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UNDERWATER SOUND SIMULATOR

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CONTENTS

Abstract	ii
Problem Status	ii
Authorization	ii
INTRODUCTION	1
NATURE AND SCOPE OF PROBLEM	1
DESIGN APPROACH	1
EQUIPMENT	2
Signal	2
Tape Transport Mechanism	3
Preamplifier	5
Transistor Power Amplifiers	5
Transducers	10
Control Circuit	13
Power Source	14
FLOAT AND CONTAINER	16
EVALUATION TECHNIQUES	20
RESULTS AND DISCUSSION	22
CONCLUSIONS	26
RECOMMENDATIONS	28
ACKNOWLEDGMENTS	28
REFERENCES	29
APPENDIX – Letter Report on Submarine Operations with Task Group Alpha	30

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ABSTRACT

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A system has been developed which can produce underwater sound very similar to the aural signatures of ships at sea. The complete system, weighing 825 pounds in air, consists of a float and an electronics package suspended at the end of a length of wire cable. The electronics package contains a tape-playback system, the necessary preamplifiers and power amplifiers, all transistorized, a high-efficiency battery, a control system, and high-performance, lightweight transducers.

The system was evaluated at NRL, and was tested in the Atlantic Ocean with Task Group Alpha. Although the response of the present system, ±2.5 db from 500 cps to 3.5 kc, is considered inadequate for simulation of many ships, some ships at high speeds can be effectively simulated, according to listening tests with the submarine sonar operators in Task Group Alpha.

The necessary frequency response for relatively effective simulation of most ships was determined to be from 100 cps to 5 kc. It may be possible to use simulator source levels of as much as an order of magnitude less than that of the original ship; a study to determine the effects of the ocean medium on the effectiveness of simulator transmission is recommended.

Although the existing system is sufficiently small for many purposes, further research on transducers, particularly in the area of efficiency when transmitting noise signals, may result in considerable size reduction. New developments in power sources and other electronic components may also add to the general efficiency of the system.

PROBLEM STATUS

This problem was closed as of June 7, 1960.

AUTHORIZATION

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INTRODUCTION

The techniques of modern submarine warfare and the increased capability of the submarine in terms of speed, maneuverability, and endurance have made essential the development of new devices and techniques for antisubmarine warfare. One such device would be a system which can simulate the aural signatures of ships, either singly or in convoy, and deceive the sonar operator on a submarine, thus decoying him away from ships or into an area of intensive ASW coverage. Such a system could be responsible for the preservation of many ships and lives as well as the detection and destruction of submarines which otherwise might remain undiscovered.

Several research programs which have direct bearing on the feasibility of such a system have been underway at the U.S. Naval Research Laboratory. These programs have resulted in the development of high-performance, lightweight transducers, power amplifiers which, utilizing transistors, are capable of high efficiency, operate at low temperatures, and are quite rugged, and batteries that are small and light in weight. Moreover, reliable tape repeater mechanisms have been developed. At the same time, considerable effort has been expended at other laboratories in obtaining and analyzing recordings of ships' signatures. The combination of these factors has made achievable a device which can transmit several octaves of a ship's signature, yet is sufficiently small, light, and durable to be launched from either ships or helicopters and is capable of several hours of operation.

NATURE AND SCOPE OF PROBLEM

This study was initiated to demonstrate that an underwater sound simulator could be developed which would reproduce original ship signatures with sufficient realism to gain plausible acceptance by a qualified sonar operator. The simulator was to consist of a recorded signal source, associated amplifier and transmitter sections, power supply, and transducers in a package capable of being launched by either a surface ship or helicopter. The frequency range of the simulator was originally intended to cover approximately one octave in the band from one to two kilocycles and was to have a source level several db above that of a typical destroyer.

The urgency of meeting the completion date requested by the Chief of Naval Operations (1) required the use of available components where possible. Furthermore, time did not permit an investigation to determine which characteristics of a surface ship's acoustic signature must be simulated to cause a sonar operator to classify the signal as a surface ship.

DESIGN APPROACH

One basic approach was considered for the simulator; however, two configurations of the electrical circuit and two arrangements for the mechanical system were analyzed. These are shown in Figs. 1a through 1d.

Note – Mr. D[redacted]rueger is at present affiliated with NASA.

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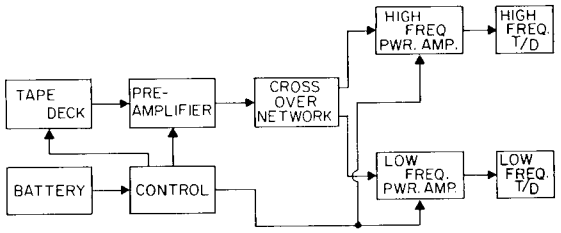
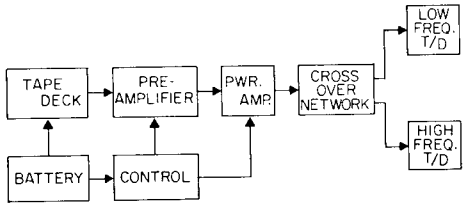
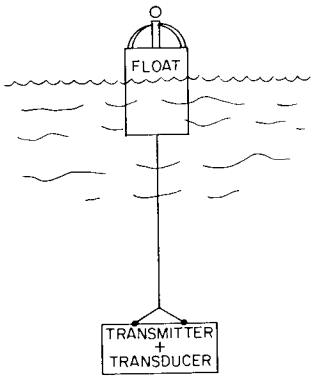


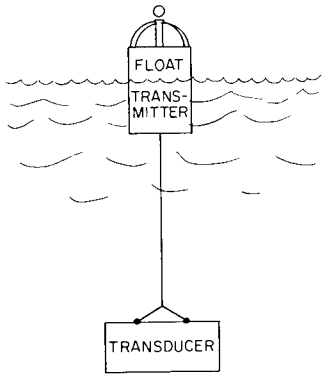
(a) Separate power amplifiers for high- and low-frequency transducers



(b) Single power amplifier for both transducers



(c) One-unit electronics



(d) Two-unit electroncis

Fig. 1 – Approaches to system design

Calculations based on the preliminary design data for the transducers revealed that 400 watts of electrical energy would be needed to produce the required acoustic output. With the available cooling, this power requirement was very near the upper limit of a single transistor amplifier. The margin of safety afforded by the higher power-handling capability of the double amplifier led to the choice of the system in Fig. 1a for the electrical circuit.

The advantages of Fig. 1d – ease of handling and testing – were offset by its one major disadvantage, the need for an electrical connection between the float and transducers. This connection would complicate the recovery and launching procedures and would decrease the reliability of the device. If recovery had not been a requirement for the engineering model, Fig. 1d would become more attractive. The final design consisted of a combination of the systems in Figs. 1a and 1c.

EQUIPMENT

Signal

Magnetic-tape recordings of the signatures from the USS BRONSON (DD 668) and the USS NORFOLK (DL 1) were obtained from the David Taylor Model Basin. The original [redacted]

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recordings had been made during noise-reduction studies off Key West in 300 fathoms of water. These master tapes were high-fidelity FM recordings covering the frequency band from dc to 5000 cycles per second.

The original recording procedure resulted in a pronounced amplitude fluctuation because of the variation in range between the ship and the recording hydrophone. The geometry of the test course was such that the ship closed to a minimum range of 100 yards as it passed the hydrophone. The frequency spectrum of the original recordings was broader than the 100 to 4000 cps range that could be produced by the available transducers. Therefore, the signals from the master tape were fed through a 100 to 4000 cycle bandpass filter. The output from the filter was monitored and manually controlled to eliminate the large variations in signal strength. This signal was then recorded on a second master. Copies of selected portions of this recording were used as the signal source for the simulator.

Five signals were used in conducting this study. They were the USS BRONSON at speeds of 8, 18, and 30 knots, the USS NORFOLK at a speed of 12 knots (2), and a convoy signal (3). This latter signal consisted of the signatures of five merchant ships, electronically adjusted to the same level, mixed, and rerecorded to present one signal. A one-half-octave analysis of the noise spectra of the five signals is included in Figs. 2, 3, and 4.

Tape Transport Mechanism

The tape-transport mechanism consists of a Mohawk Message Repeater, Jr., modified to be driven by a 30-volt dc motor. This mechanism is designed to accommodate a 2-7/8 x 2-7/8 x 3/4 in. tape cartridge, containing a continuous loop of tape, wound on a spool, to provide five minutes of recording length at a speed of 3-3/4 in. per second. In the period of approximately one year that this study has been in progress, only one cartridge failure was experienced. A picture of the tape-transport mechanism and tape cartridge is shown in Fig. 5.

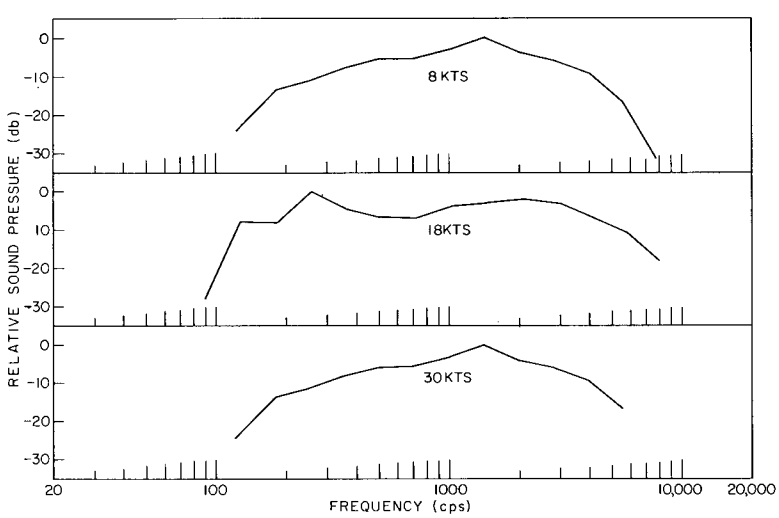

Fig. 2 – Radiated-noise spectrum of the USS BRONSON (DD 668)

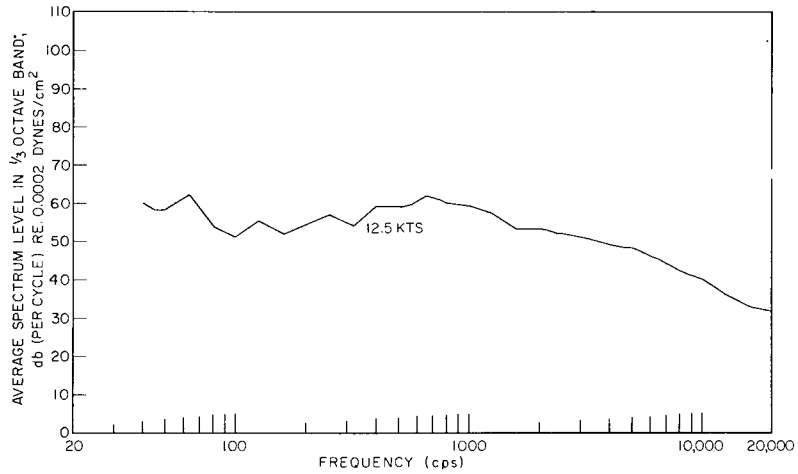

Fig. 3 – Radiated-noise spectrum of the USS NORFOLK (DL 1)

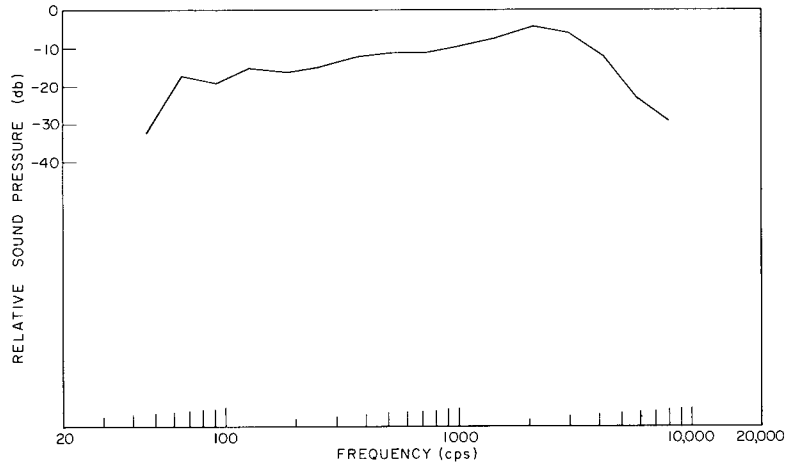

Fig. 4 – Radiated-noise spectrum of a simulated convoy

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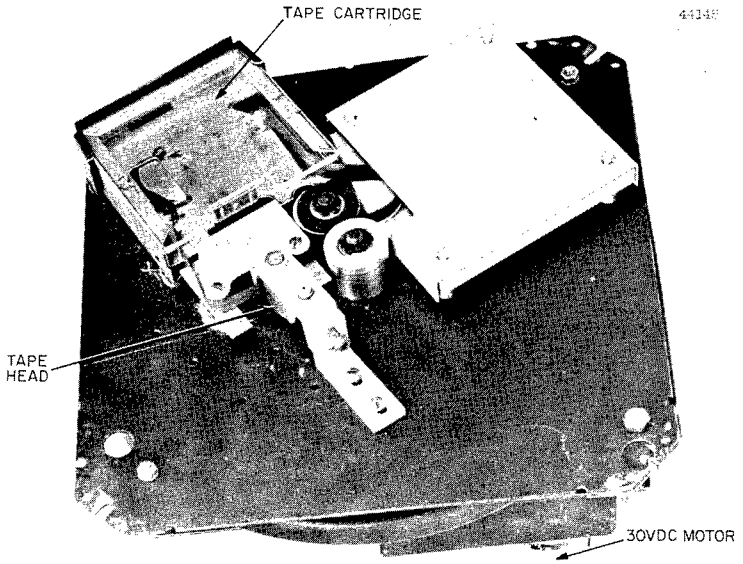

Fig. 5 – Tape-transport mechanism

Preamplifier

Commercial transistorized preamplifiers were not suitable for this application; therefore, a preamplifier was developed to fill the requirements of this system. The schematic diagram of the unit is shown in Fig. 6.

Compensation for the characteristic 6 db per octave attenuation of the tape head at frequencies below 1.2 kc is provided by the RC feedback network between the second and fourth stages. Parallel tuning of the head at 3.5 kc produced sufficient high-frequency compensation.

The frequency-crossover network consists of constant-k high-pass and low-pass filters with parallel inputs and a crossover frequency of 1.5 kc. Separate gain controls are provided for both the high- and low-frequency channels (Fig. 7).

The frequency response of the complete preamplifier driven by the tape transport mechanism, described previously, is shown in Fig. 8. Other pertinent preamplifier characteristics are given in Table 1.

Transistor Power Amplifiers

The initial amplifier used for this program was a modification of an existing transistorized power amplifier with a two-stage, class-A driver (Fig. 9). With adequate cooling, this amplifier will deliver a maximum output power of 325 watts into a matched resistive load with a single-frequency sinusoidal input signal. Data concerning the operation of this amplifier with a resistive load are given in Table 2.

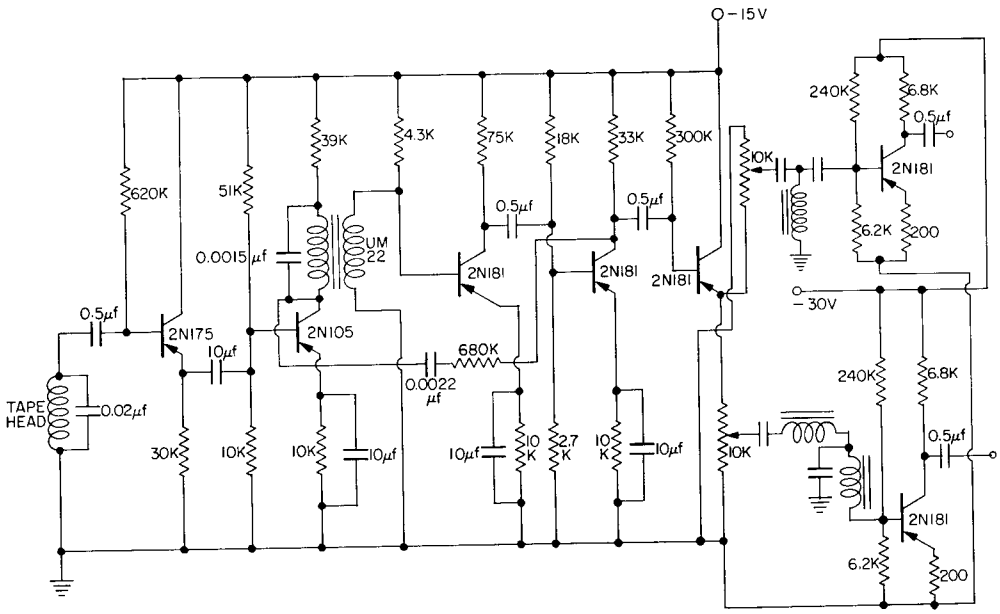

Fig. 6 – Transistorized preamplifier schematic

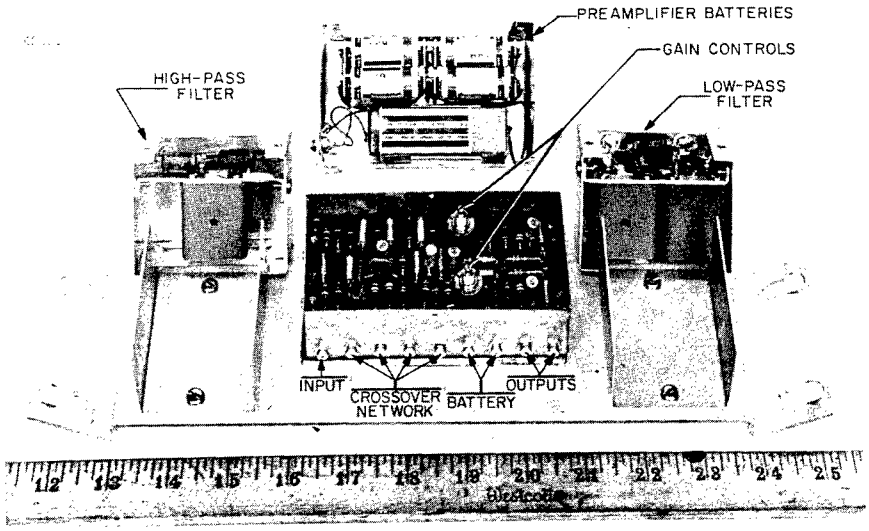

Fig. 7 – Preamplifier and power supply

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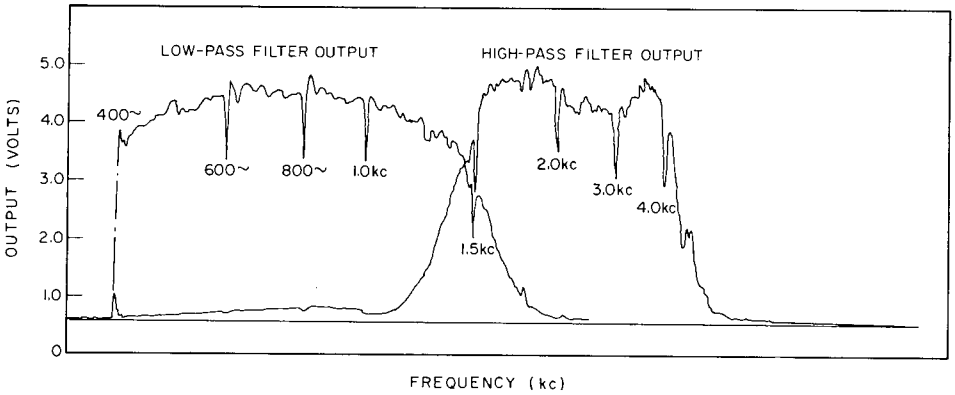

Fig. 8 – Frequency response of preamplifier, 10-k resistive load, tape speed 3-3/4 in./sec

Table 1
Preamplifier Characteristics

Characteristic	Value
Input impedance	60,000 ohms
Signal-to-noise ratio (1-mv input)	-55 db
Gain (pass band 100 to 4000 cps)	75 db
Maximum output signal (10,000-ohm resistive load)	8 volts rms
Maximum distortion	1.25 percent
Power requirements	-30 and -15 volts dc
Gain stability ($0^{\circ}C$ – $35^{\circ}C$)	±2.5 percent
Operating life *	10 hours

*1-K10 (30 volts) and 4-U10 (15 volts) batteries.

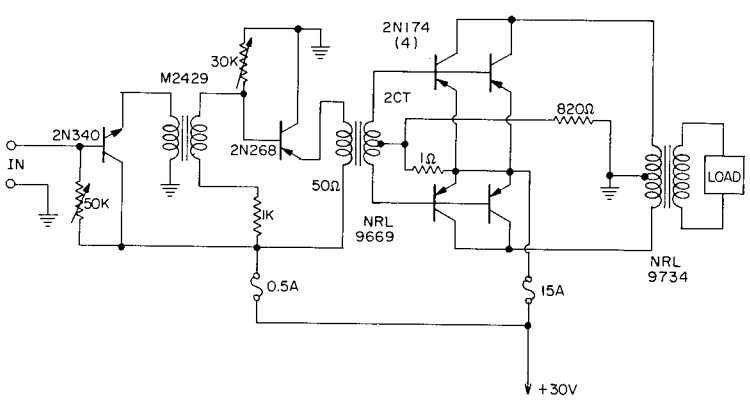

Fig. 9 – Transistorized power-amplifier schematic, 325 watts

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Table 2
Performance Characteristics of Transistor Power Amplifiers
and Matched Resistive Load

Amplifier	Power Output (watts)	Losses (watts)	Efficiency (percent)	Distortion	Response	Note
Common Emitter (Fig. 9) 1 class A driver 4 power transistors	265 at 1.2 kc	100	72.6	3.6% at 1.2 kc 180 w – 2.6%; 25 w – 10%	±0.1 db 285 – 2800 cps	1
Common Emitter (Fig. 10) 2 class B drivers 6 power transistors	450 at 2 kc	185	70.9	8.3% at 2 kc 80 w – 3.75%; 10 w – 10%	Approx. same	
Common Collector (Fig. 12)	400	244	62	0.8% 500 cycles – 5 kc	500 cycles – 5 kc	2

Notes:

1. Distortion less than 5 percent; efficiency greater than 70 percent over entire frequency range.
   Frequency range: ±1.5 db: 140 cps – 18 kc.
   Distortion less than 10 percent: 215 cps – 18 kc.
   Efficiency greater than 60 percent: 210 cps – 6.5 kc.
2. Low-frequency response was limited by the output transformer.
   The amplifier has shown a tendency to oscillate at very high frequencies. Work is continuing on the development of this amplifier.

For reasons which will be set forth later in this section, the power output proved inadequate; therefore, a third pair of power transistors was added to the circuit of Fig. 9. The operational characteristics are almost the same as with four transistors, except for an increase in distortion and a maximum-power capability of 450 watts. A class-B push-pull driver and a new impedance-matching stage were later found necessary to eliminate the severe second-harmonic distortion of the class-A 2N268 driver. A schematic of this amplifier is shown in Fig. 10. Other data concerning its operation are given in Table 2.

The two most important factors which must be considered in the design of a transistorized power amplifier are thermal resistance and signal waveform. The stated maximum powers of amplifiers with four and six transistors (325 and 450 watts, respectively) are based upon the ability of the transistors to operate at the manufacturer's maximum rating of 55 watts dissipation with a case temperature of 51°C. This requires a heat-sink thermal resistance of 0.4°C/w (total 1.2°C/w ambient-to-junction, which includes 0.8°C/w attributed to the transistor).

The transistors of the first amplifier employed (Fig. 11) were mounted on a copper bracket silver-soldered to a curved copper plate. While the thermal resistance of such a configuration by itself can be as low as 0.6°C/w when immersed directly in water, the addition of necessary mica insulating washers, the steel container walls, and particularly the interface between the curved plates and the container walls increased the thermal resistance greatly. For this reason, four transistors proved inadequate during evaluation.

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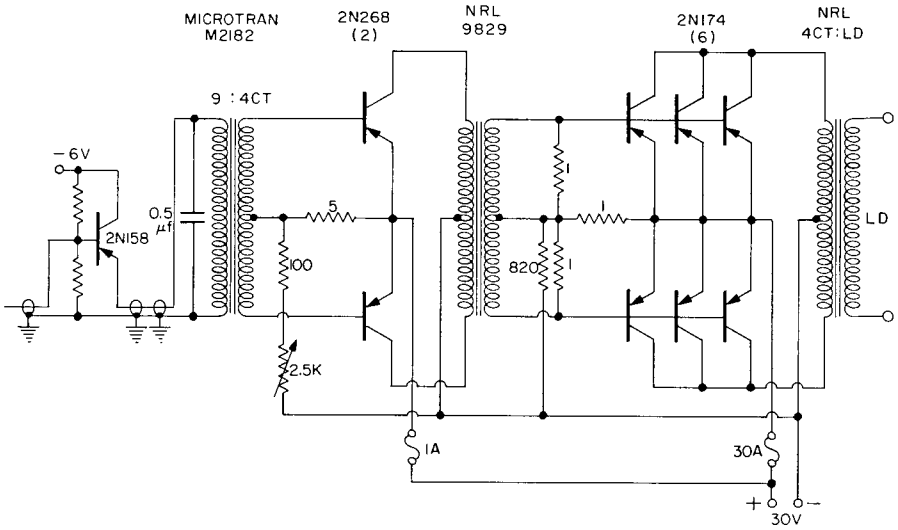

Fig. 10 – Transistorized power-amplifier schematic, 450 watts

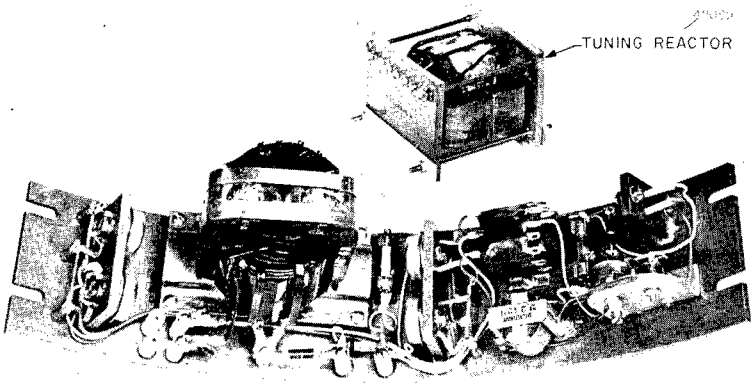

Fig. 11 – Power amplifier, 325 watts

Six transistors on a curved plate were sufficient when driven by single-frequency sinusoidal signals. However, for noise signals, with their increased peak-to-rms ratio, the resulting reduction in the average power output was not tolerable.

To increase the average power output of the noise signal, a new heat sink was designed. It consisted of a 6 x 12 x 1/4 in. copper bus-bar passing through the walls of the steel container and welded to the walls. With this configuration, the thermal resistance of the heat sink was reduced to 0.5°C/w (total 1.3°C/w, ambient-to-junction).

Even with this new heat sink, the mica washers and the inherently poor collector-current division in the common-emitter amplifier made a better amplifier design desirable. Both of the above limitations are eliminated in the final common-collector design. A schematic of this amplifier and its electrical characteristics are included as Fig. 12 and Table 2, respectively.

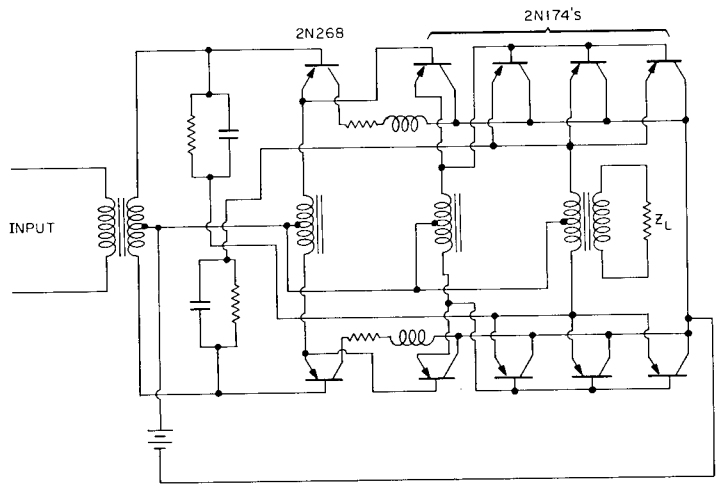

Fig. 12 – Common-collector power-amplifier schematic

Transducers

Since a single transducer was not available which could transmit a noise signal in the band from 1000 to 2000 cps, the band was split between two units. These units were constructed from barium titanate ceramic wedges cemented together to form rings (Figs. 13 and 14) and contained in a metal housing. The backs and sides of the rings have a pressure release between them and the housing (not shown in the figures). The radiating face is covered with a neoprene boot, and the entire housing is filled with castor oil or acme plastic to provide intimate acoustical contact between the ring and the boot. Two sizes of transducers were used, a 26-1/4-in.-diameter ring, designated as type XP-28A, and a 38-1/2-in.-diameter ring designated as type XP-31A. Pictures of the two units are included as Figs. 15 and 16, respectively.

Transducer XP-28A, serial number 1, resonated in air at 2.215 kc with a Q of 46. In water, at low-power input (5 watts), a similar unit resonated at 1.78 kc with a Q of 4.8 and had a transmitting response of 36.3 db re 1 dyne/cm^2 at one yard and one volt. The directivity pattern in the horizontal plane was circular from 1 to 4 kc. The ring height of 8 in. is insufficient to generate any directionality in the vertical plane at the frequencies of interest. The transmitting response, as determined from data taken at high-power levels (a maximum power at resonance of 250 watts), is shown in Fig. 17.

Transducer XP-31A, serial number 1, resonated in air at 1.49 kc with a Q of 32. In water, at low power, it resonated at 1.09 kc with a Q of 2.2 and had a transmitting response of 25.8 db re 1 dyne/cm^2 at one yard and one volt. The transmitting response determined from high-power data is shown in Fig. 18.

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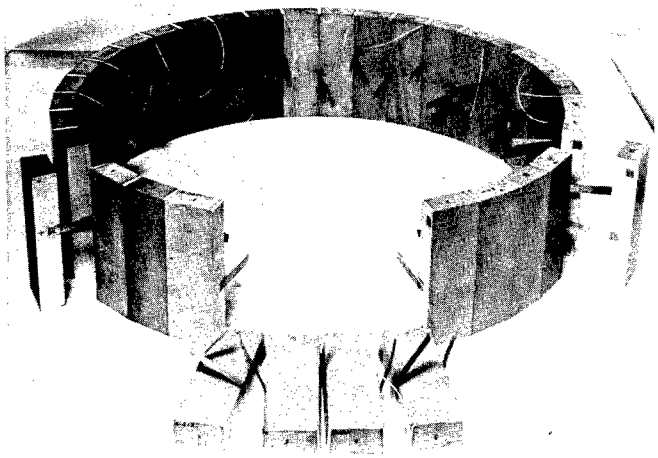

Fig. 13 – High-frequency transducer elements

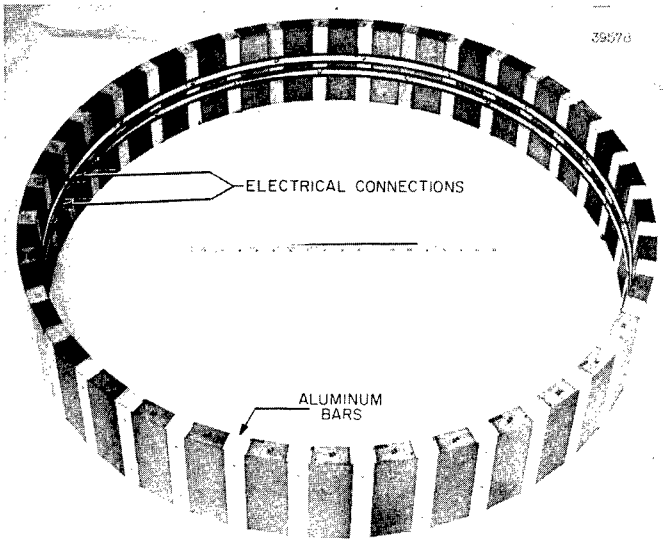

Fig. 14 – Low-frequency transducer elements

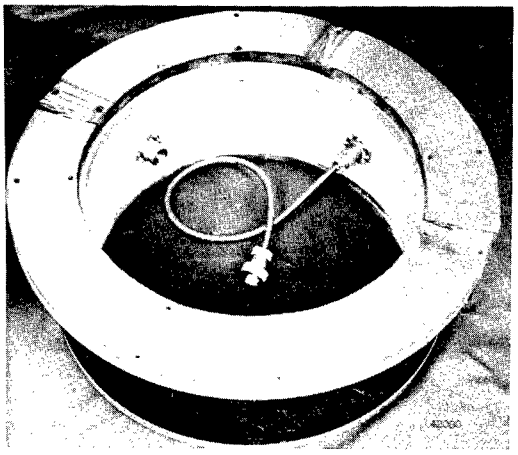

Fig. 15 – High-frequency transducer

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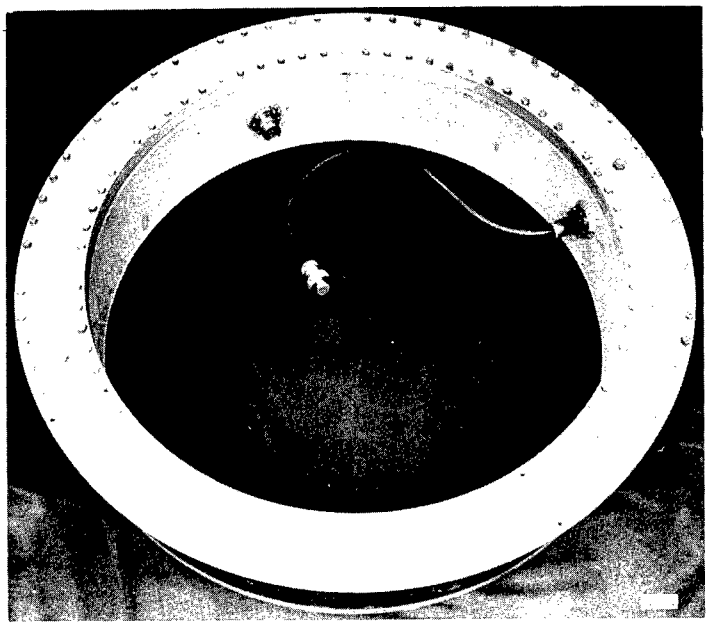

Fig. 16 – Low-frequency transducer

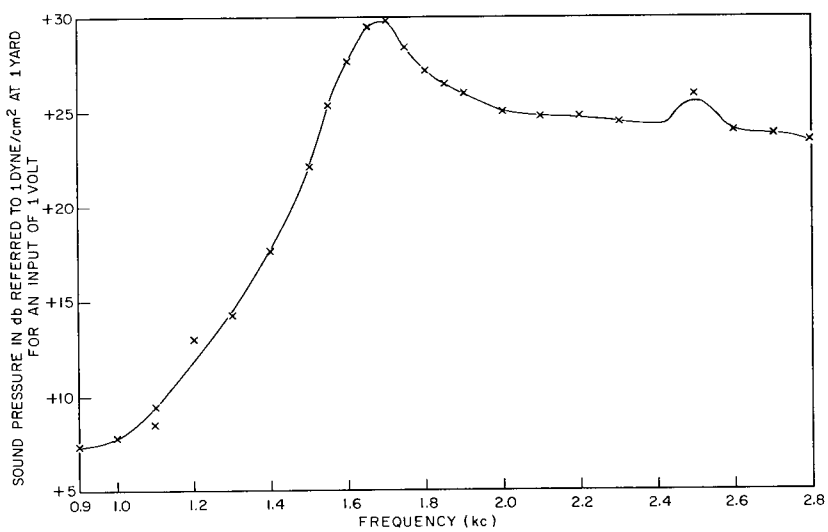

Fig. 17 – Transmitting response of high-frequency transducer at high power, transducer SR-1, 6-ft test distance, 18-ft depth

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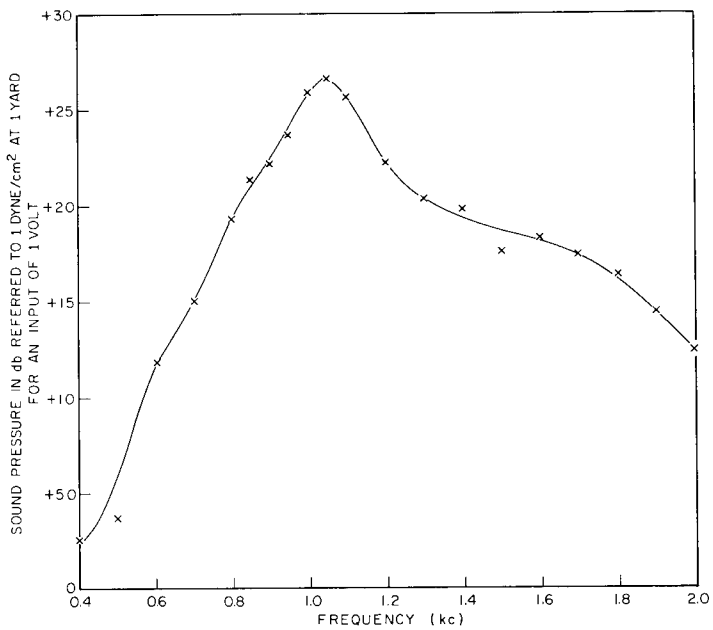

Fig. 18 – Transmitting response of low-frequency transducer at high power, transducer LR-6 (alone), 6-ft test distance, 18-ft depth

Transducers XP-28A and XP-31A connected in parallel, at low power, displayed double resonance peaks in water at 1.75 and 1.25 kc, respectively, and had corresponding transmitting responses of 34.4 db and 27.5 db re 1 dyne/cm^2 at one yard and one volt. The horizontal directivity pattern remained nearly circular from 1 kc to 8 kc. The vertical directivity pattern is circular in the desired frequency range. A transmitting response (not corrected to one volt) was obtained by connecting the individually tuned transducers in parallel and providing a constant input voltage to the driver and is shown in Fig. 19. The transmitting response at 1 kc and 2.4 kc was 30 db and 22 db, respectively, re 1 dyne/cm^2 at one yard and one volt.

All of these transducer characteristics are, of necessity, subject to error, since reliable, reproducible data were not obtainable at either the NRL Sound Barge or the Underwater Sound Laboratory's Dodge Pond. The lack of sufficient depth and reflection-free regions at both facilities are the principal reasons for these shortcomings.

Control Circuit

Since both the transducers and the amplifiers must be submerged in water during operation, some form of delayed turn-on must be used to compensate for the time required to launch the device. Further, it is desirable to limit the battery discharge to some figure less than 100-percent discharge to prevent excessive gas formation and damage to the battery. This latter requirement existed because recovery of the experimental unit was desired.

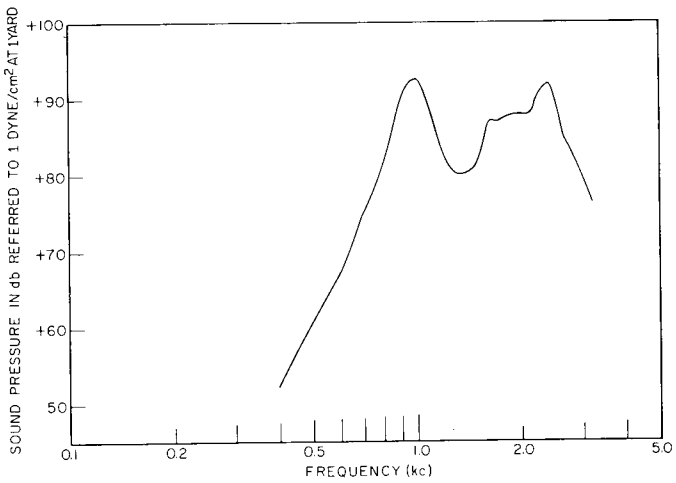

Fig. 19 – Transmitting response of high- and low-frequency transducers in parallel at high power, transducers SR-1 and LR-6, 12-ft test distance, 18-ft test depth

A control circuit was developed using several relays, including a differential relay, and a small electric clock (Fig. 20). A schematic of this circuit is shown in Fig. 21. Power to the control chassis is applied through a hydrostatic-pressure switch to insure a minimum submersion of 12 ft before operation. The clock provides for a preprogrammed delay of device activation from zero to two hours after the submersion, followed by a ten-hour operating period. Provision was made for continued operation after a two-hour delay or for lockout of the circuit, removing all loads but the lockout relay from the battery. A voltage-sensing differential relay was used as an overriding device to lockout the circuits and remove the load after the battery voltage fell below a preadjusted value.

In order to prevent oscillations when using the common-collector amplifier, a 4000-μf capacitor (not shown) was placed across the supply. The line drop during the capacitor charging time was sufficient to trip the circuit, preventing operation. This required the removal of the voltage-sensing relay from the control circuit.

Power Source

Several types of rechargeable storage batteries were investigated for use as the power source. Since the battery was to be enclosed in an airtight container, gassing features figured prominently in the initial selections. Among all types of batteries, the lead-calcium type evolves less gas upon discharge; however, the size and weight factors were prohibitive in comparison with the silver-zinc type (Table 3). The size and weight savings of the silver-zinc battery were the reasons for its selection. A typical discharge curve is shown in Fig. 22.

The silver-zinc battery presented one problem – the property of the battery to form hydrogen gas during discharge in the approximate amount of two liters. Ordinary surface atmosphere mixed with more than 6.2-percent hydrogen forms a combustible mixture. Glass wool in the amount of two pounds per cubic foot was placed in the battery compartment, allowing not more than 15-percent free-air space, to prevent combustion.

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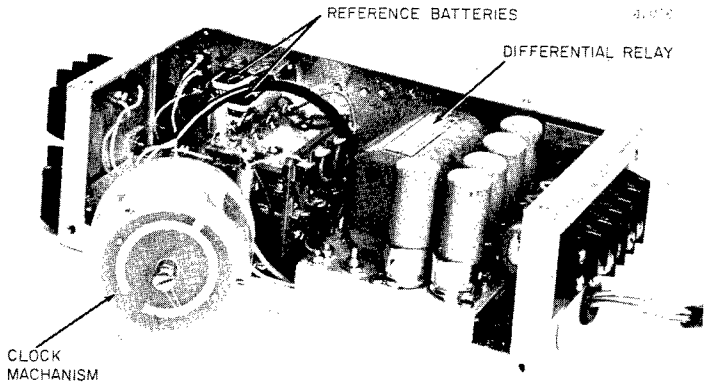

Fig. 20 – Control unit

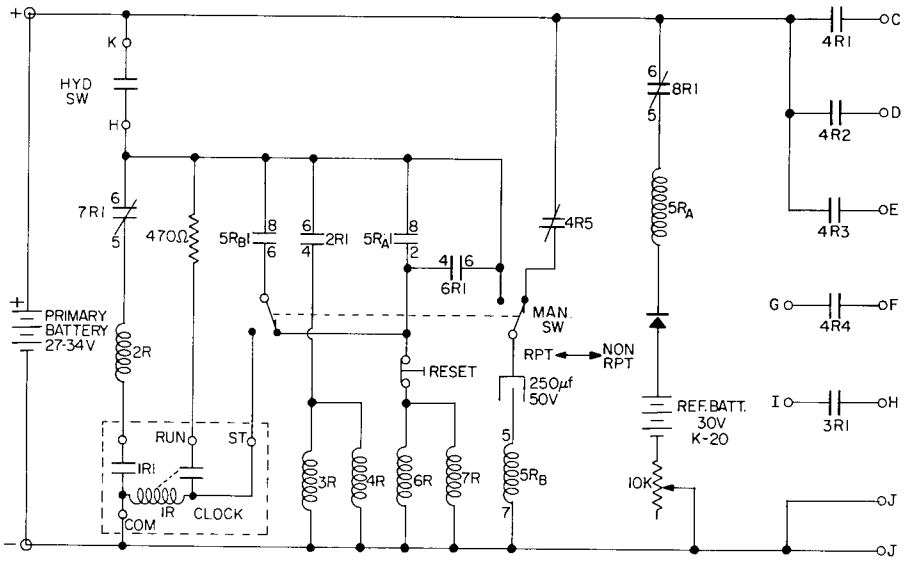

Fig. 21 – Control-unit schematic

Table 3
Storage-Battery Characteristics

Type of Battery	Size (cu ft)	Weight (lb)	Estimated Cost (dollars)	Liters of Gas Formed During Discharge	
				Hydrogen	Oxygen
Nickel-cadmium (sintered plate)	5	400	3,500	-	26
Lead-calcium	5	500	600	0.4	-
Silver-zinc	1	100	4,500	2.0	0.5

This is a summary of the pertinent data which were significant in arriving at a selection between the battery types listed. All of the above units are capable of delivering 20 amperes at 28 volts for a period of ten hours.

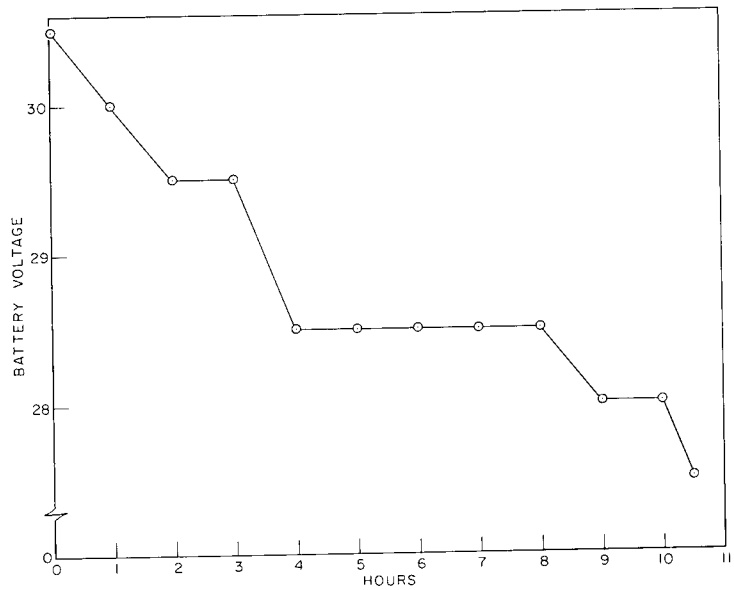

Fig. 22 – Initial test discharge of Yardney silver-zinc, 200-ampere-hour battery, discharge rate 20 amperes

A study was conducted to determine the feasibility of replacing the expensive silver-zinc battery with a gasoline-driven generator. The results of this study are very promising. On a basis of an effective operating time of 10 hours, a 1-1/2-horsepower gasoline-driven generator will produce 7.5 kilowatt-hours at a total weight of 101 pounds, occupying 3.9 cubic feet. This is the quivalent of 74 watt-hours per pound, a considerable increase over the present figure of 45 watt-hours per pound for the silver-zinc battery. The total weight of the gasoline-driven generator includes only 30 pounds of fuel. If, therefore, the effective operating time were reduced to 5 hours, the system rating would be reduced to 40 watt-hours per pound. Although this figure is somewhat lower than that of the silver-zinc battery, the motor-generator is still very attractive when the cost of the two units is compared. The total cost of the motor-generator is only $500, whereas the equivalent silver-zinc battery has a total cost of $5,000.

The gasoline-driven generator will produce several problems, the foremost being that of supplying sufficient amounts of air for combustion and cooling – a minimum of 250 cu ft/hr. If used with a stationary device, the engine could be placed in the float mechanism and a suitable breathing apparatus developed. For a self-propelled device, one possible solution to this problem would be the use of a snorkeling arrangement. Electrical start is available for these motor-generators, allowing them to be started before being placed in the water. All of the above problems, however, are of an engineering nature, and the solutions to these problems, and ultimately the practicality of the motor-generator, will be determined by the operating requirements of the system.

FLOAT AND CONTAINER

The electronic package is basically a cylinder, with sections of an ellipsoid enclosing the ends of the cylinder. The container is divided into two compartments separated by a

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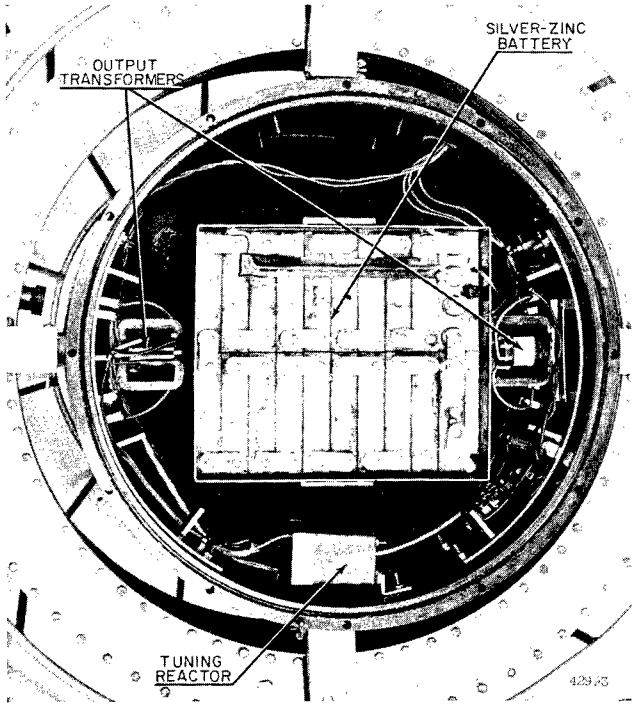

Fig. 23 – Lower electronics and battery compartment

stainless steel disk. The lower compartment (Fig. 23) contains the output transformers, tuning reactors, and battery, and would normally be filled with glass wool to absorb the hydrogen produced by the battery upon discharge.

The upper compartment (Fig. 24) contains the tape-transport mechanism, preamplifier, power amplifiers, and control circuit. Electrical connection between the two halves is made by an external, watertight cable (Fig. 25), which was chosen in preference to an internal connection because of the simplicity it affords when assembling the device.

The high- and low-frequency transducers are mounted on the outside of the container, with the electrical leads brought into the lower compartment.

The float has a cylindrical shape and is filled with polyurethane to increase its impact resistance. There is a fixed length of cable passing through the center. This cable is terminated on the device end by a sling and on the other end by a large, flexible eye, designed to support the transducer package and to aid in launching and recovery (Fig. 26). Fraying of the steel cable when the system was tested in water required the addition of a length of chain between the eye and the steel cable. Located in the outer rim of the float bottom are three small plungers, as shown in Fig. 27. These plungers are spring-loaded and latch the float to the transducer package to allow the combination to be handled as one unit. Pressure applied to the pedal on the top of the float retracts these plungers, releasing the transmitter-transducer package.

The depth of the transducers is fixed by the length of cable. Two lengths of cable were available (20 ft and 70 ft) for the tests. The 20-ft cable was used almost exclusively, however, since some difficulty was experienced in handling the 70-ft length.

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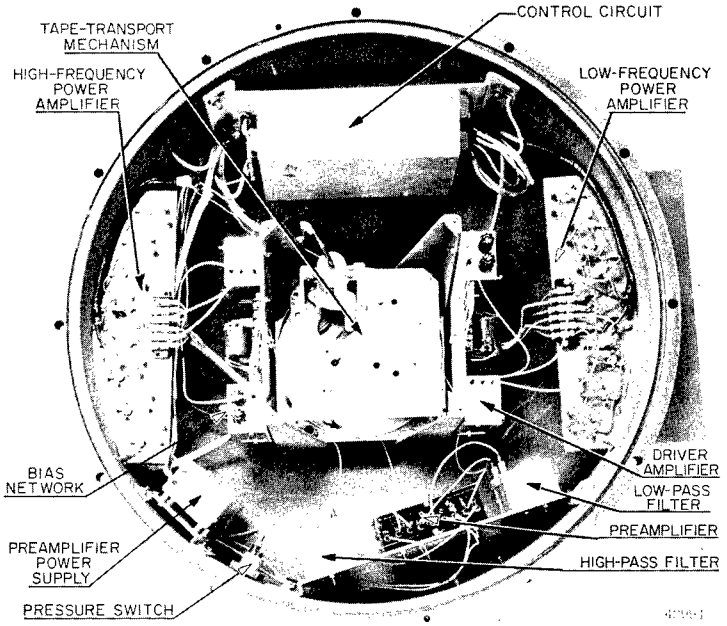

Fig. 24 – Upper electronics compartment

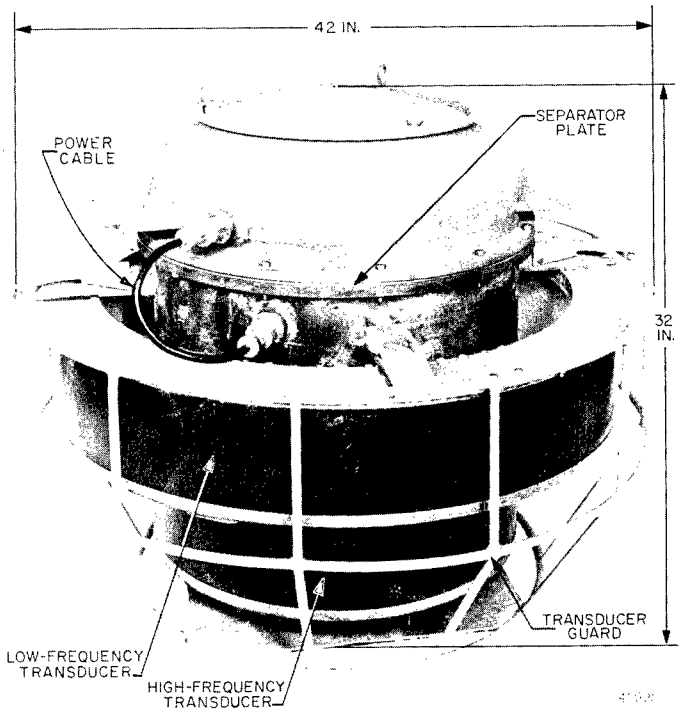

Fig. 25 – Transducers and electronics package

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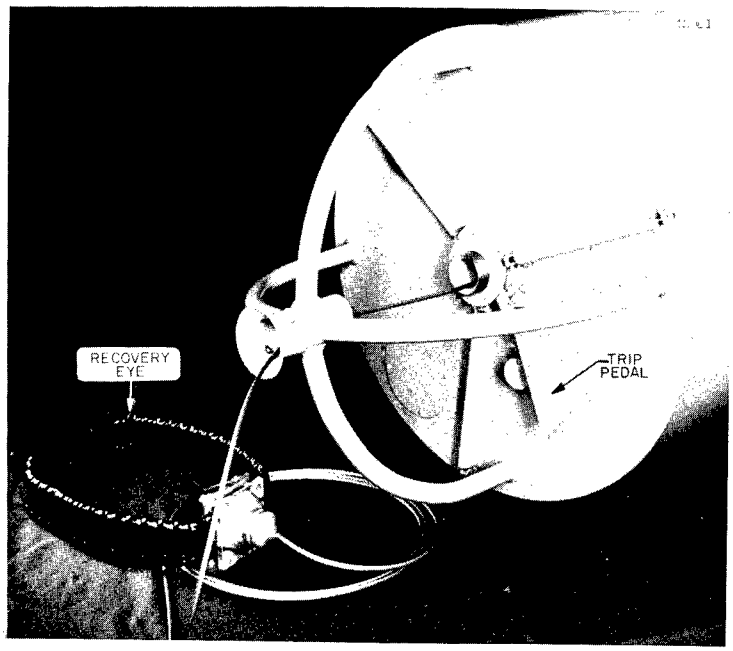

Fig. 26 – Top view of float

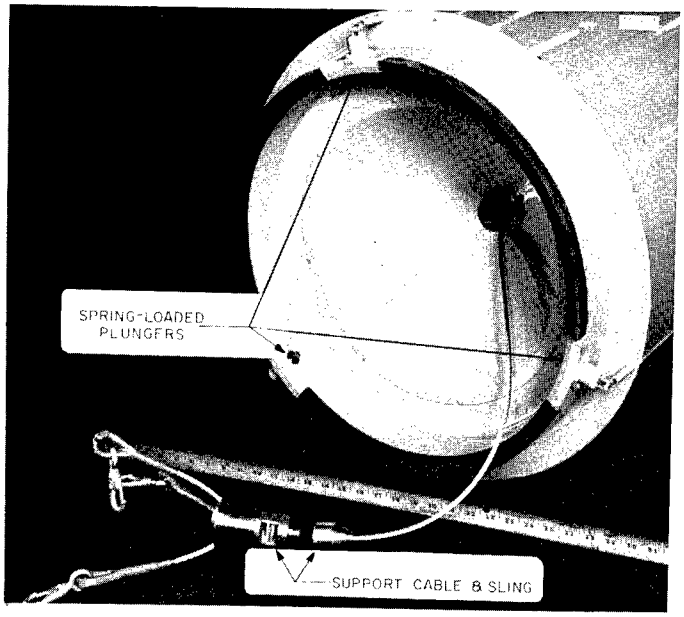

Fig. 27 – Bottom view of float mechanism

A picture of the complete system is included as Fig. 28. The size and weights of the major system components are given in Table 4.

EVALUATION TECHNIQUES

There are several different methods available for analyzing noise data. The most generally accepted methods are a one-cycle-band analysis, one-third-octave, one-half-octave, and full-octave analysis. The type of analysis used is primarily dependent upon the purpose of the measurement and the amount of time available for analysis of the data. The one-cycle-band analysis is the only method which can be utilized to produce rigorous results. This method is, nonetheless, very laborious and time-consuming and becomes prohibitive if large quantities of data are to be reduced. For this reason, most noise data are analyzed on the one-third, one-half, or full-octave basis. When methods other than the one-cycle-band analysis are used, particular care must be exercised to prevent erroneous results caused by the inclusion of a line spectrum (i.e., a narrow-band frequency component several db above the level of the neighboring frequencies). Such line spectra can result from a transmitter having either mechanical or electrical resonances. These spectra can easily be detected by ear, but they can be detected electronically only by a very-narrow-band filter system.

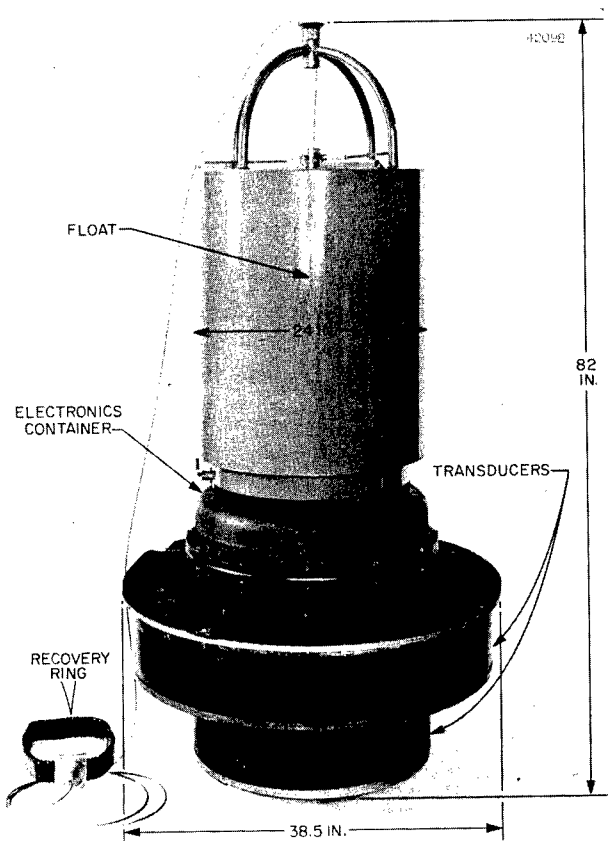

Fig. 28 – Complete simulator assembly without transducer guard

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Table 4
Weights and Sizes of System Components

Components	Weight (lb)	Size
Acoustic Source		
Low-frequency transducer	190	Height: 8 in. Diameter: 38.5 in.
High-frequency transducer	125	Height: 8 in. Diameter: 26.5 in.
Electronics container	175	Height: 32 in. Diameter: 24 in.
Electronics	45	
Battery	155	14 x 12 x 12 in.
Total	690	
Floatation and Protection Gear		
Float	100	Height: 50 in. Diameter: 24 in.
Cable	15	
Transducer guard	20	
Total	135	
Total System Weight	825 pounds in air	
Acoustic Source Weight	260 pounds in water (cable and guard)	

Unfortunately, the data obtained by the octave-analysis method cannot be compared directly to either a one-cycle-band analysis or to a fractional-octave analysis (Fig. 29). The inconsistency arises from a consideration of the amount of noise power available in the band that is being measured. The one-cycle-band analysis presents a true picture of the energy distribution of the noise power. However, in the octave and fractional-octave methods, the measuring instrument responds to the total energy in the band and presents the integral of the energy. Therefore, data taken by these methods when compared to a one-cycle-band analysis will appear to have a higher spectrum level and, as a function of frequency, will have 3 db per octave less negative slope.

In an attempt to present uniform results, most data analyzed by the octave or fractional-octave methods are later corrected to an equivalent one-cycle-band analysis. The advantage of this technique is obvious; however, it can be applied only to data which is continuous and has a relatively constant slope over the band. A complete analysis of this problem can be found in a report by R. S. Gales (4).

The preliminary tests performed with the device were conducted at the Sound Barge located at NRL. The lack of water depth and the large number of submerged objects capable of generating standing waves make this facility objectionable. The convenience of the facility, however, justified its use.

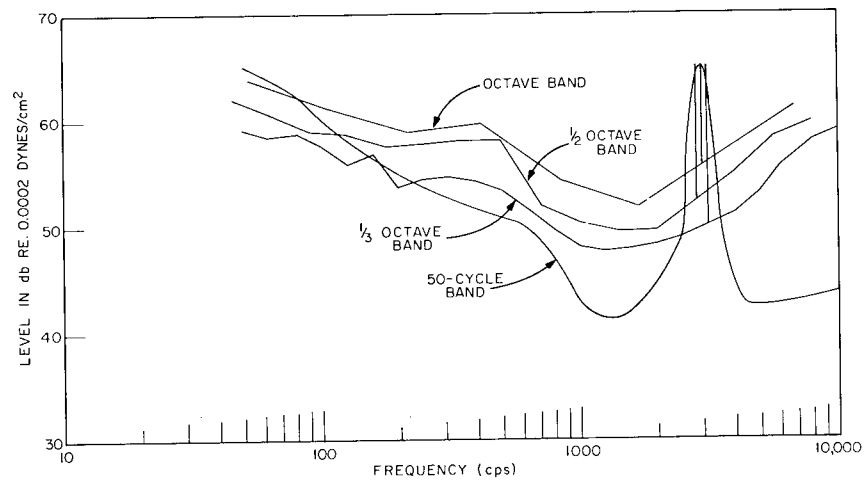

Fig. 29 – Comparison of different methods of noise-data analysis

Data recording was by magnetic tape, with later reduction using a half-octave filter set. The source levels given in this report, taken by a calibrated wide-band hydrophone, are referred to sound pressure of 1 dyne/cm^2 at a distance of one yard.

RESULTS AND DISCUSSION

Since the ultimate goal of the simulator is to deceive the human ear, it is difficult to prepare any data in the form of curves, graphs, or tables which by themselves would be capable of evaluating the effectiveness of the device. All of the methods now available for analyzing noise data give results which are a time average of the noise power in a given band. This type of analysis definitely has its technical value; however, the aural character of the sound is lost. As a result of this limitation, it is possible to obtain a frequency-response curve identical to a ship's noise signature by shaping random noise with a system of filters. It is evident, however, that the aural character of these sounds is completely different.

A ship's signature derives its aural character primarily from propulsion-plant noises and the amplitude-modulated noises generated by the screws, with the latter effect predominating. These screw noises usually have their major frequency components below 500 cps.

The total noise spectrum radiated by a particular ship is generated by a multitude of effects, such as screw noise, water flow, cavitation at the screws and hull, bearing whine, gear noise, diesel-firing noises, steam flow, various auxiliaries such as pumps, and hull resonances, and as such is peculiar to that ship alone. Thus, it is difficult to generalize about such surface-ship spectra.

However, it may be stated that, at speeds less than 8 to 10 knots, cavitation and water-flow noises are usually at a minimum, and much of the energy of the spectrum is usually concentrated below 500 cycles. In particular, screw noises are usually below 500 cycles and are sometimes below 100 cycles. As speed increases, both the distribution

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of the noise power and the individual frequencies which generate the aural effects increase. Further, when cavitation begins, a predominant shift in frequency distribution may occur. Moreover, the increased speed is generally accompanied with an increase in the overall sound intensity. The spectra of two destroyer-escorts are shown in Figs. 30 and 31. Figure 30 (5) gives the characteristics of the single-screw steam-turbine ship, USS BRIDGET (DE 1024), and Fig. 31 (5) that of the twin-screw diesel-powered ship, USS KOINER (DER 331). The latter curves are also somewhat typical of most merchant ships.

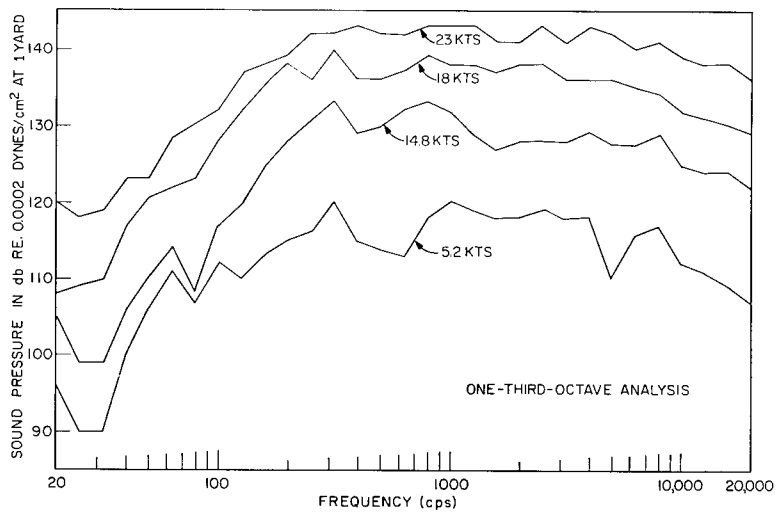

Fig. 30 – Radiated noise of the USS BRIDGET (DE 1024)

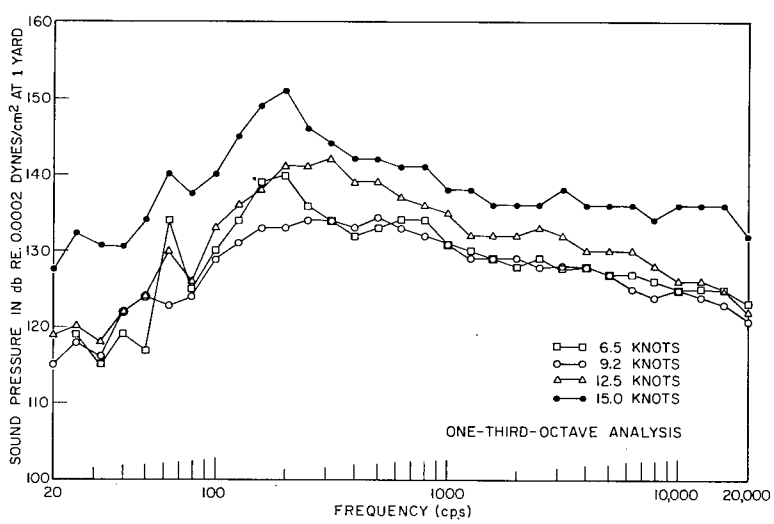

Fig. 31 – Radiated noise of the USS KOINER (DER 331)

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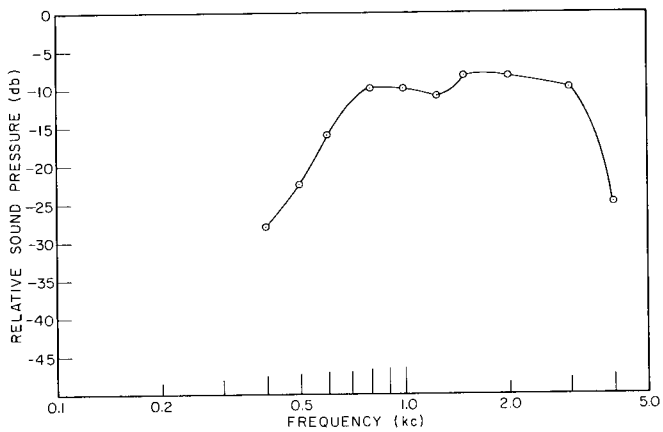

Fig. 32 – Single-frequency transmitting response of the NRL underwater sound simulator

The effective pass band of the NRL simulator was very limited, consisting of approximately two octaves between 700 cps and 2.8 kc, as shown in Fig. 32. When the 8- and 18-knot signatures of the USS BRONSON were transmitted through this system at the NRL Sound Barge, it was found that all of the characteristics of the signature which would have identified it as being that of a surface ship were missing; the sound produced by the device did not at all resemble the original signature. The 30-knot signature of the BRONSON and the convoy signal (3), however, had frequency components of the screw noise which had shifted upward by an amount sufficient to fall within the pass band of this system. When these signals were retransmitted by the simulator, the sound produced definitely contained some of the aural character of the original signature, but were, at best, poor reproductions of the original.

An evaluation of the device equipped with the convoy signal was conducted with the aid of Task Group Alpha. To insure maximum utilization of the time allotted for the tests, the listening submarine, the USS COBBLER (SS 344), was informed of the location of the simulator and the type of signal being transmitted. At the conclusion of the operation, the following statement was received in a letter (see Appendix) prepared by the COBBLER: "The concensus among sonarmen is that the device sounds more like a destroyer than most destroyers, and generates a clearer signal for any given range."

The signal used for this test was not the signature of a destroyer, but rather a combination of several merchant ships at speeds ranging from 8 to 12 knots. It is evident, nonetheless, from the original COBBLER letter, that this signal definitely resembled that of a destroyer. This fact would indicate that the most effective deception would result from a synthetic signal which contained all of the aural character of the vessel it was attempting to simulate, with emphasis placed on certain selected characteristics.

Unfortunately, sufficient time was not available to investigate the effects of transducer depth and surface-channel propagation on the transmission of a noise signal. Limited amounts of data have been obtained which indicate that at ranges exceeding several kiloyards the bandwidth of a ship's noise signature is reduced and the frequency distribution of the noise power is considerably different from data obtained at short ranges (100 yards). During the two operations conducted with Task Group Alpha, several recordings were made of the noise radiated by the USS BEALE (DDE 471) at different speeds at ranges up to the

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initial detection range. These recordings were made by the USS CUBERA and the USS COBBLER with the use of their BQR-2B sonar listening equipment. An analysis of these recordings is shown in Fig. 33. Ideally, the frequency response of the BQR-2B sonar equipment is 3 db down at 150 cps and 15 kc. It was not possible to calibrate the sonar equipment within the time available, thus making it impossible to determine what had caused the apparent loss of the low-frequency components usually found in the signature of a destroyer. However, the fact that this loss of low frequencies was observed in the recordings made on different days by two different submarines would indicate that further research is necessary in this area.

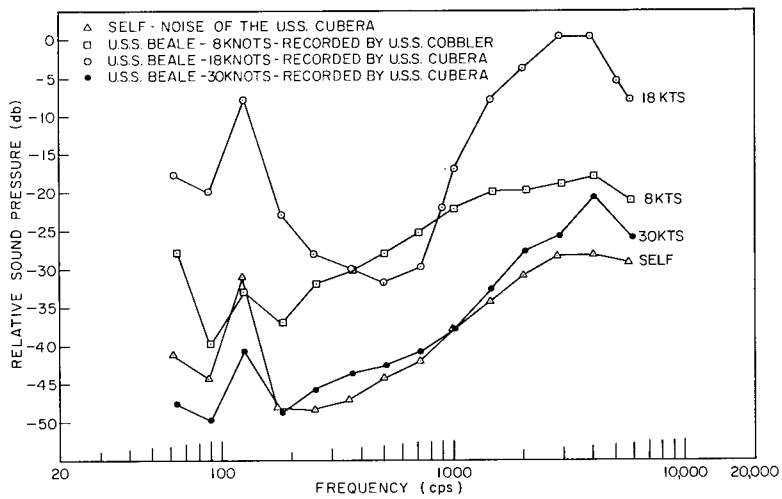

Fig. 33 – One-half-octave analysis of the noise signature of the USS BEALE (DD 471), approximate range 2000 yards

The source level of the simulator is 75 db re 1 dyne/cm^2 at one yard. This figure corresponds to an effective radiated acoustic power of approximately one watt. The source level of a destroyer at average running speeds (6), 15 to 18 knots, is 82 db re 1 dyne/cm^2. Although the source level of the simulator was lower than that of a destroyer, it was able to transmit a clearer signal for any given range (see Appendix). This phenomenon is the result of the transmission characteristic of the surface channel. For a source placed either in or below the surface channel, there is as much as a 20-db increase in the sound-intensity level from the surface of the water to a point equal to one-third the depth of the channel, with maximum sound intensity occurring at the one-third point. If this is a reciprocal process, a simulator placed at the correct depth in the channel would require a source level several db below that of a surface ship to achieve an equivalent acoustic range. However, sufficient data are not available, and further research will be necessary.

The simulator source level is approximately equivalent to an effective radiated acoustic power of one watt. The total amplifier dc input power is 400 watts, giving an overall system efficiency of 0.25 percent. This very low system efficiency is directly attributable to three factors: the transducer efficiency, the low power factor of the transducer load, and the peak-to-rms ratio of the noise signal.

It has been shown in a study of ship-noise spectra (3) that 85 percent of the energy contained in a merchant ship's signature is below 500 cps. It must be realized that any transducer having directional capabilities in the frequency band from 50 to 500 cycles is very large and would be very difficult to handle. It can, therefore, be assumed safely that any practical transducer covering this frequency band would be an omnidirectional source.

The source level of a destroyer at average running speeds (6), 15 to 18 knots, has been found to be 82 db re 1 dyne/cm^2 at one yard. This sound pressure corresponds to an acoustic output from an omnidirectional source of approximately 10 watts. The effective amplifier rating to attain this source level, accounting for the effects of peak-to-rms ratio, and transducer efficiency and power factor can be calculated. Assuming the transducer has an effective power factor of 0.2 and a mechanical efficiency of 20 percent, an acoustic output of 10 watts will require a 250-volt-ampere output from the power amplifier. The maximum theoretical efficiency for a class-B power amplifier is:

$$\eta_{max} = \frac{F}{R_p}, \tag{1}$$

where F is the form factor, R_p is the peak-to-rms ratio of the signal, and η is the efficiency. The total amplifier dissipation P_d is given by

$$P_d = \frac{(1 - \eta)\,V.A._{out}}{\eta} + V.A._{out} - P_{out}. \tag{2}$$

Measurements were made to determine the peak-to-rms ratio and the form factor of the five ship signatures used in these tests. The results are given in Table 5. These figures reveal a maximum theoretical amplifier efficiency of 40 percent. Substituting the above results in Eq. (2) gives a total amplifier dissipation of 575 watts. Assuming the maximum theoretical efficiency of 78.5 percent for a class-B amplifier design, the single-frequency sine wave rating of this amplifier would therefore be 2.1 kilowatts. From this illustration, it becomes readily apparent that any system attempting to transmit wide-band noise, utilizing a single transducer and a single power amplifier, is basically very inefficient, and that the desired results can be achieved only by the application of "brute force" methods.

CONCLUSIONS

This study has shown that an effective simulator must be a relatively wide-band device capable of reproducing a large portion of the audio spectrum. The exact limits of the bandwidth are very difficult to determine. This arises from a lack of complete and detailed knowledge of which quantities of a ship's signature must be reproduced to lead to the classification of a signal as a surface ship.

In the absence of this data, it must be assumed that the low-frequency limit will be governed only by the minimum signal-to-noise ratio at which the identification of the character of the noise is still possible. An analysis of the self-noise spectra of a submarine (7) and the noise radiated by a surface ship shows a rapid deterioration of the single-frequency signal-to-noise ratio for frequencies less than 100 to 200 cycles. On this basis, for ranges greater than several kiloyards, the low-frequency limit would therefore be 100 cycles.

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Table 5
Peak-to-RMS Ratio and Form-Factor Measurements
of Various Ship Signatures

Ship	Frequency Band	Speed (knots)	Peak*	RMS†	Average‡	R_p§	F.F.¶
BRONSON	20 cps-20 kc	8	1.40	0.33	0.27	4.25	1.22
BRONSON	20 cps-20 kc	18	1.45	0.37	0.27	3.93	1.37
BRONSON	20 cps-20 kc	30	1.65	0.29	0.23	5.7	1.26
DL 1	20 cps-20 kc	12.5	1.50	0.47	0.31	3.19	1.52
Convoy	20 cps-20 kc	8-10	2.00	0.67	0.49	2.99	1.37
BRONSON	75-106 cps	18	0.06	0.0125	0.01	4.8	1.25
	106-150 cps	18	0.67	0.11	0.11	6.1	1.00
	150-212 cps	18	0.70	0.10	0.10	7.0	1.00
	212-300 cps	18	0.60	0.10	0.10	6.0	1.00
	300-425 cps	18	0.57	0.089	0.09	6.4	1.00
	425-600 cps	18	0.65	0.125	0.125	5.2	1.10
	600-850 cps	18	0.62	0.14	0.14	4.4	1.00
	850-1200 cps	18	0.70	0.158	0.14	4.4	1.10
	1200-1700 cps	18	0.65	0.14	0.13	4.65	1.07
	1700-2400 cps	18	0.80	0.168	0.15	4.8	1.12
	2400-3400 cps	18	0.62	0.14	0.13	4.4	1.07

*By oscilloscope.
†Graphic level recorder.
‡Ballentine VTVM.
§Peak-to-rms ratio.
¶Form factor.

The frequencies above 5 kc contain very little energy and do not add appreciably to the character of the signature. Furthermore, due to the propagational characteristics of the ocean medium, these frequencies will be attenuated very rapidly with range and will soon lose their significance. The inclusion of these frequencies, therefore, would be justified only to the extent that they reduce the effectiveness of any electronic countermeasures.

It is necessary not only that all frequencies between the above band limits be provided, but also that these frequencies must generate a continuous spectrum, and, in addition, must contain all of the aural character of the original signal. It may be desirable to emphasize certain aural characteristics, such as diesel effects, reduction-gear noises, turbine whine, etc., by the inclusion of line spectra, and thus lead to the desired classification. However, this must be done subtly, to prevent obvious falseness.

It is evident that the required source level will be a function of the desired detection range as well as a function of the class of ship which is being simulated. To achieve an acoustic range equivalent to that of the ship being simulated, the source level varies between 10 watts for a destroyer and 250 watts for a battleship. The above statement,

however, assumes that the simulator is placed at a depth equal to the depth of the equivalent acoustic source for the surface ship. There is a limited amount of data available which would indicate that if the device were placed at the proper depth in the surface channel, the source level could be lowered by at least one order of magnitude for any given ship and still achieve the same acoustic range. Sufficient data are not available, and further study will be required.

The use of a wide-band amplifier with a resonant transducer results in a system which is very inefficient. The low efficiency is caused by the fact that a transducer is both mechanically and electrically resonant and will operate with maximum efficiency only when the mechanical and electrical circuits resonate at the same frequency. Additional development work will be required in this area to produce suitable wide-band acoustic sources.

RECOMMENDATIONS

As a result of this study, the following recommendations are made:

- The frequency response of the system should provide continuous coverage of the audio spectrum between the frequencies of 100 cps and 5 kc.

- A study should be conducted to determine the effects of deep water, surface-channel propagation, and range on the aural character, energy distribution, and intensity of a ship's noise signature. This study will determine the optimum source level for a simulator.

- The wide-band transducer-amplifier system is basically very inefficient and results in a system which is very bulky and heavy. Consideration should be given to the development of a system using multiple narrow-band transducers driven by narrow-band amplifiers. Research must be extended to development of broadband acoustic sources in which the amplitude-frequency spectrum can be controlled.

ACKNOWLEDGMENTS

The assistance of many groups and individuals made this work possible. Acknowledgment is made of the contribution of the Transducer Branch of NRL, and, in particular, Messrs. R. J. Colson, R. H. Carson, R. E. Faires, and E. Tuck.

The assistance provided by members of the Electrical Applications Branch are acknowledged as follows: Messrs. E. J. Aitcheson, A. T. McClinton, J. Pope, and E. Stroup.

In addition, valued services were provided by the Engineering Services Division of NRL.

Ship's forces represented by USS ROCKVILLE (EPCER 851), USS RICHARD E. KRAUS (DDE 849), USS BEALE (DDE 471), USS CUBERA (SS 347), and USS COBBLER (SS 344) also contributed valuable assistance.

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APPENDIX

LETTER REPORT ON SUBMARINE OPERATIONS
WITH TASK GROUP ALPHA

U.S.S. COBBLER (SS-344)
Care of Fleet Post Office
New York, New York

SS344/DSL/jhs
3000/SER: 003
3 NOV 59

[redacted]

From: Commanding Officer, USS COBBLER (SS-344)
To: Commander Carrier Division SIXTEEN

Subj: NRL Device; evaluation of

Encl: (1) Tape of phase BRAVO
(2) Tape of phase DELTA
(3) Tape of phase CHARLIE
(4) DRT track chart 21 OCT 59
(5) DRT track chart 23 OCT 59

1. The USS COBBLER SS344 rendezvoused with the USS BEALE DDE471 on 21 October 1959 to conduct an evaluation of the NRL Sonic Deception Device in the vicinity of Latitude 36-35 North, Long. 72-02 West. At this time the Cobbler was to evaluate an "8 knot Bronson" signal. The BEALE placed the device in the water at 0830 without difficulty. A report from BEALE indicates that the device was configured for "Convoy" rather than "8 knot Bronson" at this time. COBBLER was positioned 2 miles from the device and a signal definitely resembling a destroyer with a turn count of 180 RPM was detected. COBBLER opened in 5-mile increments to 15 miles when the signal continued to remain strong, still that of a destroyer with 180 turn count. It was believed this signal could be detected at 20 miles but could not be proven since the device was recovered before a 20-mile range was reached. The concensus among sonarmen is that the device sounds more like a destroyer than most destroyers, and generates a clearer signal for any given range. On one occasion when a merchantman came between COBBLER and the device, the destroyer signal could be heard behind the noise of the merchant.

2. Unfortunately weather prevented a good comparison of "device" versus "actual" signals. Sea state one existed during monitoring of the device, but sea states from 2 to 3 were encountered during all other tests. Other than phase BRAVO, no other phase was conducted successfully 21 October.

3. On 23 October sea states from 2 to 3 again aborted an attempt to evaluate the device, but an effort was made to conduct the phases that did not require the device. The completed phases consisted of phase DELTA, BEALE at 18 knots, and Phase CHARLIE, BEALE at 8 knots. A maximum range of 9 miles was determined from phase DELTA and 3 miles for phase CHARLIE.

[redacted]

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[redacted] SS344/DSL/jhs

4. Recordings were taken during phases BRAVO, CHARLIE, and DELTA, and are submitted as enclosures 1, 2, and 3. Track charts for the event on 21 and 23 October are submitted as enclosures 4 and 5.* The tape recorder used was a RD-173/UN communications type with variac speed control, a poor recorder for this type evaluation. At present the UNQ-7 recorder is in Norfolk and will be installed on arrival of COBBLER. This recorder is the type that should be used in an evaluation such as the NRL device.

5. Although the evaluation was incomplete, one summarization can be made. This device is effective and very realistic. As mentioned before the one signal monitored sounded more like a destroyer than the average destroyer at the ranges experienced.

6. In case further tests are to be scheduled the following recommendations are submitted:

a. Provide as best possible an area where merchant shipping is at a minimum. Hours were wasted during previous evaluations while merchants masked out signals to be recorded.

b. Run evaluation when sea state is one to provide good comparisons between all phases.

c. If available an aircraft could be assigned as middleman between destroyer and submarine to facilitate UHF communications at ranges greater than 10 miles where BEALE and COBBLER experienced difficulty. The aircraft could also give advance warning of merchant interference so that movements could be made away from the merchant's track.

/s/
F. F. CLIFFORD

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*Not in this report.

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