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This Conference was organised by the Underwater Acoustics Group of the Institute of Acoustics.

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P.D. Thorne and N.G. Pace (School of Physics, Bath University, U.K.)

15. A 75 kHz transducer array using transverse drive.
J.R. Dunn (University of Birmingham, U.K.)

16. Design, construction and matching of a 38 kHz, 4.3 degree conical beam transducer.
P.C. Stevens (Universal Sonar, Hornsea, N. Humberside, England)

PROCEEDINGS OF PREVIOUS MEETINGS

The following proceedings of meetings organised by the Underwater Acoustics Group of the Institute of Acoustics are available from:

Mr. J. Mills,
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Invoices will be issued to include postage and packing of £1.00 inland and £2.50 - £3.50 overseas.

1.	Sound Propagation and Underwater Systems. Imperial College. 10th - 11th April 1978.	£7.50
2.	Acoustic Surveying of Fish Population. Fisheries Laboratory, Lowestoft. 17th December 1975.	£7.50
3.	Recent Developments in Underwater Acoustics. A.U.W.E., Portland. 31st March/1st April 1976.	£5.00
4.	Transducer Workshop University of Birmingham. 15th December 1976.	£5.00
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6.	Acoustic Cavitation. Institute of Higher Education, Poole, Dorset. 6th - 7th December 1977.	£3.00
7.	Acoustics in Fisheries. Hull College of Higher Education. 26th - 27th September 1978.	£10.00
8.	Transducer Arrays and Array Processing. University of Birmingham. 13th - 14th December 1978.	£7.50
9.	Underwater Applications of Non-linear Acoustics. University of Bath. 10th - 11th September 1979.	£8.00
10.	Progress in Sector Scanning Sonar. M.A.F.F., Lowestoft. 18th - 19th December 1979.	£8.00
11.	Signal Processing in Underwater Acoustics University of Loughborough. 21st - 22nd May 1980.	£7.00

Proceedings of The Institute of Acoustics

TWENTY-YEAR LIFE HYDROPHONES

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BACKGROUND

Underwater sound transducers are notorious for their poor reliability. It is not uncommon for 25% or more of the transducer elements of a sonar system to be nonfunctional after 1 or 2 years due to a variety of causes. The result, of course, is the increased cost of repair, retrofit, and loss of mission capability. The argument of this paper is that poor reliability need not be the case: transducers, especially hydrophones, can be built with reliability equal to space-age equipment.

A particular application has been chosen to demonstrate that high reliability can be achieved through the use of reliability modeling, an in-depth knowledge of transducer design, careful selection of materials, and good construction techniques. This approach, although applied to a specific type hydrophone, should also be important to other designs as well.

The Underwater Tracking Range of the Atlantic Fleet Weapons Training Facility, located in deep water off the western shore of St. Croix, has utilized a short baseline tracking system for accurate three-dimensional tracking of surface and subsurface targets. An extension to a long baseline tactical tracking capability required the development of hydrophones with extremely high reliability and long service life because of the remoteness and inaccessability of the hydrophones once deployed in deep water.

OBJECTIVES

Thus, the objectives of this hydrophone development were determined by the requirements of the St. Croix range and are listed below.

a. A 95% probability that the hydrophone will function 20 years deployed on the ocean bottom at a depth of 1800 m.

b. A sensor element and preamplifier combination with an output sensitivity of -140 dB re 1 V/μPa at 13 kHz and a bandwidth of 4 kHz to 45 kHz.

c. A preamplifier with an output impedance of 50Ω and capable of driving a signal through 20 km of cable.

d. A directivity pattern to discriminate against bottom reflections.

RELIABILITY ANALYSIS

To develop a reliable hydrophone, the designer must as a first step establish failure criteria. The basis for this determination is to be found in the design objectives. The definition of failure for this hydrophone is the decrease in output sensitivity below -140 dB re 1 V/μPa at 13 kHz and a 3 dB reduction of sensitivity elsewhere in the bandwidth.

Consideration of how this failure might occur leads to the second step which is the development of a simple reliability model. Figure 1 is a block diagram by function of this hydrophone. The sensor element converts sound into

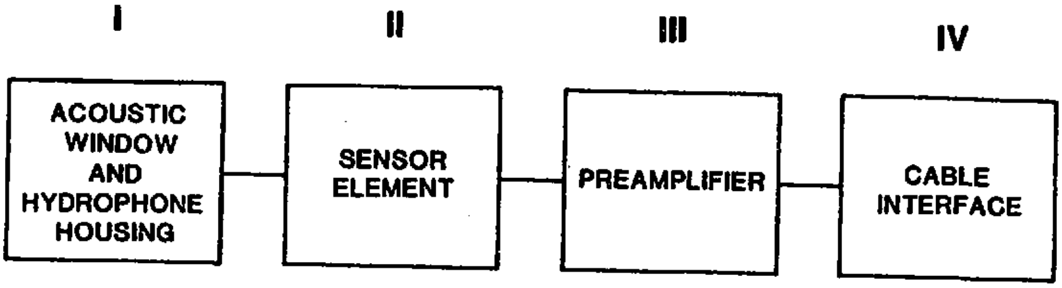

Figure 1. Simplified reliability model of the hydrophone by functional groups.

electrical signal and is usually the most important part of the hydrophone from the acoustical standpoint, but not necessarily so from the reliability standpoint. The acoustic window and housing provide protection to the sensor element and preamplifier from the sea. The preamplifier conditions the signal from the sensor element and provides it to the user via the cable interface. The cable should not necessarily be ignored because it definitely affects reliability, however, in this case, it is defined as outside the area of consideration. It is important to note that the functional groups of Fig. 1 are in reliability series, i.e., a failure in any one results in failure of the hydrophone. This is not to say, however, that the failure, or hazard, rates are equal.

The third step is to determine what the reliability demands mean in terms of failure rates. At this stage it is simplist to assume that infant-mortality is not a factor because of burn-in and acceptance testing. It is also simplist to assume the hazard rate λ is constant with time, and the reliability R, or the probability of successful operation, is

$$R = \int_t^\infty \lambda e^{-\lambda t} dt = e^{-\lambda t} \qquad (1)$$

Thus, in this hydrophone, the requirement of 95% probability of a 20 year lifetime means the total failure rate λ is equal to or less than 0.3 failures in 10^6 hours. Based upon experience the designer now estimates how the total failure rate can be distributed among the functional blocks. For this hydrophone

$$\lambda_I \leq 0.1f/10^6 hrs \qquad \lambda_{III} \leq 0.1f/10^6 hrs$$

$$\lambda_{II} \leq 0.05f/10^6 hrs \qquad \lambda_{IV} \leq 0.05f/10^6 hrs \tag{2}$$

It is important to realize that the assignment of failure rates in Eq(2) is only an estimate and serves as a guide for the design.

HYDROPHONE DEVELOPMENT

To meet the requirements, the hydrophone shown in Fig. 2 was developed. Details of assembly and the reasons for design decisions will be given below.

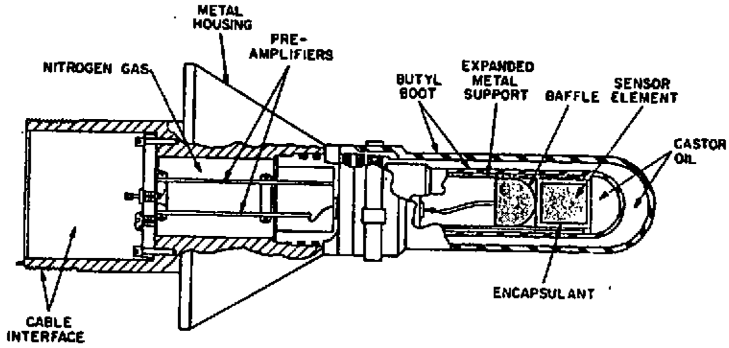

Figure 2. Cutaway view of the long-life hydrophone.

The acoustic sensor element, shown in Fig. 3, was an area ratio unsymmetrical tonpiltz composed of a longitudinally polarized lead-zirconate-titanate cylinder, provided with end caps and sealed by O-rings within an aluminum-oxide, precision-bore cylinder. There are two major advantages to this design. First, it takes full advantage of the high sensitivity given by the g_{33} polarization vector of the ceramic by shielding, and thus eliminating, the g_{31} component. Atmospheric gases sealed within the aluminum oxide housing by the O-rings represent an extreme impedance mismatch to the acoustic wave which eliminates entirely the g_{31} component to the sensitivity. Second, the sensitivity of the ceramic is effectively multiplied by the area ratio of the end caps to the ceramic cylinder. The combination of these two advantages yielded a sensitivity of -180.8 dB re 1 V/μPa, which is quite high for a small specific volume of ceramic. The metal end caps were bonded with conductive adhesive to the ends of the ceramic cylinder and served as electrodes. Electrical leads were connected to the end caps with screws and insured with

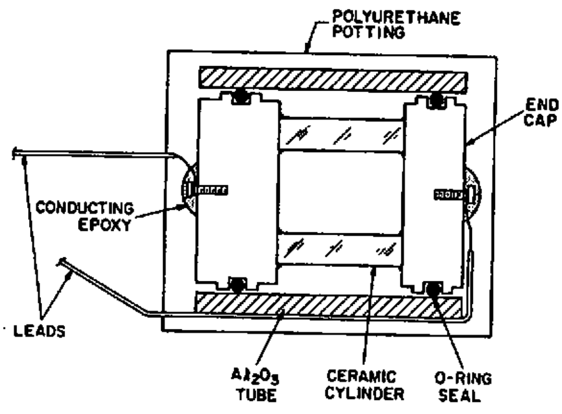

Figure 3. Acoustic sensor element

conductive adhesive. The leads were soldered at their opposite ends to glass-to-metal feed-throughs into the preamp compartment. The aluminum oxide housing with end caps and O-rings and the glass-to-metal feed-throughs were proof-tested to 135 MPa. Thus, the maximum operating pressure allowed a safety factor of 7.5. Reliability was further increased by encapsulating the ceramic sensor in a castor-oil compatible acoustically transparent polyurethane. This greatly reduced the possibility of oil leaking into the aluminum oxide housing and increased the physical integrity of the housing-ceramic cylinder-end cap assembly.

Behind the sensor element was mounted an acoustic baffle of machinable glass which, together with the conical housing, gave the hydrophone the desired cardioid directivity pattern in the forward direction.

The acoustic window, as shown in Fig. 2, consisted of inner and outer boots made of butyl rubber and each sealed to the hydrophone housing with double O-rings. The major reason for the choice of butyl was its low water vapor permeability, because water and water vapor are responsible for most failures in underwater transducers. The water permeability of most butyl compounds is 95 to 98% less than natural rubber, neoprene, polyurethane, Hypalon, or styrene rubbers. Butyl rubber is easy to mold, and bonds readily to metal parts properly prepared with the correct primers. The inner boot was molded of butyl compound B252, and the outer boot of butyl compound 70821. The major difference in the two is that the latter is an electrical grade. The ingredients and physical characteristics of both of these elastomers are given by Capps [1]. Butyl does not have a good ρc match to water, but if the wall section of the boot is uniform and small compared to the acoustic wavelength, it can be used successfully at frequencies below 100 kHz. Both boots were filled with castor oil. The salient characteristics of castor oil are high volume resistivity, close acoustic impedance match with seawater, compatibility with elastomers and other components and chemical stability. It is viscous and difficult to degas but this is a small problem for experienced technicians with proper vacuum systems.

The hydrophone could have been made with the sensor assembly encapsulated which eliminates the use of a fill fluid. But, for many encapsulants there are no general long-term immersion data available. Where data are available, many have a high rate of water vapor permeability; some are prone to bond failure; others leach their plasticizers and become stiff or brittle. Since high reliability was the objective, the proven characteristic of a dB-grade castor oil fluid filled system offered much less risk than an encapsulated system.

A low-noise preamplifier with 40.8 dB gain was designed to fit inside a nitrogen gas filled, sealed compartment within the hydrophone housing. To meet the requirements for high reliability, the preamp was redundant, consisting of identical channels A and B, as shown in simplified form in Fig. 4. However,

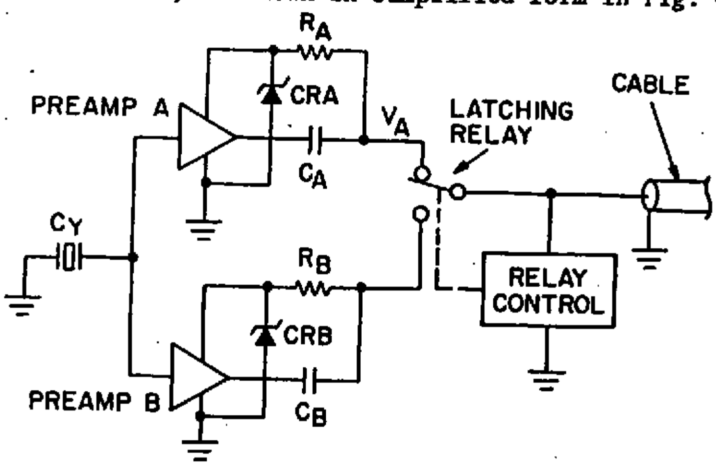

Figure 4. Dual-channel preamplifier design for high reliability.

only one channel is powered at any time with the selection made by the operator via a latching relay. DC power to the preamp and latching relay and ac output signal from the preamp share the common coaxial cable. The position of the latching relay is determined by the relay control network. This network is unenergized as long as the cable voltage is positive, which is the normal situation. In this case, the latching relay remains in its previously set state. To change preamp channels, the user activates the relay control network by momentarily applying a negative dc voltage. When the positive dc voltage is reapplied, the relay control network toggles the latching relay to its alternate position. The negative voltage has no effect on the preamp however. More details of this switching circuit can be found in a patent application [2]. Other features of the preamp included diode switch protection to the input FET from high voltage pulses or charge buildups from the ceramic sensor and to the preamp output from high voltage transients including lightning surges to 100 A.

The *Military Standardization Handbook 217B, Reliability Prediction of Electronic Equipment* was used as a guide in the preamp design. Tried and proven circuits with a minimum of parts, operating under minimal electrical stress, and qualified by adherence to military specifications to the highest levels of established reliability were used in the design. In addition a preamp burn-in at 125°C for 160 hours was conducted to eliminate infant mortality.

The cable interface shown in Fig. 2 accepted a Morrison cable seal. The seal, named after its designer, is a multilevel coaxial submarine cable seal. It has double O-rings at the interface and is designed to seal a coaxial submarine cable for 20 years at depths to 2.1 km (tested to 42 MPa). This seal assembly has been in service in the Navy for 10 years with excellent success.

RELIABILITY PREDICTION

The simple reliability model of Fig. 1 was expanded to the model shown in Fig. 5 during the design phase of the hydrophone. The increase in reliability provided by the redundancy of dual O-rings, dual boots, and dual preamps as shown in Fig. 2 over the reliability of the individual components can be seen with the model. Once the failure rate λ of each component is known the reliability of that component can be calculated from Eq(1). The reliability of the composite can then be calculated with Eq(3) for series components and Eq(4) for parallel components. Failure rates of transducer components are generally

$$R = \prod_{i=1}^{n} R_i \qquad (3) \qquad\qquad R = 1-\prod_{i=1}^{n}(1-R_i) \qquad (4)$$

not constant with time as are electronic components. However, it is customary to treat them as constants because of a lack of data. This was done here. Failure rates were assigned to each component as shown in Fig. 5 and were based on records and experience at NRL and references [3-4]. Failure rates depend upon the material, the environment, and the application.

Equations (1), (3), and (4) and the failure rates shown in parentheses in Fig. 5 were used to calculate the reliability and composite failure rate of each of the hydrophone functional groups for a life expectance of 20 years.

$$\begin{aligned} R_I &= .981 & \lambda_I &= 0.110\ f/10^6 hrs \\ R_{II} &\ \ .994 & \lambda_{II} &= 0.036\ f/10^6 hrs \\ R_{III} &\ \ .980 & \lambda_{III} &= 0.115\ f/10^6 hrs \\ R_{IV} &\ \ .991 & \lambda_{IV} &= 0.050\ f/10^6 hrs \end{aligned} \qquad (5)$$

These numbers compare closely with Eqs. (2). The product of the functional group reliabilities shows the probability of the hydrophone operating successfully for 20 years to be 94.7% which is as close to the design goal as one can come with the existing uncertainties in the component failure rates.

This prediction has been based only upon random component failure with the assumption of a constant hazard rate. No consideration has been given to wearout failure. In this hydrophone, the housing and outer boot, which are exposed to seawater, are likely to encounter wearout first. In recognition of this the housing is made of cadmium plated steel which has a well-documented corrosion rate of 0.07 mm per year. Wearout from this mode would take about 100 years. The outer boot undergoes a very slow chemical reaction with seawater but the choice of butyl ensures a wearout life well in excess of 20 years. Thompson [5] has shown that the chlorobutyl used here will gain only about 3% in weight, about 1% in swell, and about 10 shore hardness points after 20 years contact with seawater. A polyurethane potting or boot would be quite another matter. Both Thompson [5] and Sandwith [4] have shown that certain polyurethanes will

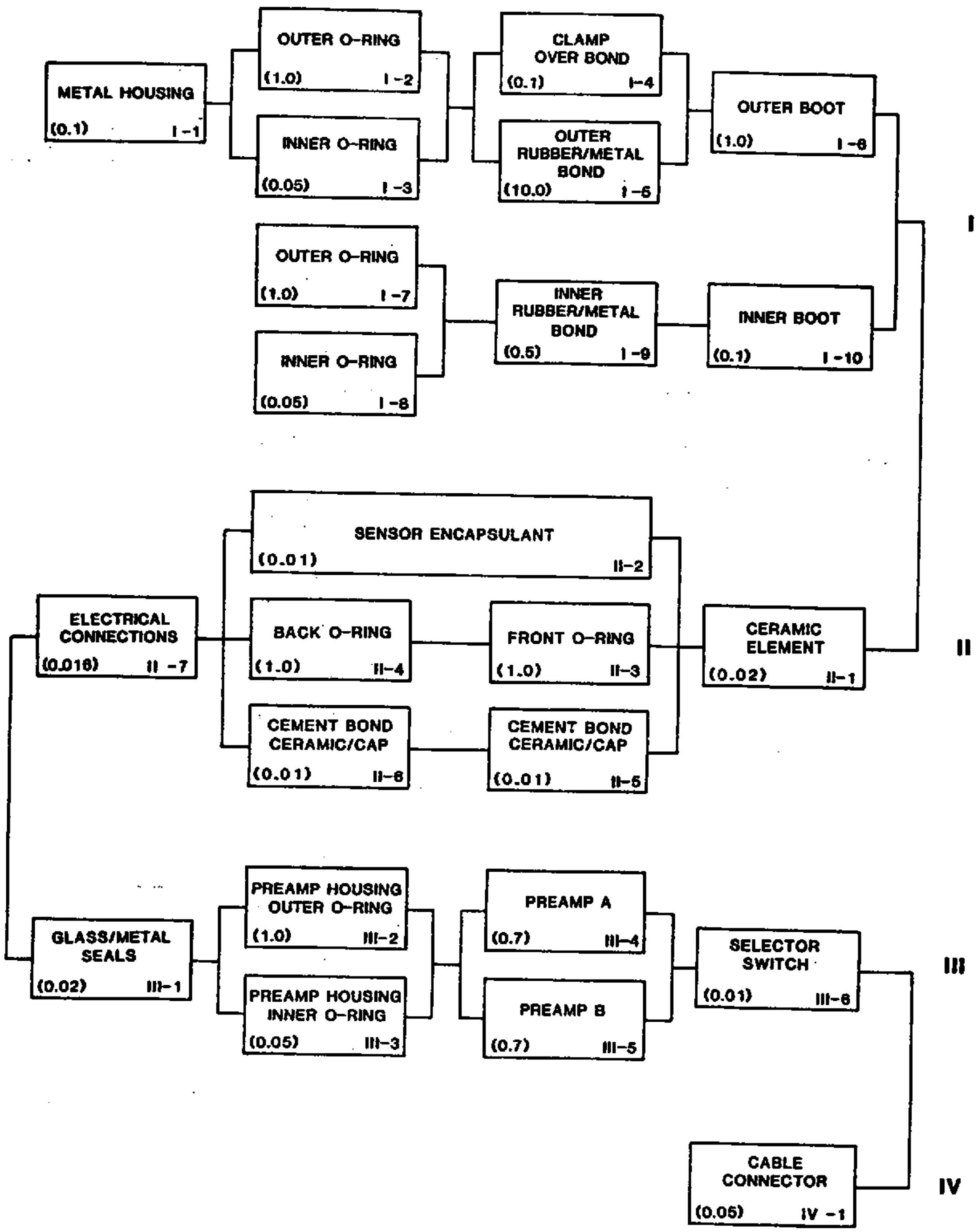

Figure 5. The reliability model of the hydrophone is shown with the components in functional groups I-IV. The failure rate of each component is shown in parentheses in failures per 10^6 hours.

wearout by cracking or complete disintegration in 5 years or less. The inner boot and other internal components have been chosen because of demonstrated compatibility with the castor oil fill fluid. Since there is no pressure or temperature cycling or handling once deployed, no additional stresses are placed upon the hydrophone so wearout within 20 years is not a problem.

An advantage of the reliability model in Fig. 5 is that it shows the value of redundancy. If the hydrophone had been designed with only one boot, single O-rings, and one preamp, the model would consist only of components I-1, I-2, I-5, I-6, II 1-7, III-1, III-2, III-4, and IV-1. The prediction of reliable operation for 20 years would be about 9%. Placing a hose clamp over the boot-metal bond can increase the reliability of 20 year life from 9% to 50%. The addition of double O-rings further increases the reliability to 70%. The double butyl boot construction increases it yet further to 85% and the redundant preamp brings the reliability to the goal. Of course, it is not surprising that the reliability can be improved by reinforcing the weak points, but the reliability model shows very clearly where attention should be placed in what order.

SUMMARY

A hydrophone has been developed with a predicted probability of 95% for a lifetime of 20 years. But, what assurance is there that this is more than an exercise with numbers?

An array of 24 of these hydrophones has been deployed for one year. Another array of 8 hydrophones that are identical except they have only one preamp channel each has been deployed for four years. No failures have occurred. However, the same reliability numbers discussed above predict there is only one chance in four that any failures would have occurred in that population during this time. So, while it is still too soon to be conclusive, there is reason for optimism that a twenty-year life hydrophone has been developed.

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