform - The failure of any production hydrophone to perform in the same manner as the approved prototype shall be regarded as failure to meet the requirements of this specification.

6.3 Where trade names or specific products are used in this specification, instructions or drawings, they are meant to be descriptive and not restrictive.

6.4 Specifications and other publications - where obtainable

6.4.1 Copies of the Specification, standards, drawings, and other publications required by the contractor in connection with this contract should be obtained as directed by the contracting officer. "American Standard Procedures for Calibration of Electroacoustic Transducers, Particularly Those for Use in Water, Z24.24-1957," may be purchased from the American National Standards Institute, Inc., 1430 Broadway, New York, N. Y. 10018. These publications may be examined at NRL Underwater Sound Reference Division, Orlando, Florida, but are not available for loan.

6.4.2 Copies of this specification - Copies of this specification may be obtained upon application to the Naval Research Laboratory, Underwater Sound Reference Division, P. O. Box 8337, Orlando, Florida 32806.

6.5 <u>Ordering data</u> - Procurement documents should specify the following:

a. Title, number, and date of this specification.

b. Level of preservation and packaging, packing and marking required (see 5.1 and 5.2).

c. One prototype (preproduction) model type H54 shall be submitted for evaluation. It is desired within 150 days after award of contract.

d. The contractor shall submit a progress report to the contracting agency every thirty days. The report shall include but shall not be limited to the following:

1. Percentage of materials ordered.

2. Percentage of required materials received.

3. Percentage of machined parts completed.

4. Number of hydrophones assembled and tested.

5. Number of hydrophones shipped.

6. Cause and duration of any anticipated delays in completion of contract.

e. One H54 hydrophone may be examined by the contractor upon request. The hydrophone remains the property of the Government and shall be returned to the USRD in good condition within 45 days after receipt.

f. Tools, materials, and jigs necessary for the manufacture of these hydrophones shall be furnished by the contractor. All rubber molds fabricated for use in the construction shall be the property of the Government and will be delivered to the activity designated at the completion of the contract.

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Instruction No. 101-70

OIL FILLING

NRL-USRD TYPE H54 HYDROPHONE

A. TYPE OIL: Baker's "DB" grade castor oil or approved equal.

B. DRYING AND FILTERING

1. Circulate the oil through a filter that will provide filtering at least equivalent to that afforded by an automotive type oil filter.

2. Heat the oil to 77°C (170°F) while under vacuum (100 micron, 0.1 mm Hg). Agitate or circulate the oil so that it is exposed to the vacuum in thin layers.

3. Maintain the vacuum and heat for at least six hours.

4. Allow the oil to cool to 29°C (85°F).

5. Do not expose the oil to room atmosphere after it has been degassed.

C. OIL FILLING THE CRYSTAL HEAD ASSEMBLY

1. Slip the assembled crystal element and inside rubber boot assembly into an oil filling jig with an inside diameter slightly larger than the rubber boot.

2. Attach the jig through a thick-wall rubber hose to a vacuum (50 micron, 0.05 mm Hg).

3. Screw a filler pipe into the oil filler hole in the crystal head assembly and then attach to the oil filling vacuum system. This hose connection should be short and have as large an inside diameter as possible.

4. Maintain at least a 50-micron (0.05 mm Hg) vacuum for two hours on the crystal boot assembly prior to oil filling.

5. Without breaking the vacuum on the boot assembly, allow the degassed filtered oil to enter the rubber boot by releasing the vacuum to the oil container. (NOTE: If the vacuum is opened directly to the room atmosphere, only dry filtered air or dry nitrogen should be allowed to contact the castor oil. It is preferred that the oil filling setup include a rubber bladder in the oil container so when the vacuum is released the air does not come in direct contact with the oil, but is separated by the rubber bladder. The bladder is inflated by the atmospheric pressure, thus forcing the oil into the rubber boot.)

6. Close the stopcock to the oil container after the rubber boot is filled with oil. Again place a vacuum on the crystal head assembly until gas bubbles cease to come from within the rubber boot. Also place the oil storage supply under vacuum.

7. Repeat steps 5 and 6 three times. (If, after four times, there is still considerable evidence of gas coming from within the rubber boot, the crystal head assembly should be examined closely for leaks. Should a leak be found, repairs should be effected before proceeding further.)

8. Maintain the vacuum on the oil filling jig. Release the vacuum on the oil filler pipe and remove the pipe. Screw the plug, AM 2436, with O-ring into the oil filler hole after it has been thoroughly wet with castor oil. Be careful not to trap any air under the plug.

9. Release the vacuum on the oil filling jig and remove the crystal element - rubber boot assembly.

10. Install the outer boot and repeat steps 1 through 9 to fill the cavity between the inside and outside boot.

11. Clean away all excess oil.

12. Twenty-four hours after oil filling, measure and record d-c resistance, capacitance, and dissipation factor.

Test Data Sheet No. 102-70

H54 HYDROPHONE

Serial _____

(All measurements made at 24 to 26°C (76 to 78°F) with relative humidity 40 to 50%.)

Measurement Conditions	Resistance (ohms)	Capacitance at 1.0 kHz (pF)	Dissipation Factor (%)	Measured between
12 hrs after completing crystal assembly				high and low leads
After mounting crystal element and attaching leads				high and low leads
24 hrs after oil filling boot				high and low leads
				high lead and case
				low lead and case

Measured by ______________________

Date: ______________________

COUPLING MEASUREMENTS

	100 Hz	1 kHz	10 kHz	25 kHz	50 kHz	75 kHz	100 kHz
Gain in dB at end of 23-m cable							

Measured by ______________________

Date: ______________________

Instruction No. 103-70

COUPLING MEASUREMENTS

USRD TYPE H54 HYDROPHONE

1. Apply 12 to 25 volts as required to the hydrophone, as shown in Fig. 1.

2. Apply a calibration voltage across the calibration circuit with a 10-ohm ±1 percent resistor connected in series with the calibration circuit of the preamplifier.

3. The applied calibration voltage shall not be greater than 0.1 volt across the external 10-ohm resistor.

4. Measure the input and output voltages at 100 Hz, 0.1, 10, 25, 50, 75, and 100 kHz.

5. Express the ratio of the input to output voltage in decibels and record on Data Sheet 102-70 for each hydrophone.

CABLE GLAND MOLDING

USRD TYPE H54 HYDROPHONE

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1. Degrease end cap BM 2432.

2. Prepare the cable as shown on BM 2431.

3. Buff the outside neoprene sheath down to new rubber completely around the cable for 13 cm (5-1/8 inches) from the end of cable to be molded. (Do not touch the buffed section with the bare hands or otherwise contaminate.)

4. Slip the buffed end of the cable through the end cap BM 2432 until the end of the cable jacket is flush with the bottom of part BM 2432. Swage the copper tube with 7 grooves 0.762 mm deep, spaced 6.35 mm apart.

5. Check the continuity of each wire, the resistance from each lead to every other lead and the resistance of each lead to the metal end cap. The resistance between each lead and the resistance between each lead and case shall exceed 1000 megohms unless otherwise specified.

6. Apply a brush coat of Chemlok No. 203 to the metal end cap BM 2432 on the area to be molded. Air dry for 30 minutes and then apply a brush coat of Chemlok No. 220 over both the metal and the buffed area on the cable. Air dry for two hours.

7. Wrap the coated area with "H" type neoprene tape 0.762 mm thick by 1.90 mm wide (Bi-Prene type H tape, Bishop Manufacturing Co., Cedar Grove, New Jersey) until the shape approximates that of the mold. Cut two strips of tape 10.2 cm long for the top and two strips 10.2 cm long for the bottom of the mold and place in position before closing the mold.

8. Place the mold and cable in a press with heater platens and apply approximately 0.689 MPa (100 psig). Apply heat to the mold. Increase the pressure to 34.47 MPa (5000 psig) when the temperature reaches 90-100°C. Cure in press at 150°C for 30 minutes.

9. Cool the mold and remove from press. Remove the cable from the mold. Trim the flashing.

10. Check the resistance and continuity as in step 5.

11. Connect the cable leads to the hermetic seals in part AM 2433. Assemble part AM 2433 to part BM 2432. Use a syringe to fill the cavity with Eccobond #51 potting compound. Install the 1.57-mm pipe plug and cure.

12. Clean the connector thoroughly, removing any excess potting compound.

13. Make the resistance measurements outlined in step 5 and if the resistance does not meet the values specified, the cause shall be determined and corrected.

Naval Research Laboratory
UNDERWATER SOUND REFERENCE DIVISION
P. O. Box 8337, Orlando, Florida 32806

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K03-30
15 July 1968

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CALIBRATION REPORT

Subj: H54 hydrophones serials 1 through 4; calibration of

Encl: (1) Drawings USRD 54401, 54410 through 54416, and 45001

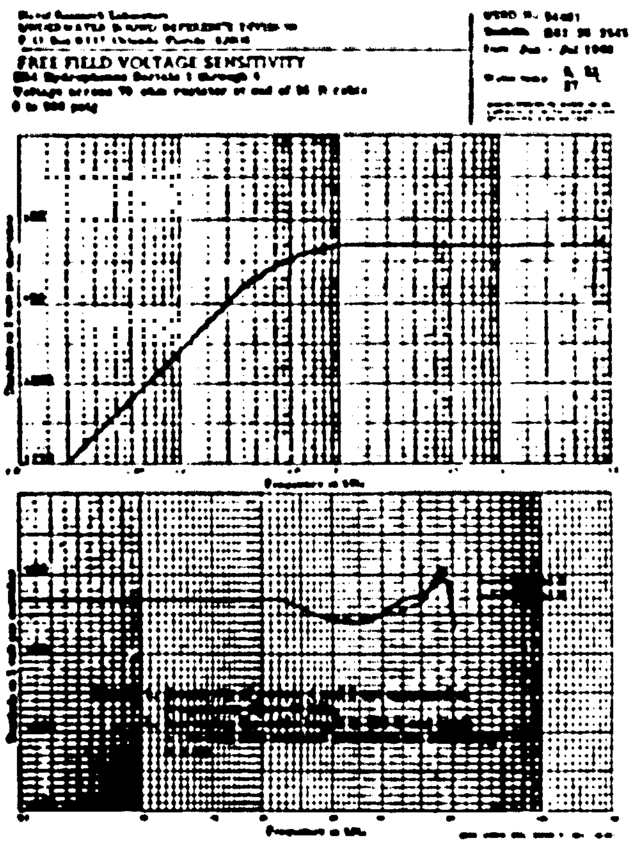
1. The subject hydrophones were designed and built at the USRD for use by the Naval Research Laboratory, Ocean Acoustics Branch. The electro-acoustic element consists of three magnesium-capped PZT-4 ceramic cylinders connected electrically in series; it is coupled to a USRD-designed transistorized preamplifier. The element is enclosed in a double boot of butyl rubber.

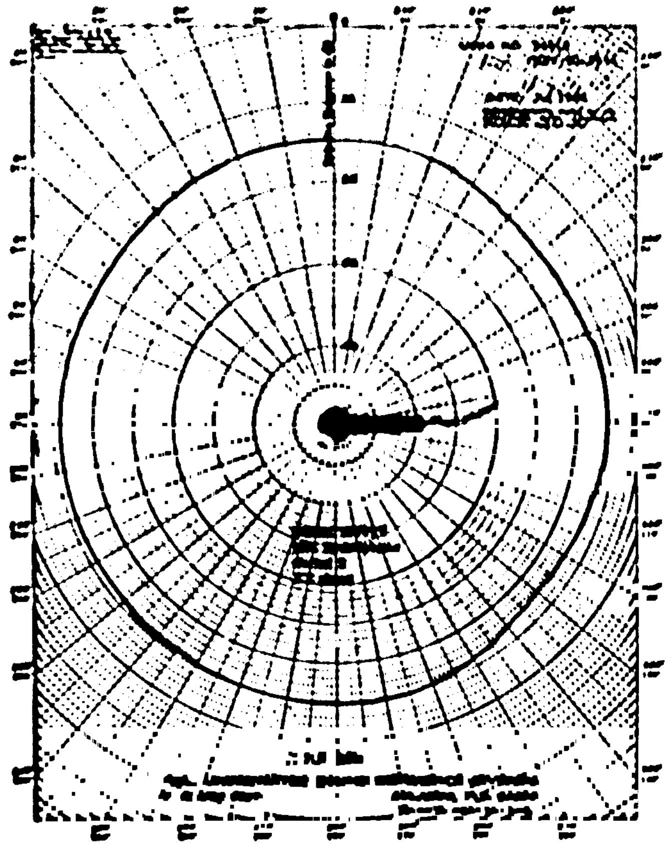
2. Free-field voltage sensitivity in the range 2 to 1000 Hz was measured in the low-frequency facility at the temperatures 5 and 22°C and at hydrostatic pressures to 500 psig. Sensitivity of the four hydrophones in the frequency range 100 Hz to 20 kHz and directivity of hydrophone serial 2 in the horizontal (XY) and vertical (XZ) planes were measured in open water at the temperature 27°C and the depth 400 cm. Sensitivities of hydrophones serials 2 and 4 in the range 2 to 60 kHz were measured in the anechoic-tank facility at the temperature 5°C and at hydrostatic pressures to 500 psig. The results are shown on the drawings, enclosure (1). Sensitivity of hydrophone serial 1 in the range 20 to 4000 Hz was measured in the low-frequency facility at the temperature 22°C and the hydrostatic pressures 0 and 2500 psig. The pressure reduced the sensitivity by less than 1 dB.

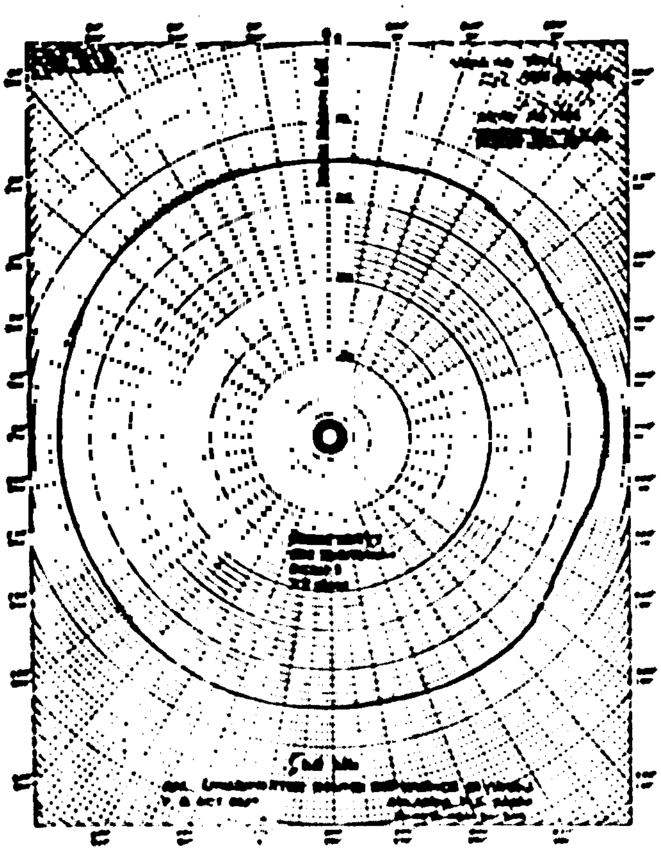
3. Hydrophone serial 2 was omnidirectional within ±0.7 dB in the horizontal (XY) plane at frequencies to 50 kHz. Directional characteristics in the vertical (XZ) plane at the frequencies 3, 5, 10, 20, 30, 40, and 50 kHz are shown on drawings USRD 54410 through 54416.

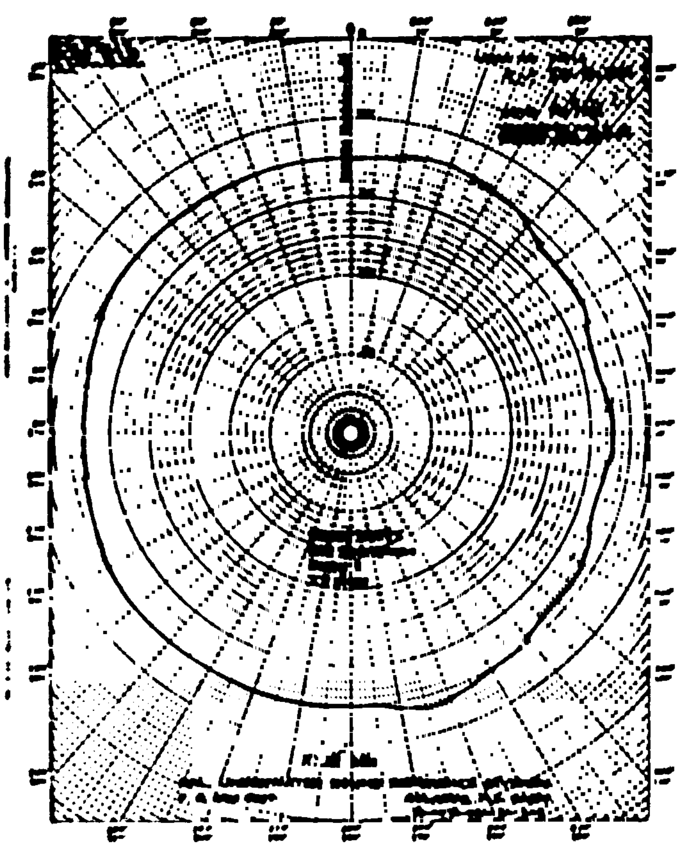
4. Orientation was according to the method described for a cylinder on drawing USRD 45001. A point 11 cm from the top of the rubber boot, in the direction of the type number on the metal case, served as the zero-degree reference. The cable extended in the direction of the +Z axis.

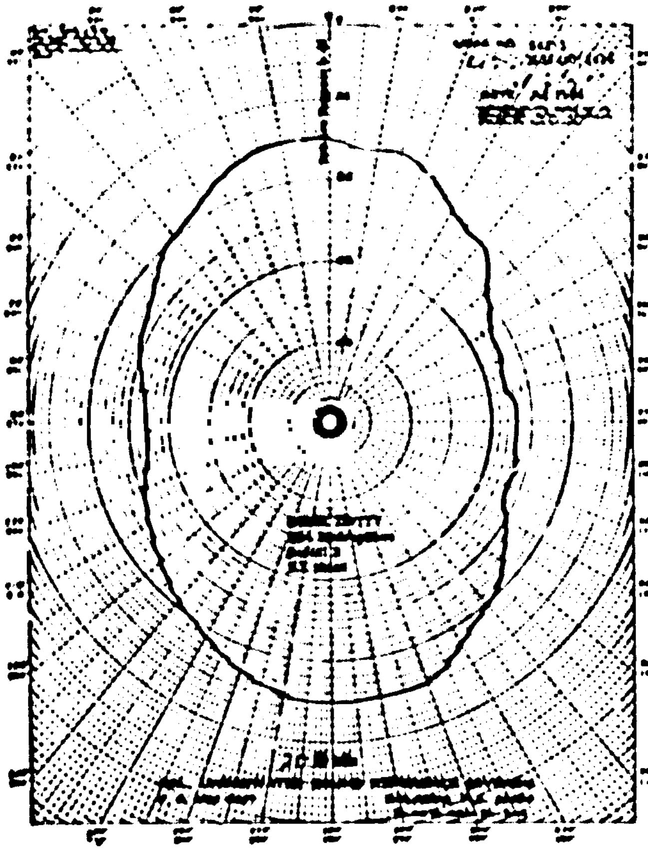
5. All measurements reported here that are described in "American Standard Procedures for Calibration of Electroacoustic Transducers, Particularly Those for Use in Water, Z24.24-1957" were made in accordance therewith.

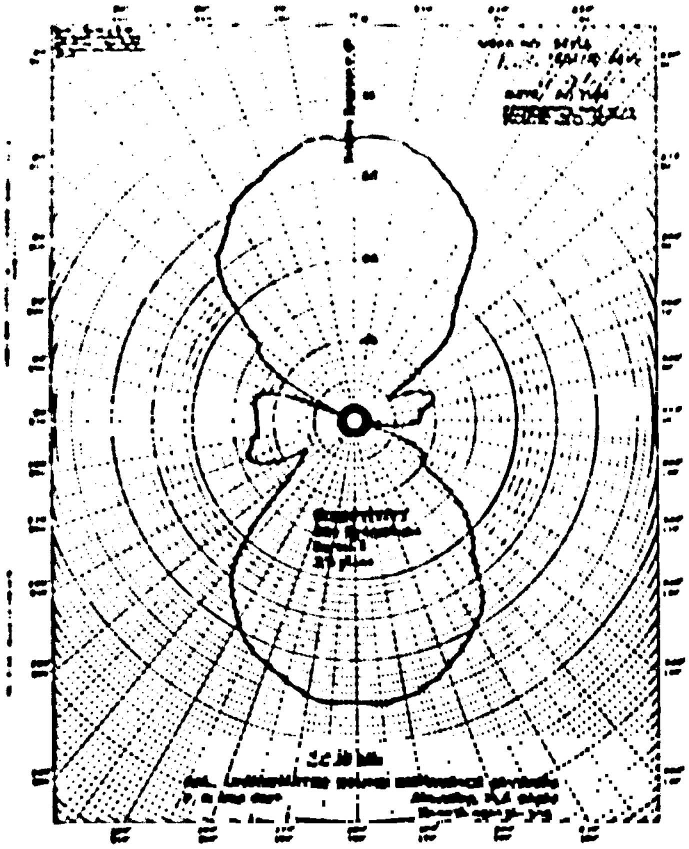

FREE FIELD VOLTAGE SENSITIVITY

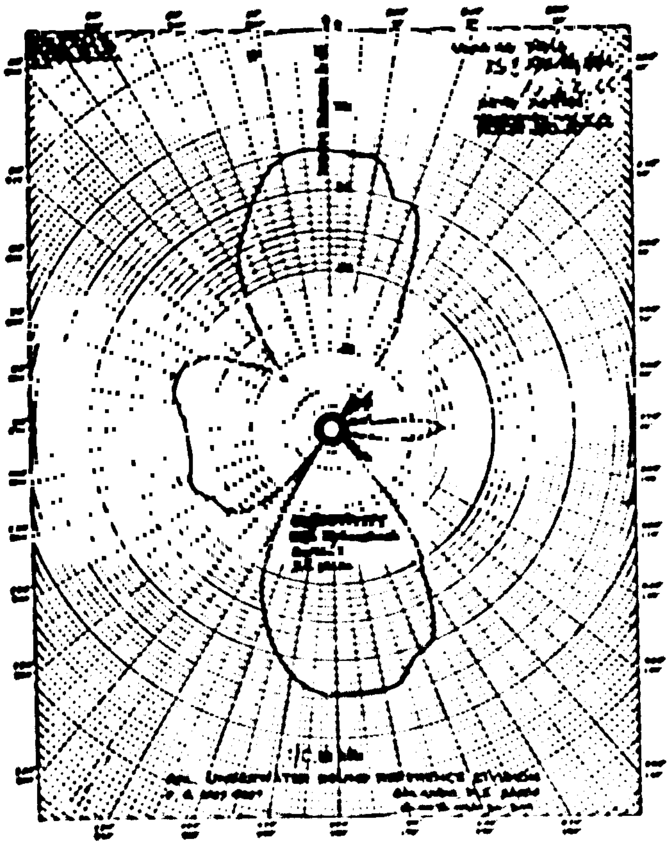


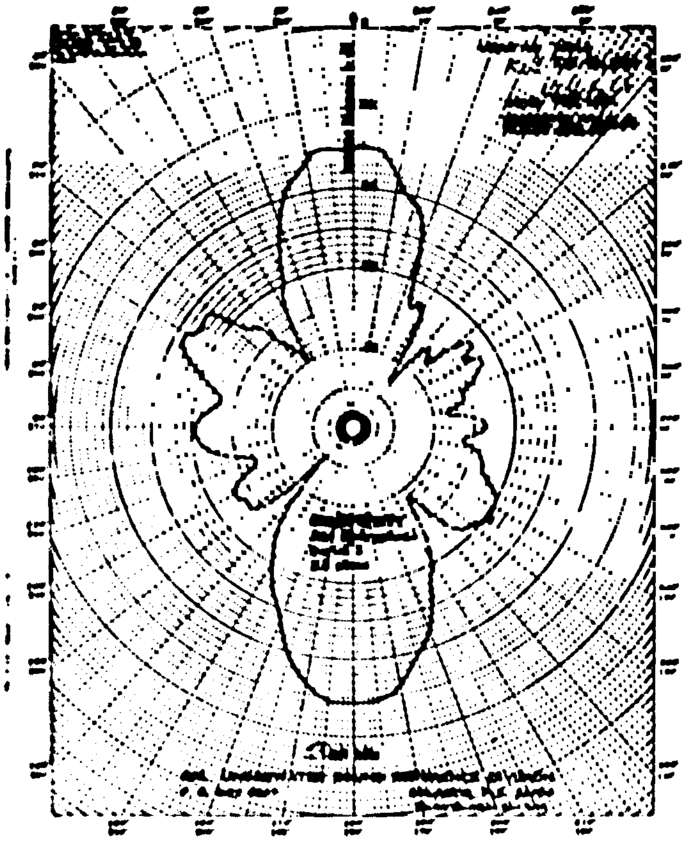






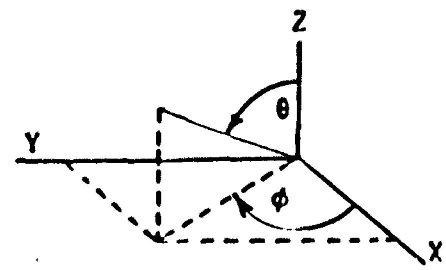






COORDINATE SYSTEM FOR TRANSDUCER ORIENTATION

The left-handed coordinate system of the American Standard Procedures for Calibration of Electroacoustic Transducers Particularly Those for Use in Water, Z24.24-1957, is used. The transducer is fixed with respect to the coordinate system and has its acoustic center at the origin. The angle ϕ is equivalent to the azimuth angle in sonar operation.



PLACEMENT OF TRANSDUCER IN COORDINATE SYSTEM

Transducer Type	Transducer Orientation in Coordinate System
Point, or Spherical	Points on surface that coincide with the X and Z axes shall be specified.
Cylindrical, or Line	The axis of the cylinder or line shall coincide with the Z axis. A reference mark in the XZ plane and in the direction of the positive X axis will be specified.
Plane, or Piston	The plane or piston face shall be in the YZ plane with the X axis normal to the face at its acoustic center. A reference mark in the XZ plane and in the direction of the positive Z axis will be specified.
Other Configurations	Orientation shall be shown by sketch or description. This category includes line and piston types of transducers operated in an orientation other than those specified above.

ORIENTATIONS FOR RESPONSE AND DIRECTIVITY MEASUREMENTS

Response. The calibration measurements are made for sound propagated parallel to the positive X axis ($\phi = 0$, $\theta = 90$), unless otherwise specified on the response curve.

Directivity. The plane of the pattern is specified, and the following conventions are observed, if another orientation is not specified on the pattern:

XY Plane: The positive X axis ($\phi = 0$, $\theta = 90$) coincides with the zero-degree direction on the pattern and the positive Y axis ($\phi = 90$, $\theta = 90$) is at 90 degrees measured in a clockwise direction. Rotation is around the Z axis; the positive Z axis is directed upward from the plane of the paper.

XZ Plane: The positive X axis coincides with the zero-degree direction and the positive Z axis ($\theta = 0$) is at 90 degrees measured in a clockwise direction. Rotation is around the Y axis; the negative Y axis is directed upward from the plane of the paper.

YZ Plane: The positive Y axis coincides with the zero-degree direction and the positive Z axis is at 90 degrees measured in a clockwise direction. Rotation is around the X axis: the positive X axis is directed upward from the plane of the paper.

Appendix E

EFFECT OF HYDROSTATIC PRESSURE ON THE WATER VAPOR PERMEABILITY OF SOME ELASTOMERS AND PLASTICS

Material	Permeant	Pressure Range				Permeability[a]	
		Low		High		at low pressure	at high pressure
		kPa	psi	kPa	psi		
Butyl	distilled water	103	15	68900	10000	22[b]	3.6[b]
Low-density polyethylene	fresh water	345	50	34500	5000	47[c]	18[c]
	salt water	345	50	34500	5000	29[c]	29[c]
Nylon	fresh water	345	50	103400	15000	295[c]	86[c]
	salt water	345	50	68900	10000	256[c]	256[c]
Polyurethane	water	2	0.3	20700	3000	3000[b]	600[c]

[a] Units: gram water/cm^2/cm/hr/mm Hg × 10^{-10}.

[b] A. Lebovits, U. S. Naval Applied Science Laboratory, Naval Base, Brooklyn, N. Y.

[c] J. W. Herrick, AVCO Corporation, Wilmington, Mass.