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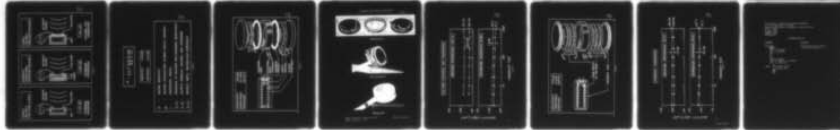
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FLEXURAL DISC PIEZOELECTRIC POLYMER HYDROPHONES.(U)
MAR 77 T D SULLIVAN, J M POWERS

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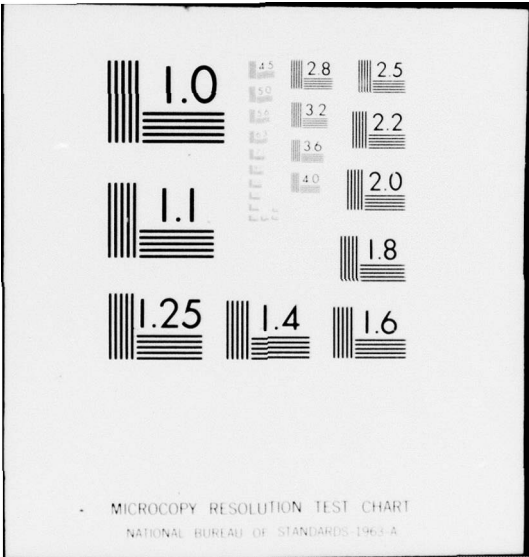
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unit uses two air-backed flexural discs with a stack of four pieces of 30 μm polymer film glued to each disc, resulting in a combined capacitance of 1 nF. This hydrophone has a mass of 24 g in air and is neutrally buoyant in water. A theoretical analysis which shows the variation of hydrophone performance as a function of design parameters is presented, and the material properties of piezoelectric polymer and piezoelectric ceramic are compared.

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Technical Memorandum

FLEXURAL DISC PIEZOELECTRIC POLYMER HYDROPHONES*

Date: 16 March 1977

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*Presented at 92nd meeting of the Acoustical Society of America,
San Diego, California, 16-19 November 1976

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ABSTRACT

Piezoelectric polymer (poled polyvinylidene fluoride), a Japanese development recently introduced into high fidelity technology, shows promise as a hydrophone material because of its flexibility, ruggedness, low density, and potentially low cost. A family of lightweight flexural disc hydrophones which use piezoelectric polymer are described. Measurements on a 3.8 cm diameter unit gave a sensitivity of -199 dB re 1 V/ μ Pa with good stability over ranges of 2 Hz - 1 kHz, 0-22°C, and 0-600 psi static pressure. This particular unit uses two air-backed flexural discs with a stack of four pieces of 30 μ m polymer film glued to each disc, resulting in a combined capacitance of 1 nF. This hydrophone has a mass of 24 g in air and is neutrally buoyant in water. A theoretical analysis which shows the variation of hydrophone performance as a function of design parameters is presented, and the material properties of piezoelectric polymer and piezoelectric ceramic are compared.

ADMINISTRATIVE INFORMATION

This memorandum was prepared jointly under two project numbers: (1) A68099, Piezoelectric Polymer Hydrophone Development; Sponsoring Activity, Naval Electronics Systems Command, Washington, D. C. 20360; Program Manager, J. Sinsky, and (2) A72001, Transduction Techniques for Navy Sonar Transducers; Sponsoring Activity, Naval Sea Systems Command, Washington, D. C. 20362; Program Manager, C. Walker. The principal investigator for both programs is C. L. LeBlanc, NUSC/NL, Code 3161.

The authors of this memorandum are located at the New London Laboratory of the Naval Underwater Systems Center, New London, Connecticut 06320.

Piezoelectric polymer, discovered a few years ago by the Japanese, is a relatively new material to the field of underwater acoustics. The Navy has been investigating this material recently for use in hydrophones. This paper describes a piezoelectric polymer hydrophone which can be used under static pressures up to 600 psi, and has firmly established the feasibility of using this material in underwater acoustics.

Shown on the left in Figure 1 is a roll of polyvinylidene fluoride film, a polymer which is used in electrical devices and in paint. Also shown are some samples of the piezoelectric version of this polymer, and for comparison, some samples of piezoelectric ceramic. To make the polymer piezoelectric, both sides of the film are electroded by vacuum depositing aluminum onto the surfaces, and then applying a high D. C. voltage to the electrodes at an elevated temperature. The polymer used for this investigation was electroded and poled by Seymour Edelman of the National Bureau of Standards. The sample of this polymer, shown at left center, is 2" by 6" by 1 mil thick and was poled at 2000 volts for 30 minutes at 80° centigrade.

Piezoelectric polymer has recently become commercially available. Figure 2 compares the manufacturer's published data to the properties of PZT-4 ceramic.

The coupling factor, frequently used as a figure-of-merit, is 1/3 that of ceramic, ruling out practically all underwater sound projector applications unless the material is significantly improved. The dielectric constant is very low, compared to ceramic, which usually results in low hydrophone capacitance. The piezoelectric stress or g -constant is relatively high and the piezoelectric strain or d -constant is relatively low, usually indicating high voltage sensitivity and low charge sensitivity. The " gd product," also sometimes used as a figure-of-merit, is 3.5 times higher than that for ceramic. The density is only 1/4 that of ceramic, a useful feature for applications requiring lightweight hydrophones. The unique property of piezoelectric polymer is its softness and flexibility which is reflected in its relatively high compliance, 30 times that of ceramic.

As indicated in Figure 3, polymer film offers several potential advantages pertinent to underwater sound applications. Mechanical flexibility allows the piezoelectric material to conform to unusual surfaces, making possible whole new classes of hydrophones which are impractical or impossible to build with ceramic. Because it is pliable, it is also highly shock resistant, which is a traditional problem for

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ceramic. Lighter weight hydrophones can be constructed due to the polymer's low density and thinness. Polymer has the potential to become the first piezoelectric material which can be manufactured in large dimensions and inexpensively. Techniques are currently under study to enable polymer to be poled and electroded on a continuous roll basis.

The purpose of our initial efforts was to establish the feasibility of using piezoelectric polymer in hydrophones by building a hydrophone which could perform to the following specifications: a sensitivity of $-200 \text{ dB//1 V//}\mu\text{Pa}$; a capacitance of 1 nanofarad; an operating pressure capability of 600 psi.

Figure 4 shows how polymer film can be used in the planar piezoelectric coupling mode. One technique for applying this mode is to stretch the polymer over a cylindrical air-filled cavity, like a drum head, making a membrane microphone which is shown on the left. Incident acoustic waves cause inward and outward excursions of the taut polymer film producing consequent alternating stresses in the plane of the polymer. A resultant voltage proportional to the planar stress is produced across the electrodes. In actuality, a slight concavity in the equilibrium position of the taut film is required to prevent frequency doubling of the output voltage. This mechanical bias can be provided by a slight pressure differential between the enclosed cavity and the external medium. Such a device was built and tested and produced a sensitivity of $-179 \text{ dB//1 V//}\mu\text{Pa}$ in fluid at atmospheric pressure. This device could not be used underwater at depths of more than a few feet without collapsing from static water pressure.

To make a hydrophone out of this device, the cavity must be stiffened to provide static pressure capability. This was accomplished by cementing small plastic compliant tubes designed to withstand 600 psi to the microphone backplate and filling the cavity with oil, as indicated in the center figure. A stiffer cavity naturally implies smaller amplitude excursions of the taut polymer and a corresponding reduction in sensitivity. The finished unit produced a sensitivity of -209 dB , only 9 dB short of our goal. However, this approach was fraught with inconvenient complications which persuaded us to develop another approach, shown on the right.

Here a relatively stiff diaphragm is placed over the air cavity. The polymer is glued directly to the surface of the diaphragm and is stressed as the diaphragm flexes. This type of device is known as a flexural disc hydrophone and is commonly made with piezoelectric

ceramic. The diaphragm stiffness provides pressure capability and eliminates the necessity to mechanically bias the polymer. A single sheet of polymer on a diaphragm capable of withstanding 600 psi produces a sensitivity of -212 dB. This lower sensitivity is compensated for by reliability of design and simplicity of construction.

An expression for the sensitivity of this hydrophone shown in Figure 5 can be developed from the stress equations of circular plates and from the material parameters of the diaphragm and the polymer. The expression will vary in complexity, depending upon the relative radii of the polymer and the diaphragm, the piezoelectric isotropy of the polymer, the diaphragm boundary conditions, etc. The simplest expression, shown here, is for small deflections of a supported-edge diaphragm, with polymer of the same radius as the diaphragm. Material elasticity limits are observed and material homogeneity and isotropy are assumed.

Parameters for the flexural disc hydrophone were studied using this equation. For example, common practice for ceramic is to use thin, supported-edge diaphragms made of stiff metal, since ceramic itself is very stiff. Our analysis indicated that the thick, supported-edge diaphragm made of compliant plastic would be more suitable for polymer hydrophones. This is reflected in an increased value for the hydrophone sensitivity which results when the lower value of the diaphragm modulus is used in the denominator of the equation.

As mentioned, several hydrophones of this design, built to withstand 600 psi, consistently produced sensitivities of -212 dB. Using a value for the g-constant derived from rough measurements on the membrane microphone shown earlier, this equation predicted a sensitivity of -219 dB, 7 dB less than the measured value. Since the material parameters and dimensions are all measurable to within a few percent and because the formula accurately predicts sensitivity changes, the 7 dB difference between prediction and measurement is attributed to the roughness of the preliminary g-constant measurements from the membrane microphone. More accurate g-constant measurements are currently being done, which is expected to greatly improve the agreement between calculation and measurement. The math model has been of value primarily in choosing materials and dimensions in designing this hydrophone for specific applications.

The sensitivity of -212 dB for the single diaphragm hydrophones was 12 dB below our goal, and their capacitance, 3.6 nanofarads, was considerably above the 1 nanofarad originally specified. Capacitance was

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therefore traded off to get increased sensitivity by building a dual diaphragm device using 4 pieces of polymer electrically connected in series as shown in Figure 6. This theoretically should increase the sensitivity by 12 dB and reduce the capacitance to 1/4 of its original value. In fact, the sensitivity increased 10 dB to -202, and the capacitance reduced to .9 nanofarad as expected. As shown here, two pieces of polymer are glued together as a stack, and then glued to the inner surface of the plastic diaphragm. The polymer is thus protected and all wiring is internally contained, leaving a simple two-terminal output through the aluminum cylinder. Neoprene rubber washers are mounted between the diaphragms and the aluminum cylinder to act as hinges, approximating a supported-edge condition for the diaphragms.

Figure 7 shows the finished unit in various stages of assembly. It is neutrally buoyant, weighs 25 grams without the cable, and measures 1 5/8" in diameter by 3/4" thick.

Figure 8 shows a temperature and pressure calibration performed at NRL/Underwater Sound Reference Division, Orlando, Florida. A 4.5 dB decrease in sensitivity occurred between 100 and 600 psi at 22° centigrade and a 1.5 dB sensitivity loss occurred over a temperature decrease to 0° centigrade at 6 psi.

The neoprene washers were suspected as the most significant cause of these sensitivity changes, so another hydrophone was built as shown in Figure 9. To permit the elimination of the neoprene washers, grooves were cut around the perimeter of the diaphragm allowing it to be cemented directly to the aluminum ring. Four pieces of polymer were glued together in series in each stack instead of two, and the two stacks were connected in parallel to reach a capacitance of 1 nanofarad.

As shown in Figure 10 these modifications produced a sensitivity of -199 dB as compared to the -202 dB of the previous hydrophone, and was flat from 2 Hz to 1 kHz. The pressure induced sensitivity loss, which had been 4.5 dB, decreased to about 1.5 dB, and the temperature induced sensitivity loss, which was 1.5 dB before was practically eliminated.

Improvements in construction techniques, use of multiple layers of polymer, improvements in boundary structures, and optimal use of high-strength, low-modulus diaphragm plastics will further improve the sensitivity and reduce the pressure dependence of this device.

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In conclusion, a hydrophone using piezoelectric polymer has been built which performs with good sensitivity to pressures of 600 psi and temperatures to 0° centigrade. Descriptive mathematical expressions have been developed which provide accurate guidelines for mechanical design requirements and which predict sensitivities of constructed units to within a few dB. Thus the feasibility of using piezoelectric polymer in underwater acoustics has been thoroughly demonstrated.

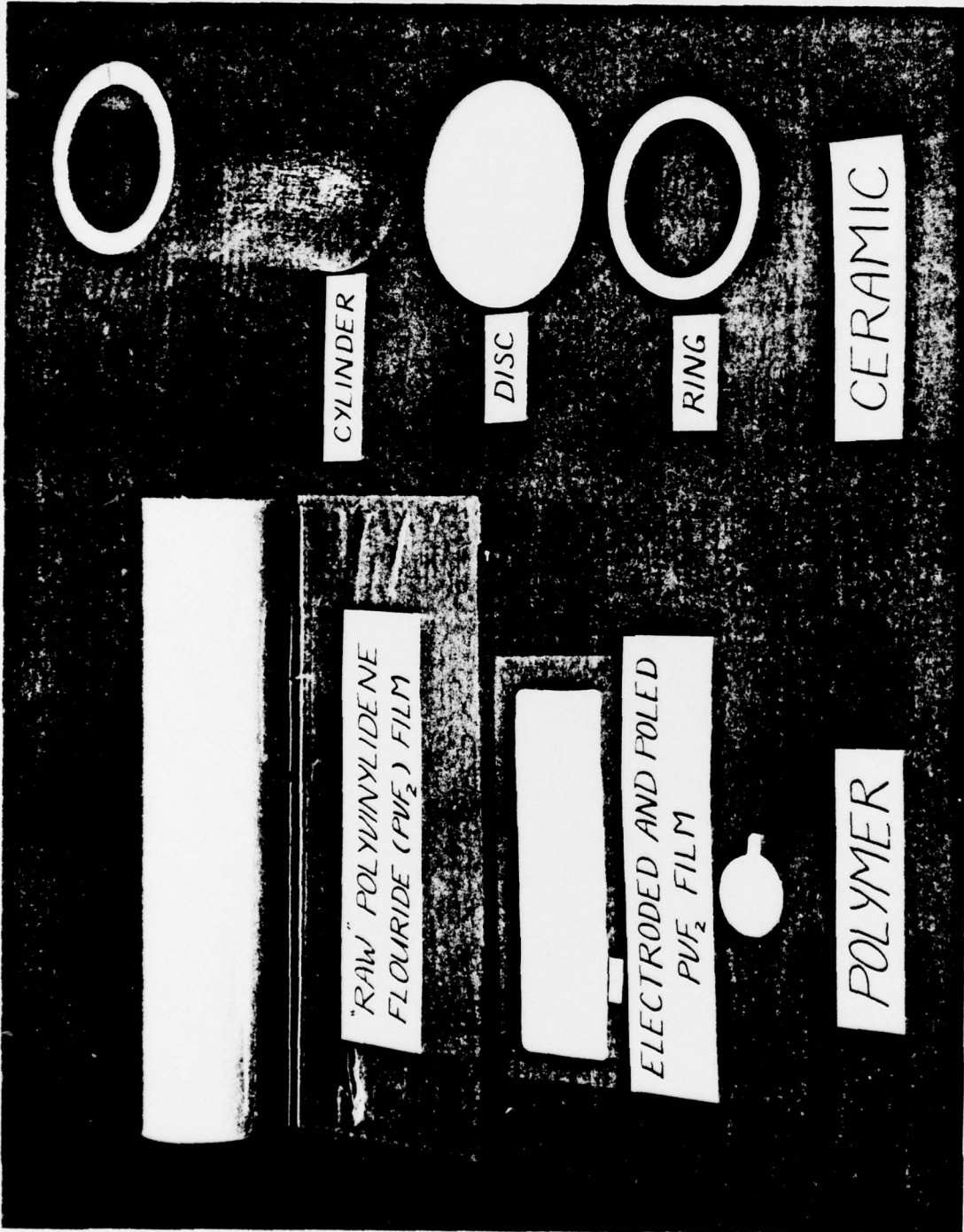


FIGURE 1

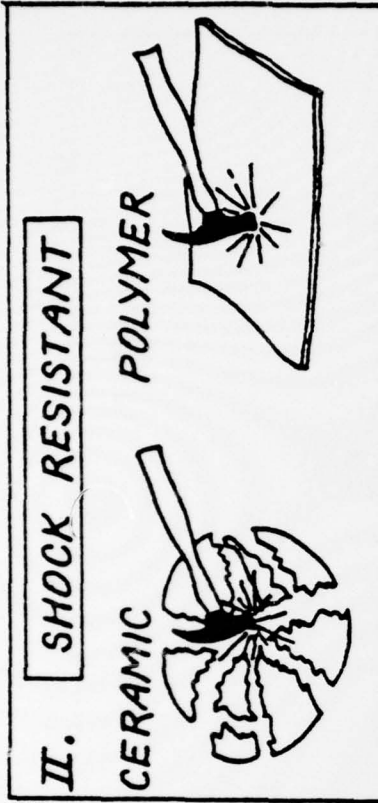
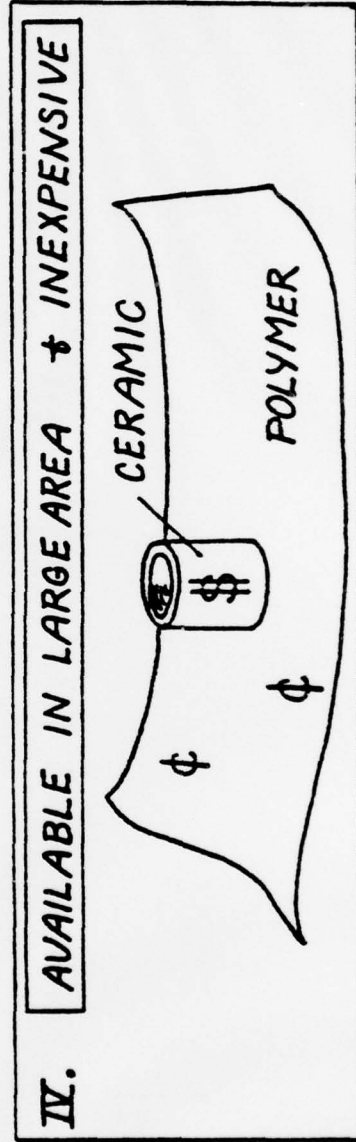
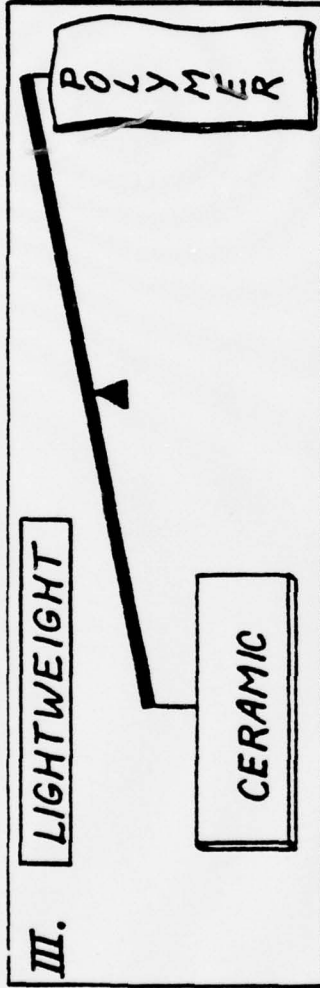
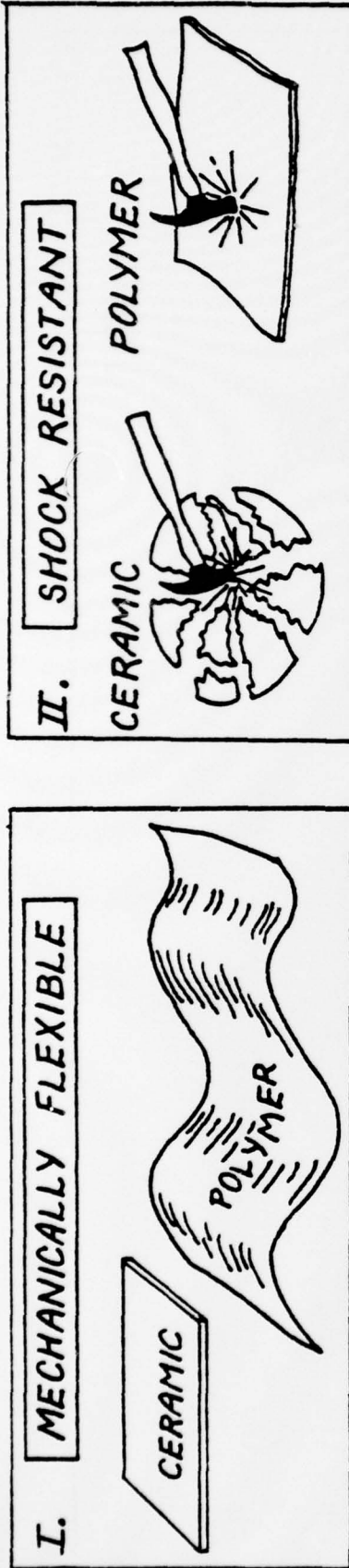
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<u>SYMBOL</u>	<u>PROPERTY</u>	<u>POLYMER</u>	<u>CERAMIC</u>
k_{31}	PIEZOELECTRIC COUPLING FACTOR	.117	.334
$\epsilon_{33}^T / \epsilon_0$	RELATIVE DIELECTRIC CONSTANT	13	1300
g_{31} ($10^{-3} \frac{V-m}{\mu}$)	PIEZOELECTRIC STRESS CONST.	200	11.1
d_{31} ($10^{-12} \frac{m}{V}$)	PIEZOELECTRIC STRAIN CONST.	23	123
$(gd)_{31}$ ($10^{-12} \frac{m^2}{\mu}$)	"gd PRODUCT"	4.6	1.36
ρ ($10^3 \frac{kg}{m^3}$)	DENSITY	1.8	7.5
s_{11}^E ($10^{-12} \frac{m^2}{\mu}$)	ELASTIC COMPLIANCE	330	12

FIGURE 2

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FIGURE 3

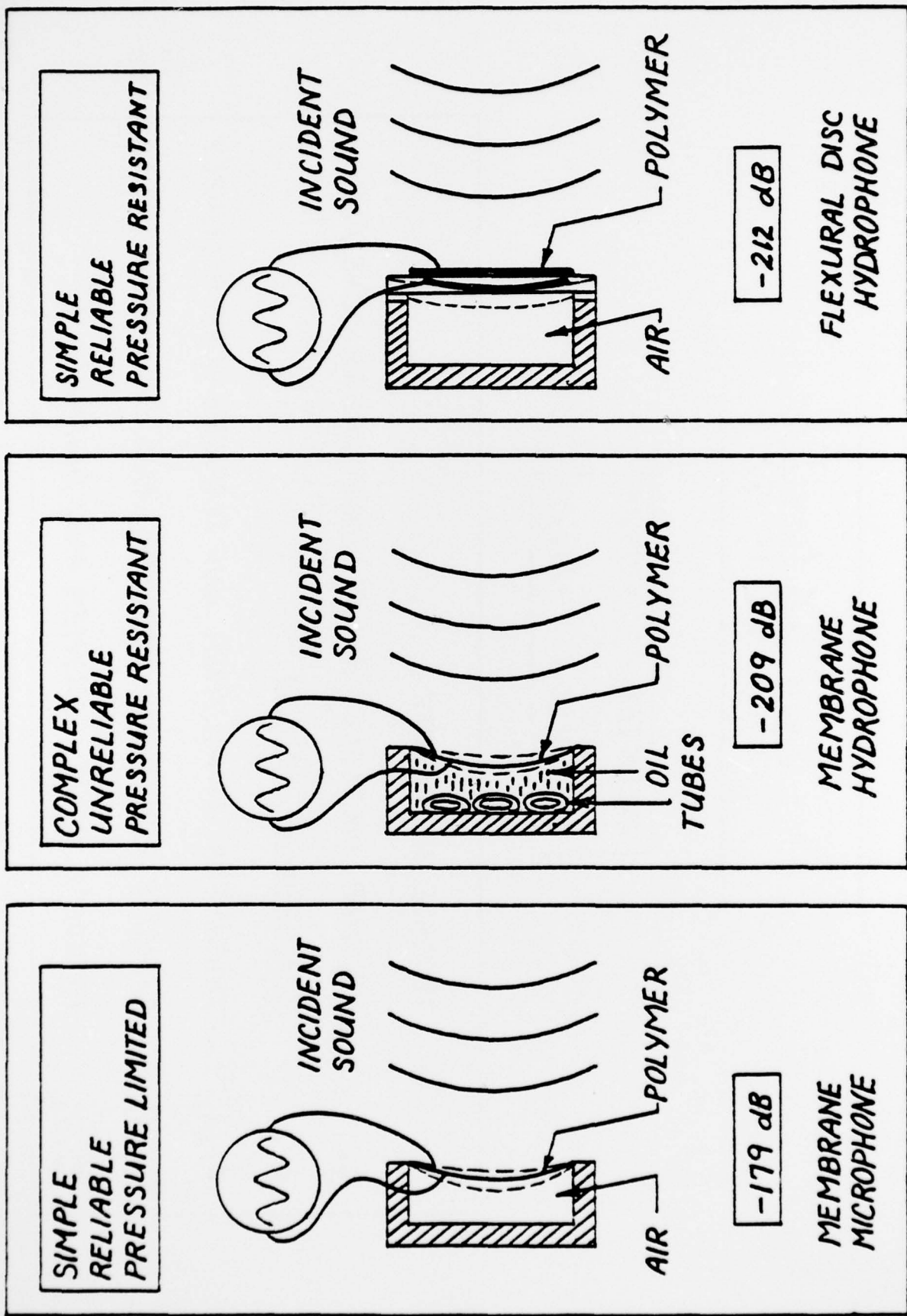


FIGURE 4

$$M = \frac{3}{2} g_p \alpha^2 \frac{t_p Y_p (1 - \sigma_d)}{t_d^2 Y_d (1 - \sigma_p)}$$

PREDICTED	-219dB
MEASURED	-212 dB

M	-	VOLTAGE SENSITIVITY
g_p	-	POLYMER PIEZOELECTRIC PLANAR STRESS CONSTANT
α	-	DIAPHRAGM RADIUS
t_p, t_d	-	THICKNESS OF POLYMER AND DIAPHRAGM, RESPECTIVELY
Y_p, Y_d	-	ELASTIC MODULUS, POLYMER AND DIAPHRAGM
σ_p, σ_d	-	POISSON'S RATIO, POLYMER AND DIAPHRAGM

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FIGURE 5

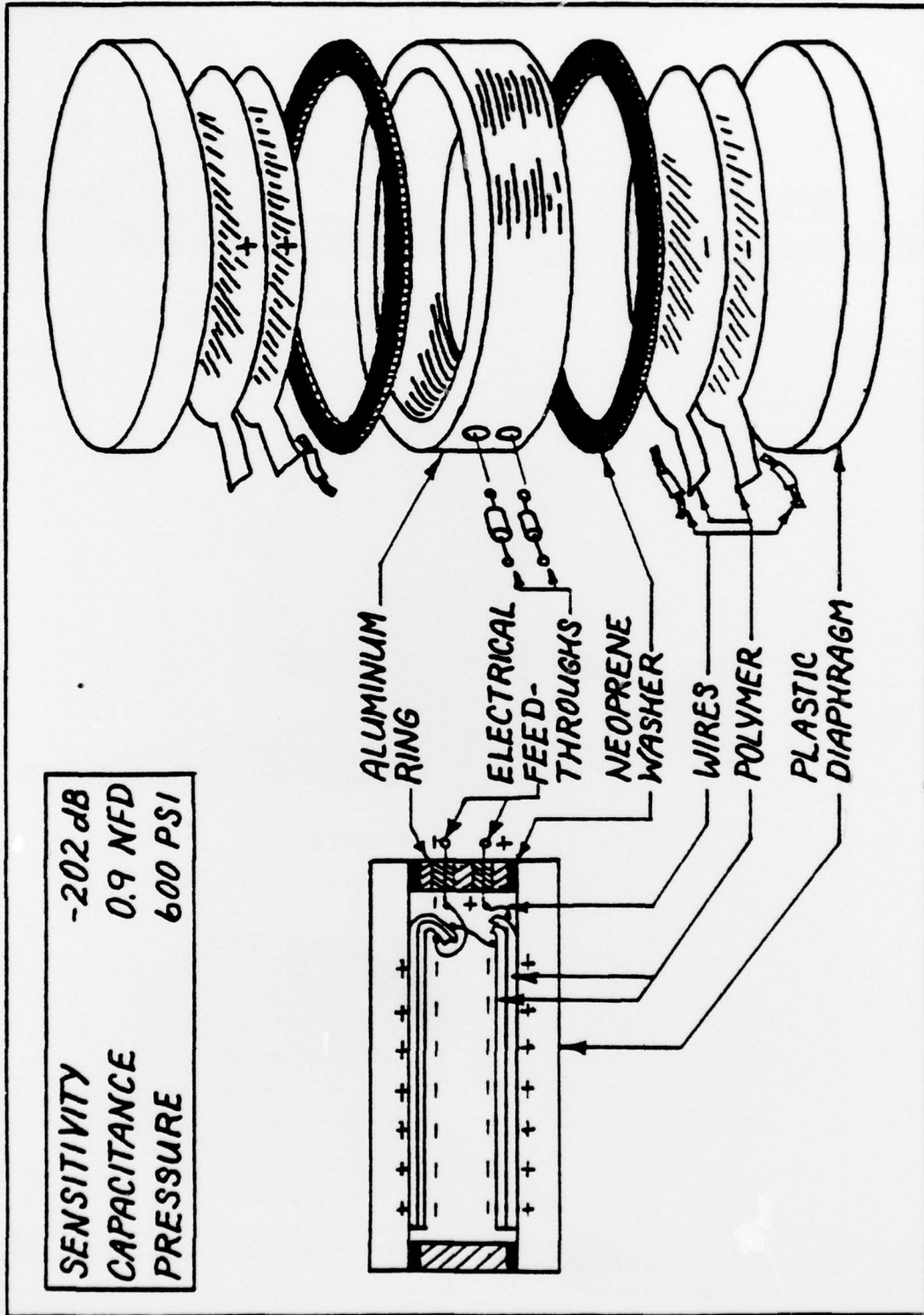


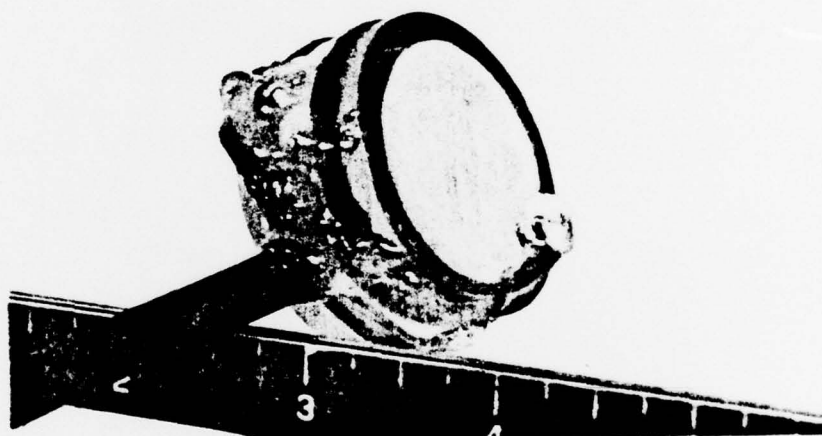
FIGURE 6

Flexural Disc Polymer Hydrophone

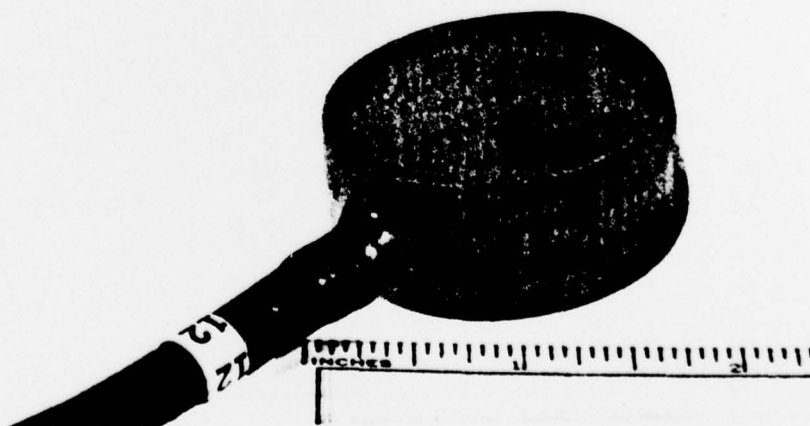
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Subassemblies



Fully Assembled



Waterproofed
FIGURE 7

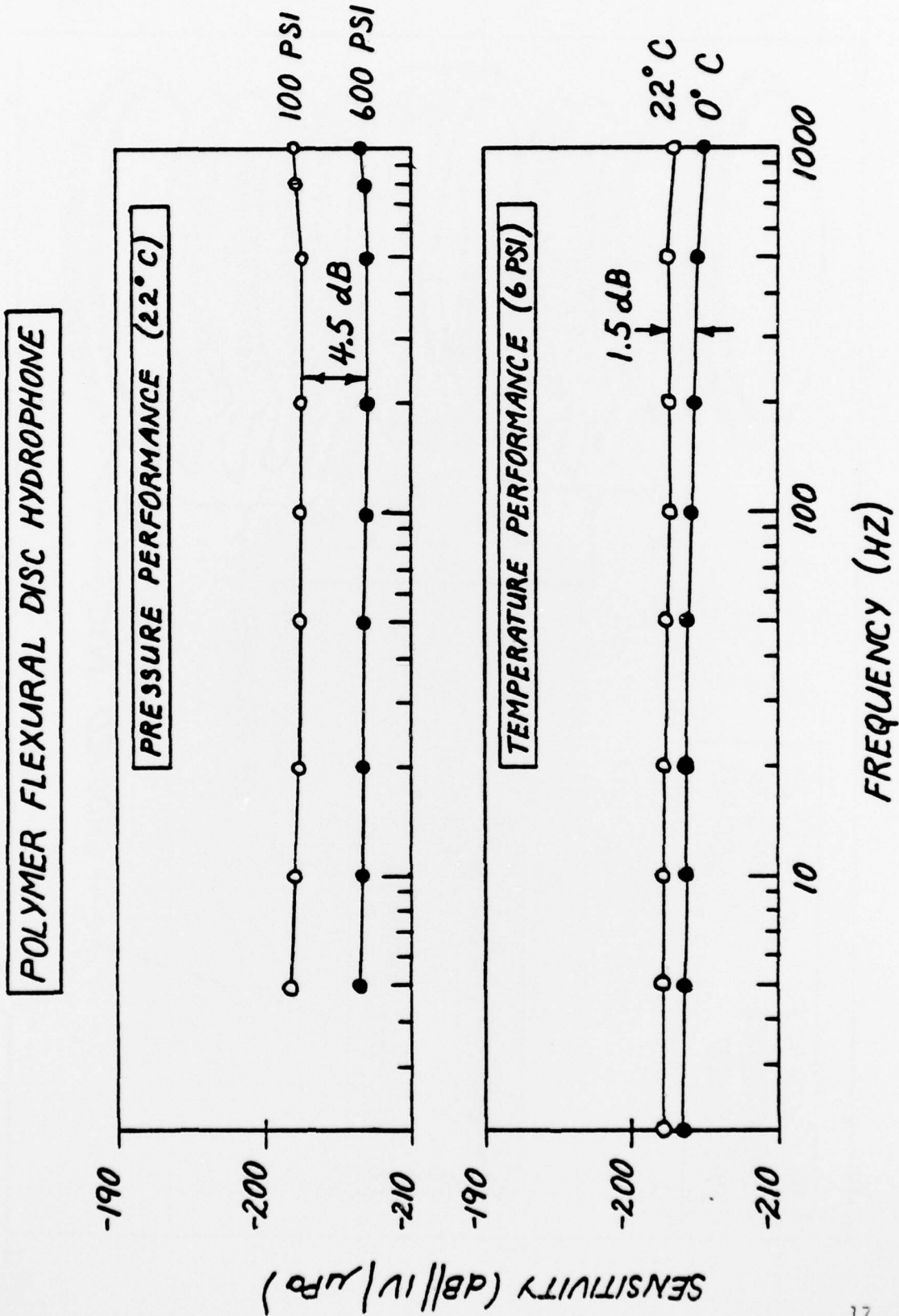


FIGURE 8

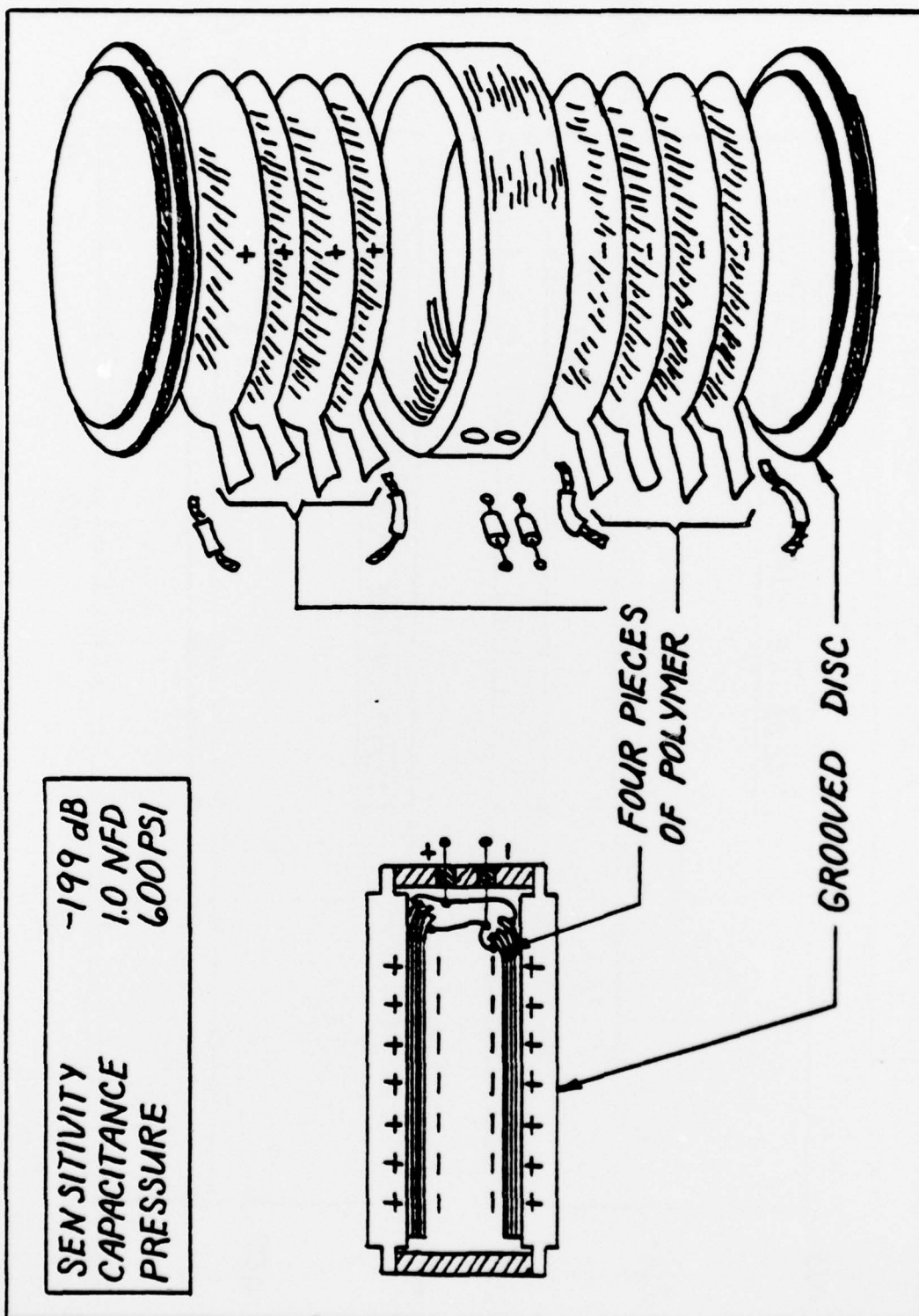


FIGURE 9

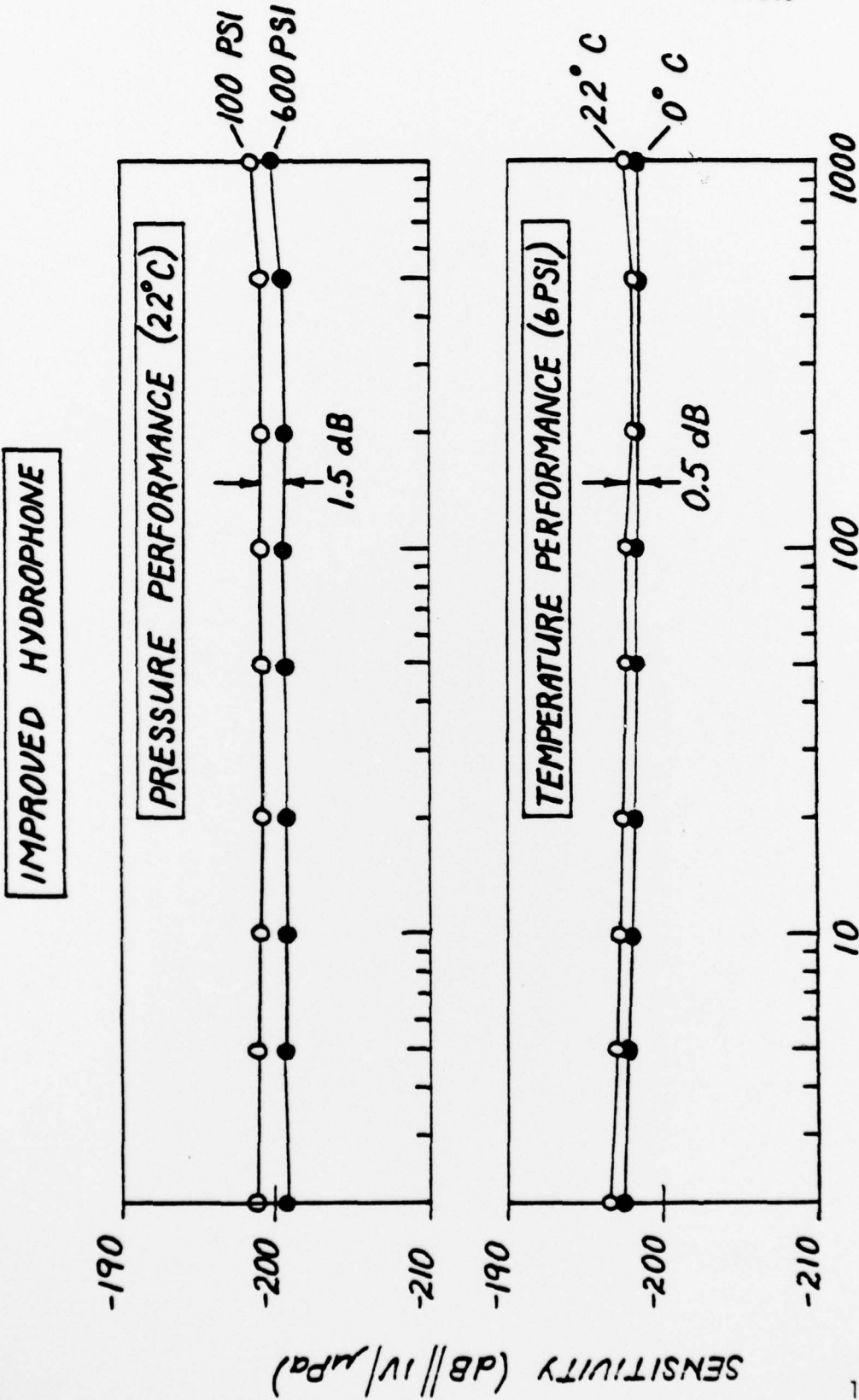


FIGURE 10

Flexural Disc Piezoelectric Polymer Hydrophone
T. D. Sullivan and J. M. Powers
Special Projects/Sonar Transducers & Arrays Division
TM No. 771043
16 March 1977
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