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NAVAL RESEARCH LABORATORY REPORT

16 October 1935

TRANSMISSION OF SOUND IN SEA WATER ABSORPTION AND REFLECTION COEFFICIENTS AND TEMPERATURE GRADIENTS

By
E. B. Stephenson

Report No. S-1204

Classification changed from Confidential
To Unclassified
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File No. Dated 1920

NAVY DEPARTMENT
OFFICE OF NAVAL RESEARCH
NAVAL RESEARCH LABORATORY
WASHINGTON 20, D. C.

Unclassified

16 October [illegible] NRL Report No. [illegible]

NAVY DEPARTMENT

BUREAU OF ENGINEERING

Report on

Transmission of Sound in Sea Water

Absorption and Reflection Coefficients and Temperature Gradients

NAVAL RESEARCH LABORATORY
ANACOSTIA STATION
WASHINGTON, D. C.

Unclassified

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Date of Work: July 1935.

Prepared by: E. B. Stephenson, Senior Physicist

Reviewed by: H. C. Hayes, Principal Physicist

Approved by: H. M. Cooley, Captain, U.S.N.
Director

Distribution: BuEng (5)

Classification changed from [illegible]
To Unclassified
By Navy Regulations
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ABSTRACT

Studies of absorption and reflection coefficients of high frequency sounds were made in deep water off the New London area in July 19[illegible]

The apparatus and technique are satisfactory for accurate quantitative data but the water conditions in the area were variable. There are relatively large horizontal and vertical temperature gradients which limited the range and consistency of the results. Values of the absorption coefficient were found that lie between $\alpha = 0.0005$ and $\alpha = 0.0020$.

Data are given on the background of noise on the [illegible] as a function of speed, frequency, and training of the transceiver.

A range chart is given showing the possible gain in range to be obtained by increasing the initial sound output, by lowering the noise level, or by selecting a frequency to give a low value of absorption.

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Appendices

I. INTRODUCTION

Authorization

1. This work was authorized by the Bureau of Engineering letters listed as references.

References: (a) BuEng let. C-S68(11-27-W6) of 5 December 1933.
(b) BuEng let. C-S-172/S41(12-18-Ds) of 14 July 1934.

Statement of Problem

2. The fundamental problem of this investigation was to obtain the absorption and reflection coefficients of sea water as a function of frequency for different water conditions and for different conditions of operation. The practical importance of these coefficients lies in the fact that if these constants are known with reasonable accuracy for the various conditions it is possible to apply well established mathematical theory in the design of equipment and to predict approximately the ranges obtainable under specified conditions of power output, frequency, dimensions of transceivers, speeds of the two ships, aspect of target, and water conditions, particularly depth, temperature and purity.

Previous Data

3. A considerable volume of data on supersonics have been accumulated by both Laboratory and Service personnel during the past ten years, chiefly in the form of direct signal and echo range data. These data have often been conflicting (e.g. maximum echo ranges varying from 700 yards to 7,000 yards) and the explanation was not always obvious. There are three principal factors in determining obtainable ranges; namely, apparatus, water conditions, and personnel. At first the variations were attributed to apparatus, but the last few years water conditions, particularly temperature gradients, have been found to be big factors, and, of course, there will always be variations in personnel. Unfortunately, most of the service range data reports have not been accompanied by exact statements of the other conditions.

4. The expeditions of the Eagle boats in 1931 and 1933 obtained considerable range data under known conditions and established the fact that there is a great difference between the waters of Panama Bay, the San Pedro area and the Hawaiian area, and that the conditions in any area vary with the seasons. This general conclusion has been checked by the submarines in Coco Solo and Pearl Harbor. In Panama from January to July the ranges obtained are relatively short, the water is full of animal and vegetable growth and there is a steep temperature gradient. These conditions disappear more or less in the fall and ranges improve. In the Hawaiian area conditions are more uniform throughout the year and ranges are greater and more constant.

5. In the New London area in the fall of 1934 echo ranges of [illegible] to 6000 yards were obtained in the shallow water of the Sound, but in the summer of 1935 with the same apparatus, personnel, and area, echo ranges were generally limited from 1,000 to 1,[illegible]00 yards with a few striking exceptions apparently showing a "skip distance" effect

6. In the early spring of 193[illegible] excellent results were obtained by the Eagle 58 in the Guantanamo, Cuba, area, and the temperature gradient was found to be very small.

7. The development of adequate measuring equipment has been a major problem in supersonics. Equipment has now reached the stage where sufficiently accurate measurements can be made to evaluate some of the different factors concerned in transmission of sound through water.

Theoretical Considerations

8. The expression for the absorption coefficient is derived from the fundamental equation for the transmission of wave energy.

9. If a conical wave of sound is being sent out from a transceiver into a homogeneous medium of infinite extent, the intensity I of the sound; i.e., the rate of flow of sound energy through unit area at a given distance will be proportional to the initial intensity, I_o, inversely porportional to the square of the range, R, and will be subject to an exponential absorption. Expressed in a formula, where R_o is unit distance

$$I_R = I_o \cdot \frac{R_o^2}{R^2} \cdot 10^{-\alpha R}$$

If the intensities I_1 and I_2 are measured at two different ranges R_1 and R_2, we have the equations

$$I_1 = \frac{I_o R_o^2}{R_1^2} 10^{-\alpha R_1} \qquad (1)$$

$$I_2 = \frac{I_o R_o^2}{R_2^2} 10^{-\alpha R_2} \qquad (2)$$

Dividing (1) by (2) to eliminate I_o and R_o

$$\frac{I_1}{I_2} = \left(\frac{R_2}{R_1}\right)^2 10^{\alpha(R_2 - R_1)} \qquad (3)$$

The intensities are measured in decibels above a standard reference level I_s as defined by the equation

$$db = 10 \log \frac{I}{I_s} \qquad (4)$$

and

$$db_1 - db_2 = 10 \log \frac{I_1}{I_2} \qquad (5)$$

Taking logs of both sides of (3) and substituting (5)

$$\log \frac{I_1}{I_2} = 2 \log \frac{R_2}{R_1} + a \ (R \ - R \ )$$

$$a = \frac{0.1 \ (db_1 - db_2) - 2 \log \frac{R_2}{R_1}}{R_2 - R_1} \qquad (6)$$

10. The value of a defined by equation (6) is seen to depend on the difference in intensities and on the range. The value of the initial intensity I_o must be maintained constant, but it is not necessary to know its absolute value. Since a may depend on the frequency, it is necessary to keep the frequency constant during an experiment.

11. In practice the ideal conditions assumed in the derivation of the formula for a seldom obtain as the medium is neither infinite nor homogeneous. The experimental value obtained, however, is quite practical as it is an over-all value that includes all the losses. If a value can be obtained under approximately ideal conditions, then deviations from the ideal value are an indication of the effect and importance of other conditions.

12. The effective reflection coefficient μ may be defined as the ratio of the intensity of the echo to the intensity of the direct signal which has passed through the same distance in the water (twice the echo range)

$$\mu = \frac{I_e}{I_d} \qquad (1)$$

Intensities are measured in decibels above some arbitrary level defined by the equation

$$db = 10 \log \frac{I}{I_o} \qquad (2)$$

Taking the logarithm of both sides of (1) and substituting (2)

$$\log \mu = \frac{db_e - db_d}{10}$$

This same formula may be derived in a manner analogous to the absorption coefficient. Let a sound beam be incident on an area at a range R with an intensity I_1, then

$$I_1 = \frac{I_o R_o^2}{R^2} \ 10^{-a R} \qquad (1)$$

If there is a reflector at this area, the new source becomes I_r, where $I_r = \mu I_1$, μ being a fraction. The intensity of the echo, I_e,

going back over the range R is

$$I_e = \frac{I_r R_o^2 \, 10^{-aR}}{R^2} = \frac{\mu \, I_i R_o^2 \, 10^{-aR}}{R^2} = \frac{\mu \, I_o R_o^2 \, 10^{-2aR}}{R^4} \qquad (2)$$

If there is no reflector at the area I_i and the sound continues in the same direction a further distance R from I_i (the same source as the echo but without loss from reflection or $I_i = I_r$.)

$$I_d = \frac{I_i R_o^2 \, 10^{-aR}}{R^2} = \frac{I_o R_o^2 \, 10^{-2aR}}{R^4} \qquad (3)$$

Dividing (2) by (3)

$$\frac{I_e}{I_d} = \mu \quad \text{and } \log \mu = \frac{db_e - db_d}{10}$$

13. The experimental procedure is to transmit a signal of constant intensity and frequency and to measure the intensity of the direct signal on the target ship and of the echo on the transmitting ship. This is done at a series of ranges to give the data for both absorption and reflection coefficients. The reflection coefficient is affected by all the factors which affect the absorption coefficient and in addition is affected by the target. The ideal reflecting target would be an infinite plane perpendicular to the axis of the beam, but this is not even approximated under service conditions. The coefficient obtained will vary with the configuration of the target and the angle of approach. It will also vary with the frequency or wave length. To have specular reflection, as contrasted with scattering, the reflecting area must be large compared with the wave length and this area will vary with the configuration in the direction perpendicular to the axis of the beam. The experimental coefficient is a practical value, however, as it includes all the losses from any cause and makes no assumptions as to the mechanism of reflection. The experimental procedure requires that the measuring apparatus for both the echo and the direct signal be calibrated against the same standard.

14. The temperature affects sound transmission particularly if there are either horizontal or vertical stratifications. The velocity of sound increases with the temperature. If there is a considerable difference in temperature between the surface and lower levels the sound beam is refracted downwards and may pass too far beneath a surface ship to be detected. Also, where there is an abrupt change in temperature between a warm surface layer and a colder deeper layer, the two layers are usually moving with respect to each other producing a turbulence at the boundary that absorbs or scatters the sound. It is frequently possible to get a good echo from this boundary layer in the Gulf Stream or in Panama Bay. Obviously if such a boundary layer will give an echo it must interfere with the normal transmission of the sound.

Laboratory Work

15. Considerable laboratory work was necessary to develop the two sets of apparatus for making the quantitative measurements and in standardizing them so that results would be comparable. Also practice is necessary for the personnel to get accurate and consistent results.

II. METHODS

Materiel

16. The essential measuring apparatus consists of two transceivers and two sound analyzers. One transceiver was designed to give a flat response over a wide range of frequencies. The other was a standard JK type. The two analyzers are identical in principle. They have a sensitivity that is uniform within 1 db from 10 to 50 kilocycles and a selectivity such that the response is 10 db down at ± 500 cycles from any selected frequency. Number 1 has a total attenuation range of 0 - 70 db in 2 db steps and Number 2 has a total range of 0 - 140 db. Measurement may be made on a thermal meter which measures the amplified high frequency energy directly, or on phones by heterodyning and detecting. No audio amplification is used. For phones the zero level is minimum audibility and the zero on the meter can be adjusted at a known db level above this. Each analyzer has a self contained standard signal generator for adjusting the frequency and the amplifier gain.

17. The two complete equipments were calibrated by installing them in the two wells in the main sound room of the SEMMES and transmitting a signal of constant intensity and known frequency from the D-2 unit in the after sound room for simultaneous measurement on the two analyzers. This calibration is independent of the absolute value of the signal from the D-2 driver.

18. For the absorption and reflection studies, Number 1 analyzer and transceiver were mounted in the main sound room of the U.S.S. SEMMES. The Number 2 analyzer and JK transceiver were installed on the S-20.

Experiments

19. An elaborate schedule of tests had been planned, particularly for the reflection coefficient determinations, but due to the limitations of time and the adverse water conditions only a simple program could be carried out in the New London area in July 1935.

20. The SEMMES and the S-20 proceeded to deep water on the 1,000 fathom curve at approximately Lat. 40° N. and Long. 70° W. The two ships took the same and parallel courses abeam, the S-20 submerged to periscope depth and ran at 3 knots. The SEMMES transmitted a signal of constant strength and known frequency and the S-20 measured the intensity of the direct signal. The SEMMES measured the range and the intensity of the echo. The range was then increased by the SEMMES and the measurements were repeated for a series of ranges. The SEMMES recorded the injection water temperatures at regular intervals and the S-20 recorded the temperatures on a thermometer outside an eyeport in the conning tower. At least once each day the S-20 made a deep dive to obtain the vertical temperature gradient.

21. The data taken during the sound analysis of the S-20 in October 1934 and August 1935 may also be used to calculate absorption coefficients as a function of frequency since intensities of the propeller noises were measured at two different ranges and at twenty different frequencies between 10 and 45 kilocycles. It should be understood that the values obtained apply with certainty only under the conditions stated.

Personnel

22. The technical work was done by Dr. E. B. Stephenson, Mr. W. W. Wiseman, and Mr. W. F. Curtis assisted by the radio personnel on the two ships.

III. DATA OBTAINED

Data

23. The data obtained on two days in deep water at 17.3 kilocycles are shown in Plate 1. All the determinations made are shown. The range was increased by steps to some 4,000 yards and then decreased. The measurements extended over some 6 hours in time and 18 miles in distance on July 25 so that changed conditions may account for the scattering. Lines are drawn that are considered to give a group average and α is calculated from the curves for the two days. The fit for July 24 is pretty good as all of the points except two are within 2 db. The values of α for the two curves on July 24 are close but they are on different levels for the two runs. This may be explained by the fact that the technique improved after the first run on the first day. On the July 25 curve slightly more weight is given to the high values as there was considerably fading and it is easy to get low readings.

24. The data for 23 kilocycles are shown in Plate 2. The points are scattered and the line is an approximation at best. It should pass below the two short range points (Refs. comment on Plate 5).

25. Plate 3 shows data obtained on the Eagle 58 expedition in 1934. The Number 1 analyzer and transceiver was used for receiving but the frequency was 30 kilocycles. There was no temperature gradient. The ranges are greater and the data more consistent.

26. Plate 4 shows the relation between absorption coefficient and frequency for propeller noises in deep and shallow water at short ranges of 1,000 to 2,000 yards. Each point is the average of ten or more separate determinations under different conditions. Note that the scale for deep water is ten times that for shallow water.

27. Plate 5 shows five curves calculated from the formula

$$I = \frac{I_0 R_0^2}{R^2} 10^{-\alpha R}$$

for $R_0 = 1$, an assumed reasonable value of I_0, and different values of α that cover the range of the experimental values. When written in the logarithmic form to facilitate calculation,

$$db = 10 \log I = 10 (\log I_0 - 2 \log R - \alpha R)$$

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$$db = 10 \log I = 10 (\log I_0 - 2 \log R - \alpha R)$$

it will be noted that the 2 log R term is numerically large compared to α R at the short ranges but that at the longer ranges the α R term is the larger. Thus, there is an approximately linear relation between db and range beyond 1,000 yards. The "best" straight line drawn through the points between 1,000 yards and 4,000 yards would not be in error more than 2 db. This justifies the use of straight lines in Plates 1 and 2 and also justifies drawing them below the short range points.

28. Plate 6 shows the vertical temperature data taken by the S-20 in different areas at different times. In deep water there was a layer of warm water of fairly uniform temperature about 30 feet deep on top of a much colder layer. From 30 to 50 feet below the surface there was a drop of 5° C or more. In the shallow water of Block Island Sound there was considerably mixing by the tidal currents and the total differences are not so large nor is the change so abrupt.

29. Plate 7 shows some horizontal temperature data taken by the two ships on different days. The data taken by the S-20 are probably accurate to 0.2° C. and on the SEMMES to 1.0° F. The curve for August 16 shows the largest and most rapid variations.

30. Plate 8 shows some interesting data on the background of noise on the SEMMES as a function of speed and frequency. Too much weight should not be given to the frequency relations because the X-2 transceiver does not have a uniform response with frequency. The data apply only for this transceiver. The readings were made on the analyzer meter whose zero level is about 40 db above minimum audibility on the phones. It will be noted that the background is fairly constant up to a speed of 12 knots but increases rapidly up to 20 knots. Other tests have shown that 15 knots is about the maximum speed for echo ranging in shallow water on account of the background of noise. The noise is less in deep water.

31. The X-2 transceiver has a rubber case but the front and back faces are flat. Plate 9 shows the effect of the bearing of the transceiver on the noise at two different speeds. The bearing difficulty has been largely eliminated by the use of a spherical transceiver.

32. The reflection coefficient data are unsatisfactory due primarily to the variable water conditions. The data taken in deep water on two different days and at two different frequencies for echo ranges from 800 yards to 2560 yards are given in Table 1. The data would indicate that the port side of the S-20 is a much better reflector than the starboard side but there is no obvious reason for such a result and the data are not sufficiently accurate to warrant such a conclusion. It will also be noted that the reflection coefficient is largest where the absorption coefficient is also large. This is not inherent in the formula or the method of measurement and is assumed to be accidental.

33. The sensitivity and reliability of the apparatus and technique give readings that would be correct to within ± 2 db but the water conditions were such that this degree of precision could not be maintained for any extended series of readings, nor were there a sufficient number of readings to permit statistical treatment other than plotting and drawing the "best" line through a number of points. The data are not sufficient to warrant any conclusions on the variation of α or μ with frequency, or on the variation of μ with bearing of the submarine. The

variation of absorption coefficient with frequency for propeller noises in shallow water is probably valid since each point is the average of 10 or more readings. The reflection coefficient data is particularly unsatisfactory due to the changing conditions and the limited amount of data. However since α is a logarithmic function of the intensities as measured one must think of the numerical values as orders of magnitude rather than percents.

IV. CONCLUSIONS

Facts Established

34. Absorption coefficients have been determined that lie within the limits of $\alpha = 0.0005$ and $\alpha = 0.0020$. The most consistent previous results were obtained in the Hawaiian area where $\alpha = 0.00065$.

35. The reflection coefficient data are too irregular to warrant conclusions.

36. The temperatures in the New London area are irregular and show both horizontal and vertical gradients.

Opinions

37. The New London area has at no time been found suitable for accurate quantitative work. The weather is variable and the distance to deep water is too great. Satisfactory data cannot be obtained in shallow water due to irregular bottom reflections.

38. The apparatus and technique would give accurate quantitative data if water conditions were suitable.

Recommendations

39. It is recommended that these experiments be continued in a suitable area as soon as possible. Guantanamo, Cuba, is known to be a suitable area from January to March inclusive.

V. DISCUSSION

40. A consideration of Plate 5 shows the possible lines of development in sound gear to increase the range. They are

(a) Increase the initial intensity, I_0.
(b) Lower the noise level.
(c) Operate at a frequency where α is low.

It is possible to increase the initial sound intensity by increasing the electrical input into the transceiver, or by improving the efficiency of the conversion of electrical energy into sound energy, or by a combination of both. Suppose that it is possible to increase the sound output by a factor of 10, what will be the increase in range of the direct signal? A factor of 10 in power corresponds to 10 db. On the curve $\alpha = .0010$ the increase in range would be approximately 1,000 yards. Exactly the same gain in range can be obtained by lowering the effective noise level 10 db. Increasing the gain of the amplifier is effective only up to the point where the water noise is approximately at the signal level.

41. The absorption coefficient is inherently a property of the water, but it is a function of frequency and by a proper choice of frequency the effect of a may be reduced. At present there are no quantitative data on the relation of a or μ to frequency except for the special condition of propeller noises but the qualitative data for a point definitely to the lower frequencies.

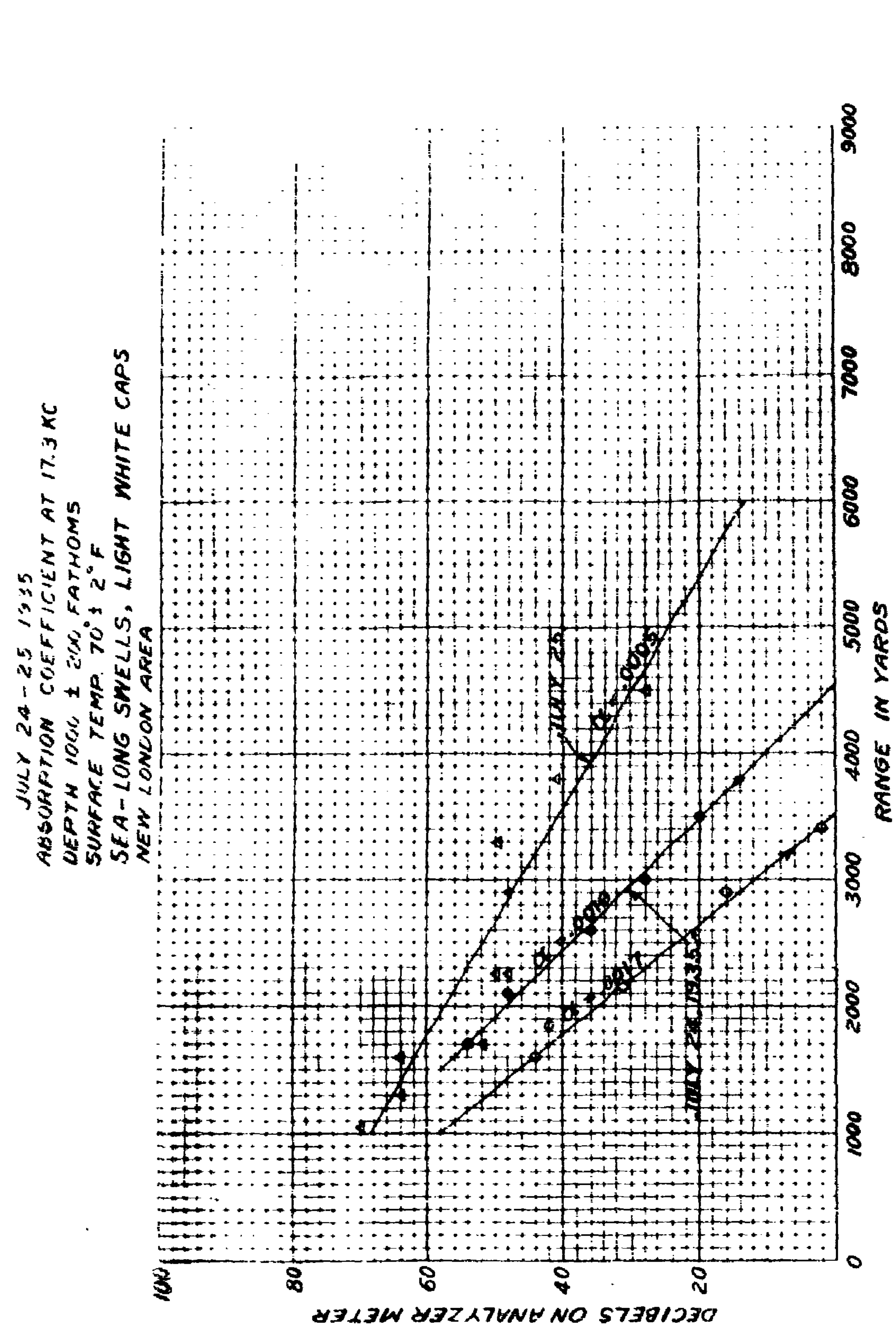
42. The effective reflection coefficient is also believed to be a function of frequency but there are no satisfactory data.

43. The importance of a fairly accurate knowledge of the absorption and reflection coefficients as functions of frequency and other variable conditions is obvious in that they vitally affect the further development of underwater sound apparatus.

Table 1

Reflection Coefficients in Deep Water

Date	Time	Bearing	Echo Range	Echo at R	Direct Signal at R	Direct Signal at 2R	Log μ	μ
24 July	1450	92	1600	00	44	10	-1.0	0.10
17.3 kcs	1520	97	1840	-24	42	0	-2.4	0.004
	1725	82	2000	-2	48.5	11	-1.3	0.05
	1730	84	1700	+6	54	23	-1.7	0.02
25 July	0625	262	1300	+2	64	51	-4.9	1.3×10^{-5}
17.3 kcs	0637	280	1050	+6	70	56	-5.0	1.0×10^{-5}
	0655	277	1600	+4	64	44	-4.0	1.0×10^{-4}
25 July	1315	300	800	-8	72	56	-6.4	4.0×10^{-7}
23 kcs	1340	274	1120	-24	58	48	-7.2	6.3×10^{-8}
	1407	275	2560	-26	44	16	-4.2	6.3×10^{-5}



JULY 24 - 25 1935
ABSORPTION COEFFICIENT AT 17.3 KC
DEPTH 1000 ± 200 FATHOMS
SURFACE TEMP. 70° ± 2° F
SEA - LONG SWELLS, LIGHT WHITE CAPS
NEW LONDON AREA
JULY 25
.0005
.0010
.0017
RANGE IN YARDS
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
DECIBELS ON ANALYZER METER
100
80
60
40
20

PLATE I

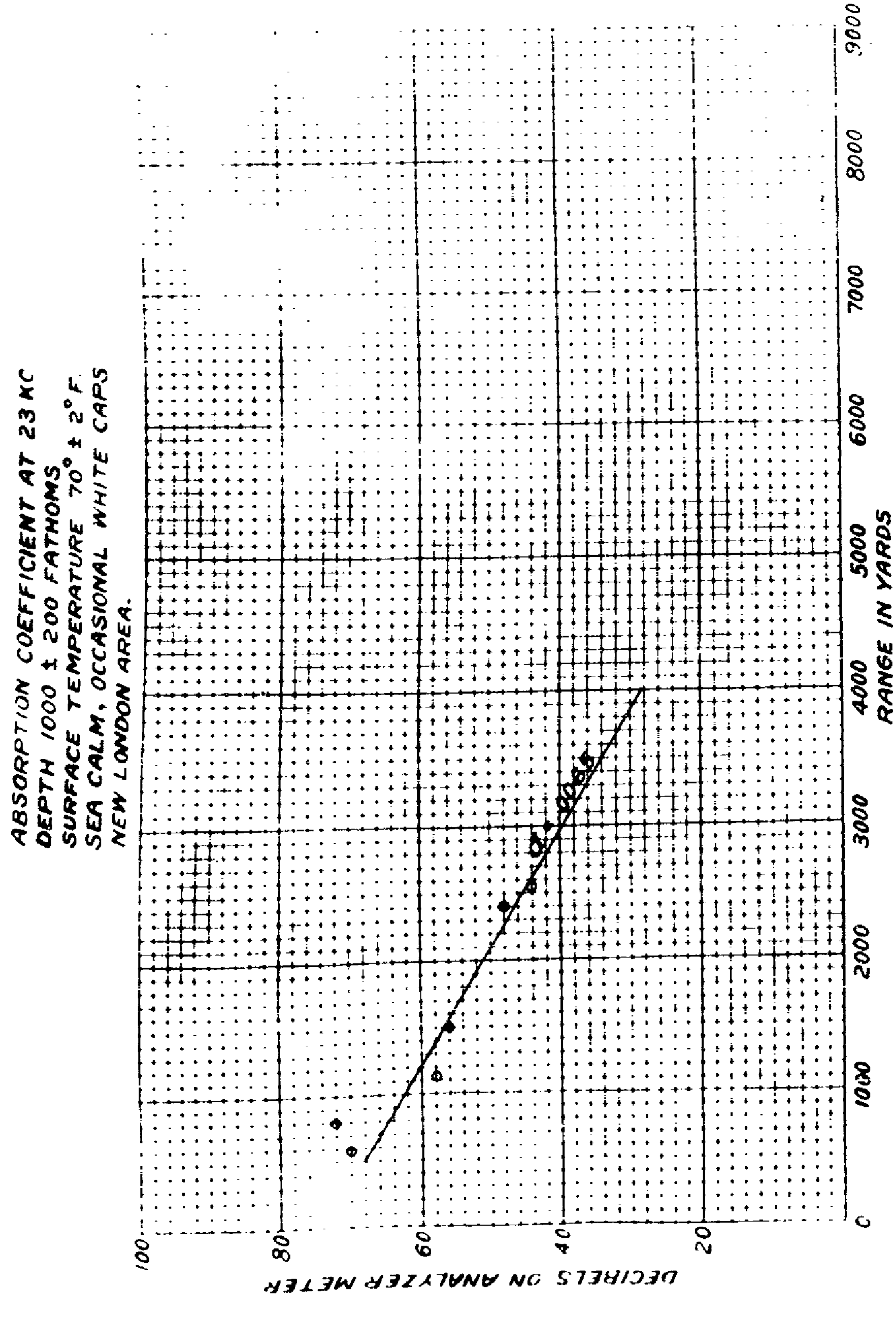
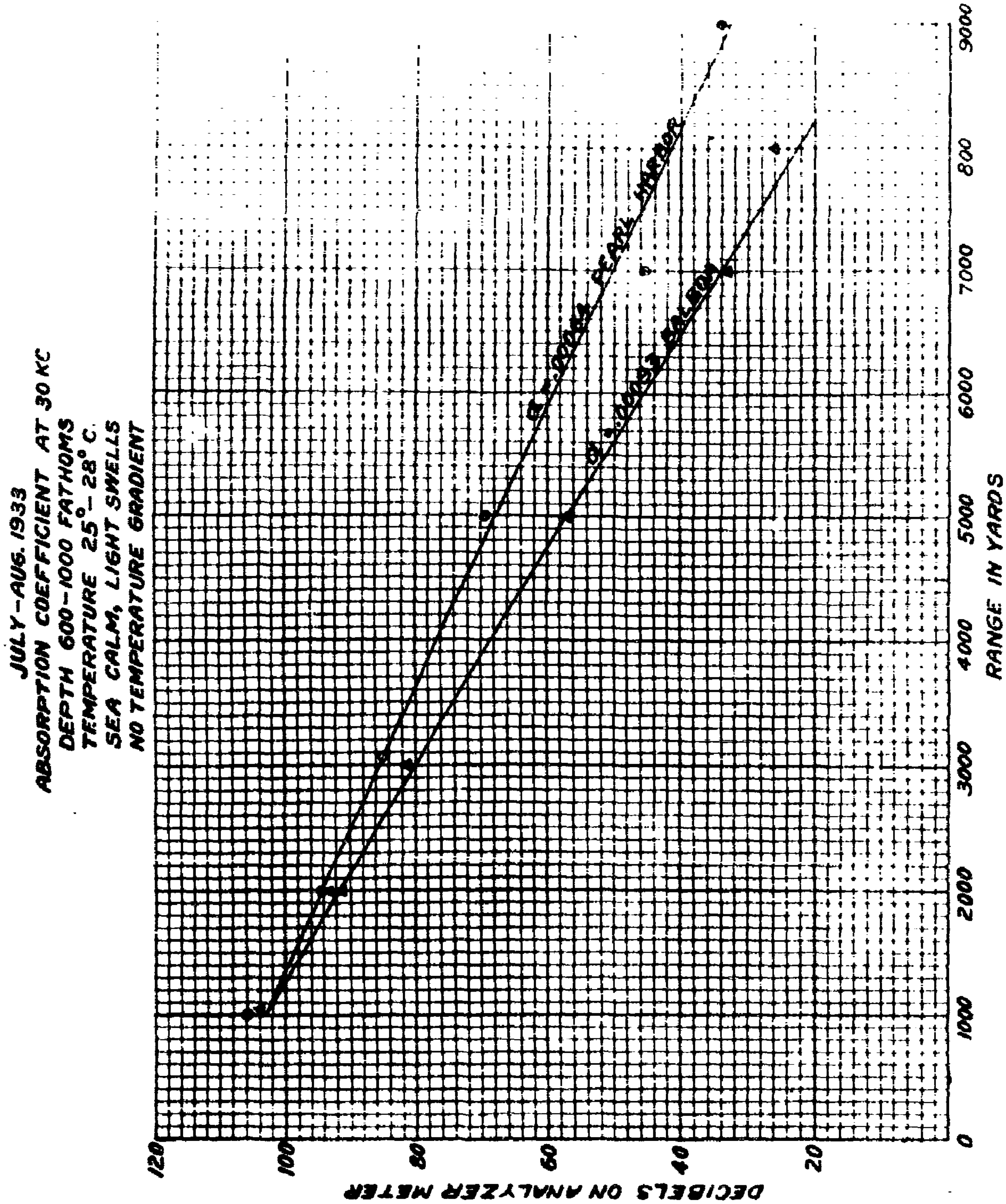

ABSORPTION COEFFICIENT AT 23 KC
DEPTH 1000 ± 200 FATHOMS
SURFACE TEMPERATURE 70° ± 2° F.
SEA CALM, OCCASIONAL WHITE CAPS
NEW LONDON AREA.
RANGE IN YARDS
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
DECIBELS ON ANALYZER METER
100
80
60
40
20

PLATE 2



JULY—AUG. 1933
ABSORPTION COEFFICIENT AT 30 KC
DEPTH 600-1000 FATHOMS
TEMPERATURE 25°-28° C.
SEA CALM, LIGHT SWELLS
NO TEMPERATURE GRADIENT
RANGE IN YARDS
DECIBELS ON ANALYZER METER

PLATE 3

PROPELLER NOISE AT SHORT RANGE
LOSS COEFFICIENT VS FREQUENCY
NOTE:- EACH POINT ON THE CURVES
IS THE AVERAGE OF 10 OR MORE READINGS
NEW LONDON AREA

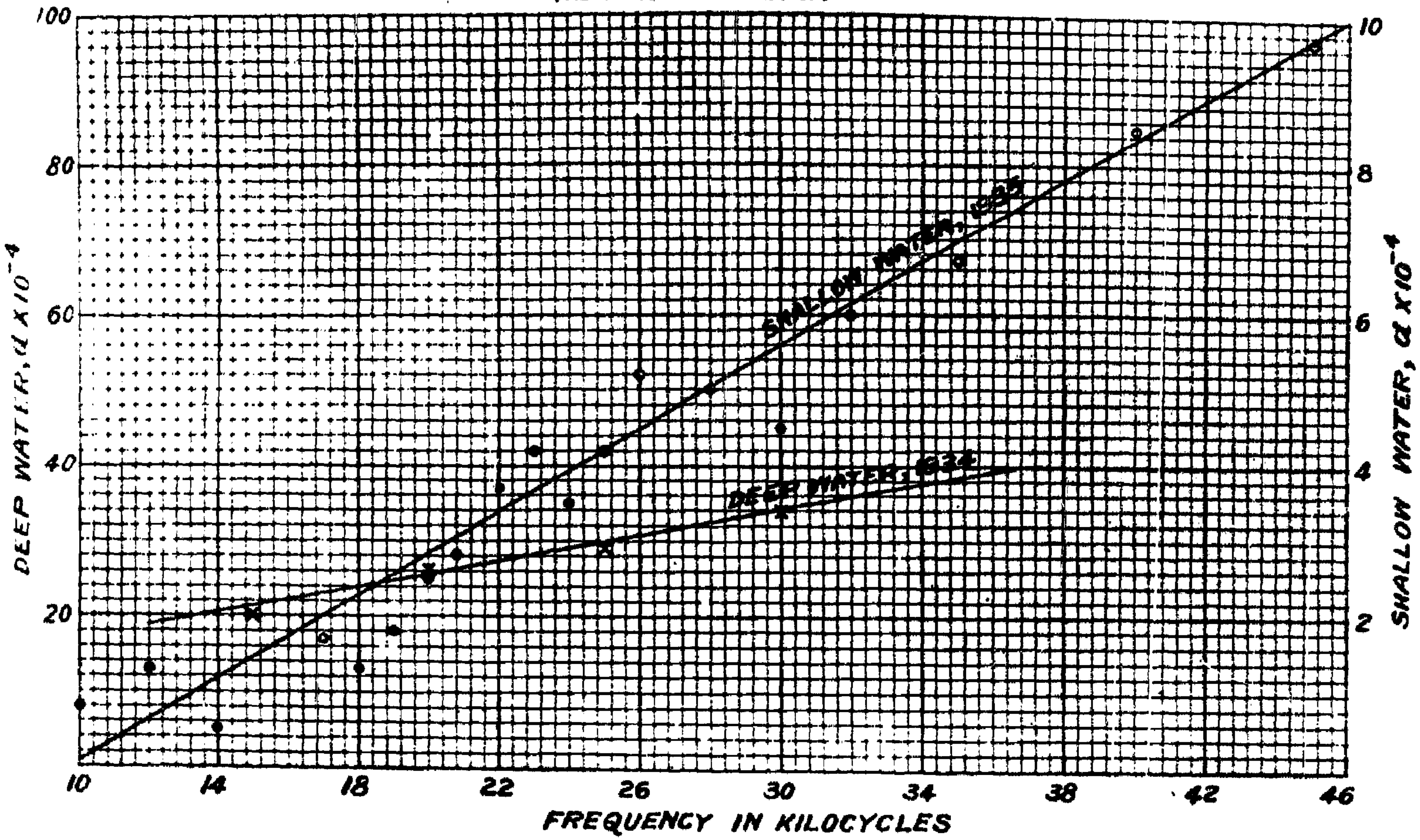


PLATE 4

SEPT. 1935

CALCULATED RANGE CURVES

FROM FORMULA $I = \frac{I_0}{R^2} 10^{-\alpha R}$

FOR ASSUMED VALUES OF I_0 AND α

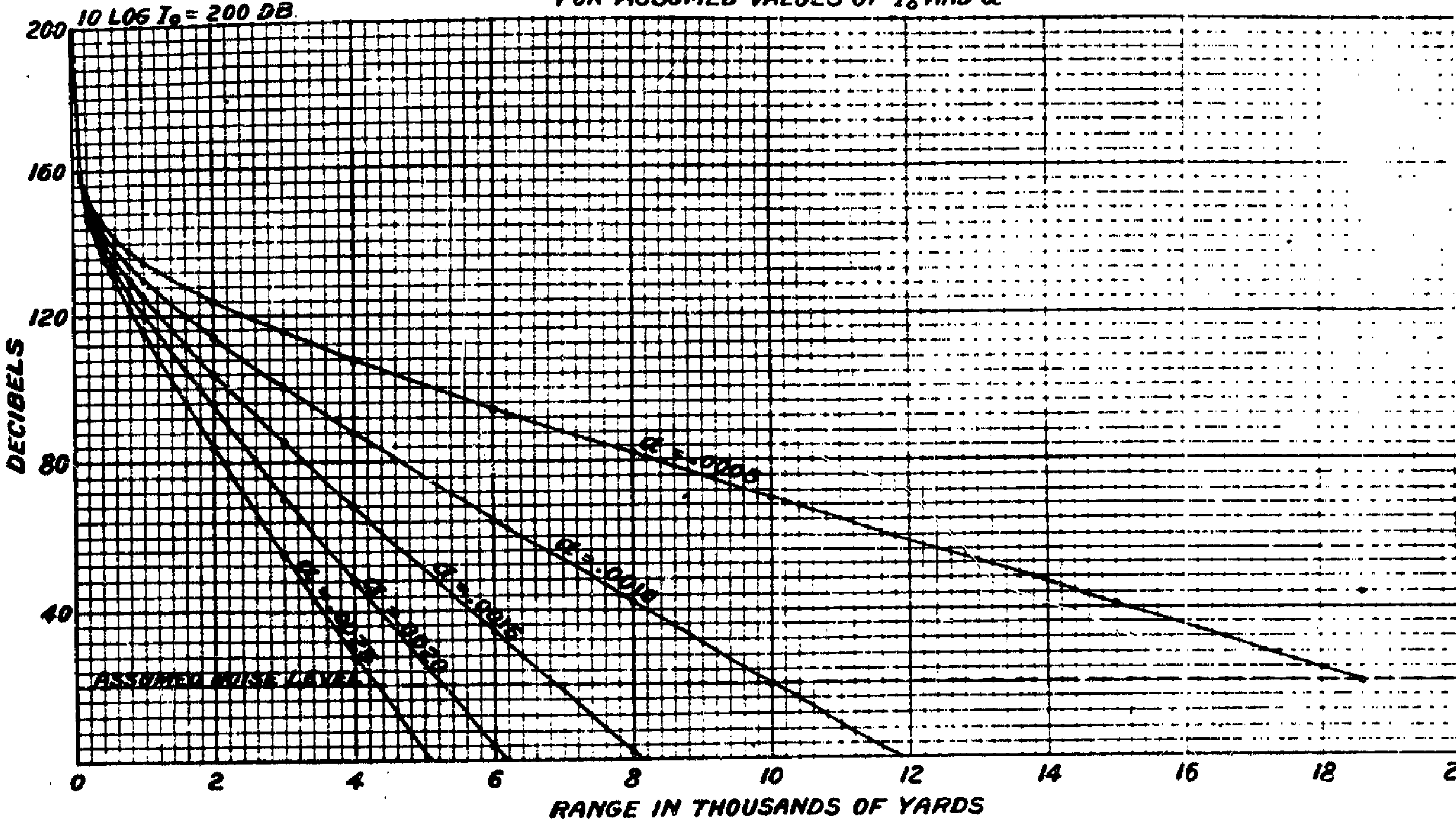


PLATE 5

JULY – AUG. 1935
VERTICAL TEMPERATURE GRADIENTS
NEW LONDON AREA

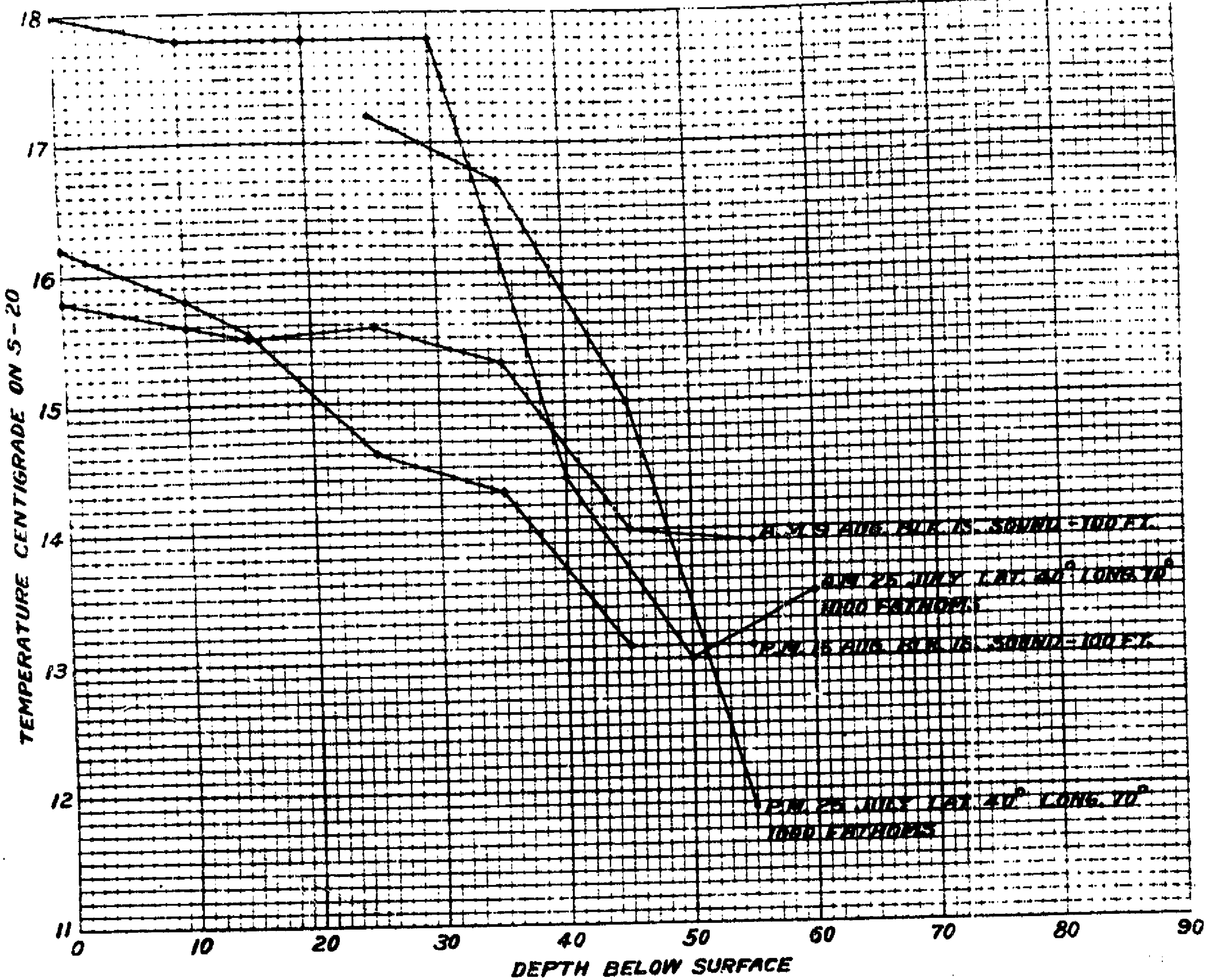


PLATE 6

JULY-AUG. 1935
HORIZONTAL TEMPERATURE GRADIENTS
NEW LONDON AREA

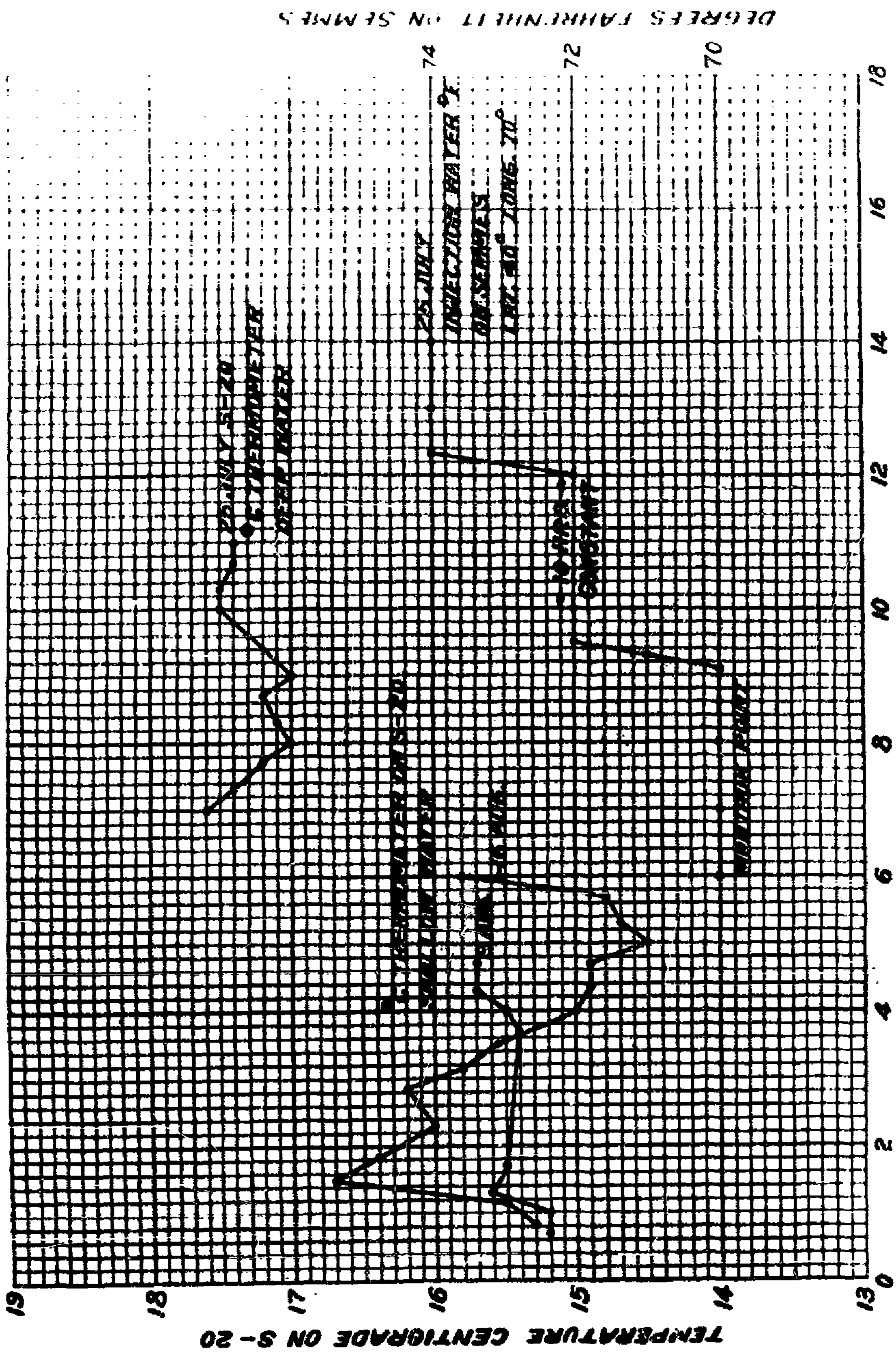
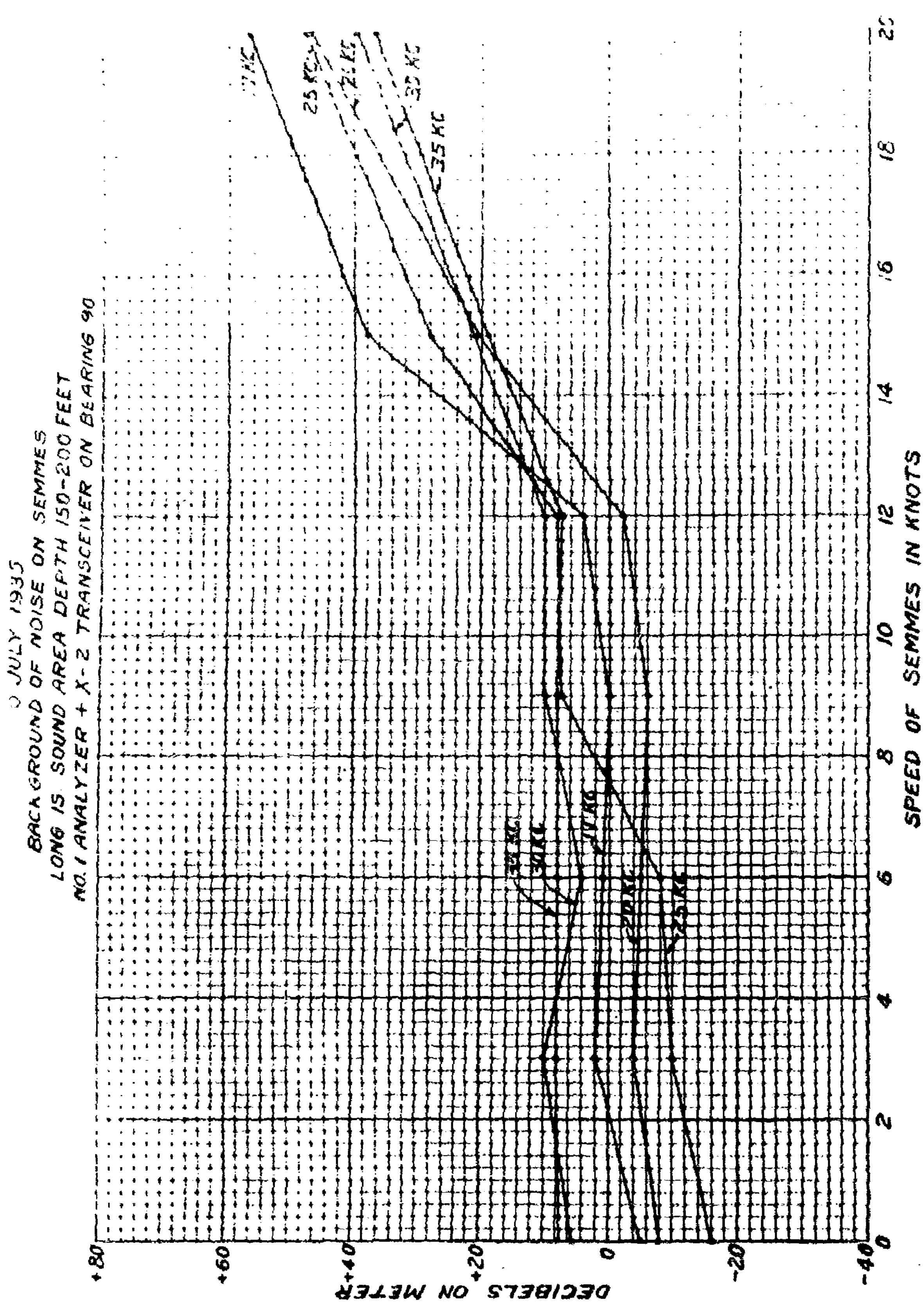


PLATE 7



JULY 1935
BACKGROUND OF NOISE ON SEMMES
LONG IS. SOUND AREA DEPTH 150-200 FEET
NO. 1 ANALYZER + X-2 TRANSCEIVER ON BEARING 90
SPEED OF SEMMES IN KNOTS
DECIBELS ON METER
+80
+60
+40
+20
0
-20
-40
0
2
4
6
8
10
12
14
16
18
25 KC
35 KC
20 KC
12.5 KC

PLATE 8

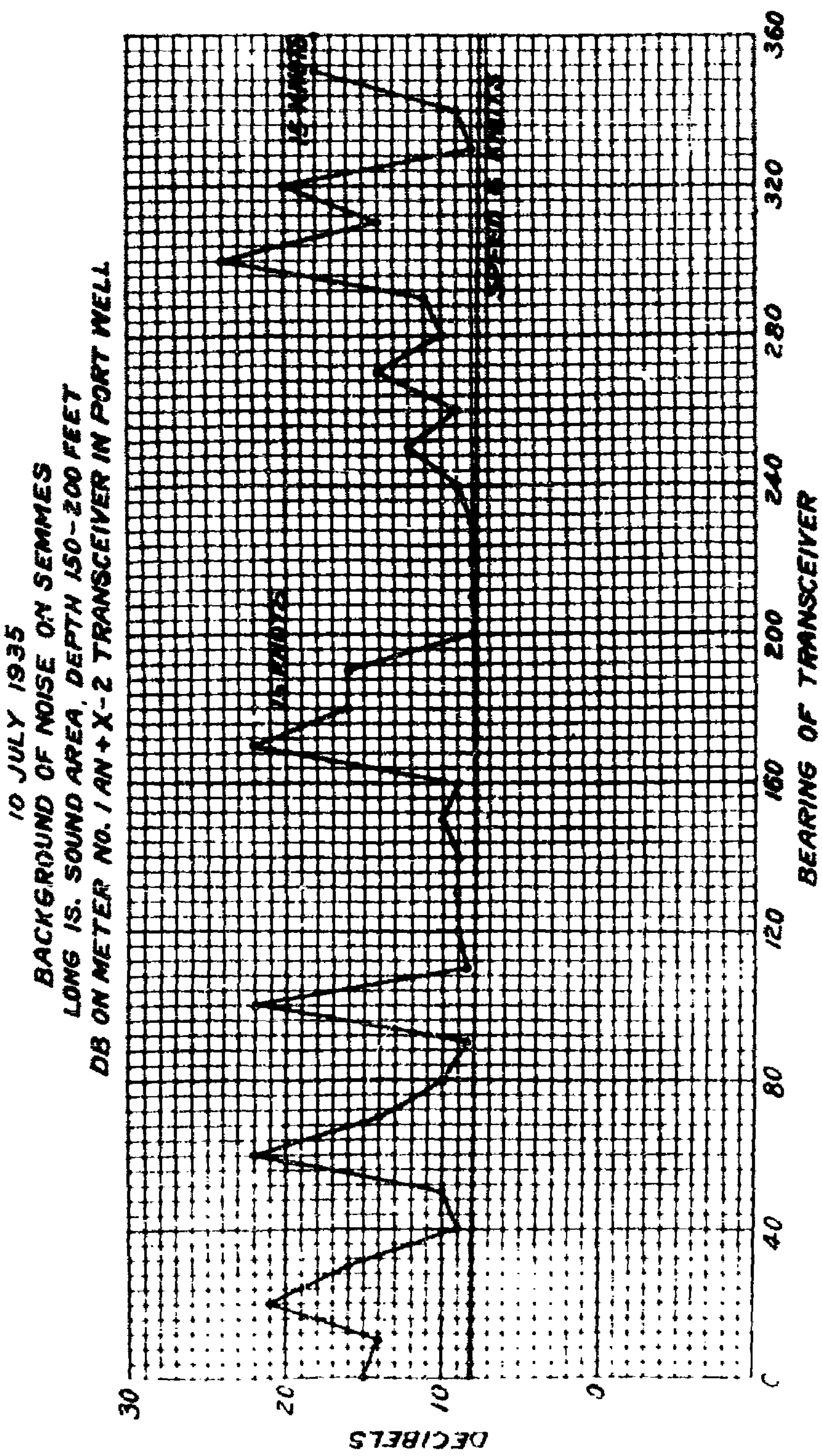


PLATE 9

Unclass Conf.
Navy Regulations 1920
76pp 5bl

UNITED STATES GOVERNMENT

memorandum

7103/911

DATE: 25 August 1999

FROM: Burton G. Hurdle (Code 7103)

SUBJECT: REVIEW OF REFS. (a) THROUGH (c) FOR REMOVAL OF RESTRICTIONS

TO: Code 1221.1 8/27/99

VIA: Code 7100

REF: (a) NRL Report S-1204, 16 Oct 1935, E.B. Stephenson AD-491 574
(b) NRL Report S-1670, 3 Dec 1940, E.B. Stephenson AD-135 780
(c) NRL Report S-1722, 11 April 1941, E.B. Stephenson and F.J. Woodsmall AD 221 613

1. References (a) through (c) are a series of reports and documents in underwater acoustics. Refs. (a-c) have been declassified earlier, but restrictions still exist.

2. The science, technology, equipment and operational utility of these reports have long been superseded. The current value of these reports is historical.

3. Based on the above, it is recommended that references (a) through (c) be available with no restrictions.

Burton G. Hurdle
BURTON G. HURDLE
Acoustics Division

CONCUR:

Edward R. Franchi 8/26/99
EDWARD R. FRANCHI Date
Superintendent
Acoustics Division