AN UNDERWATER SOUND LEVEL METER

APPROVED:

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AN UNDERWATER SOUND LEVEL METER

by

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THESIS

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PREFACE

This thesis describes the development of an underwater sound level meter. The instrument measures ambient noise levels in water.

The author wishes to express his appreciation to Dr. C. W. Horton and Dr. E. L. Hixon for their suggestions and supervision. Appreciation is also due to Dr. C. M. McKinney who originally suggested the development of the instrument. This work was carried out under U. S. Navy Contract NObsr-93124, Task I, at Defense Research Laboratory, The University of Texas at Austin.

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I. INTRODUCTION

Sound may be defined as the oscillation in pressure, particle displacement, or particle velocity in an elastic medium such as water.[1] Sound pressure is measured in terms of a unit called the microbar, which is a pressure of one dyne per square centimeter. Sound pressure level in decibels is twenty times the logarithm to the base ten of the ratio of the pressure of the sound to a reference pressure of one microbar.[2]

In a particular sonar system, signals which hinder the detection of the desired signals are called noise. Noise may be generated by the sonar itself. Thermal noise generated by detection equipment may hinder the operation of both active and passive sonar equipment. In active sonar systems, signal detection is further hindered by reverberation, or the unwanted reflection of the transmitted pulse by surfaces of the water, or inhomogeneities in the water.[3]

Another phenomenon which hinders the operation of a sonar is ambient noise. Ambient noise is the random acoustic signals from all sources in the water except noise inherent in the measuring equipment and the apparatus associated with the detectors such as the platform. Ambient noise may degrade or make impossible the operation of a sonar receiver. However, due to limitations on the bandwidth and noise of the hydrophone

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[1] Vernon M. Albers, Underwater Acoustics Handbook, Vol. II, The Pennsylvania State University Press, University Park, Pennsylvania, 1965.

[2] Arnold P. G. Peterson and Ervin E. Gross, Jr., Handbook of Noise Measurement, General Radio Company, West Concord, Massachusetts, p. 7.

[3] Claude W. Horton, Signal Processing of Acoustic Waves, The Defense Research Laboratory, Austin, Texas, DRL-A-251, November 1965, pp. 6-8.

and the associated electronic equipment, a study of the ambient noise may be impossible with standard sonar receivers. For this reason it is desirable to build a separate instrument for the measurement of ambient noise. An underwater sound pressure level meter would be useful also for the study of the noise fields of various bodies of water.

Many commercial instruments are made for the study of airborne sound pressure levels. Different requirements exclude the use of these instruments from use as an underwater sound pressure level meter. For example, a hydrophone must be used in the place of a microphone; the amplifier gain must be higher; and the noise level in the amplifier must be lower for the underwater case than for the airborne case.

This thesis contains a description of the design and operation of an instrument for use as an underwater sound pressure level meter. Detailed descriptions are given of the techniques used to eliminate sources of error due to such limitations as thermal noise in the detection equipment and the lack of omnidirectionality of the hydrophone response. Data are presented comparing the thermal noise limit of both the hydrophone and the preamplifier to the equivalent noise level of Sea State zero. The use of the instrument is demonstrated by measuring the acoustic noise level in a low noise environment of an anechoic tank.

II. AMBIENT NOISE

Ambient noise can be considered a characteristic of the medium. When measured at a point in a body of water, the ambient noise level is expressed in terms of an "equivalent" isotropic noise field at the observing hydrophone. An isotropic noise field is a noise field with equal noise contributions from all directions. An equivalent isotropic noise field is one that would produce, at the output of the measuring system, a response equal to that produced by the noise actually present. The noise found at a given point is the sum of the noises from a large number of independent sources.

Common sources of ambient noise are:

1) thermal noise caused by molecular agitation in the medium, which is particularly important at high frequencies in deep water since it limits the hydrophone threshold at frequencies above 50 kHz;

2) sea surface noise which is dominant in open-sea deep water in the frequency range from 100 Hz to 50,000 Hz;

3) biological noise caused by snapping shrimp, croakers, and various other soniferous sea creatures, occuring locally in shallow water, which is important for frequencies up to 20 kHz;

4) noise caused by collapsing bubbles;

5) man-made noise, including that from distant ships and from industrial sources in and near busy harbors which is often the dominant source of noise up to 1 kHz;

6) rain noise;

7) noise produced by surf on the coast or reefs;

8) flow noise caused by current flow over rocky bottoms and hydrostatic pressure changes produced by waves which normally has only very low frequency noise components, and

9) terrestrial noise caused by earthquakes, volcanoes, microseisms, and distant storms.[4]

Ambient noise in the open sea was studied by Knudsen, Alford, and Emling during World War II. The results of their studies are summarized in a set of curves known as Knudsen Curves for Sea States 0 to 6. Figure 2.1 shows these curves in pressure spectrum level as a function of frequency.[5] A value of the spectrum pressure level always refers to a bandwidth of 1 Hz. Table I shows a description of the sea states.[6]

The noise level in shallow water is usually much higher than the deepwater noise level shown in Knudsen Curves because of soniferous marine life and man-made disturbances. M. D. Fish has shown that noise produced by croakers and snapping shrimp can be high enough to hinder seriously the operation of a sonar system. Spectrum pressure levels greater than 0 dB re 1 microbar/ $\sqrt{\text{Hz}}$ have been observed at frequencies between 100 Hz and 1000 Hz.[7] Knudsen, Alford, and Emling showed that the noise in a busy harbor may have a spectrum level as high as -- 10 dB re 1 microbar/ $\sqrt{\text{Hz}}$ at frequencies below 200 Hz.[8]

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[4]Albers, op cit, pp. 109-111.

[5]Knudsen, Alford, and Emling, "Survey of Underwater Sound, Ambient Noise," 6.1-NDRC-1848, Report No. 31, Sept. 26, 1944.

[6]Staff of the Sound and Vibration Section Research and Development Department, "A Handbook of Sound and Vibration Parameters" General Dynamics, Electric Boat Division, p. 26.

[7]M. D. Fish, "An Outline of Sounds Produced by Fishes in Atlantic Coastal Waters--Sound Measurement and Ecological Notes," Narragansett Marine Laboratory, Special Report No. 1, 53-1, January, 1953.

[8]Knudsen, op cit.

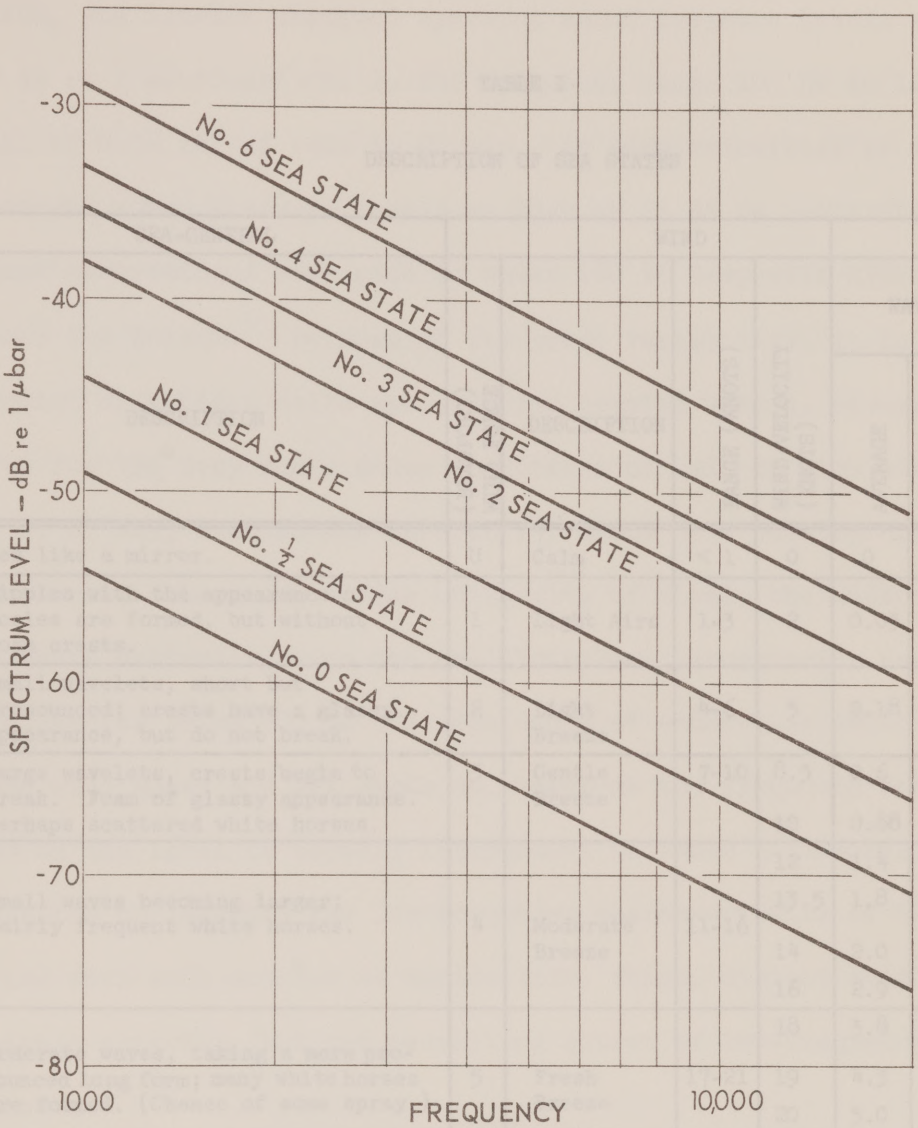

FIGURE 2.1
KNUDSEN CURVES FOR SEA STATES 0 TO 6

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TABLE I

DESCRIPTION OF SEA STATES

SEA STATE	SEA-GENERAL DESCRIPTION	WIND FORCE (BEAUFORT)	WIND DESCRIPTION	RANGE (KNOTS)	WIND VELOCITY (KNOTS)	WAVE HEIGHT FEET AVERAGE	WAVE HEIGHT FEET SIGNIFICANT	WAVE HEIGHT FEET AVERAGE 1/10 HIGHEST
0	Sea like a mirror.	U	Calm	< 1	0	0	0	0
	Ripples with the appearance of scales are formed, but without foam crests.	1	Light Airs	1-3	2	0.05	0.08	0.10
1	Small wavelets, short but pronounced; crests have a glassy appearance, but do not break.	2	Light Breeze	4-6	5	0.18	0.29	0.37
	Large wavelets, crests begin to break. Foam of glassy appearance. Perhaps scattered white horses.	3	Gentle Breeze	7-10	8.5	0.6	1.0	1.2
					10	0.88	1.4	1.8
2	Small waves becoming larger; fairly frequent white horses.	4	Moderate Breeze	11-16	12	1.4	2.2	2.8
					13.5	1.8	2.9	3.7
3					14	2.0	3.3	4.2
					16	2.9	4.6	5.8
4	Moderate waves, taking a more pronounced long form; many white horses are formed. (Chance of some spray.)	5	Fresh Breeze	17-21	18	3.8	6.1	7.8
					19	4.3	6.9	8.7
					20	5.0	8.0	10
5	Large waves begin to form; the white foam crests are more extensive everywhere, (Probably some spray.)	6	Strong Breeze	22-27	22	6.4	10	13
					24	7.9	12	16
					24.5	8.2	13	17
6					26	9.2	15	20
	Sea heaps up and white foam from breaking waves begins to be blown in streaks along the direction of the wind. (Spindrift begins to be seen.)	7	Moderate Gale	28-33	28	11	18	23
					30	14	22	28
					30.5	14	23	29
					32	16	26	33

Rain, hail, and snow increase the ambient noise level. Heindsmann, Smith, and Arneson observed spectrum sound pressure levels as high as -- 20 dB re 1 microbar/$\sqrt{Hz}$ in the frequency range 100 Hz to 10,000 Hz for a fall of 0.52 in. of rain in 90 min. At wind velocities of 100 mph, they observed sound pressure levels as high as 25 dB re 1 microbar/$\sqrt{Hz}$ at 1000 Hz. These observations were made in water 120 ft deep with hydrophones placed 4 ft above the bottom.[9] Because of its great variability, it is impossible to predict an ambient noise spectrum for coastal waters, rivers, lakes, and even for the deep ocean under conditions of rain or high winds. Also, studies by U. S. Navy Electronics Laboratory, Woods Hole Oceanographic Institution, the Marine Laboratory of the University of Miami, the Hudson Laboratories of Columbia University, and the Bell Telephone Laboratories have shown that at frequencies below 500 Hz the dependence of underwater ambient noise levels upon wind speed and sea state decreases as the frequency decreases, and below 100 Hz the level is usually independent of these influences. It is often possible to identify the low-frequency characteristics of the underwater noise with such sources as marine life, ships, distant ship travel, and seismic activity, but the prevailing source of low-frequency noise is still unknown.[10]

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[9] T. E. Heindsmann, R. H. Smith, and A. D. Arneson, "Effect of Rain Upon Underwater Noise Levels", J. Acous. Soc. Am., Vol. 27, pp. 378-379, (1955).

[10] Gordon M. Wenz, "Some Periodic Variations in Low-Frequency Acoustic Ambient Noise Levels in the Ocean", J. Acous. Soc. Am., Vol. 33, p. 64.

III. THE MEASUREMENT OF AMBIENT NOISE

Most of the noise pressure levels reported in the previous chapter were measured using a hydrophone or hydrophone arrays fixed at the bottom of the body of water being studied. This technique is very useful for obtaining information about ambient noises and their sources; however, such apparatus is not always available or practical for the measurement of noise levels. In such cases a portable instrument would be desirable. The instrument must be capable of measuring and analyzing the frequency dependence of the types of noises described in the previous chapter. To indicate the level in a selected frequency range, a meter could be used or the noise voltage could be recorded from an output provided on the instrument.

Many of the features of an underwater sound level meter can be identical to those for a standard sound level meter. However, airborne noises above the audible frequency range are usually not of interest; whereas, high frequency noises are of much interest in water. One would like the frequency range of the underwater sound level meter to be 10 Hz to 100 kHz, as compared to 10 Hz to 20 kHz for an airborne sound level meter. A single hydrophone cannot give optimum performance over such a large frequency band. A hydrophone with a high sensitivity at low frequencies must be of large size, but a hydrophone of large size has mechanical resonances and diffraction effects which seriously affect the sensitivity within the frequency range of interest. In this study a hydrophone which covers the audio frequency range of 10 Hz to 20 kHz was found to be feasible, and consequently this limitation on the frequency range was accepted. The instrument can be used for the higher frequencies if one changes the hydrophone and uses a different set of filters. The desirable features which need to be considered for the design of an underwater sound level meter are:

1) the hydrophone should be omnidirectional at all frequencies of interest;
2) the equivalent acoustic hydrophone and preamplifier self-noise should be as far below the noise level of Sea State zero as possible;
3) the instrument should have a means for self-calibration;
4) the frequency response should be flat over the frequency range of interest;
5) the instrument should be battery operated;
6) the instrument should have a meter for indicating the true rms noise level with adjustable time constants;
7) the instrument should have an output for recording;
8) the dynamic range of the instrument must be large enough to insure that clipping of very high peaks does not occur;
9) the amplifiers must have a stable gain; and
10) the filters must be simple to operate with stable bandwidth to insure accuracy.

Figure 3.1 shows a block diagram of an underwater sound level meter designed to fulfill these requirements. The system consists of a hydrophone and hydrophone preamplifier, an amplifier, an octave filter set, and a voltmeter for reading the rms of the noise voltage.

The hydrophone was constructed of a ceramic spherical shell which had an outer diameter of 2 in. This shell had a mechanical resonance at 32,000 Hz. A sphere was used in order to achieve omnidirectionality over

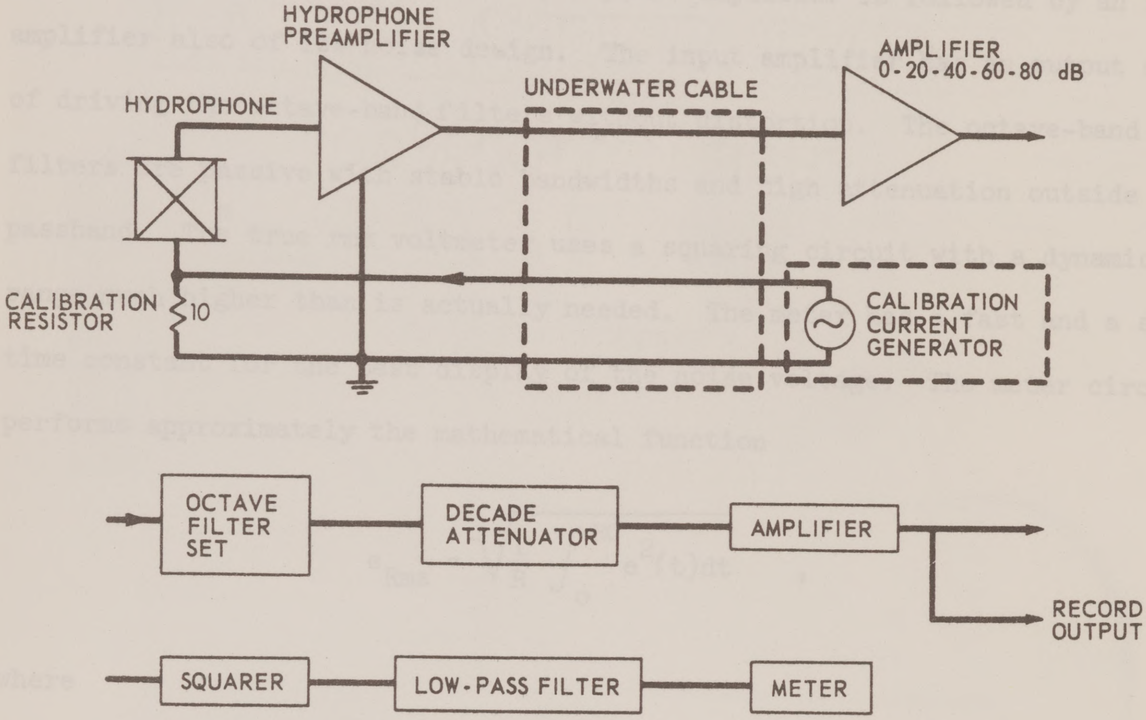

FIGURE 3.1
BLOCK DIAGRAM FOR UNDERWATER SOUND LEVEL METER

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the entire frequency band from 10 Hz to 20,000 Hz. In the final design the electrodes were split into four segments to achieve high sensitivity.

The hydrophone preamplifier is a low noise design, which was installed inside the ceramic shell to shorten the inputs' leads and to improve the low noise performance. The hydrophone amplifier is followed by an input amplifier also of low noise design. The input amplifier has an output capable of driving the octave-band filters without distortion. The octave-band filters are passive with stable bandwidths and high attenuation outside the passband. The true rms voltmeter uses a squaring circuit with a dynamic range much higher than is actually needed. The meter has a fast and a slow time constant for the best display of the noise voltage. The meter circuit performs approximately the mathematical function

$$e_{Rms} = \sqrt{\frac{1}{R} \int_{o}^{RC} e^2(t)dt} \quad ,$$

where

RC is the time constant of the meter circuit.

Figure 3.2 shows the entire set of equipment for the underwater sound level meter. The next chapters contain descriptions of the construction of each part of the instrument.

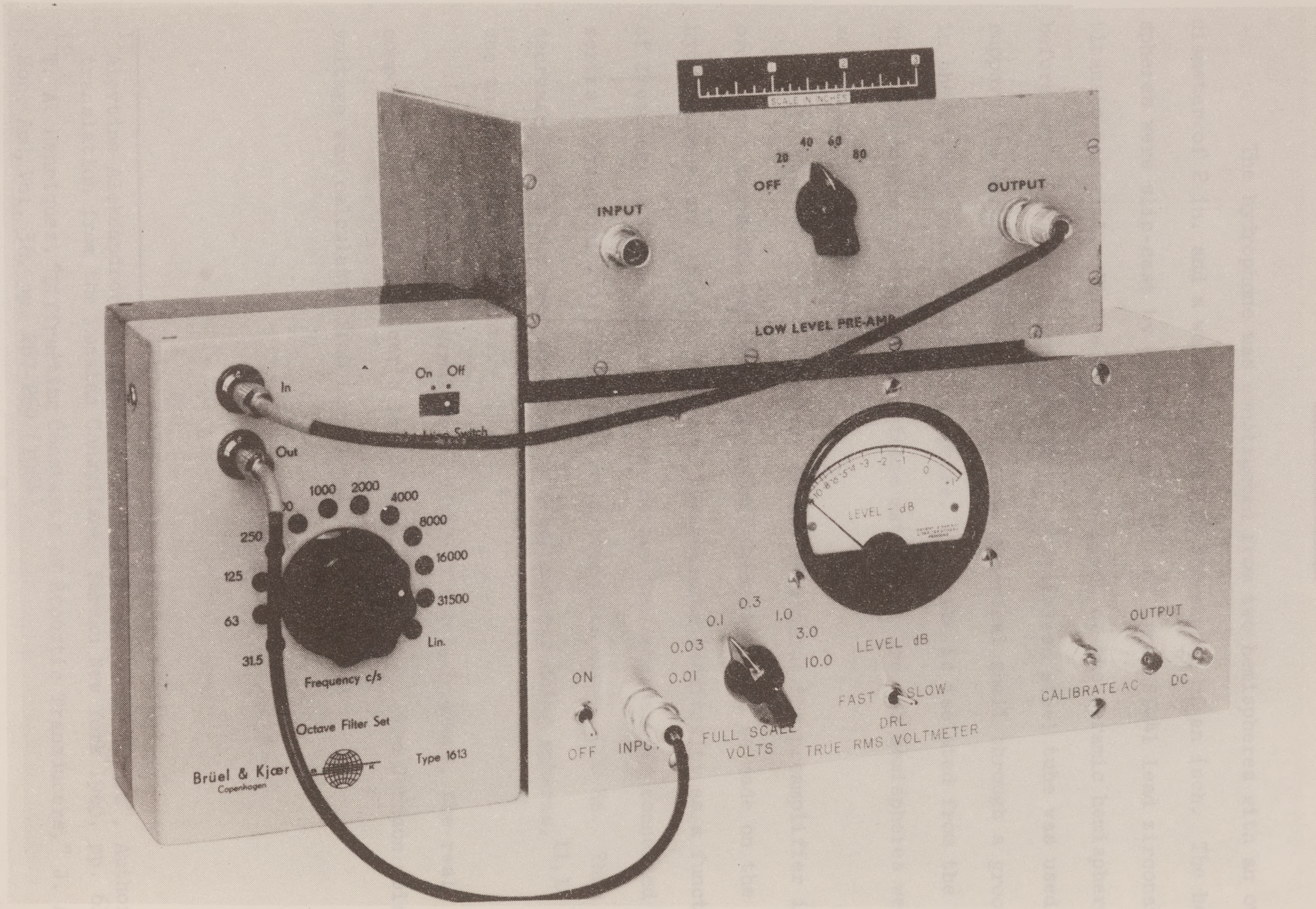

FIGURE 3.2
EQUIPMENT FOR AN UNDERWATER SOUND LEVEL METER

IV. THE HYDROPHONE

The hydrophone was constructed from two hemispheres with an outside diameter of 2 in. and a wall thickness of one-eighth of an inch. The hemispheres were slip-cast by Gulton Industries of type HST-41 lead zirconate-lead titanate material. Figure 4.1 is a photograph of the ceramic hemispheres before assembly with the preamplifier. A stainless steel tube was used to support the sphere. The tube enters the spherical shell through a groove filed in the edge of each ceramic hemisphere. The tube is isolated from the ceramic shell by corprene, a pressure release material. The two hemispheres were sealed together with epoxy.

The hydrophone was first assembled without the preamplifier in order that impedance and sensitivity measurements could be made on the hydrophone alone. Figure 4.2 shows the measured sensitivity as a function of frequency when the electrodes of the two hemispheres were connected in series. The sensitivity decreases at frequencies above 2000 Hz. This decrease, which has been observed by other authors using spheres,[11,12] is due to diffraction effects.

To find the thermal noise limit of the hydrophone, the real component of the transducer's impedance was measured. The Johnson noise voltage was calculated from the equation

$$(e_n)^2 = 4kTBZ(R) \quad , \qquad (4.1)$$

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[11] Alevtina Aleksandrovna Anadena, "Ceramic Acoustic Detectors", Authorized translation from the Russian Consultants Bureau New York 1965, pp. 61-62.

[12] T. A. Henriquez, "Diffraction Constants of Acoustic Transducers," J. Acous. Soc. Am., Vol. 36, pp. 267-269 (1964)

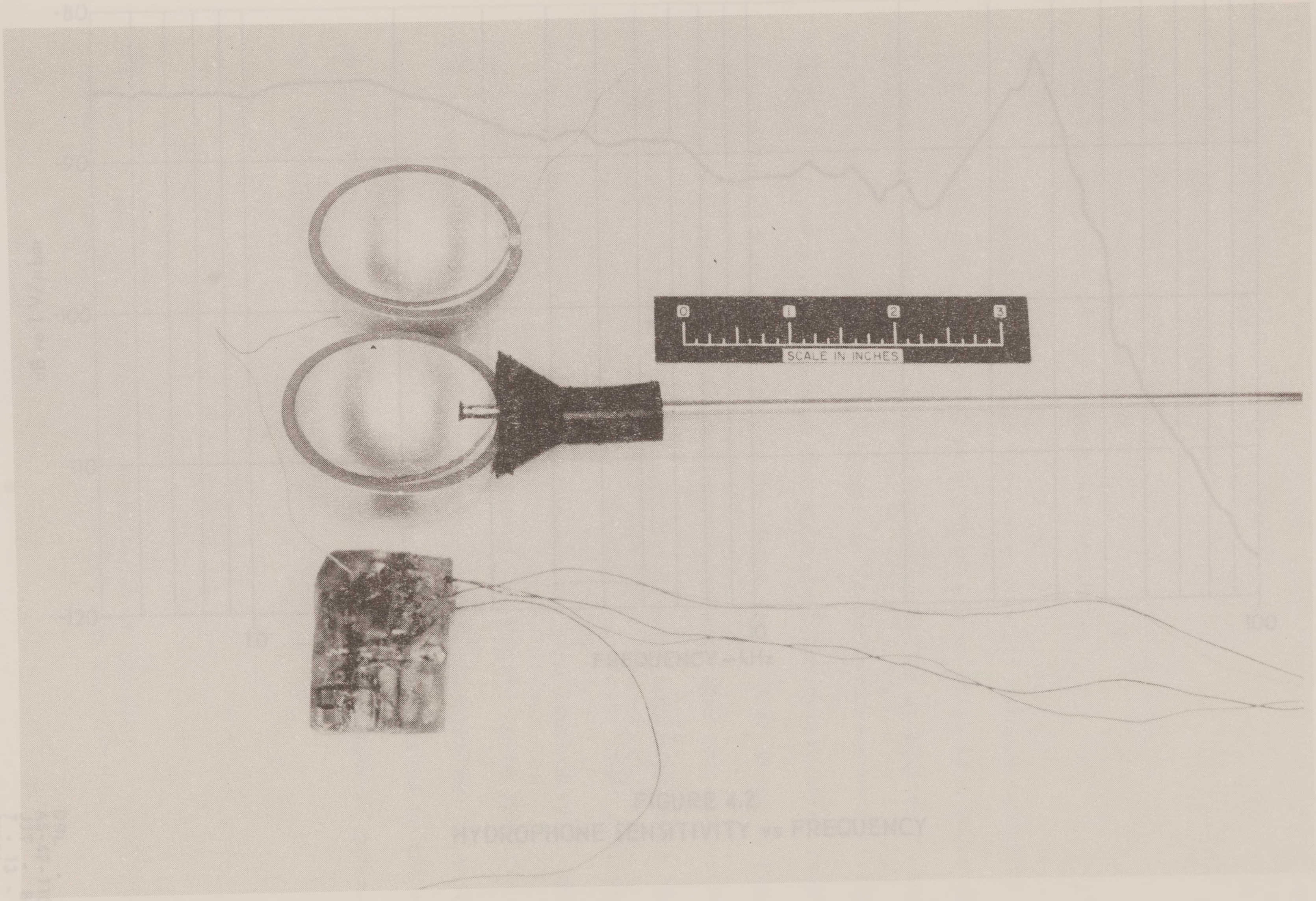

FIGURE 4.1
HYDROPHONE AND PREAMPLIFIER

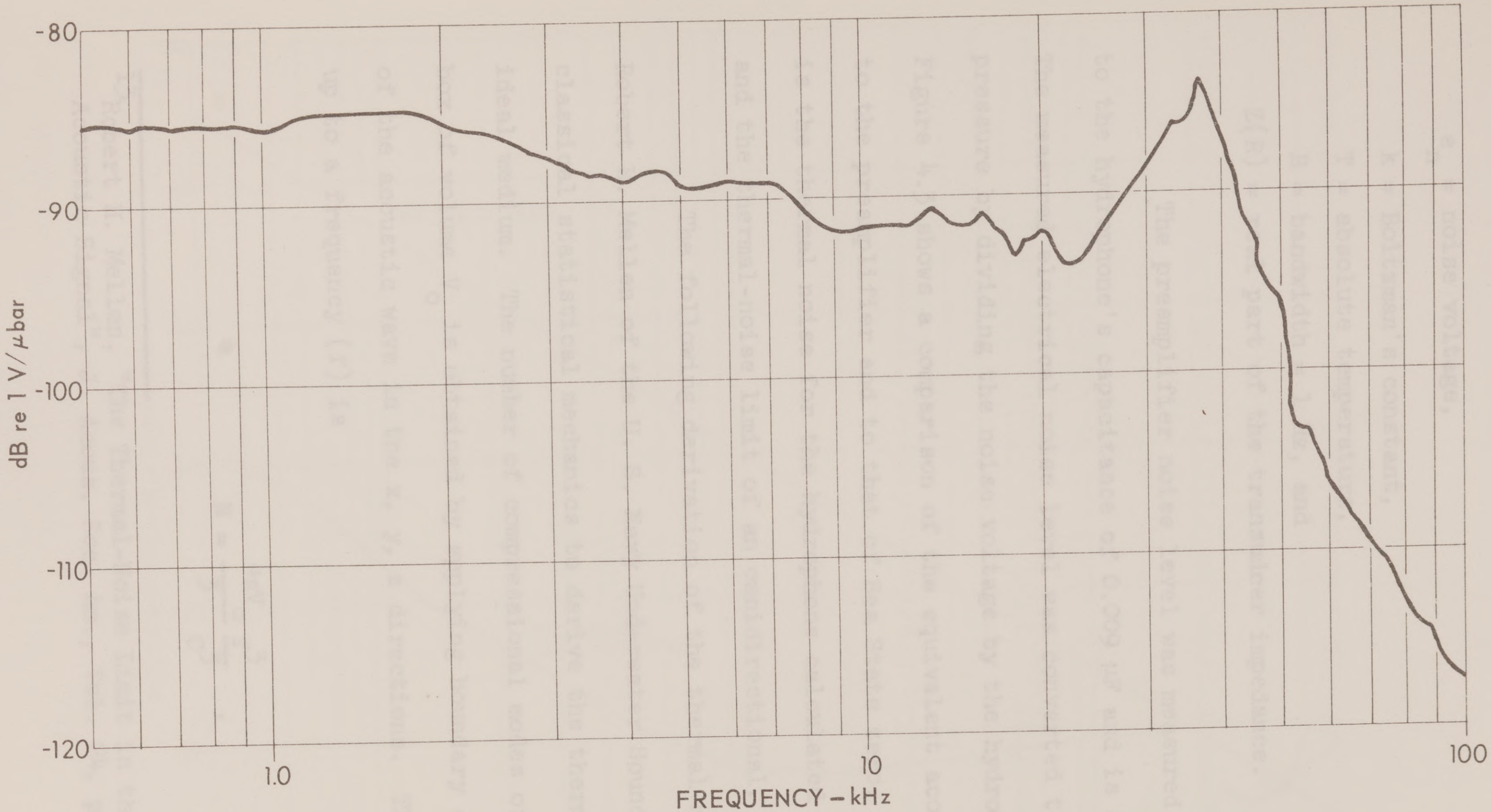

FIGURE 4.2
HYDROPHONE SENSITIVITY vs FREQUENCY

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where

e_n = noise voltage,

k = Boltzman's constant,

T = absolute temperature,

B = bandwidth = 1 Hz, and

Z(R) = real part of the transudcer impedance.

The preamplifier noise level was measured using a capacitor equal to the hydrophone's capacitance of 0.009 μF and is shown in a later chapter. The measured electrical noise level was converted to an equivalent acoustical pressure by dividing the noise voltage by the hydrophone's sensitivity. Figure 4.3 shows a comparison of the equivalent acoustical noise level due to the preamplifier and to that of Sea State zero. Also shown in Fig. 4.3 is the thermal noise for the hydrophone calculated from the above equation, and the thermal-noise limit of an omnidirectional, unit-efficiency hydrophone.

The following derivation of the thermal-noise limit follows that of Robert H. Mellen of the U. S. Navy Underwater Sound Laboratory.[13] Mellen uses classical statistical mechanics to derive the thermal-noise spectrum for an ideal medium. The number of compressional modes of vibration in a cubic box of volume V_o is obtained by applying boundary conditions to the components of the acoustic wave in the x, y, z directions. The number of normal modes up to a frequency (f) is

$$N = \frac{4\pi V_o}{3} \frac{f^3}{C^3} \quad , \qquad (4.2)$$

[13] Robert H. Mellen, "The Thermal-Noise Limit in the Detection of Underwater Acoustic Signal", J. Acous. Soc. Am., Vol. 24, pp. 478-480.

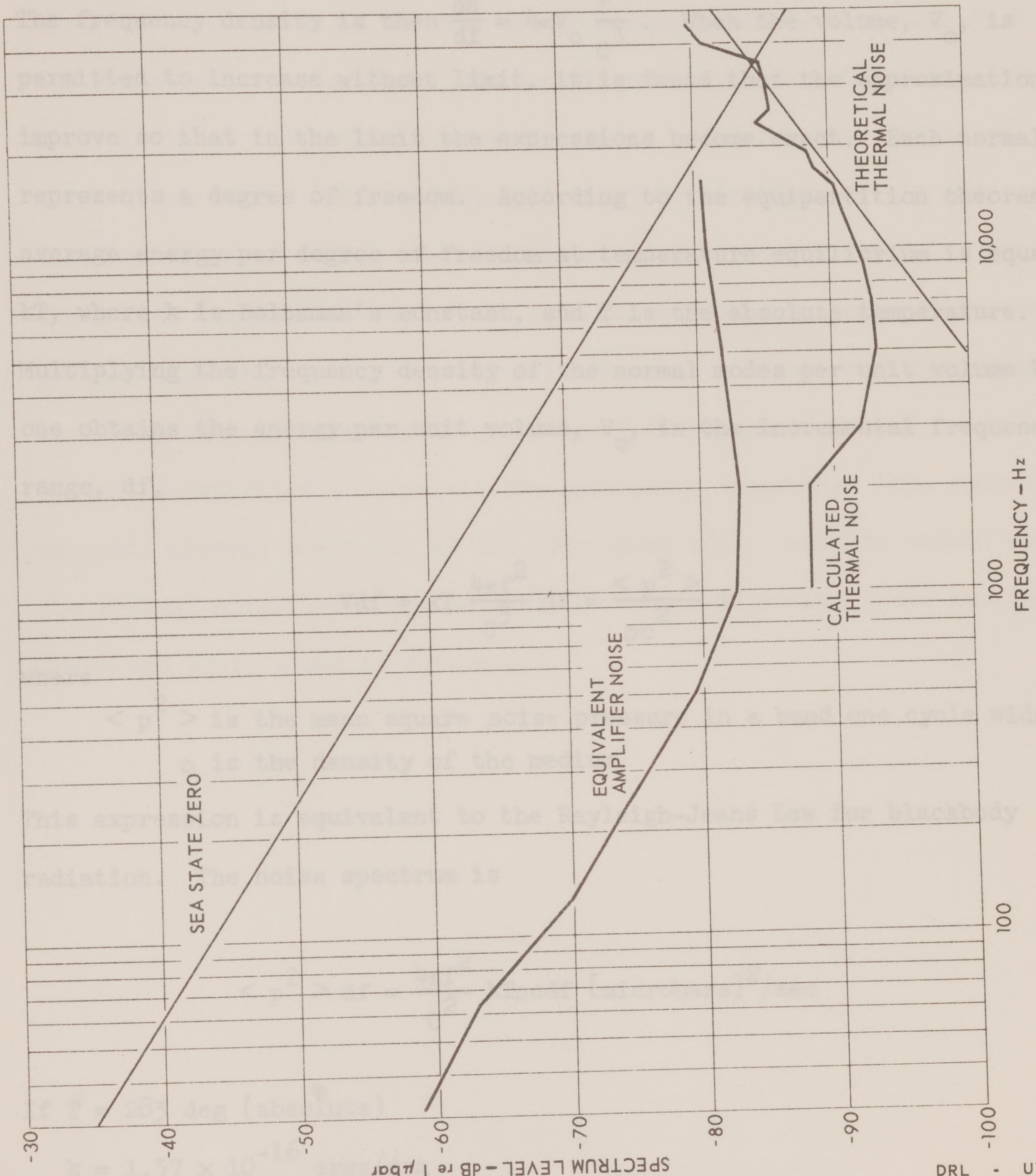

FIGURE 4.3
ACOUSTIC NOISE LEVEL OF AMPLIFIER AND HYDROPHONE

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when

$$V_o \gg \frac{f^3}{C^3}, \text{ and}$$

C = velocity of sound.

The frequency density is then $\frac{dN}{df} = 4\pi V_o \frac{f^2}{C^3}$. When the volume, V_o, is permitted to increase without limit, it is found that the approximations improve so that in the limit the expressions become exact. Each normal mode represents a degree of freedom. According to the equipartition theorem, the average energy per degree of freedom at temperature equilibrium is equal to kT, where k is Boltzman's constant, and T is the absolute temperature. Multiplying the frequency density of the normal modes per unit volume by kT one obtains the energy per unit volume, V_o, in the incremental frequency range, df,

$$Vdf = kT \frac{4\pi f^2}{C^3} df = \frac{< p^2 >}{\rho c^2} df \quad , \qquad (4.3)$$

where

$< p^2 >$ is the mean square noise pressure in a band one cycle wide and

ρ is the density of the medium.

This expression is equivalent to the Rayleigh-Jeans Law for blackbody radiation. The noise spectrum is

$$< p^2 > df = \frac{4\pi f^2}{C^2} kT\rho c df \ [\text{microbars}]^2/\text{sec} \qquad (4.4)$$

If T = 283 deg (absolute)

$k = 1.37 \times 10^{-16}$ ergs/deg

$\rho c = 1.54 \times 10^5$ gm/cm^2 sec

the spectrum level is

$$L_n \cong -115 + 20 \log f \ (\text{dB}/1\mu\text{bar}/\sqrt{\text{Hz}}) \quad . \qquad (4.5)$$

The frequency, f, is in kHz, and L_n is the thermal noise level in dB with reference to 1 μbar for a one cycle band.

The noise levels shown in Fig. 4.3 indicate that the equivalent acoustic noise level of the hydrophone preamplifier is less than 5 dB below the noise level of Sea State zero at frequencies above 10,000 Hz. The sensitivity of the hydrophone was increased, lowering the equivalent acoustic noise level of the elements, by splitting the electrode of the hemisphere. The four segments of the two hemispheres were wired in series. Figure 4.4 shows that the sensitivity of the hydrophone with four segments in series is greater than the sensitivity shown in Fig. 4.2. Figure 4.5 shows the resulting equivalent acoustic noise level of the preamplifier using a 0.0022 μF capacitor to simulate the hydrophone impedance. The equivalent acoustic thermal noise due to the hydrophone was assumed to remain unchanged. The thermal noise level for an ideal medium, and the Sea State zero noise level are again shown as references.

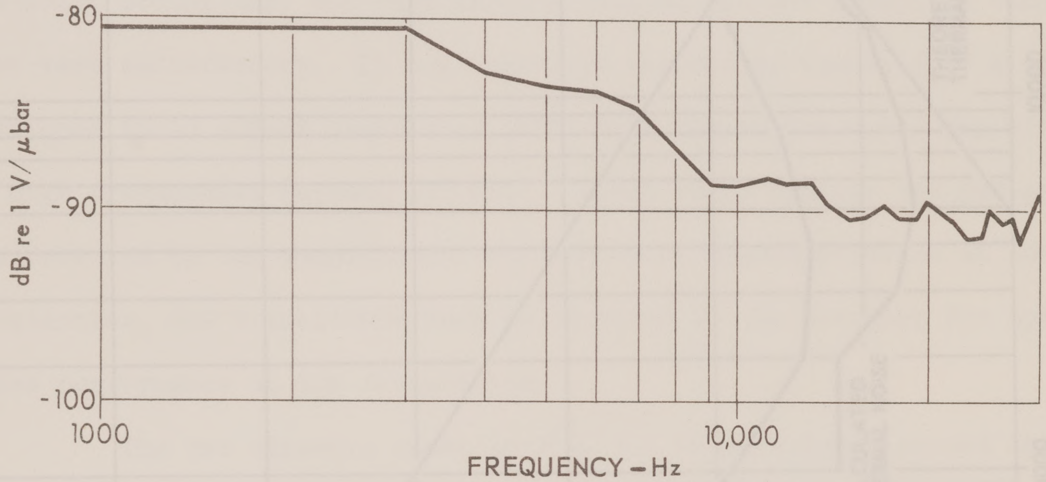

FIGURE 4.4
HYDROPHONE SENSITIVITY SERIES CONNECTION
vs
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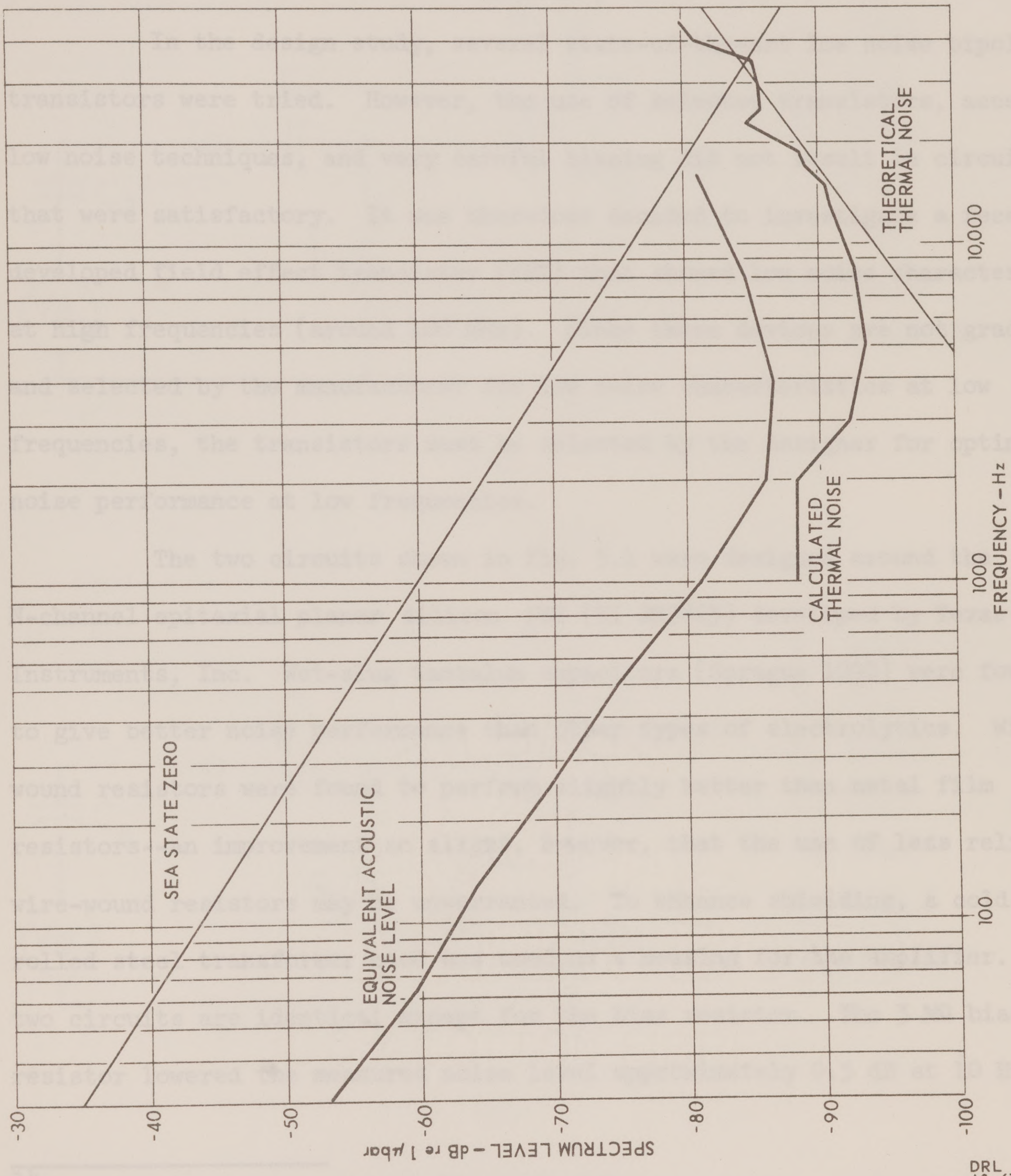

FIGURE 4.5
ACOUSTIC NOISE LEVEL OF AMPLIFIER AND HYDROPHONE

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V. PREAMPLIFIER AND AMPLIFIER

The amplifier design used to construct the hydrophone preamplifier is the result of an extensive design study of low noise preamplifiers.[14]

In the design study, several state-of-the-art low noise bipolar transistors were tried. However, the use of selected transistors, accepted low noise techniques, and very careful biasing did not result in circuits that were satisfactory. It was therefore decided to investigate a recently developed field effect transistor (FET) that showed low noise characteristics at high frequencies (around 100 MHz). Since these devices are not graded and selected by the manufacturer for low noise characteristics at low frequencies, the transistors must be selected by the designer for optimum noise performance at low frequencies.

The two circuits shown in Fig. 5.1 were designed around the N-channel epitaxial planar silicon FET (TI 2N3823) developed by Texas Instruments, Inc. Wet-slug tantalum capacitors (Sprague 109D) were found to give better noise performance than other types of electrolytics. Wire-wound resistors were found to perform slightly better than metal film resistors--an improvement so slight, however, that the use of less reliable wire-wound resistors may be unwarranted. To enhance shielding, a cold rolled steel transformer case was used as a housing for the amplifier. The two circuits are identical except for the bias resistor. The 3 MΩ bias resistor lowered the measured noise level approximately 0.5 dB at 10 Hz.

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[14] J. J. Truchard and J. E. Stockton, "Extremely Low Noise Preamplifier for Audio Frequencies", Defense Research Laboratory, The University of Texas at Austin, Austin, Texas, March, 1967.

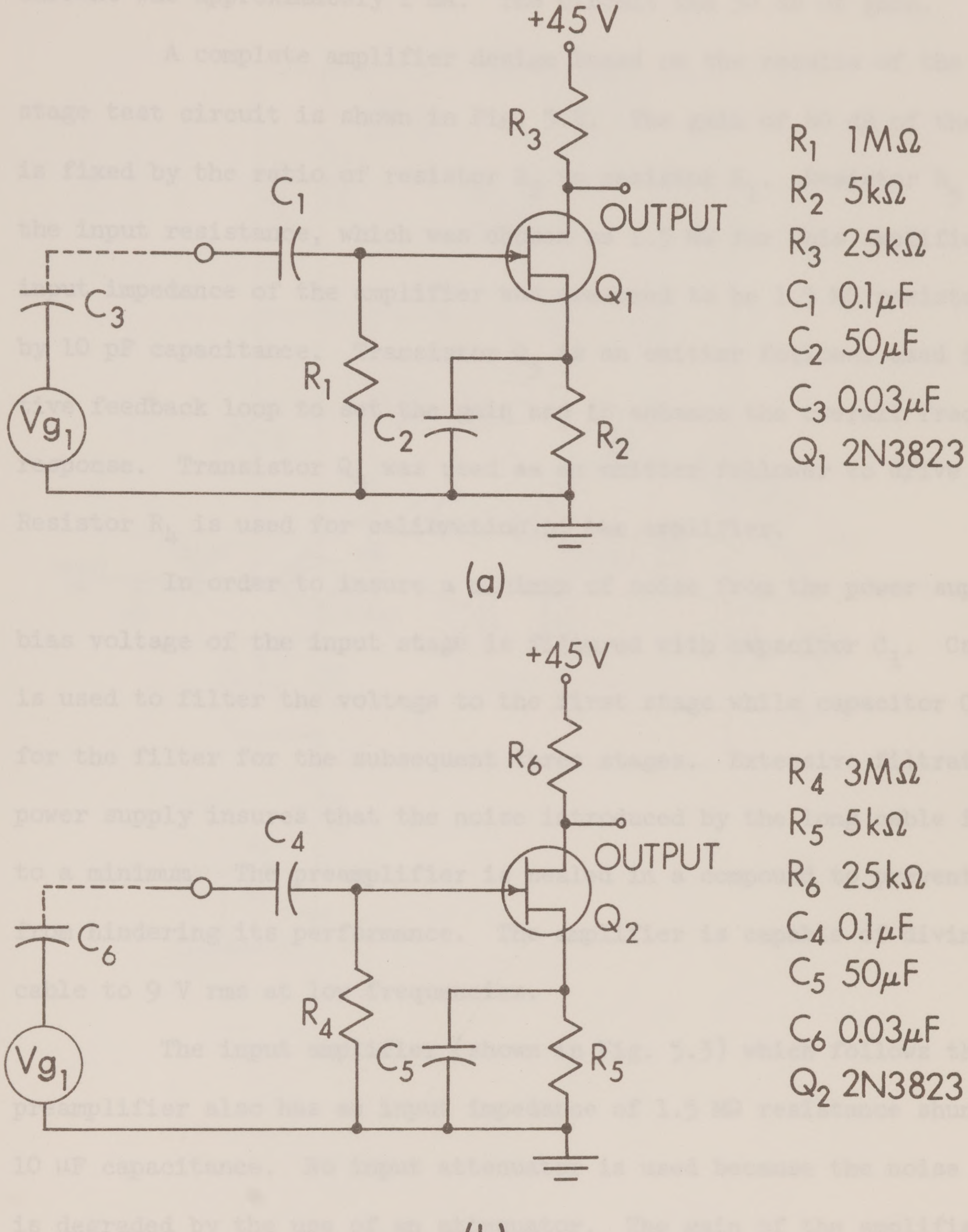

FIGURE 5.1
PREAMPLIFIER BREADBOARD CIRCUITS

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In both circuits, the voltage from drain to source was 15 V and the drain current was approximately 1 mA. The circuit had 32 dB of gain.

A complete amplifier design based on the results of the single stage test circuit is shown in Fig. 5.2. The gain of 40 dB of the amplifier is fixed by the ratio of resistor R_2 to resistor R_1. Resistor R_3 determines the input resistance, which was chosen as 1.5 MΩ for this amplifier. The input impedance of the amplifier was measured to be 1.5 MΩ resistance shunted by 10 pF capacitance. Transistor Q_3 is an emitter follower used in a negative feedback loop to set the gain and to enhance the overall frequency response. Transistor Q_4 was used as an emitter follower to drive the cable. Resistor R_4 is used for calibration of the amplifier.

In order to insure a minimum of noise from the power supply, the bias voltage of the input stage is filtered with capacitor C_1. Capacitor C_2 is used to filter the voltage to the first stage while capacitor C_3 is used for the filter for the subsequent three stages. Extensive filtration of the power supply insures that the noise introduced by the long cable is reduced to a minimum. The preamplifier is sealed in a compound to prevent moisture from hindering its performance. The amplifier is capable of diving the cable to 9 V rms at low frequencies.

The input amplifier (shown in Fig. 5.3) which follows the preamplifier also has an input impedance of 1.5 MΩ resistance shunted by 10 μF capacitance. No input attenuator is used because the noise performance is degraded by the use of an attenuator. The gain of the amplifier is changed by changing the feedback of the amplifiers. The input noise level remains constant when the gain of the amplifier is changed. The circuit consisting of Q_1, Q_2, and Q_3 for the first 40 dB of gain is the same circuit

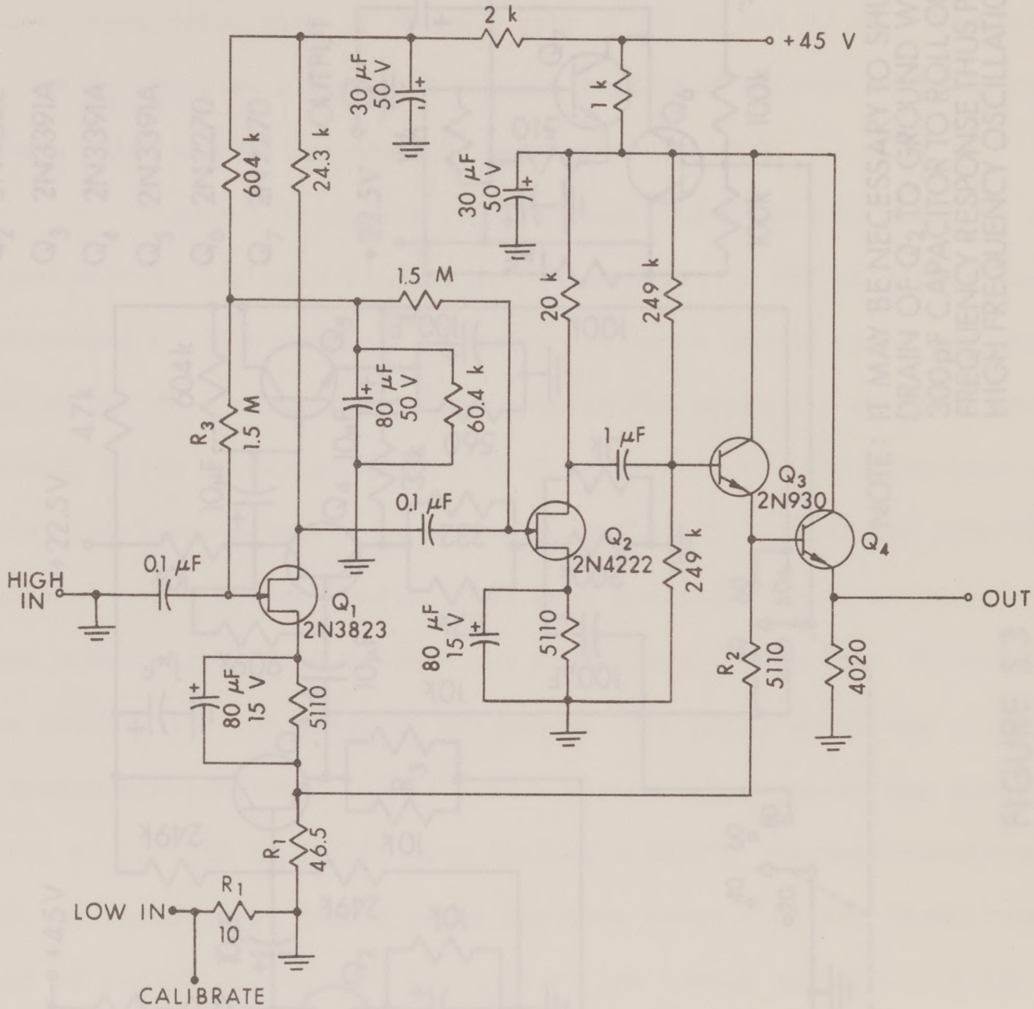

FIGURE 5.2
HYDROPHONE PREAMPLIFIER

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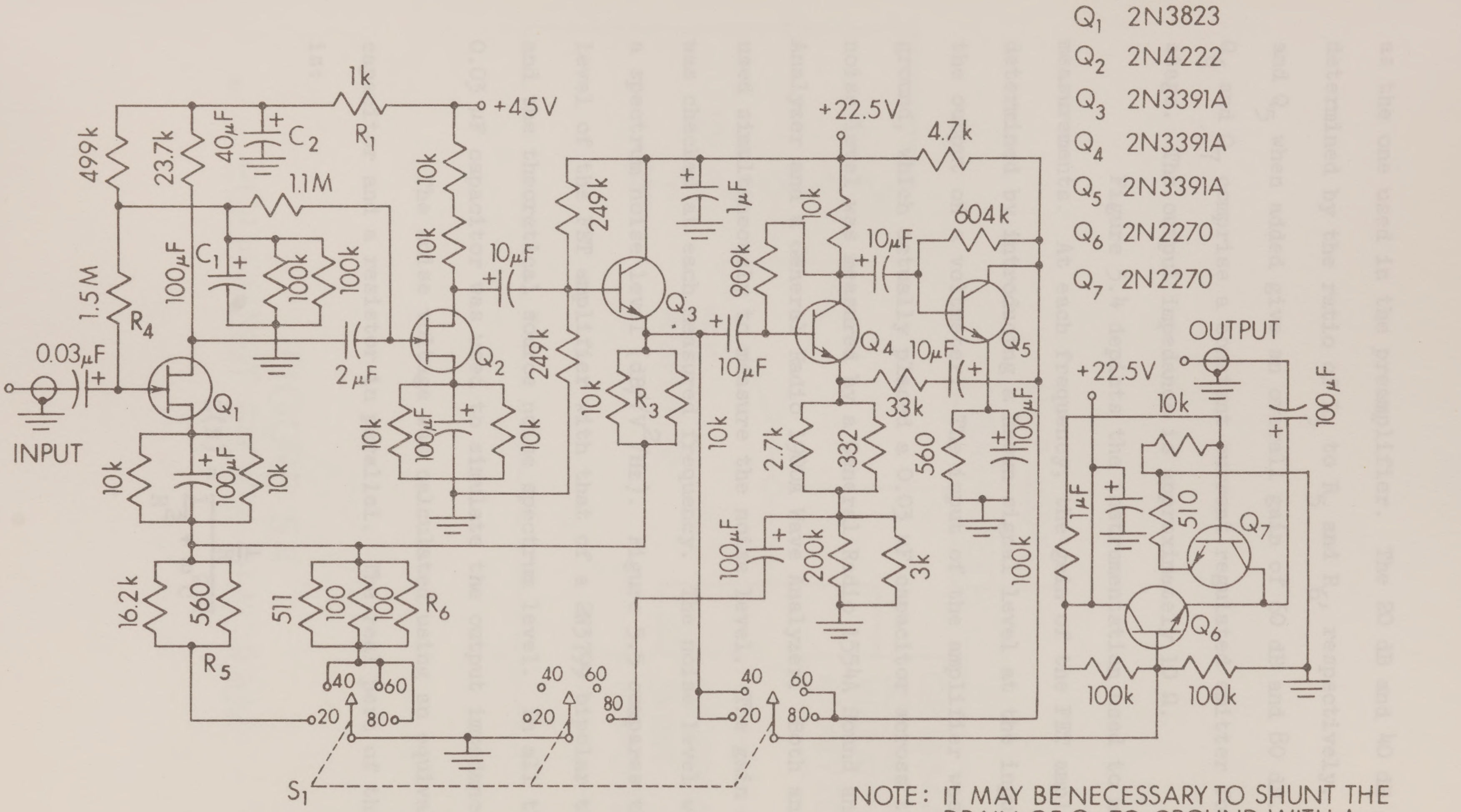

NOTE: IT MAY BE NECESSARY TO SHUNT THE DRAIN OF Q_2 TO GROUND WITH A 300 pF CAPACITOR TO ROLL OFF HIGH FREQUENCY RESPONSE THUS PREVENTING HIGH FREQUENCY OSCILLATIONS.

FIGURE 5.3
LOW-NOISE PREAMPLIFIER

as the one used in the preamplifier. The 20 dB and 40 dB gain steps are determined by the ratio of R_3 to R_5 and R_6, respectively. Transistors Q_4 and Q_5 when added give an overall gain of 60 dB and 80 dB. Transistors Q_6 and Q_7 comprise a constant current regulated emitter follower output stage. The output impedance is approximately 10 Ω.

Figure 5.4 depicts the instrumentation used to make the noise measurements. At each frequency, the gain of the FET amplifier was determined by introducing a known signal level at the input and measuring the output on a voltmeter. The input of the amplifier was then shorted to ground, which actually placed a 0.03 μF capacitor across the input, and the noise level was measured by a General Radio 1554A Sound and Vibration Analyzer and a General Radio 1900A Wave Analyzer. Both analyzers were used simultaneously to measure the noise level. The gain of each analyzer was checked at each measured frequency. The noise level was converted to a spectrum noise level (dB//V^2/Hz). Figure 5.5 compares the spectrum noise level of the FET amplifier with that of a 2N3799 bipolar transistor circuit and the theoretical source noise spectrum level. In all three cases, a 0.03 μF capacitor was used to simulate the output impedance of the transducer.

The noise voltage was calculated using an equivalent circuit of a capacitor and a resistor in parallel. The real part of this source impedance is:

$$Z(R) = \frac{\frac{1}{R}}{\frac{1}{R^2} + \omega^2 C^2} , \qquad (5.1)$$

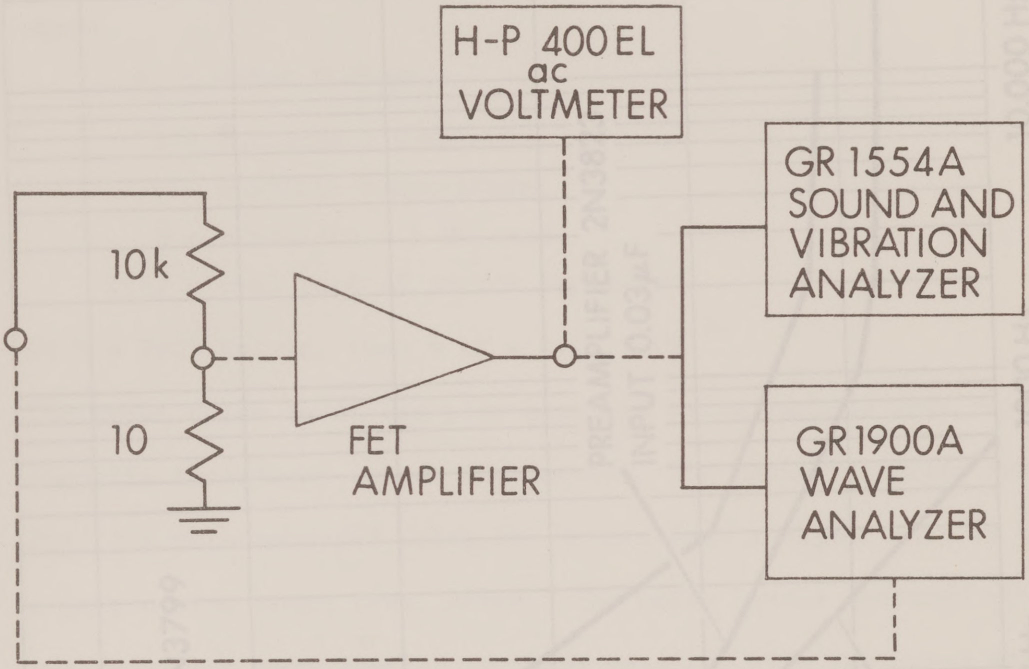

FIGURE 5.4
EQUIPMENT BLOCK DIAGRAM

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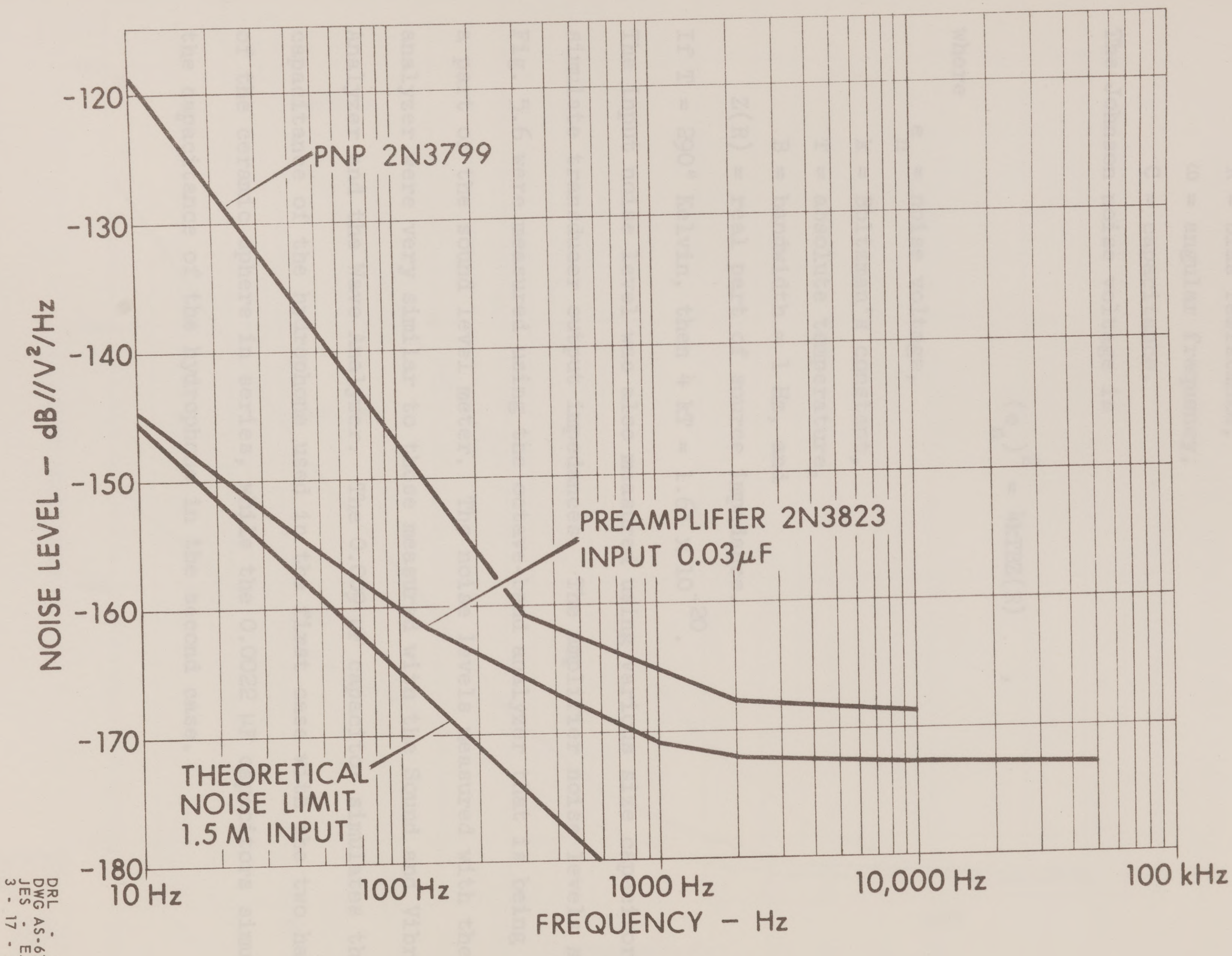

FIGURE 5.5
NOISE LEVEL vs FREQUENCY

where

$Z(R)$ = real part of source impedance,

R = bias resistance,

ω = angular frequency,

C = capacitance.

The Johnson noise voltage is

$$(e_n)^2 = 4kTBZ(R) \quad , \tag{5.2}$$

where

e_n = noise voltage,

k = Boltzman's constant,

T = absolute temperature,

B = bandwidth = 1 Hz, and

$Z(R)$ = real part of source impedance.

If $T = 290°$ Kelvin, then $4\ kT = 1.63 \times 10^{-20}$.

The input noise level was also measured using various size capacitors to simulate transducer output impedances. The amplifier noise levels shown in Fig. 5.6 were measured using the octave-band analyzer that is being used as a part of the sound level meter. The noise levels measured with the octave analyzer were very similar to those measured with the Sound and Vibration Analyzer and the Wave Analyzer. The 0.009 μF capacitor simulates the capacitance of the hydrophone used in the first case with the two halves of the ceramic sphere in series, while the 0.0022 μF capacitors simulated the capacitance of the hydrophone in the second case.

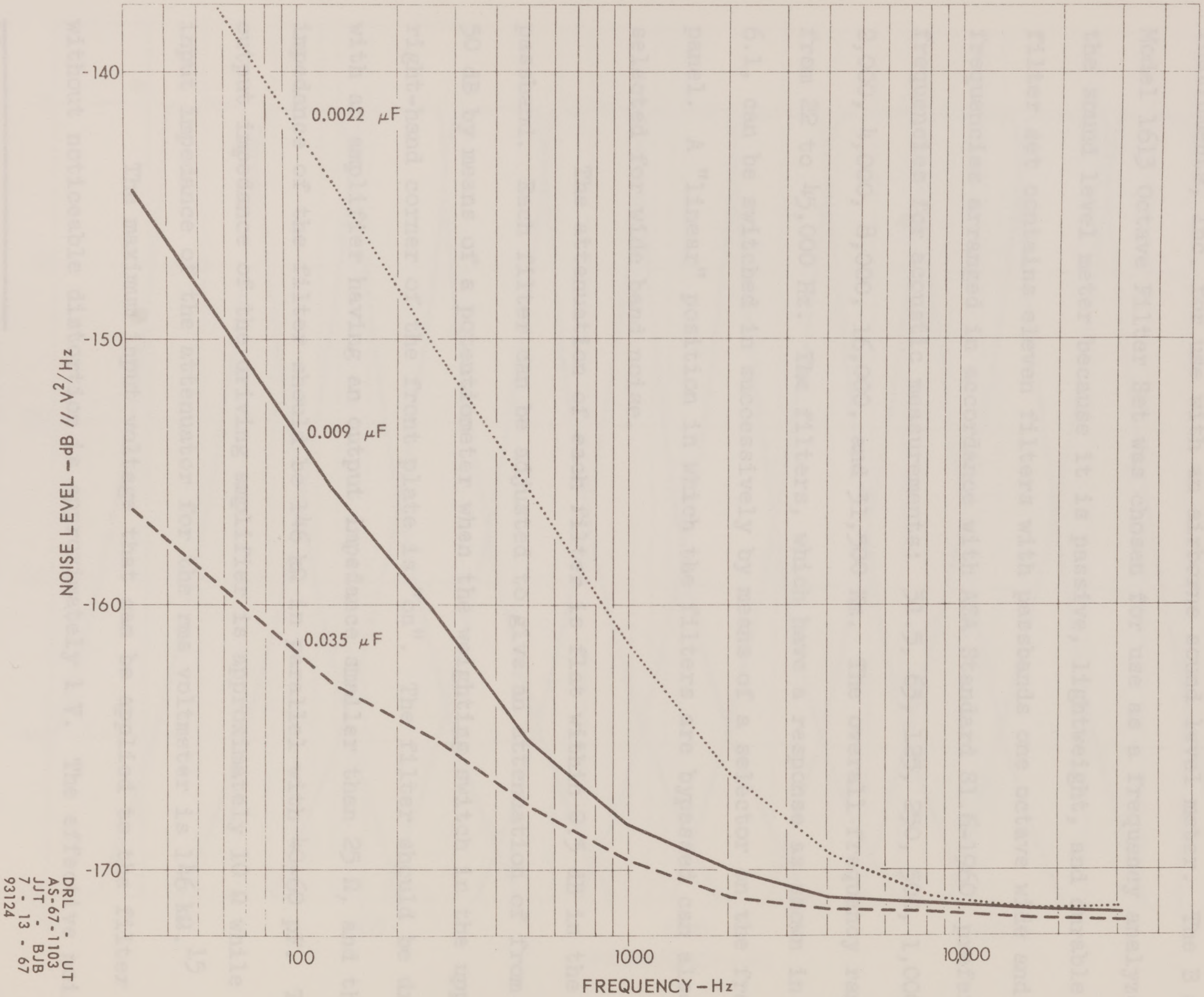

FIGURE 5.6
HYDROPHONE PREAMPLIFIER NOISE LEVEL vs FREQUENCY

VI. OCTAVE FILTER SET

The octave filter set is a commercial unit built by B and K Instruments, Inc. for use with an airborne sound level meter. The B and K Model 1613 Octave Filter Set was chosen for use as a frequency analyzer for the sound level meter because it is passive, lightweight, and durable. The filter set contains eleven filters with passbands one octave wide and center frequencies arranged in accordance with ASA Standard S1.6-1960, preferred frequencies for acoustic measurements: 31.5, 63, 125, 250, 500, 1,000, 2,000, 4,000, 8,000, 16,000, and 31,500 Hz. The overall frequency range is from 22 to 45,000 Hz. The filters, which have a response as shown in Fig. 6.1, can be switched in successively by means of a selector on the front panel. A "linear" position in which the filters are bypassed can also be selected for wide band noise.

The attenuation of each filter is flat within 0.5 dB in the passband. Each filter can be adjusted to give an attenuation of from 0 to 50 dB by means of a potentiometer when the weighting switch in the upper right-hand corner of the front plate is "on". The filter should be driven with an amplifier having an output impedance smaller than 25 Ω, and the load impedance of the filter should be 146 kΩ in parallel with 40-60 pF. The output impedance of the driving amplifier is approximately 10 Ω while the input impedance of the attenuator for the rms voltmeter is 146 kΩ.[15]

The maximum input voltage that can be applied to the filter without noticeable distortion is approximately 1 V. The effective noise

[15] Brüel and Kjaer, Copenhagen, Denmark, 1966, B and K Instruments, Inc. pp. 161-162.

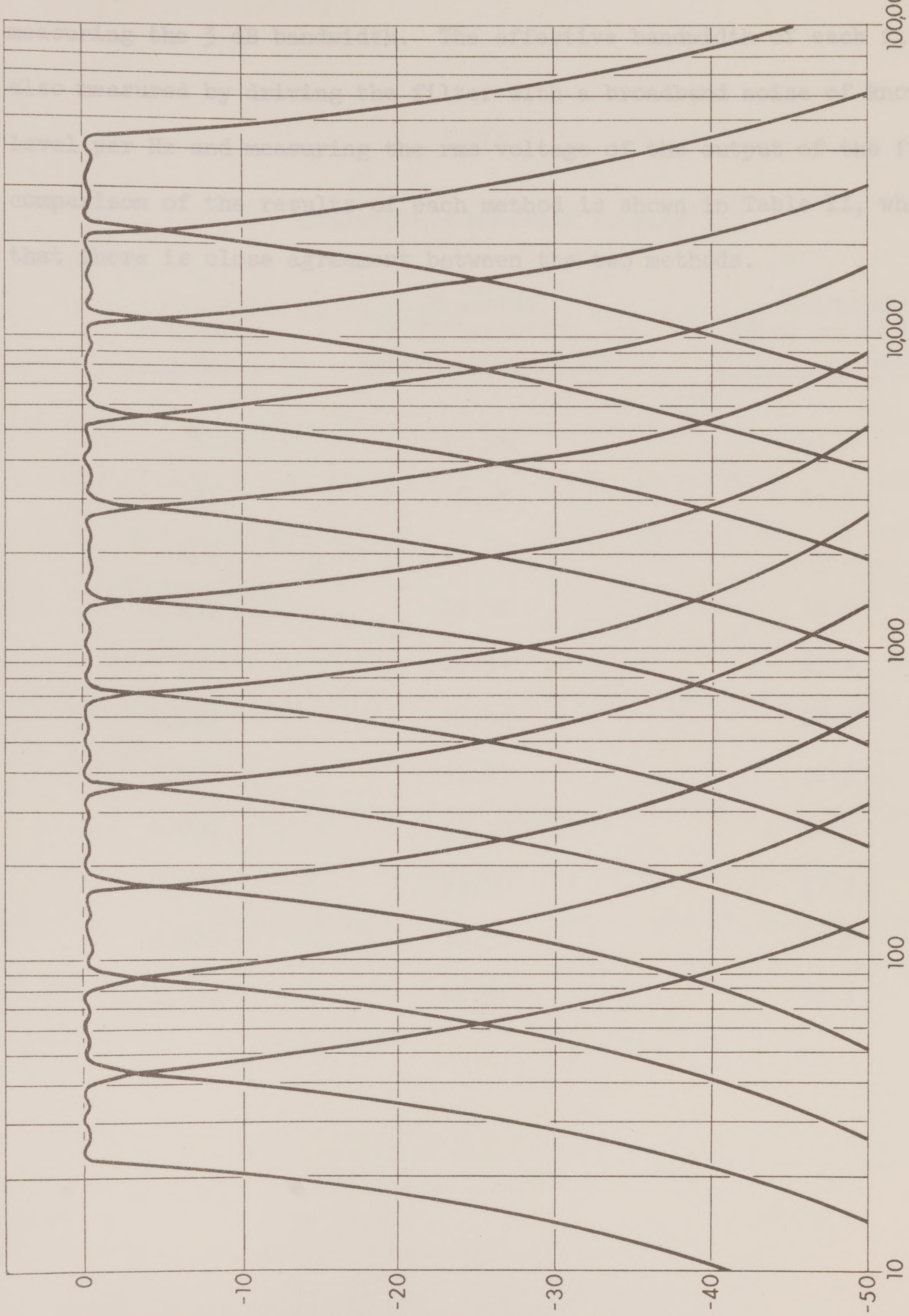

FIGURE 6.1
BRÜEL & KJAER OCTAVE FILTER TYPE 1613

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bandwidth of each filter was obtained by using pure tone signals and measuring the 3 dB bandwidth. The effective bandwidth of each filter was also measured by driving the filter with a broadband noise of known voltage level per Hz and measuring the rms voltage of the output of the filters. A comparison of the results of each method is shown in Table II, which shows that there is close agreement between the two methods.

TABLE II

BANDWIDTH FOR OCTAVE FILTERS

Center Frequency Hz	Measured 3 dB Bandwidth 10 log (Bandwidth)	Measured Noise Bandwidth 10 log (Bandwidth)
31.5	13.36	13.4
63	16.53	16.5
125	19.49	19.5
250	22.50	22.5
500	25.54	25.6
1,000	28.36	28.5
2,000	31.47	31.5
4,000	34.30	34.5
8,000	37.50	37.5
16,000	40.50	40.5
31,500	43.51	43.5

VII. THE TRUE ROOT-MEAN-SQUARE VOLTMETER

The true rms voltmeter consists of an input attenuator, a 40 dB gain amplifier, an emitter follower driver for the output ac voltage, and an emitter follower to drive the squaring circuit. A transformer is used to isolate the driver from the squaring circuit which drives a microammeter.

The input attenuator attenuates the signal in 10 dB steps. The input impedance of the attenuator is made to equal the recommended load for the filter set. After being attenuated, the signal is amplified 40 dB and attenuated with a variable gain control used to calibrate the gain of the entire system. Figure 7.1 shows the circuit for the input attenuator and the 40 dB amplifier.

The output and the squaring circuit is shown in Fig. 7.2. Two emitter followers are used--one to drive the output voltage and one to drive the squaring and meter circuit.

Transistor Q_3 is a field effect transistor used to square the voltage. The circuit was designed by the author and Dan Allen of the Defense Research Laboratory (DRL), The University of Texas at Austin, Austin, Texas. The circuit utilizes the square-law characteristic of a field effect transistor. The conductance of a field effect transistor is

$$G_o = G_{oo} \left(1 - \frac{V_g}{V_p}\right) \qquad (7.1)$$

where

G_o = conductance from drain to source,

G_{oo} = conductance for zero gate voltage,

V_g = gate voltage, and

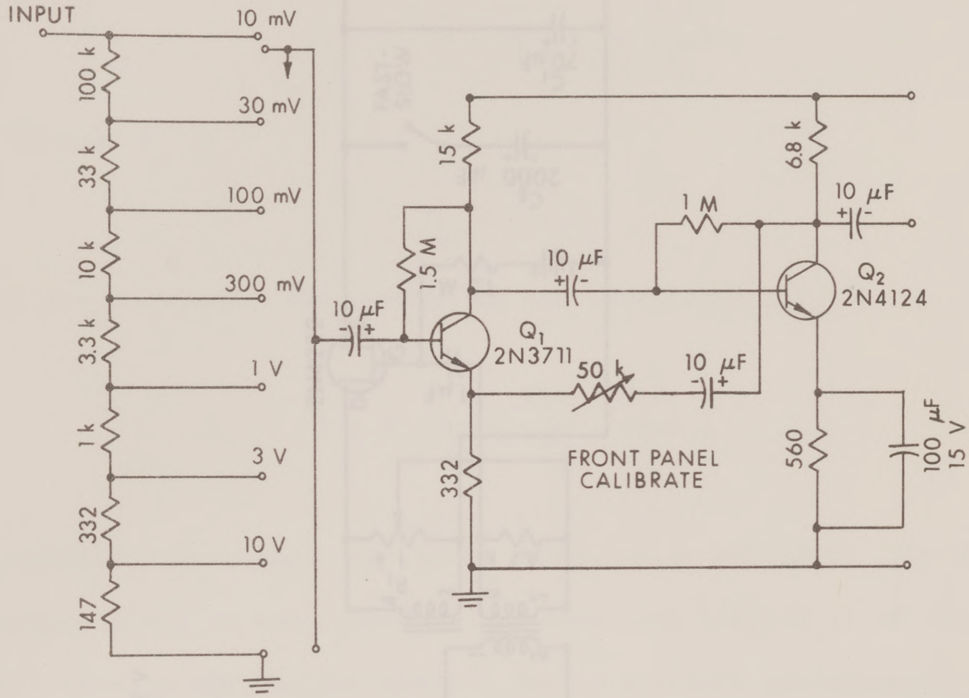

FIGURE 7.1
AMPLIFIER FOR RMS VOLTMETER

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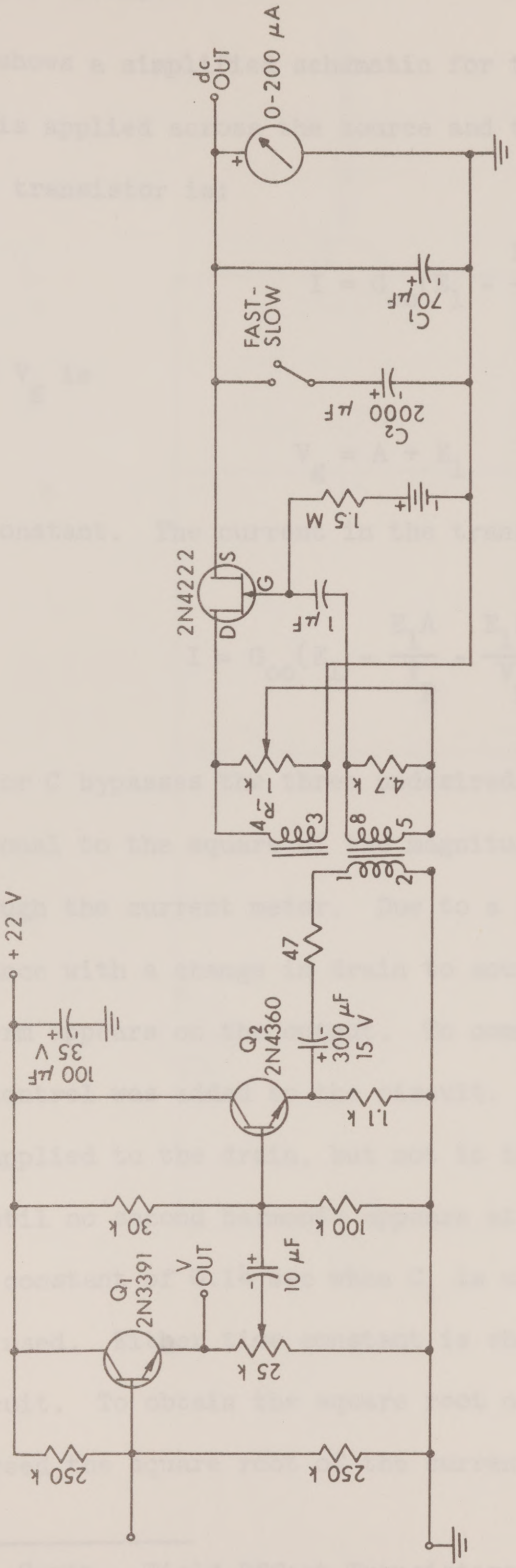

FIGURE 7.2
RMS VOLTMETER

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V_p = pinch-off voltage.[16]

Figure 7.3 shows a simplified schematic for the squaring circuit. If a noise voltage E_1 is applied across the source and the capacitor C_1, the current through the transistor is:

$$I = G_{oo}(E_1 - \frac{E_1 V_g}{V_p}) \quad . \tag{7.2}$$

The voltage V_g is

$$V_g = A + E_1 \tag{7.3}$$

where A = constant. The current in the transistor is:

$$I = G_{oo}(E_1 - \frac{E_1 A}{V_p} - \frac{E_1 E_1}{V_p}) \quad . \tag{7.4}$$

The capacitor C bypasses the three undesired ac voltages. The direct current is proportional to the square of the magnitude ($|E_1||E_1|$) of the noise that passes through the current meter. Due to a slight nonlinearity in the change in conductance with a change in drain to source voltage, an unwanted second harmonic term appears on the output. To compensate for this effect, a linearity control was added to the circuit. To adjust the linearity, a signal is applied to the drain, but not to the gate, and the control is adjusted until no second harmonic appears at the output. The meter circuit has a time constant of 0.14 sec when C_1 is used, and a time constant of 4 sec when C_2 is used. Either time constant is chosen by switching C_2 in and out of the circuit. To obtain the square root of the signal, the meter is calibrated to read the square root of the current applied to it.

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[16] Leonce J. Sevin, Field Effect Transistors, McGraw-Hill, 1965.

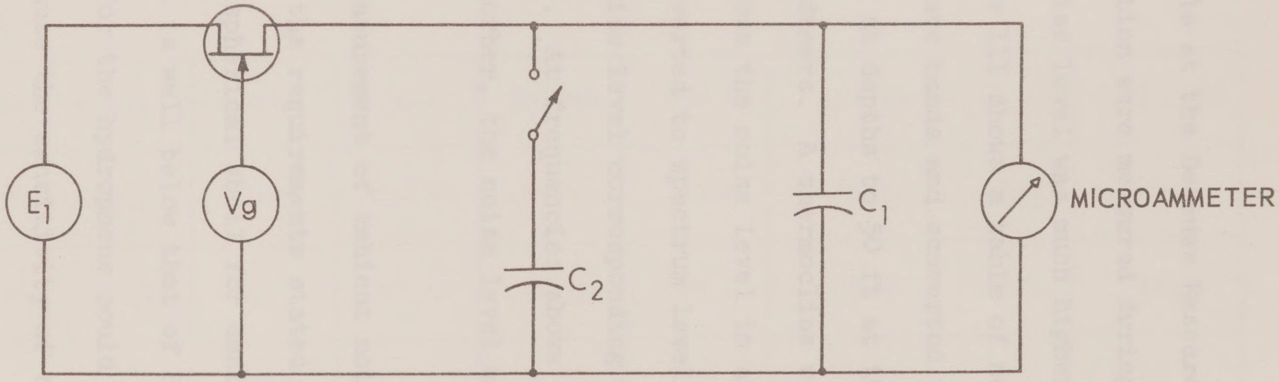

FIGURE 7.3
SIMPLIFIED SCHEMATIC FOR SQUARING CIRCUIT

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VIII. ACOUSTIC MEASUREMENTS AND CONCLUSION

Noise levels at the Defense Research Laboratory's Lake Travis Calibration Test Station were measured during and after working hours. During working hours the noise level was much higher than the noise level after working hours. Table III shows a table of noise levels measured after working hours in octave bands and converted to spectrum levels. These noise levels were measured at depths to 50 ft at the location normally used for calibration of transducers. A thermocline was present at a depth of forty feet. Figure 8.1 shows the noise level in an anechoic tank measured in octave bands and converted to spectrum levels. The noise level of the amplifier and the noise level corresponding to Sea State zero are also shown in this figure. At frequencies above 1 kHz where the tank wall lining was an effective absorber, the noise level measured was primarily due to the amplifier.

For the measurement of ambient noise, the underwater sound level meter meets most of the requirements stated in Chapter III. The hydrophone is constructed of a spherical shell for omnidirectionality. The equivalent acoustic noise level is well below that of Sea State zero to 10 kHz. A flat frequency response for the hydrophone could not be achieved over the entire frequency range because the sensitivity of the sphere decreases above 3 kHz due to defraction of the sound around the sphere. The choice of hydrophone involves some compromise. High sensitivity, omnidirectionality, and flat frequency response cannot be obtained simultaneously. The hydrophone for the underwater sound level meter sacrifices flat frequency response in order to obtain high sensitivity and omnidirectionality. The instrument

TABLE III

SPECTRUM NOISE LEVELS AT LAKE TRAVIS CALIBRATION STATION

dB re 1 microbar

BAND CENTER FREQUENCY

DEPTH - FEET	16 kHz	8 kHz	4 kHz	2 kHz	1 kHz	500 Hz	250 Hz	125 Hz	63 Hz	31.5 Hz
10	-56.5	-55.5	-52.3	-48.5	-44.4	-34.5	-25.5	-22.0	-5.0	-16.9
20	-57.5	-54.5	-49.3	-49.5	-45.4	-34.5	-28.0	-23.0	-5.5	-16.9
30	-56.5	-53.5	-49.3	-48.5	-43.4	-35.5	-27.5	-25.0	-6.0	-13.9
40	-50.5	-45.5	-49.3	-48.5	-46.4	-34.5	-17.5	-14.5	-5.5	-6.9
50	-59.5	-55.5	-50.3	-47.5	-45.4	-33.5	-28.0	-24.5	-7.0	-13.9

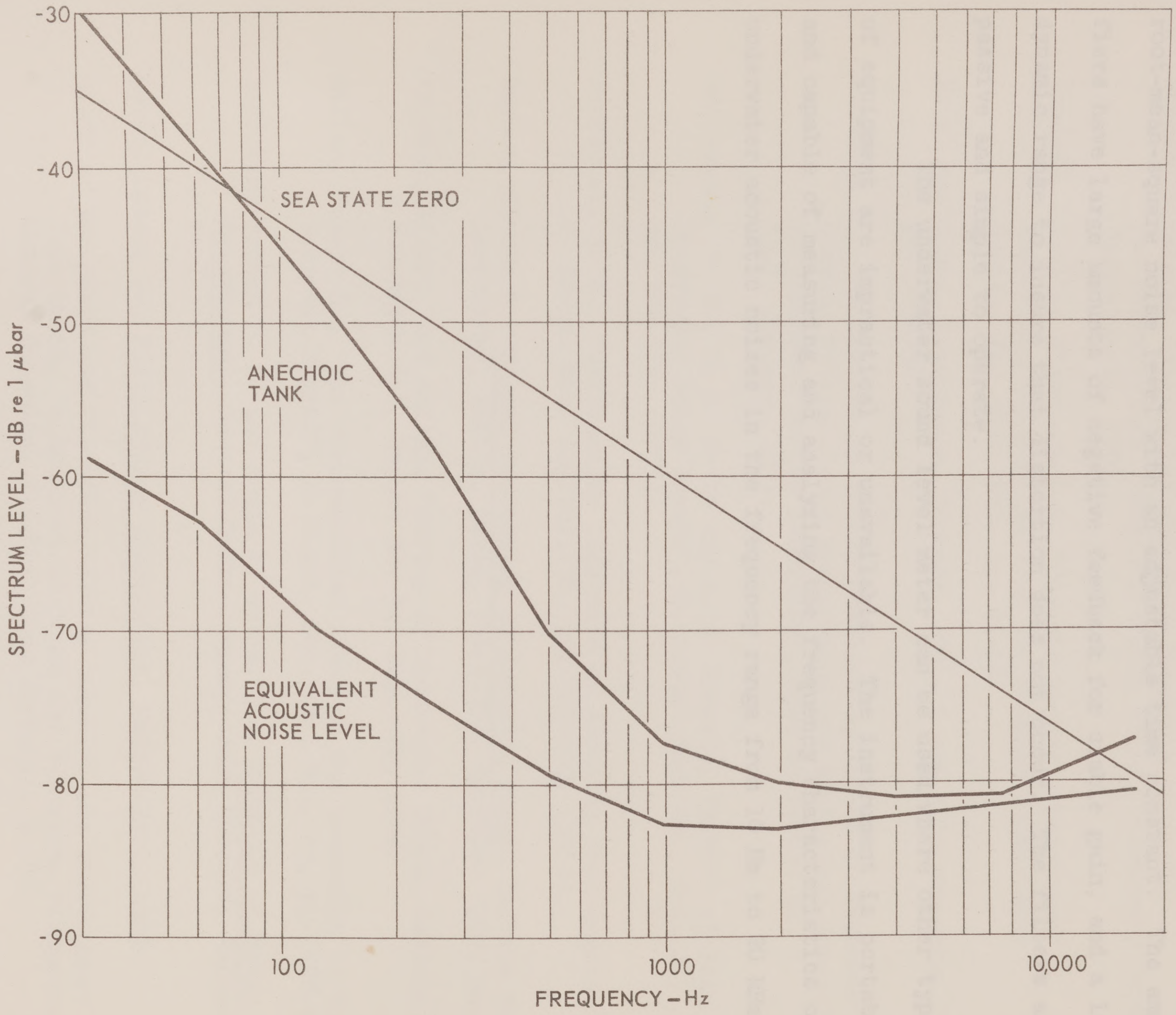

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FIGURE 8.1
NOISE LEVEL IN AN ANECHOIC TANK

contains a means for calibration but it does not have an internal oscillator. The instrument is battery operated and has a meter for indicating the root-mean-square noise level with an adjustable time constant. The amplifiers have large amounts of negative feedback for stable gain, and a large dynamic range to insure that distortion does not occur. The filters are passive and simple to operate.

The underwater sound level meter can be used where other types of equipment are impractical or unavailable. The instrument is portable and capable of measuring and analyzing the frequency characteristics of underwater acoustic noises in the frequency range from 10 Hz to 20 kHz.

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