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Reported by:

H. C. Hayes, Principal Physicist
Superintendent, Sound Division

Approved by:

H. G. Bowen, Rear Admiral, USN., Director.

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ABSTRACT

By the use of geometric analysis checked by available data, this preliminary report discusses and predicts the nature and intensity of the sounds from a ship's propeller as received by a microphone located on or near sea bottom.

Its conclusions tend to limit the problem of acoustic mine sweeping to a band of approximately 200 to 300 cps, and indicate an efficient method of sweeping by means of a series of two or more sound generators mounted vertically on the bow of a ship.

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ANALYSIS OF SHIPS' PROPELLER SOUNDS

A Preliminary Report.

INTRODUCTION

1. This preliminary report on analysis of ships' propeller sounds defines the purpose and aims of the undertaking, describes the method and means employed, considers briefly the nature of the results that may be expected, and compares these predictions with a partial analysis of the propeller sounds of three different types of ships.

2. It will be seen that the character of the submarine sound received from a passing propeller is dependent to a large extent on the location of the receiver, and that the results of its analysis cannot safely and effectively be used to design submarine acoustical devices unless the receiver is mounted in approximately the same location that such devices will occupy. Since the purpose of the present analysis is to provide information that can aid in the understanding and development of acoustical mines and of methods and means of sweeping such mines, and since the immediate problems involved are primarily concerned with mines resting on the sea bottom, the data, comments and conclusions of this report refer only to the response of a receiver mounted near the sea bottom.

EXTENT OF PROGRAM

3. The problem, as submitted by the Bureau of Ships, may be interpreted as calling for an analysis throughout the entire frequency range from zero to the high supersonics. So interpreted, the problem, because of the different experimental methods and means required, divides somewhat definitely into three parts, the subsonic, the sonic, and the supersonic. Since mines operating within the sonic range are now employed, and since the problem of sweeping them effectively has yet to be solved, it was decided to concentrate on the subsonic and the sonic parts of the problem.

4. While the development of receivers suitable for use in these frequency bands was under way, it was ascertained that the Bureau of Ordnance had submitted this same problem to its scientific staff and that they were to investigate the subsonic region first. This led to a decision that duplication of effort would be avoided and the prosecution of the problem as a whole accelerated, if our efforts were first directed toward analyzing the sonic range of frequencies. Following this decision, a conference between Dr. E. B. Stephenson and Dr. E. L. Klein of the Naval Research Laboratory and Dr. E. A. Johnson and Dr. S. L. Quimby of the Bureau of Ordnance group agreed on such a program. It was decided at this conference that the sonic analysis should be extended downward to 100 cps and the subsonic upward to 200 cps in order to provide, for comparison purposes, an overlapping band between these frequencies.

5. Thus the program that is being prosecuted by this Laboratory aims to measure in absolute units, at a point near the sea bottom, the intensity of the sound field generated by a passing ship throughout the frequency band 100 - 10,000 cps, and to determine the relations between the intensity spectrum and the range, depth, and speed for different classes of ships.

APPARATUS

6. The apparatus employed (described in detail in Appendix A) consists of a small-dimensioned pressure-type receiver employing tourmaline crystals as the pressure-sensitive element, and a two stage preamplifier mounted adjacent to the crystal receiver. The amplifier output connects with the analyzer and recorder through a 1500 foot multiple-conductor shielded cable. Both A and B voltages for the amplifier are supplied through the cable. The grid of the first amplifier tube connects with the ungrounded crystal electrode and also with the output of a standard-signal generator at the shore end through a lead provided in the cable. Thus, the input to the amplifier can be given any desired voltage or frequency within the range (0 - 17 Kc) of the signal generator, and the voltage response of the crystal receiver to sounds of any frequency within its range can be determined directly by substitution. The relation between the intensity of a sound and the voltage which it generates by pressure action on the receiver is discussed in Appendix B wherein a technique is described which permits determination of the sound intensity in absolute units, when the equivalent input voltage is known. The intensities so determined are reported in terms of decibels above 10^{-16} watts per square centimeter.

7. The present procedure employs four receivers, each coupled to a separate recorder through a separate cable. These four receivers are shockproof-mounted with their sensitive elements about fifteen inches above the bottom of a supporting steel frame, the base of which has been floored with a plate to prevent it from sinking unduly in a mud bottom. It is presumed that this arrangement will make the average elevation of the receivers about one foot above sea bottom, or approximately the elevation of the receiver of a cylindrical-shaped acoustical mine lying lengthwise on the sea bottom.

GEOMETRIC ANALYSIS

a) Receiver Location

8. It may be noted that the character of the received propeller sound is affected by the height of the receiver above the sea bottom since its response is due primarily to the vector sum of the sound traversing the direct path from the source and the indirect path involving one reflection from the sea bottom. It can be shown that the receiver response, at all frequencies below which the difference between the lengths of these two paths is less than a quarter of a wavelength, is practically unaffected by its height above sea bottom. It follows that the receivers, as mounted, should give an

undistorted response to all waves greater than four feet in length, or at all frequencies below 1200 cps. Above this frequency range their response will tend to pass through maxima and minima as the difference of the two path lengths equals an even or an odd number of half wavelengths respectively. Although an analysis made with a highly selective receiving system should show the existence of such maxima and minima, they would become less and less apparent as the band of reception was widened. Therefore they fail to appear definitely in our band type of analysis. It appears probable, moreover, that any attempt to utilize such maxima and minima would prove impractical.

GEOMETRIC ANALYSIS
b) Receiver Dimensions

9. A consideration of the subject problem from the standpoint of geometrical acoustics leads to conclusions which point the way to a solution of the problems both of designing and of sweeping acoustical mines planted on the sea bottom and employing non-directive receivers. And since the dimensions of a mine are too small to permit the use of a receiving area greater than about 18" in diameter, it follows that all acoustical mines designed to operate within the sonic range, 0 - 10,000 cycles, must employ non-directive receivers.

GEOMETRIC ANALYSIS
c) Receiver Response - Maxima and Minima

10. The response of a sound receiver mounted near the sea bottom at depth H to a sound source located at depth h below the surface and at a horizontal distance x is equal to the vector sum of the sound traversing both the direct and the several reflected paths as indicated in Plate 1. But since scattered reflection at the sea bottom and increased path length greatly weakens the contribution of all the paths that involve reflection from the sea bottom, the general nature of the response as a function of x will be given by considering only the sound traversing the direct path and the indirect path with one surface reflection.

11. Obviously the receiver response will pass through maxima when the contributions along both these paths arrive in phase, and through minima when they arrive a half wavelength out of phase. The path difference, Δ, as shown in Plate 1, is:

$$\Delta = \sqrt{x^2+(H+h)^2} - \sqrt{x^2+(H-h)^2},$$

and allowing for a half wave change of phase on reflection at the surface, it follows that the receiver response will be a maximum or a minimum when Δ equals an odd or an even number of half wavelengths respectively. Stated mathematically, these relations are:

a. $(2n+1)\frac{\lambda}{2} = \sqrt{x^2+(H+h)^2} - \sqrt{x^2+(H-h)^2}$ Condition for maximum

b. $2n\frac{\lambda}{2} = \sqrt{x^2+(H+h)^2} - \sqrt{x^2+(H-h)^2}$ Condition for minimum.

When the sound source is directly over the receiver, x becomes zero, and these relations simplify to

a'. $(2n+1)\frac{\lambda}{2} = 2h$ Condition for maximum

b'. $2n\frac{\lambda}{2} = 2h$ Condition for minimum.

GEOMETRIC ANALYSIS

d) General Limitations

12. If the receiver represents an acoustically operated mine, then h becomes the depth of submergence of the ship's propeller, and its magnitude will be limited to an approximate range of from 8 to 22 feet, with an average depth of 15 feet. H will represent the depth of the mine, and will be limited to an approximate range of from 40 to 120 feet, with an average depth of 80 feet. The frequency to which the receiver is tuned should be such as to insure that:

a. The mine will fire when the ship passes within the range of destruction, and
b. The mine will not fire when the ship passes outside of this range.

13. These two requirements are best met by providing conditions for a maximum receiver response when the ship passes directly over the mine. Thus the frequency will be determined through the relation:

$$(2n+1)\frac{\lambda}{2} = 2h = 30 \text{ feet.}$$

Substituting integral values for n, starting with n = 0, gives the wavelengths (λ) that will make the receiver response a maximum when the ship passes directly over the mine as 60', 20', 12', 8.6', 6.7', etc. Assuming a velocity of 4,800 feet per second for sound in sea water, we find that these wavelengths correspond respectively with frequencies of 80, 240, 400, 560, 720, etc. cps.

14. It remains to determine which of these wavelengths serves best to confine within destruction limits the range within which the ship will fire the mine. The curves of Plate 2 serve to answer this question. Each curve shows the intensity of a definite frequency component of a ship's sound as received by a mine at all points along a horizontal range of 225 feet. Curves are shown for the definite frequencies of 80, 240, and 400 cps, using values of 80 and 15 feet for H and h respectively. The computations assume a zero absorption coefficient since over the short ranges involved this effect is relatively small. Also, in applying the inverse square law the median (m) of Plate I has been used.

15. It will be noted that the received intensity at each of these discrete frequencies is high when the ship passes directly over the mine and that, so far as firing the mine under these conditions is concerned, its receiver may be tuned to any one of them, or indeed, as

will be seen later, to any frequency within the audible range.

GEOMETRIC ANALYSIS

e) Limitations for Non-Firing Zone

16. Both these discrete frequencies do not meet equally well the requirement that the mine shall not fire when the ship passes outside the zone of destruction. A consideration of this family of curves in connection with the zone of destruction, as represented by the cross-hatched section, shows that a frequency of 80 cps gives a maximum that extends far beyond the zone of destruction, and that a ship passing well outside the destruction area could fire the mine.

17. The broken-line curve for 60 cps characterizes the relation between receiver response and range for all frequencies below 80 cps. These frequencies give a lower peak of intensity directly over the receiver and show a general widening of the maximum, conditions directly opposite to those required. A mine employing a receiver tuned within the sound frequency range of 0 to 80 cps would respond to a ship passing well outside of the destructive range of the mine unless its receiver were highly insensitive, in which case it might miss ships passing within this range.

18. The curve for a frequency of 240 cps comes close to meeting all requirements. If we assume the width of the destructive zone as equal to about twice the width of a ship, which may average about forty feet, the central maximum will be confined to this width if the receiver sensitivity is adjusted to operate the mine at a sound level corresponding roughly to 0.6 on the ordinate scale. This leaves plenty of sensitivity reserve and, of still more importance, leaves a wide margin of safety between the firing intensity level and the intensity level 0.15 of the secondary maxima. This not only insures that the mine will not fire when a ship passes over a secondary maximum, but it also increases the difficulty of sweeping.

19. The curve for a frequency of 400 cps is distinctly less favorable, but it might possibly serve for greater depths. If the ship is to operate the mine within the limits of its maximum range of destruction, the firing sensitivity of the receiver must be set at the approximate level of 0.33 on the ordinate scale. But this is less than its response to the secondary maxima. Not only would the mine fire when a ship passed over a secondary maximum, but it could readily be swept. To employ this frequency, the sensitivity of the mine receiver must be lowered until an intensity represented by about 0.70 on the ordinate scale would be required for firing. But this would reduce its operating range to about 70% of the total range of destruction.

20. Frequencies above 400 cps would magnify these unfavorable features to such an extent as wholly to prohibit their use.

21. Curves 1, 2 and 3 of Plate 3 give the form of the 240

cycle intensity profile for depths of 40, 80 and 120 feet respectively. They show that increasing the depth weakens the peak intensity of the primary maximum, increases its width, and reduces the difference in intensity between the primary and the secondary maxima. Each of these effects tends toward rendering the mine less reliable. Decreasing the peak intensity of the primary maximum increases the probability that the sound intensity from a ship passing within destructive range might fail to reach the firing threshold; widening the maximum makes the boundary of the firing area less definite; and reducing the difference in intensity between the primary and the secondary maxima increases the possibility that the mine might be fired by a ship passing over a secondary maximum. With decrease in depth, on the other hand, the trend of these same variables is toward an improvement both in the effectiveness and in the reliability of this type of mine. A consideration of the curves of Plate 3 and of others of the same nature leads to the conclusion that the non-directive acoustical mine may prove very effective for depths within about 80 feet, but will probably prove unreliable for depths beyond 100 feet.

22. Thus far our study of the response of a sound receiver mounted on the sea bottom to sound generated by a passing ship has been confined to areas where the received sound contains both direct and surface-reflected components. It will be seen that these are the areas over which the mine should not fire.

23. The conclusions reached through this study hold only for conditions where the dimensions of the sound source are not greater than one quarter of the approximately 20 foot wavelengths involved. It follows that they do not hold for areas behind a ship where the dimensions of the sound source are approximately the dimensions of the area swept out by the propellers. But over the areas forward of the propellers and adjacent to the ship's course - the only areas that concern our problem - the shielding of the hull reduces the effective radiating area to the tips of the propeller blades along the extreme horizontal limits of their circular path. Thus the conditions over these critical areas are such that our study and its conclusions may be expected to hold reasonably well.

GEOMETRIC ANALYSIS
f) Limitations for Firing Zone

24. Our study will now be directed to areas where sound reaching the receiver from an approaching ship contains no surface-reflected components. These areas comprise a strip immediately forward of the ship and the area subtended by its hull. Obviously, the mine should fire within the portion of this area shadowed by the ship's hull.

25. The character and intensity of the sound reaching this area are determined by factors different from those that obtain over other areas. These factors - hull contour, thickness of hull plating, number and type of propellers, character of sea bottom and depth -

differ somewhat widely from one ship to another and from one locality to another, yet the nature of the sound path or paths from propeller to receiver is sufficiently alike in all cases to warrant the belief that the general form of the received intensity profile obtained when any type of ship approaches and steams directly over the receiver will approximate the predicted form shown in Plate 4 (b).

26. The nature of the path or paths by which the propeller sound reaches the receiver may be understood by an examination of the diagram on Plate 4a which shows the hull contour of a ship with a propeller clear of the keel line. In this diagram H represents the depth of the water, h the depth of the ship's propeller below the surface, d the draft of the ship, and R - R' the positions of the receiver relative to the ship as she approaches, passes over, and finally recedes from the receiver. Starting at a point somewhat forward of the ship's bow and continuing to a point aft of her stern, the path over which the propeller sound reaches the receiver may be regarded as comprising six distinct sections. The predicted intensity of sound received at all points in each of these sections is indicated by the profile on Plate 4b.

27. Section 1 extends horizontally from R, the original position of the receiver, to a point where the ship's bow cuts the water at the surface. It is characterized by a cross-section determined primarily by the depth of the water (H). Starting with a relatively weak receiver response, the intensity in this section will gradually increase at a rate roughly in accord with the inverse distance, since the sound waves can expand horizontally but are constrained vertically.

28. Section 2 is a relatively short transition line between Sections 1 and 3. It includes roughly the area subtended by the curves of the ship's prow. As these various curves pass over the receiver the intensity tends to rise somewhat abruptly to meet the higher intensity of the still more restricted path under the ship's hull.

29. Section 3 extends back to the point where sound from the lowest portion of the propeller first reaches the receiver by direct path. It is characterized by a cross-section determined primarily by the depth of the water below the ship's hull, or by H - d. Intensity changes here more nearly resemble those found in Section 1, though the rise is more rapid because this section is nearer to the sound source.

30. Section 4 extends on to a point where no part of the propeller is shadowed by the ship's hull. Here the intensity rises at a rapidly increasing rate. This results partly from the operation of the inverse square law, and partly from the increasing exposure of the sound source (the propeller) as this section of the sound path moves across the receiver.

31. Section 5 carries on to the point where the plane of the ship's propeller intercepts the receiver. The location of this point with respect to the ship depends upon the depth and upon the tilt of

the propeller. Normally it will fall somewhat forward of the propeller. Here the sound intensity reaches a maximum through a final rapid increase as the more intense propeller sounds directed along its plane meet the receiver.

32. It may be noted that the space relations between the propeller and all five sections of the sound path so far considered have been such as to discourage any vigorous interference or re-inforcement between direct and reflected components reaching the receiver. It should, therefore, be expected that the intensity profile would not exhibit any marked maxima or minima, and that its general form would be about the same for any band of frequencies within the audible range. This, however, should not hold for a continuation of the intensity profile astern of the ship.

33. Section 6 represents such a continuation. It starts with a rapid decrease of intensity as the highly directed propeller sounds pass beyond the receiver. Then the sound intensity decreases more and more slowly in accord with the inverse square law. When the propeller has reached a distance sufficient to prevent its dimensions from introducing appreciable phase differences at the receiver, then interference and reinforcement between the direct, the surface reflected, and the hull reflected components reaching the receiver should produce maxima and minima in the intensity profile. The location of such configurations with respect to the ship will depend on the nature of the ship itself. Obviously, this part of the intensity profile has little or no bearing on the present problem.

34. The above considerations lead to the conclusion that over the sea bottom area subtended by a ship, an analysis of the character and intensity of its propeller sound throughout the audible range will disclose no definite and marked maxima, minima, or other localized phenomina that can be utilized in designing non-directive acoustical mines. They do, however, indicate that the sound intensity underneath any propeller-driven ship is sufficient to operate an acoustical mine pitched anywhere within the sonic range of frequencies.

EXPERIMENTAL DATA

35. The curves in Plates 5 - 11 show the results of actual measurements of the sounds of three different types of ships: the USS CARDINAL, a Coast Guard cutter, 136 feet in length with a 14 foot draft; the USS HAMILTON, a 1200 ton destroyer; and the battleship USS ARKANSAS. Plate 5 refers to the USS CARDINAL steaming at 11 knots over the standard receiver located on sea bottom at a depth of 30 feet. The ordinates give the peak value of the propeller sound over a frequency range of from 200 to 9000 cps. This curve shows a falling off of intensity toward the higher frequencies at an approximately uniform rate. The curves on Plates 6 and 7 refer to the USS HAMILTON steaming at 15 knots over receivers located at depths of 60 and 90 feet respectively. Both of these curves show, for the lower frequencies, much the same characteristics as those found in the curve on Plate 5,

but both show a much more rapid dropping off at higher frequencies. In Plate 6 the change in rate takes place shortly after 1000 cycles have been reached; in Plate 7 at approximately 1300 cycles. The relation of intensity to depth fails to follow consistently the inverse square law.

36. Plates 8 and 9 show the effect of the speed of the USS HAMILTON on the intensity of the noise generated as she steamed over receivers located at depths of 60 and 90 feet respectively. The curves on Plate 8 represent the overall noise at various speeds, and those on Plate 9 the noise within a fifty cycle band centered at 750 cps. The three curves of Plate 10 give somewhat similar information in respect to the USS ARKANSAS. The first curve represents the overall noise at different speeds, and the second and third curves the response after passing through fifty cycle band pass filters centered at 100 and 200 cps respectively. All the USS ARKANSAS tests were made with the receiver at a depth of 60 feet.

37. The sound intensity data recorded by these curves pertain to the sea bottom area subtended by the ship and are affected little or none by surface reflected components. They are in agreement with our predictions for this area in that they show sufficient intensity throughout the audible range to operate a properly designed acoustical mine.

38. On Plate 11 are reproduced typical sound intensity records for the three entirely different types of ships. These also show fair agreement with the predicted form shown on Plate 4b. In the case of the USS ARKANSAS, where the ship's length is large with respect to the depth of the water, the agreement is very close. In the case of the other two ships, where this ratio is less, sections 1 to 5 become foreshortened, and tend to fuse and lose their identity. The curves for both the USS CARDINAL and the USS HAMILTON show this foreshortening effect.

39. A comparison of the intensities at equal distances fore and aft of the propeller peak in these three profiles shows that the intensities decrease more rapidly forward than they do astern. Moreover this discrepancy appears to be greater in shallow water or in cases where the ratio of the ship's length to the depth of the water is great. This raises a serious question as to whether or not an acoustically operated relay can be made to function at even short ranges forward of a large ship steaming in a 40 foot channel, or even over somewhat greater depths. The answer to this question will have a direct bearing on the development of echo and acousti-magnetic types of mines.

MINE SWEEPING

40. There remains for consideration the problem of sweeping non-directional acoustical mines planted on the sea bottom. It will help to clarify and define this problem if we return for a moment to

certain conclusions made earlier in this report. We found that in order to be most effective and reliable a mine should be tuned within the relatively narrow band of 200 - 300 cps. This indicates that in all probability the mines to be swept will be set to respond only to frequencies within this band and that, therefore, mechanically tuned sound generators, which have a relatively high acoustical efficiency, might be used for sweeping. We also found that in order definitely to limit their operation to the zone of destruction such mines must be sharply tuned. This, in turn, immediately suggests the possible use of an impulse type of generator as a sound source. Since, however, a comparatively weak sustained tone should be sufficient to fire the mine, and since the defined frequency limits are such as permit the use of tuned generators, it appears probable that tone sweeping should prove more effective than impulse sweeping.

41. A question now arises as to the optimum location and depth of submergence of the sound source. A consideration of the curves of Plate 12 throws some light on this question. Plate 12 gives, up to a range of 650 feet, the sound intensity profile of a single generator placed at the respective depths (h) of 5, 10, 15, and 20 feet below the surface of the water. The receiver in each case is located on sea bottom at a depth (H) of 80 feet. All four profiles pass through maxima and minima as explained in paragraph 11. It will be noted that each curve has passed the last maximum permitted by the depth (h) of its transmitter before reaching a desired sweeping range of, say, 200 yards, and that at such a range all four have dropped to practically the same intensity. Since the intensity at this range is very low in comparison with the firing intensity produced by a ship passing within destruction range, it may be expected that a powerful sound generator will be required for sweeping and that such a generator will prove equally effective when submerged at any practical depth.

42. At shorter ranges, approaching the danger zone, where the curves pass through maxima and minima, the effectiveness of a sound generator is largely dependent upon its depth of submergence. If the practical limit of submergence is set at, say, 20 feet, then the best value of h, for a single generator, will be about 10 feet. This gives a good maximum at a range of just under 100 feet, which is probably outside the destruction area. Better intensity profiles are given when two or three separate generators, spaced vertically along the bow of a ship at various combinations of the depths already mentioned, are used simultaneously.

43. The curves on Plates 13 and 14 show the intensity profiles from such groups at various depths. The generators in each group are assumed to be identical and to be in phase. The sound output assigned to each group, regardless of the number of units, is identical with that used in calculating the curves for the individual generators shown on Plate 12. A consideration of the curves on Plates 13 and 14 shows unmistakably the superiority of the group method for sweeping purposes. For example, compare the peak intensities reached by a single unit (h = 10), a double unit (h = 10 and 15), and a triple

unit (h = 10, 15, and 20). All three maxima register approximately 0.35 on the arbitrary intensity scale. If we assume that an intensity of 0.3 on this scale is sufficient to fire a mine, then the single unit will sweep a radius of 118 feet, the double unit a radius of 178 feet, and the triple unit a radius of 213 feet. Or compare the relative intensities of the three types at a fixed distance of, say, 300 feet. The combined units still are clearly more efficient than is the single generator. It appears, then, that the use of two or more relatively small sound generators, properly disposed at quarter wave-length intervals along a vertical line, will serve better for mine sweeping than would a single more powerful generator placed at any point along this line. This arrangement, moreover, avoids the inherent difficulties encountered in maintaining the diaphragms of powerful underwater low-pitched sound generators.

44. Finally it may be stated that the acoustical mine now employed by the Germans conforms so strictly with the deductions and conclusions of this report as to warrant a belief that its development followed similar reasoning. The Germans use a non-directive mine with a sharply tuned receiver. So far as can be judged from the few samples that have been recovered, its frequency has been varied between about 245 and 280 cps. In no case has its frequency passed outside of the predicted 200 - 300 cps band, and there is good reason for believing that its frequency will continue to remain within this band. Moreover, it can be predicted with some certainty that if, in the future, the Germans launch a new type of acoustical mine it will be pitched outside the sonic frequency range and probably in the fairly high supersonic range.

CONCLUSIONS

45. The foregoing analysis, together with available experimental data, shows that:

(a) Mine receivers pitched within the audible range must necessarily be non-directive and fairly sharply tuned.

(b) Mines with receivers tuned sharply to any frequency within the audible range may be expected to work satisfactorily at depths up to about 80 feet, but will probably prove unreliable at depths greater than 100 feet.

(c) To be most effective and reliable, mine receivers designed for use within the audible range, should be tuned within a band of approximately 200 to 300 cps.

(d) In mine sweeping, the use of the same power divided equally between two or three tuned sound generators, mounted vertically at intervals of a quarter wave-length, should prove more effective than a single generator, or than any method of impulse sweeping.

APPENDIX A

EQUIPMENT AND PROCEDURE

Most of the data discussed in this report were gathered on the Degaussing Ranges operated by the Bureau of Ordnance. Sound records were made on various types of ships while magnetic calibrations were being prepared on these same ships. Usually the microphones were planted in the center of the range and about 100 feet north of it, so as to prevent fouling of the numerous cables leading from the range to the station ship. The latter carried all the analyzing and recording equipment, and supplied the necessary power. Plate 15 shows the relative positions of the ships and of the microphones with respect to the range. A complete subaqueous unit with four receivers is shown on Plate 16.

Generally two underwater microphones, each in a separate housing together with its own preamplifier, were mounted rigidly on a steel frame which was lowered to the sea bottom. The required water-tight electrical junction boxes were an integral part of this steel structure. About 1500 feet of multiconductor submarine cable connected the microphone units to their power supplies aboard the station ship. This arrangement enabled the operators not only to control and check the output of the preamplifiers on the sea bottom, but also to select the microphone best suited to the recorder and frequency range.

The microphones consist of mosaics of piezoelectric tourmaline crystals which respond to pressure. The sound field existing in the water is directly impressed upon the faces of the crystal slabs. This pressure generates an emf on the terminals of the microphone. Plates 17, 18, and 19 show the construction of three types of microphones used. In each case the compressional sound waves in the water reach the crystal elements through a rubber window and castor oil surrounding the crystals. These media were chosen because their acoustic impedances are practically identical with that of water; hence the sound transmitted through them is unaltered. The dimensions of each microphone is such as to make it non-directional and non-resonant in the acoustic range assigned.

The preamplifier, which is housed together with the sound sensitive element, was designed for this particular application. Its stability and freedom from microphonics under the divers conditions to which the listening gear was subjected have proved of value in these tests. Plate 20 gives a schematic representation of this preamplifier. The Calibrating lead (C), normally grounded during measurements, is provided for the purpose of introducing a known signal across R_2 to check the gain of the amplifier at any time. Plates 21 and 22 show the frequency and overload characteristics of these amplifiers. Each amplifier was provided with a five conductor shielded cable, and, except for a common ground connection, was completely independent of the other channels.

The analyzing and recording equipment included two types which could be used interchangeably. One of these consisted of the Erpi Sound Analyzer, Model 277-B, with Graphic Recorder No. 246. The frequency range of this apparatus is from 10 to 9500 cps. The 50 cycle band-pass crystal filter embodied in this equipment was generally used throughout the measurements. The other analyzer-recorder was of the General Radio design and consisted of a Sound Level Meter No. 759-A, a Sound Analyzer No. 760-A, a Logarithmic Amplifier No. P-466, and an Esterline-Angus Recorder, Model AW. The frequency range of this assembly is from 25 to 7500 cps, with a constant percentage band width of 1% at 3 db down from the maximum. In addition, special keying circuits were devised and used, which enabled an observer on the deck of the station ship to make interval marks on the recorder chart for later use in indexing the results.

The method of operation was relatively simple and direct. The analyzer units were set to the desired frequency, or for overall response, and the chart drive of the recorders started as the ship approached the range. Each moving chart gave a record in db of the sound received as the ship approached and passed beyond its respective receiver. An observer on the station ship, by keying a relay circuit, impressed a time line on the moving chart when the ship's bow and then her stern crossed the range line. These lines, together with the known speed of the chart and the length of the ship, served to check the position of the microphone with respect to the ship at all points along the recorded intensity profile. The lateral displacement of the ship's course with respect to the microphone was taken from the degaussing records of the several coils spaced along a line normal to her course. Since the intensity coordinates of the profiles are given in terms of db, they supply no direct information about the energy involved.

APPENDIX B

CALCULATIONS AND CALIBRATION

The calibration of the apparatus consists of a correction curve from which it is possible to convert, at each fequency, apparatus dial readings or record scale readings into sound, pressures in the water at the microphone. The apparatus readings are in db, representing the voltage gain of the amplifier system. The sound pressures are also expressed for convenience in db, representing the sound pressure level in the water, above a chosen threshold pressure.

If it were possible to record directly the apparatus reading corresponding to a sound of known pressure level generated in the water, for a series of frequencies, the calibration could be made by simple experiment. This is not possible, owing to the difficulty of measuring absolute sound intensities. It is considered sufficient to compute a correction curve, which will take account of various factors which intervene between sound pressure level in the water and voltage level reading on the final record.

The scale readings may be converted into water borne sound pressures as follows. We know from tests that 850 microvolts applied across the grid resistor of the preamplifier results in a scale reading of 128 db on the final record. Since this reading is about the maximum to be expected in an experimental study of ship sounds in water, it was chosen as a convenient basis for the calibration. The figure of 128 db reading for an input of 850 microvolts is accurate to $\pm$ 0.5 db for all frequencies within the range used in this investigation.

The amplifier-recorder system is also linear in the sense that for inputs of less than 850 microvolts the db scale readings are reduced in the same proportion as the logarithm of the ratio of input voltages.

It is necessary first to compute the sound pressure in water, at each frequency, which will give 850 microvolts at the grid of the preamplifier, and hence recorder scale reading of 128 $\pm$ 0.5 db. The conversion of sound pressure in the water into voltage at the amplifier grid, may be considered in two stages. The first stage is the transformation of sound pressure into open circuit voltage, by means of a piezoelectric tourmaline crystal in the microphone. According to the most reliable data, tourmaline generates (into an open circuit) three microvolts per bar of alternating pressure. This provides a simple relation between sound pressure and open circuit voltage, E_o.

The second stage is the conversion from open circuit voltage across the microphone crystal to useful voltage across the grid resistor of the preamplifier. For this, the effects of microphone housing capacitance and amplifier tube admittance are taken into account by means of the following formula:

$$E_o = E_g \sqrt{\left(1 + \frac{C_s}{C_o}\right)^2 + \frac{1}{C_o^2 R_g^2 \omega^2}}$$

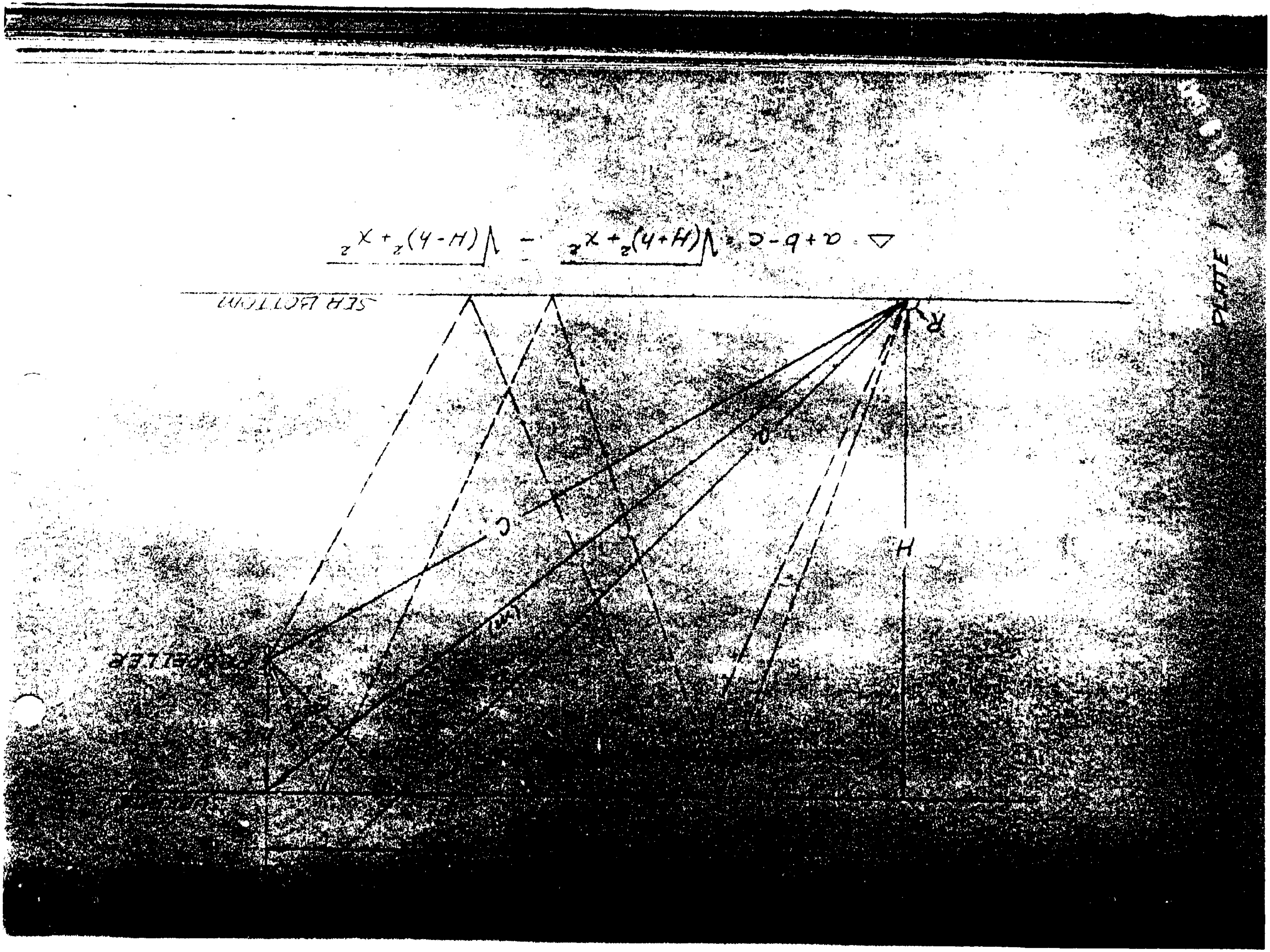
where

E_o = open circuit voltage across crystal
E_g = voltage across grid resistor = taken 850 μv.
R_g = grid resistor = 250,000 ohms
C_o = capacitance of crystal unit = 530 $\mu\mu$f
C_s = capacitance of housing plus reflected capacitance of vacuum tube = 174 $\mu\mu$f
ω = $2\pi f$ = angular velocity of frequency, f.

Using this formula we compute, for a series of frequencies covering the range from 100 cps to 10,000 cps, a set of values of E_o corresponding to E_g = 850 μv across the input grid resistor. These values of E_o versus frequency are converted into values of sound pressure in bars (i.e. in dynes/cm²) by dividing each value of E_o by the piezoelectric constant, 3 microvolts per bar. We have now computed the water sound pressures expressed in bars, necessary to produce 850 microvolts at the amplifier input. (This voltage input gives a reading of 128 db on the record)

A convenient calibration requires that both sound pressures and recorder readings be expressed in the same units, i.e. db. Sound pressures can be expressed in db by choosing a convenient reference pressure, p_o, and writing each pressure value, p, as a ratio p/p_o. The pressure level in db is then, by definition, equal to 20 log p/p_o. The reference pressure for sound in water, which was adopted for these data, is the pressure, p_o, at which the sound intensity, I_o, has the value 10^{-16} watts/cm². Giving I_o this value in the well known formula, $I_o = p_o^2/\rho c$, and taking ρ c for water = 1.5 x 10^5, it is found that p_o = 0.01225 dynes/cm² will produce the desired threshold sound intensity. It may be noted that the sound pressure in water corresponding to an intensity of 10^{-16} watts/cm² is much higher than the sound pressure in air necessary to produce the same threshold intensity. The threshold pressures in water and in air are in the ratio 0.01225/0.000204 = 60, which is equivalent to 35.56 db.

For each frequency in the useful range, it is now known what theoretical sound pressure at the microphone, expressed in db, will give a recorder reading of 128 db. Call this value $\bar{X}$ in db. For each frequency the difference (128 − $\bar{X}$) is computed, and plotted on Plate 23. This curve may now be used to convert, at any frequency in the useful range, the apparatus dial reading into sound pressure level in the water at the microphone. In each case the correction taken from Plate 23, is to be subtracted from the apparatus reading in order to give the true sound pressure level. Recorder readings, corrections, and sound pressure levels are all expressed in db.


$\Delta = a+b-c = \sqrt{(H+h)^2+x^2} - \sqrt{(H-h)^2+x^2}$
SEA BOTTOM
R
H
C
PLATE 1

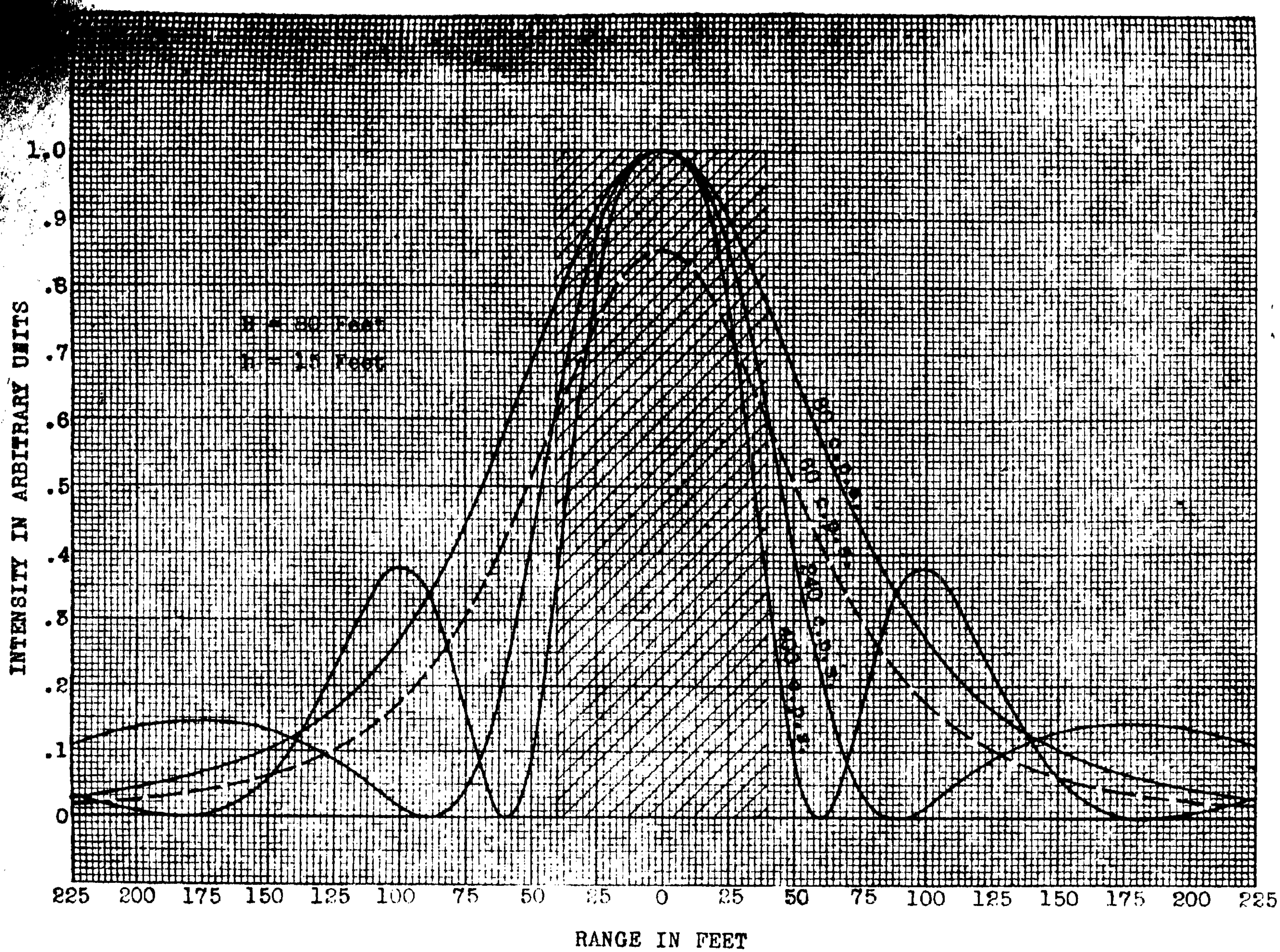

INTENSITY IN ARBITRARY UNITS
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
30 c.p.s.
90 c.p.s.
240 c.p.s.
400 c.p.s.
225 200 175 150 125 100 75 50 25 0 25 50 75 100 125 150 175 200 225
RANGE IN FEET

PLATE 2

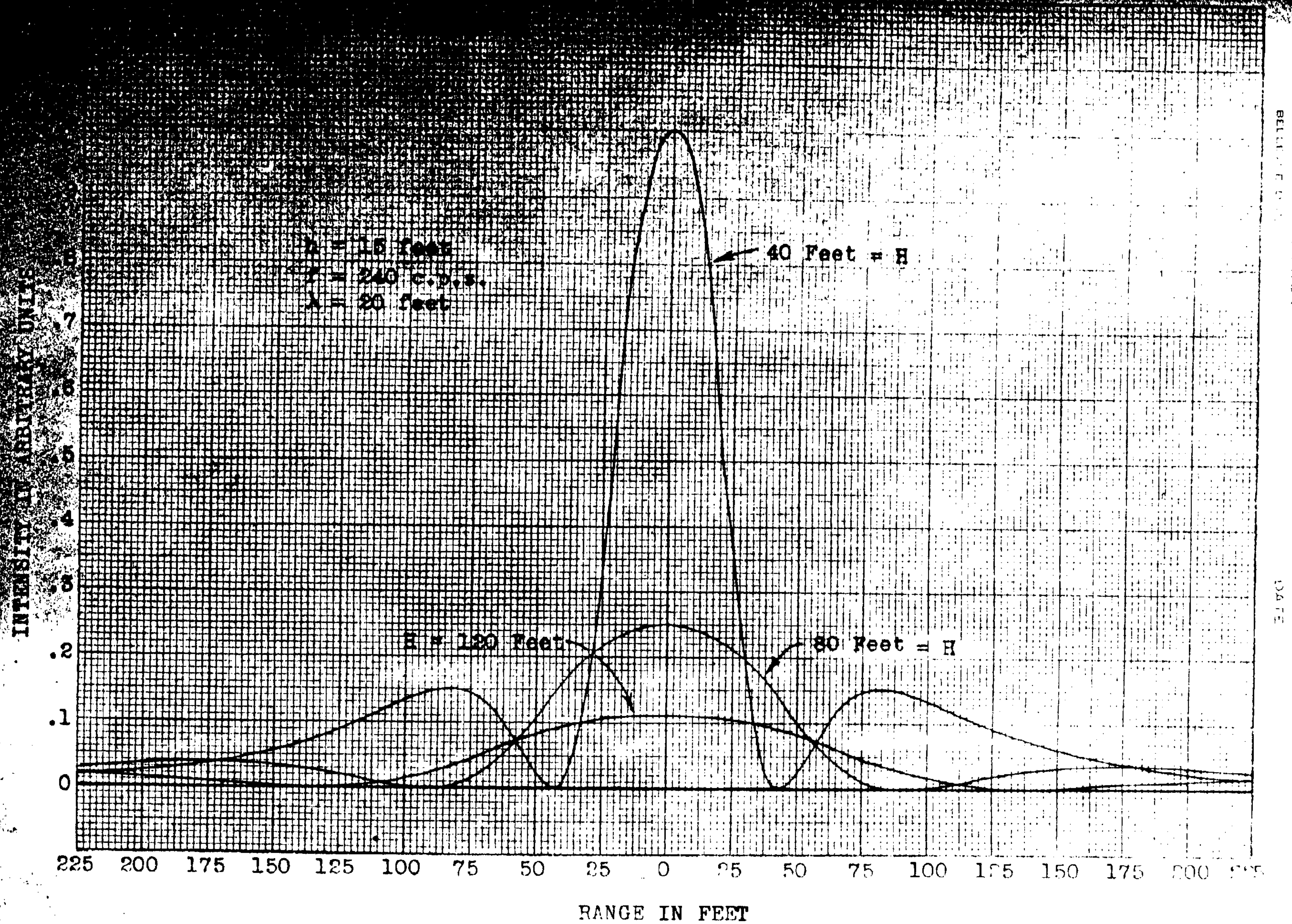


PLATE 3

UNCLASSIFIED

UNCLASSIFIED

PLATE 6

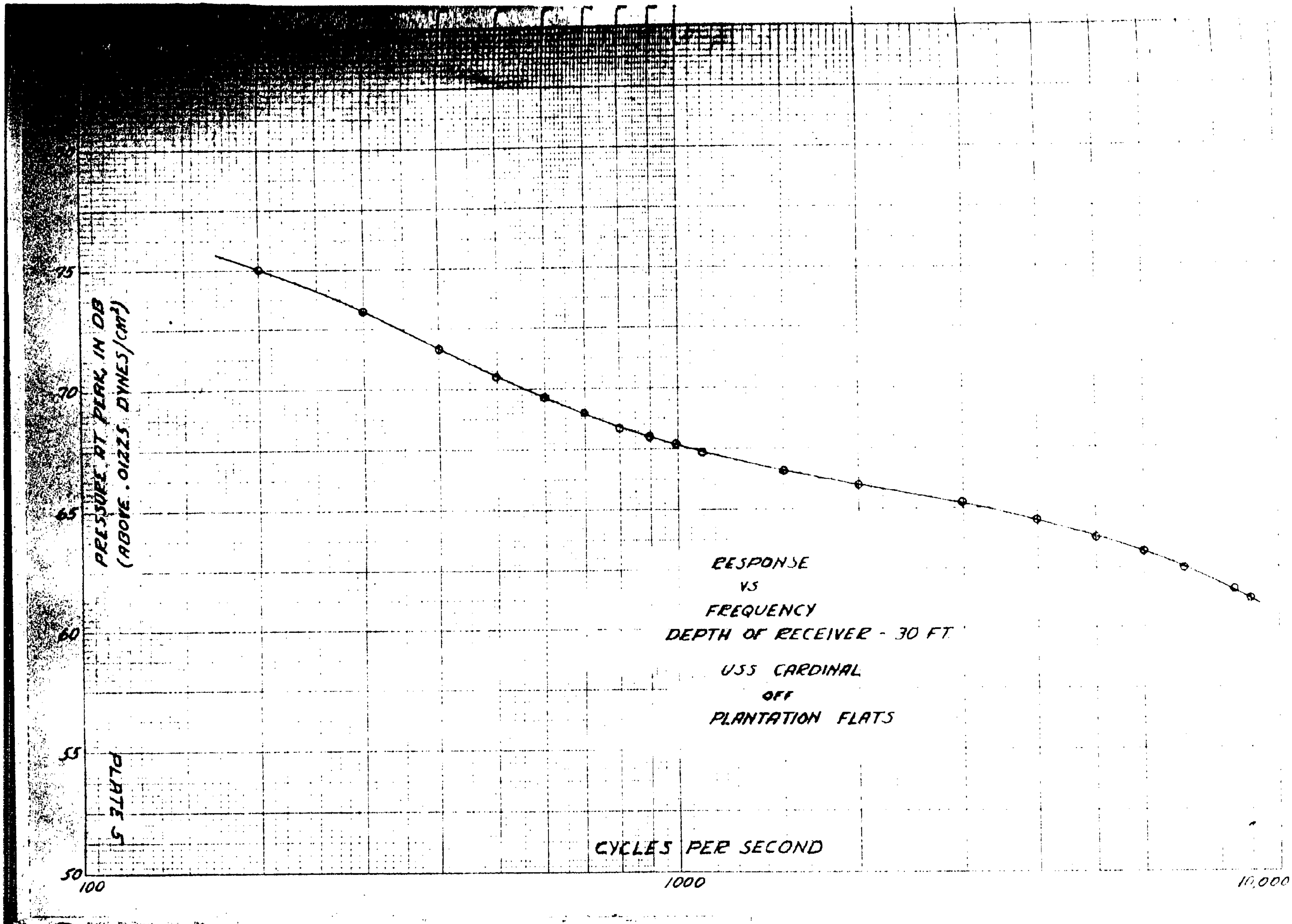

RESPONSE
VS
FREQUENCY
DEPTH OF RECEIVER - 30 FT.
USS CARDINAL
OFF
PLANTATION FLATS
PRESSURE AT PEAK IN DB
(ABOVE .01225 DYNES/CM²)
75
70
65
60
55
50
100
1000
10,000
CYCLES PER SECOND

PLATE 5

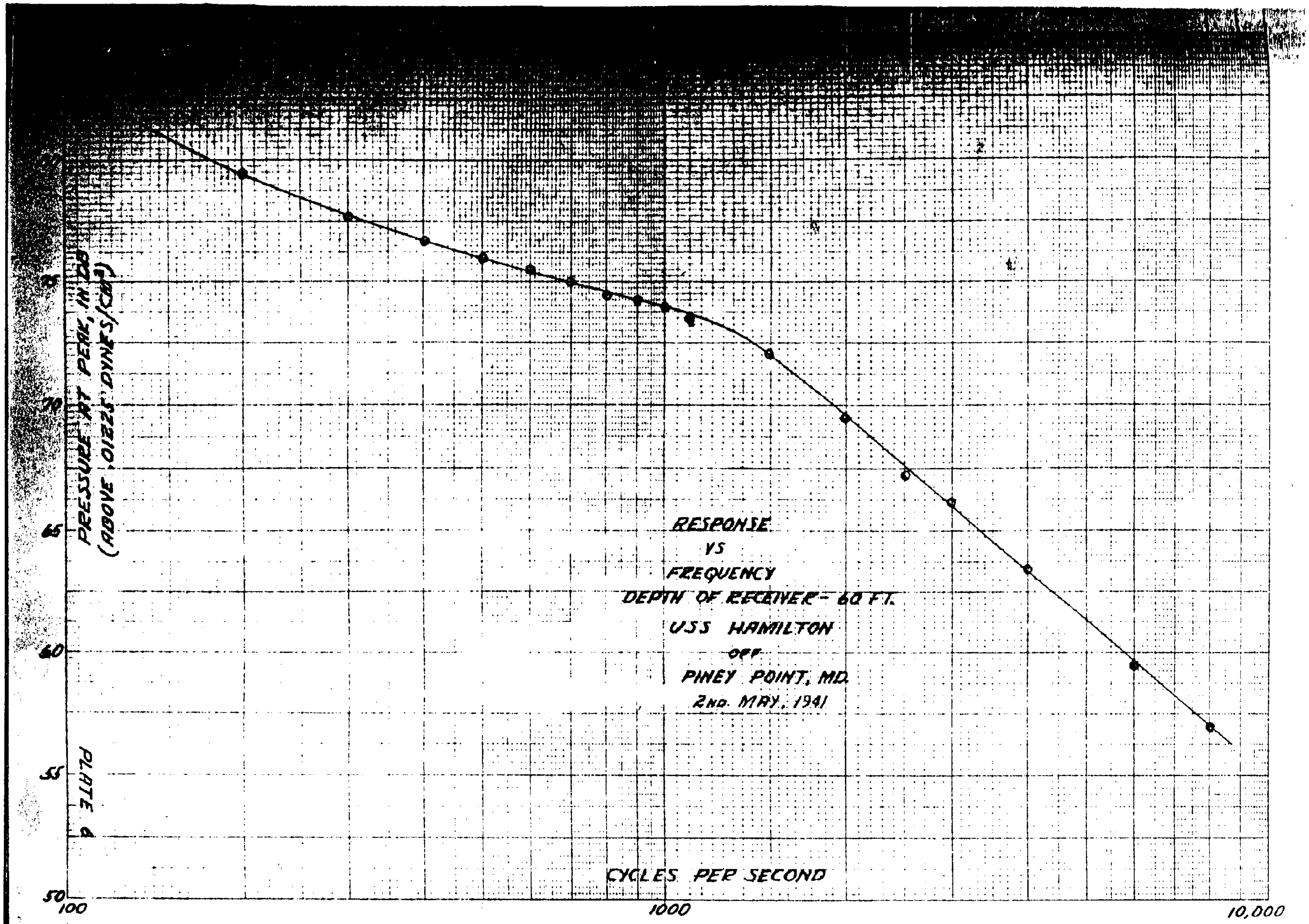
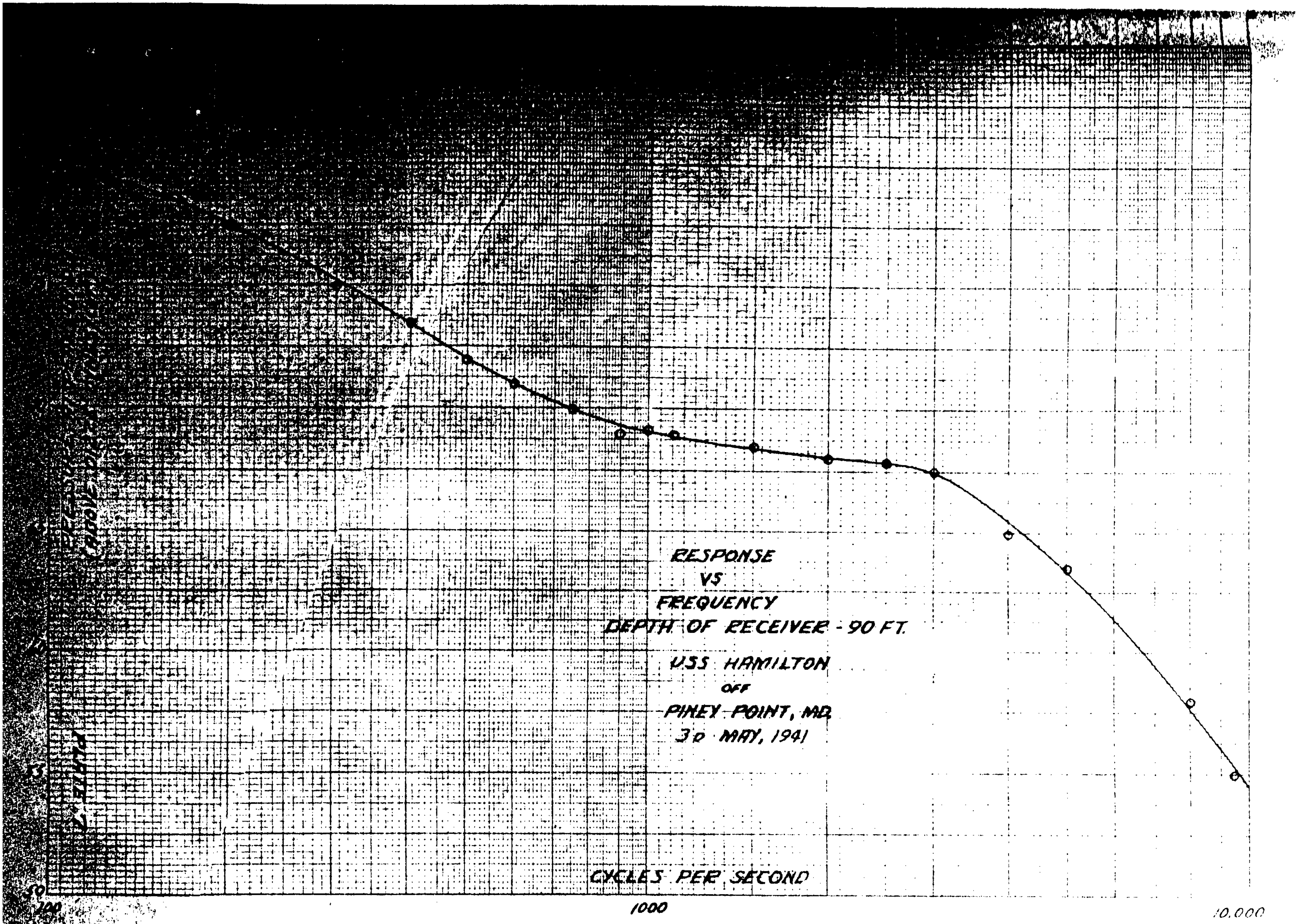

PRESSURE AT PEAK, IN DB
(ABOVE .0122 DYNES/CM²)
RESPONSE
VS
FREQUENCY
DEPTH OF RECEIVER - 60 FT.
USS HAMILTON
OFF
PINEY POINT, MD.
2ND. MAY, 1941
CYCLES PER SECOND
70
65
60
55
50
100
1000
10,000

PLATE 6


RESPONSE
VS
FREQUENCY
DEPTH OF RECEIVER - 90 FT.
USS HAMILTON
OFF
PINEY POINT, MD.
30 MAY, 1941
CYCLES PER SECOND
100
1000
10,000
PLATE 7

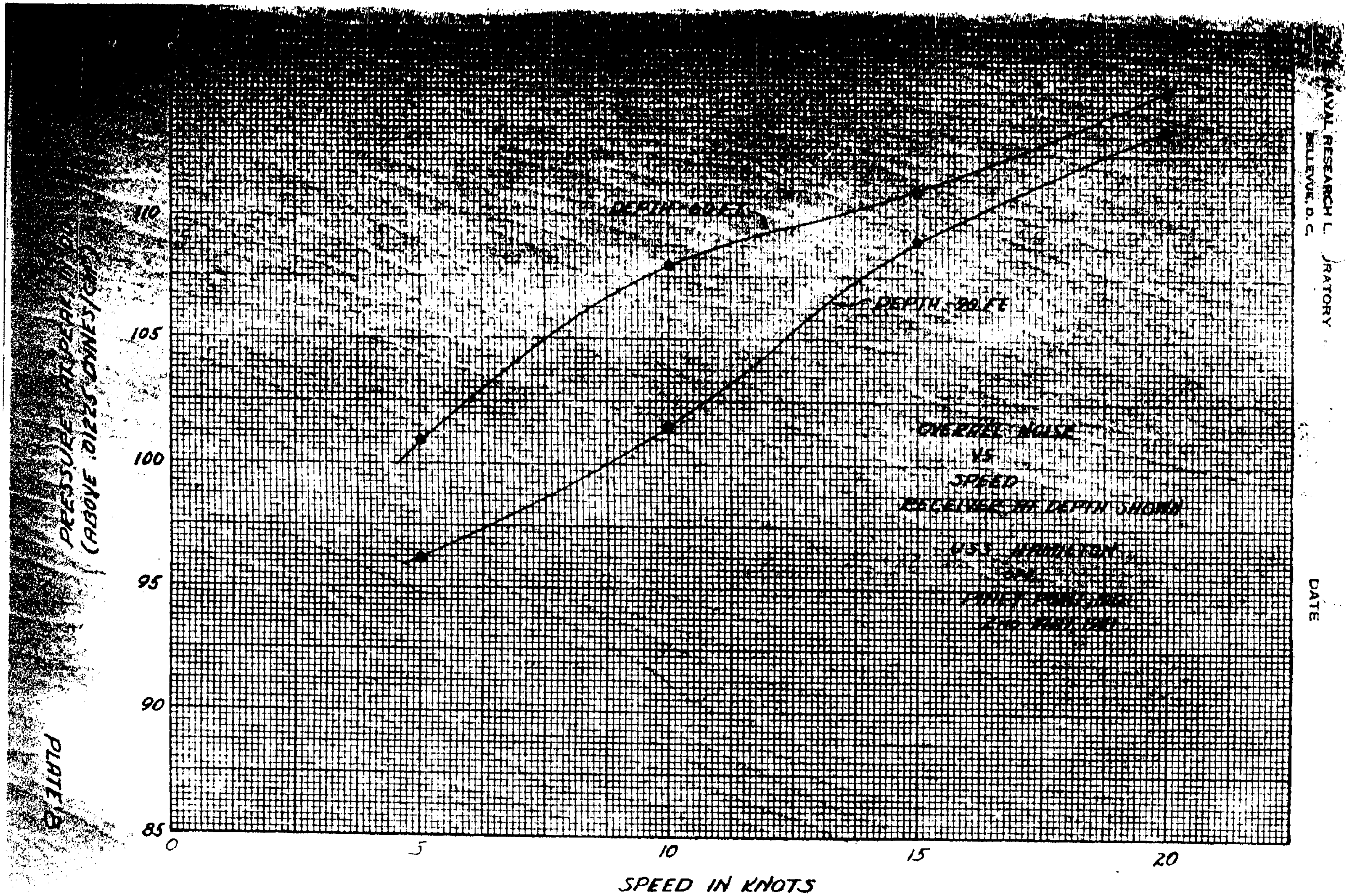


PLATE 8

UNCLASSIFIED

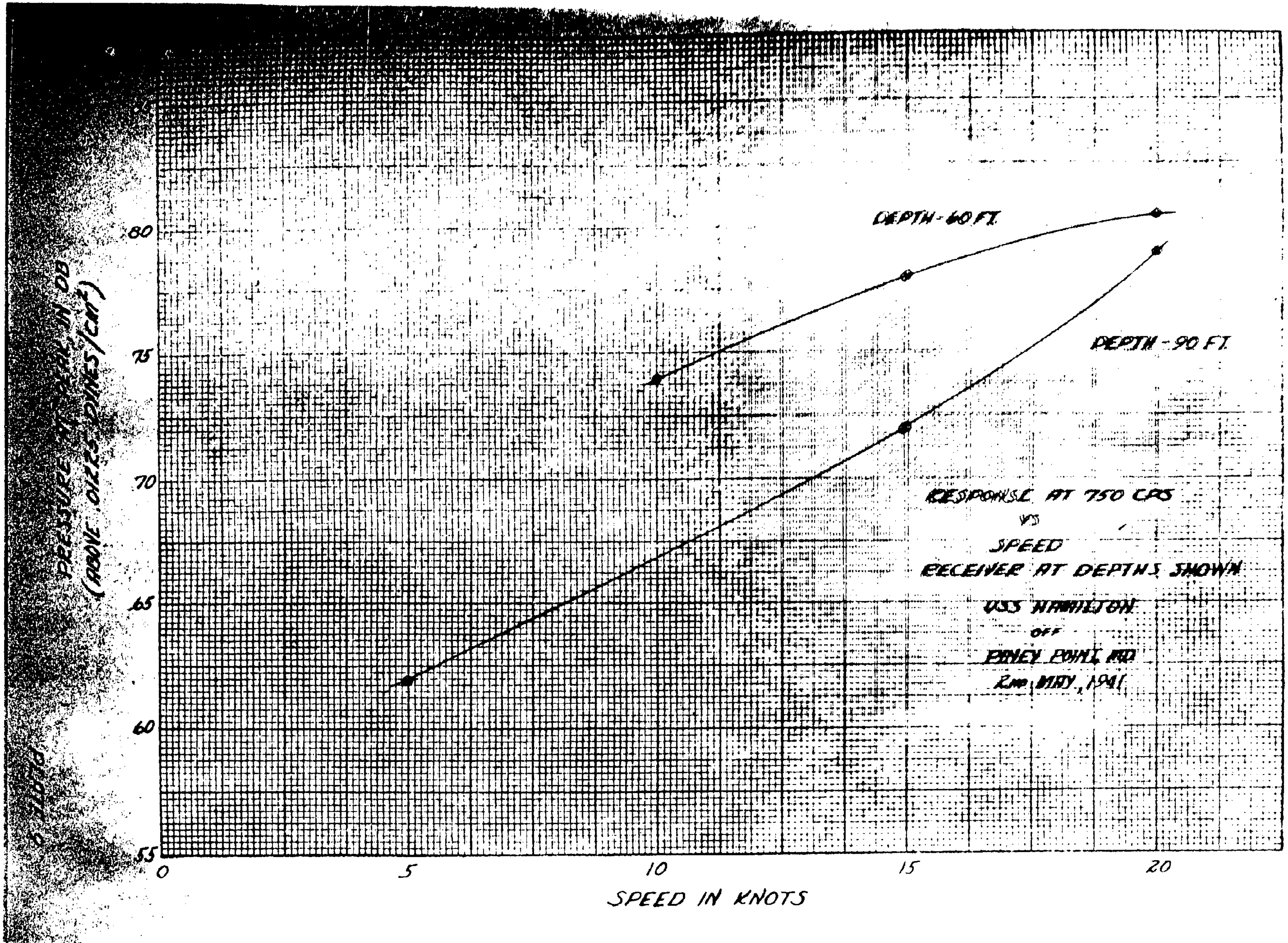


PLATE 9

UNCLASSIFIED

BELLEVUE, D.C

UNCLASSIFIED

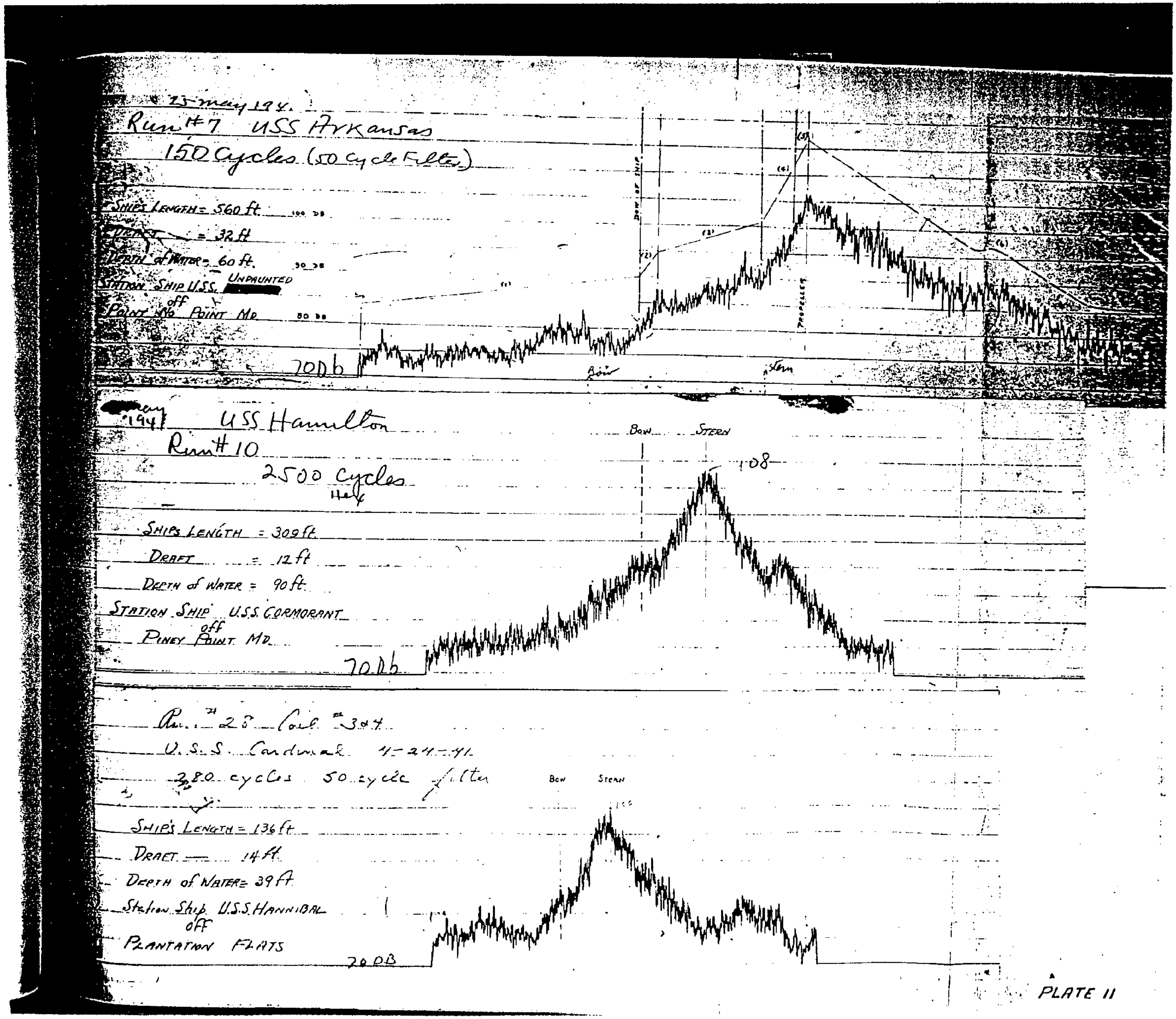
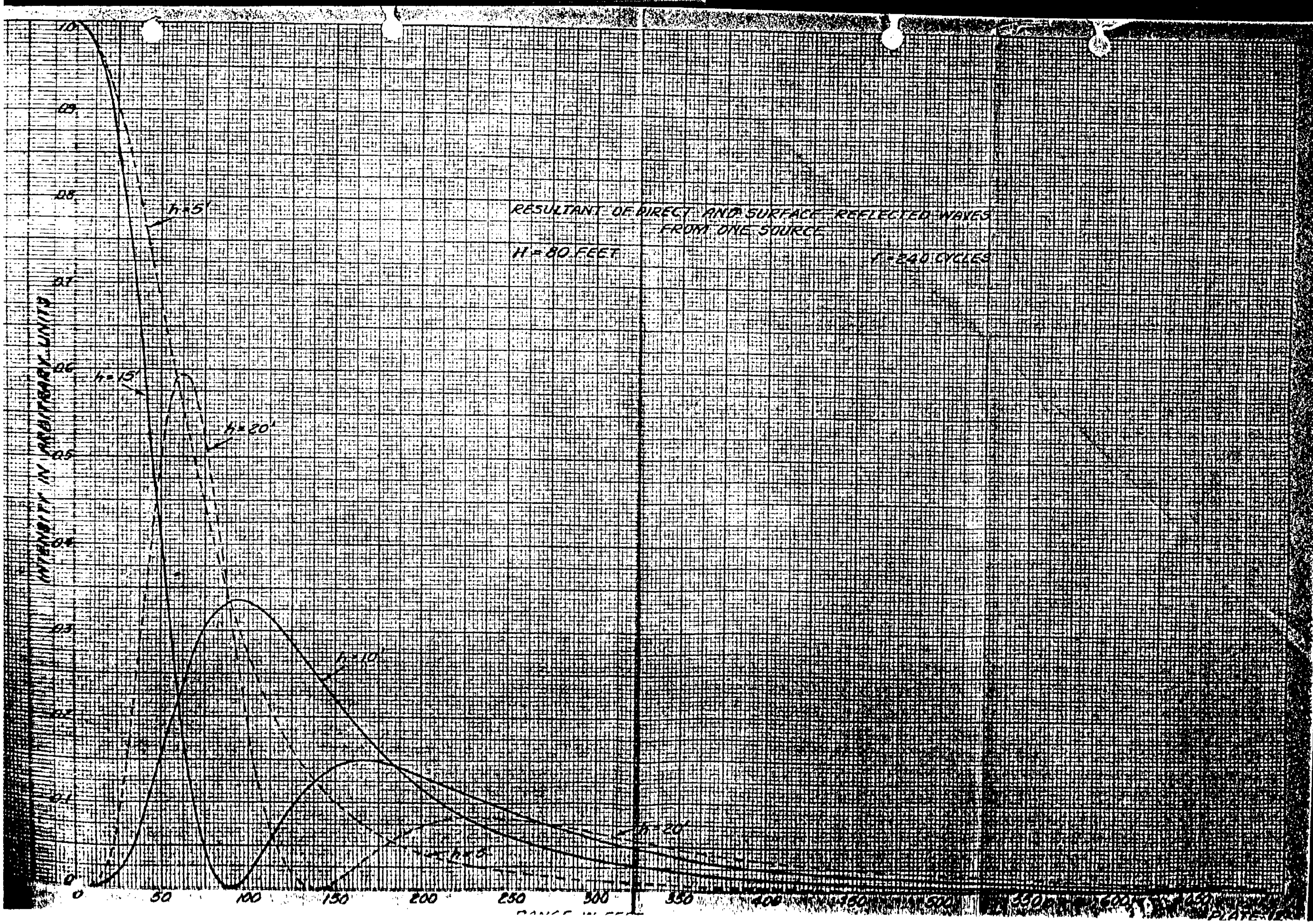

23 May 194
Run #7 USS Arkansas
150 Cycles (50 cycle Filter)
SHIPS LENGTH = 560 ft
= 32 ft
DEPTH of WATER = 60 ft.
STATION SHIP U.S.S. [redacted] UNDAUNTED
off
POINT NO POINT MD
100 DB
90 DB
80 DB
70 Db
BOW OF SHIP
PROPELLER
Bow
Stern
1941
USS Hamilton
Run #10
2500 Cycles
SHIPS LENGTH = 309 ft
DRAFT = 12 ft
DEPTH of WATER = 90 ft.
STATION SHIP U.S.S. CORMORANT
off
PINEY POINT MD.
70 Db
BOW
STERN
108
U.S.S. Cardinal 4-24-41
380 cycles 50 cycle filter
SHIP'S LENGTH = 136 ft
DRAFT = 14 ft
DEPTH of WATER = 39 ft
Station Ship U.S.S. HANNIBAL
off
PLANTATION FLATS
70 DB
BOW
STERN

PLATE 11


RESULTANT OF DIRECT AND SURFACE REFLECTED WAVES
FROM ONE SOURCE
H = 80 FEET
f = 240 CYCLES
INTENSITY IN ARBITRARY UNITS
h = 5'
h = 15'
h = 20'
h = 10'
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
50
100
150
200
250
300
350
400

UNCLASSIFIED

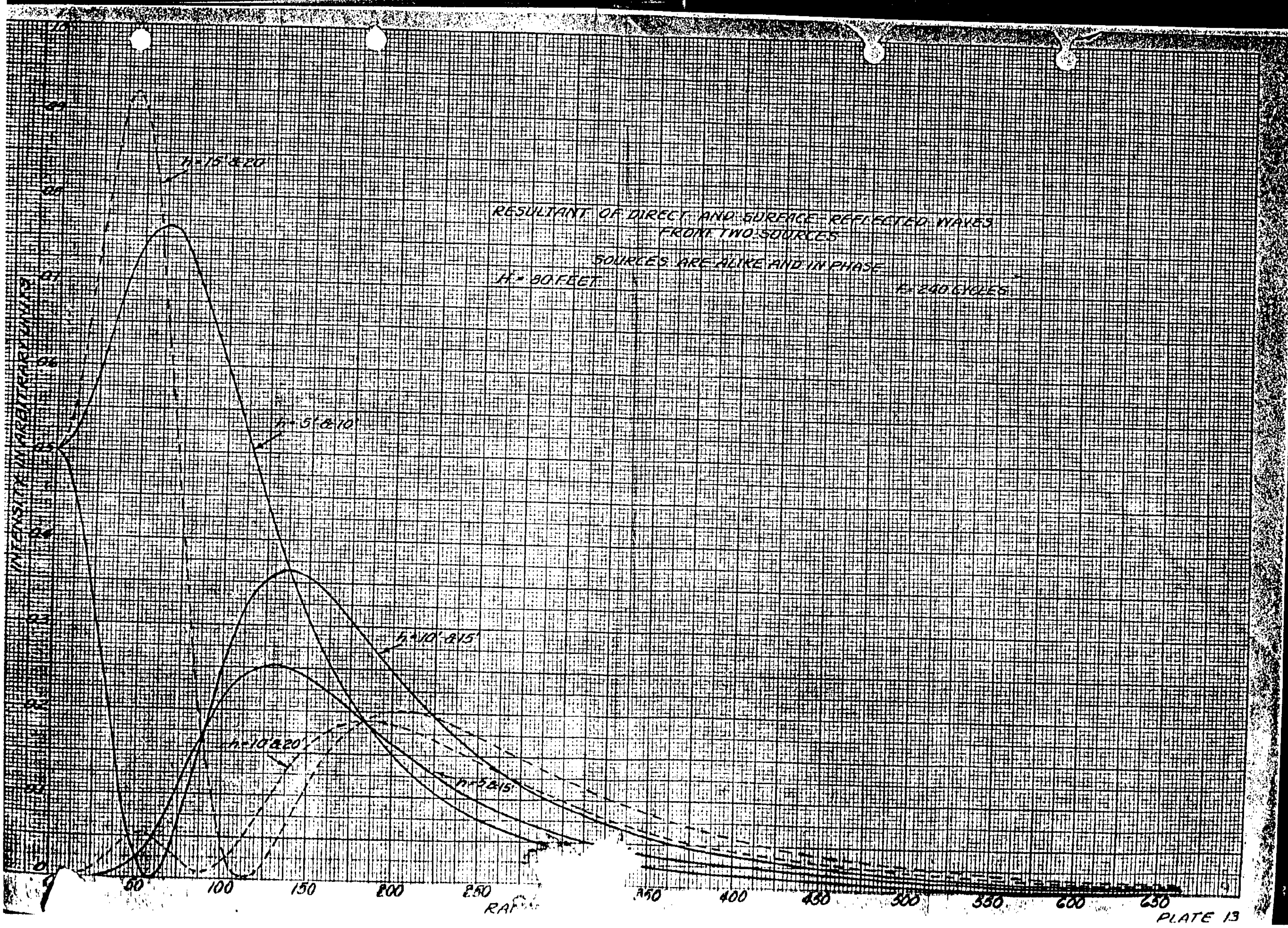


PLATE 13

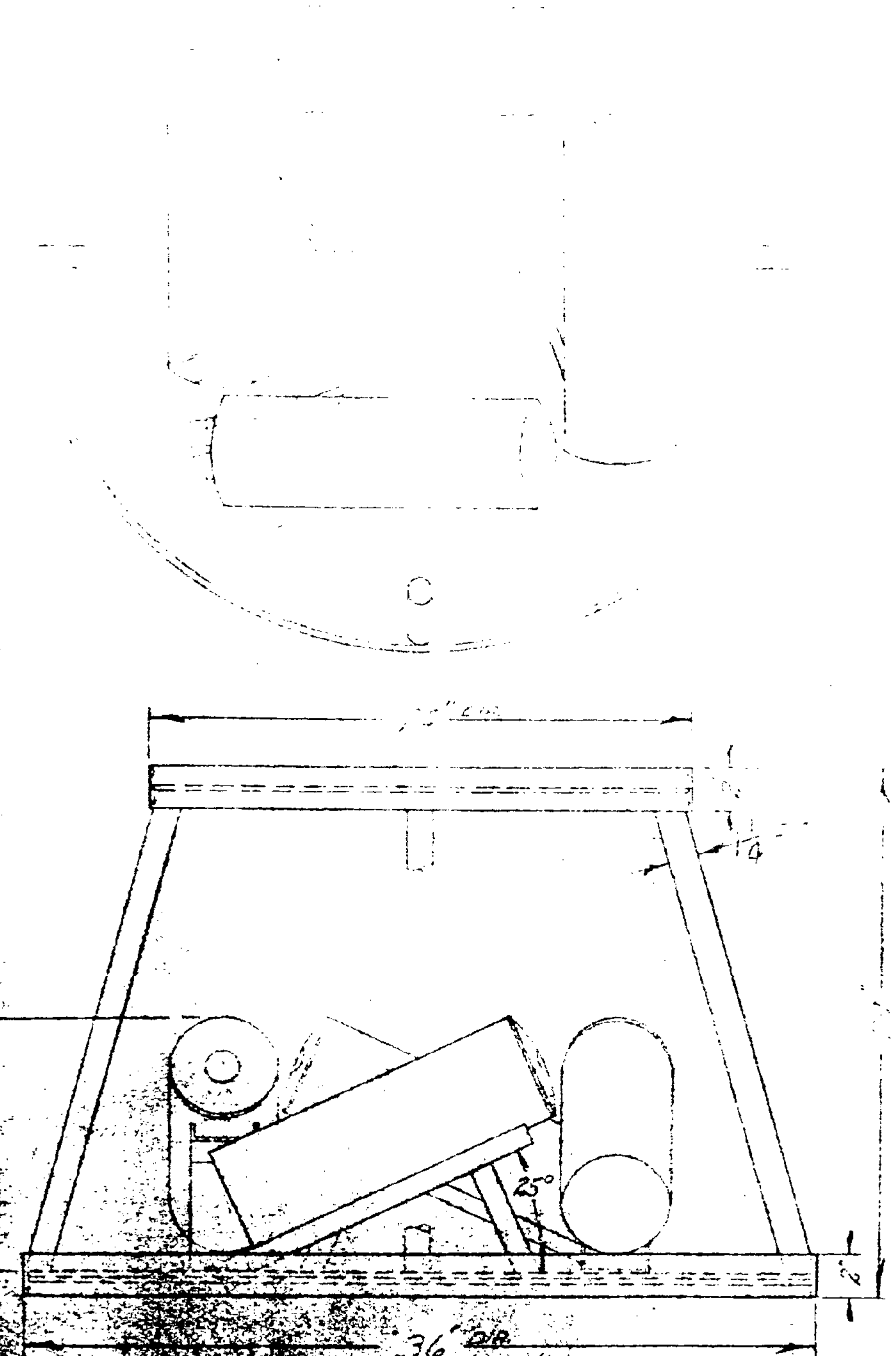


PLATE 16

UNCLASSIFIED

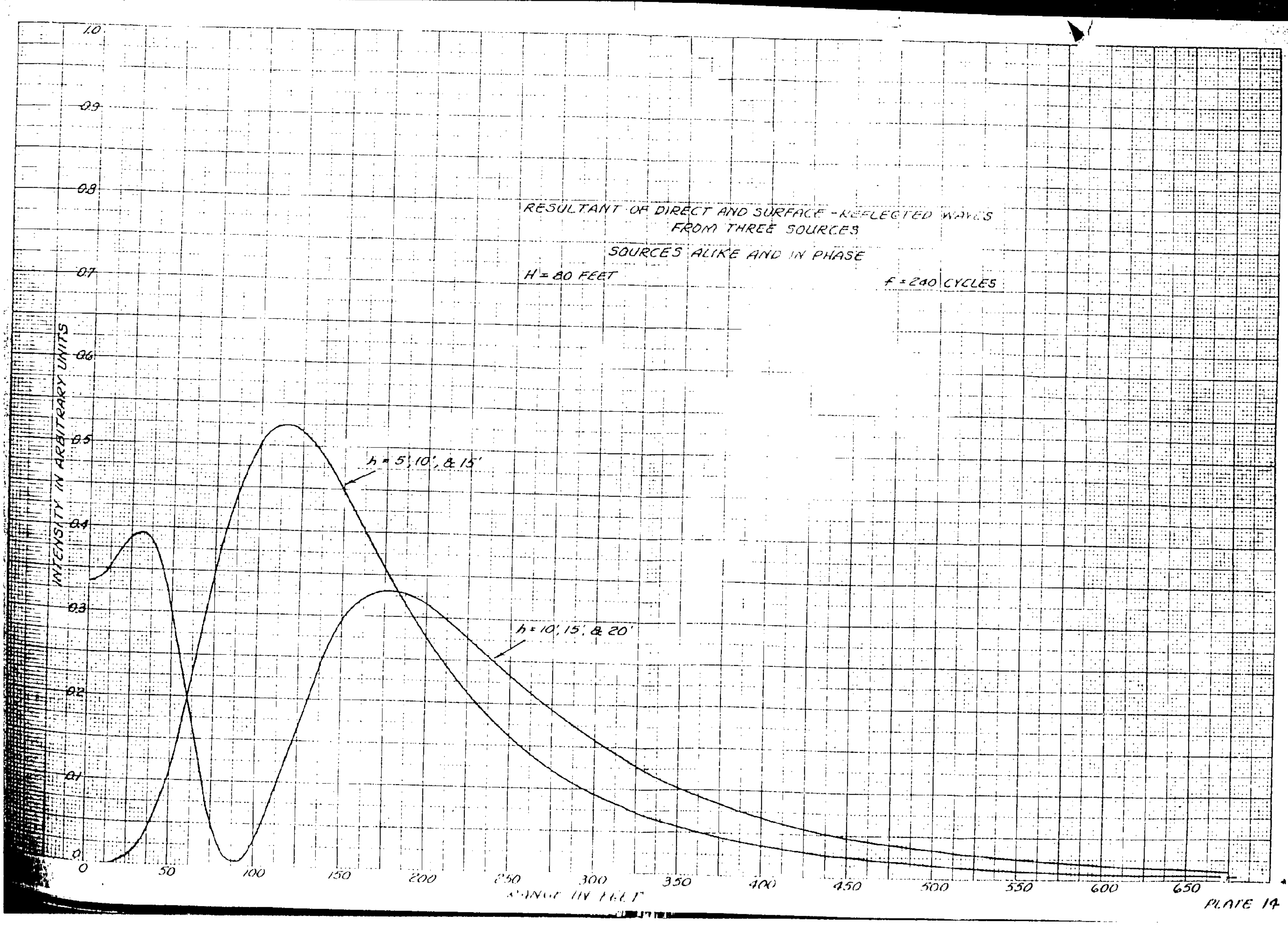
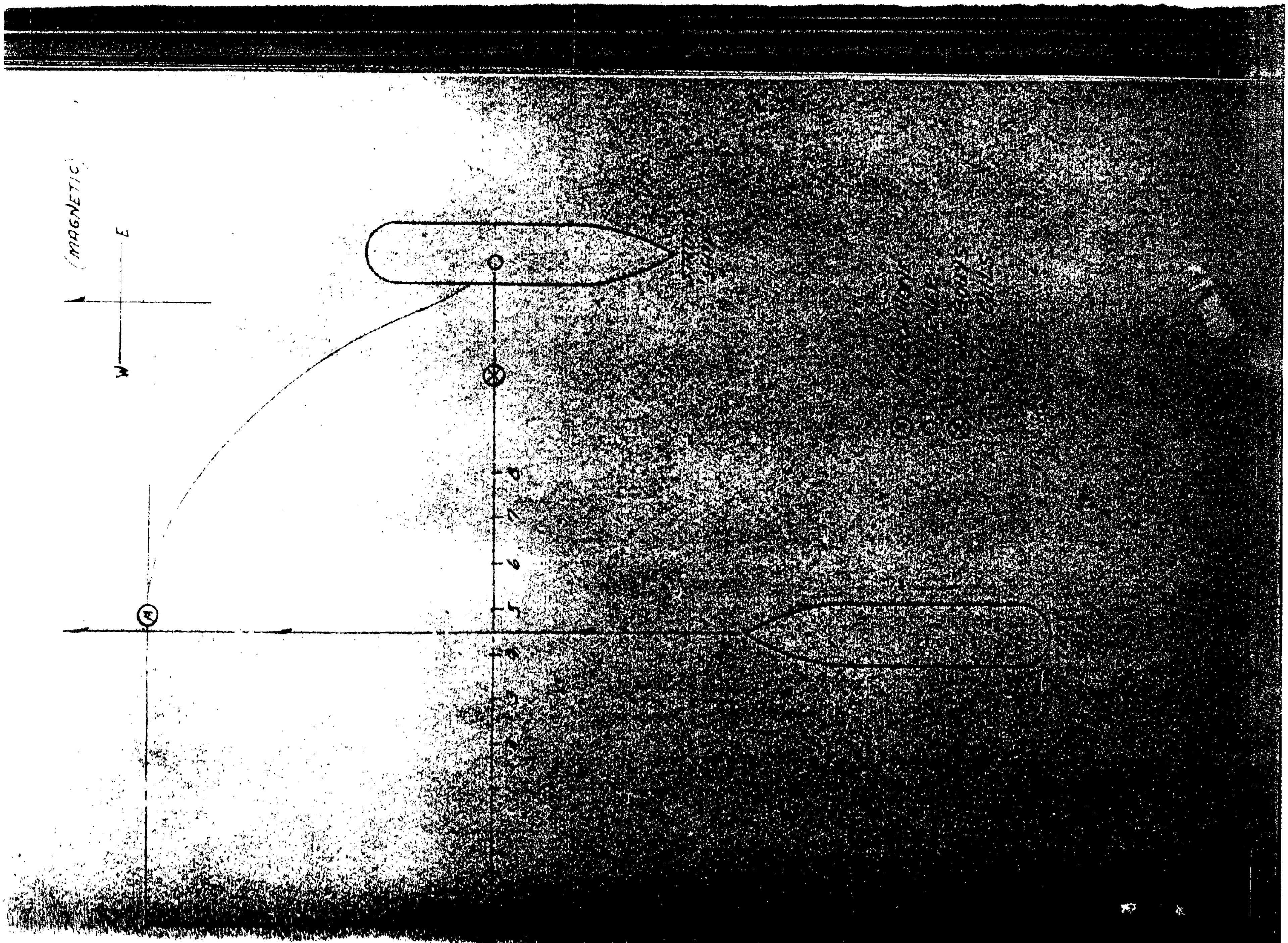
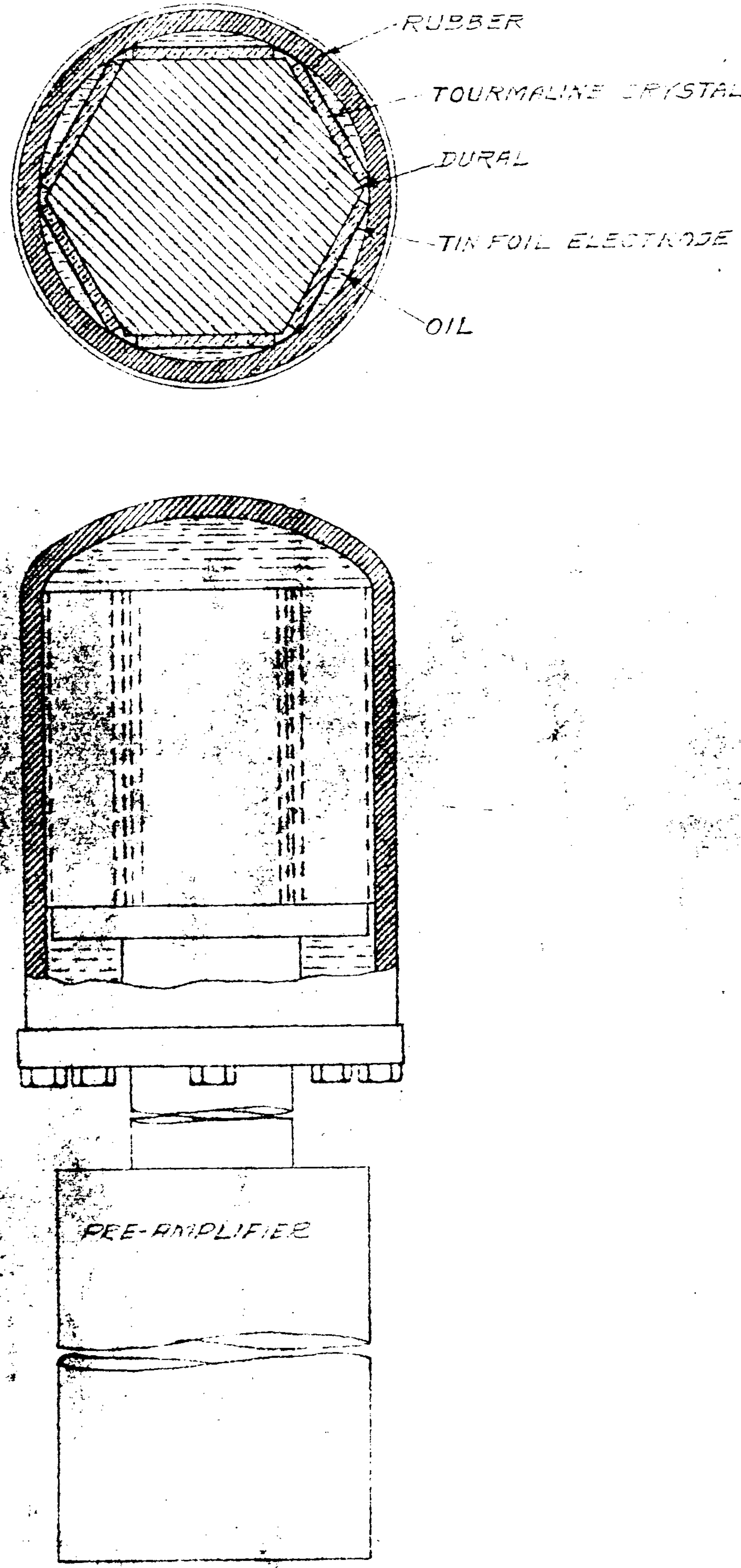


PLATE 14

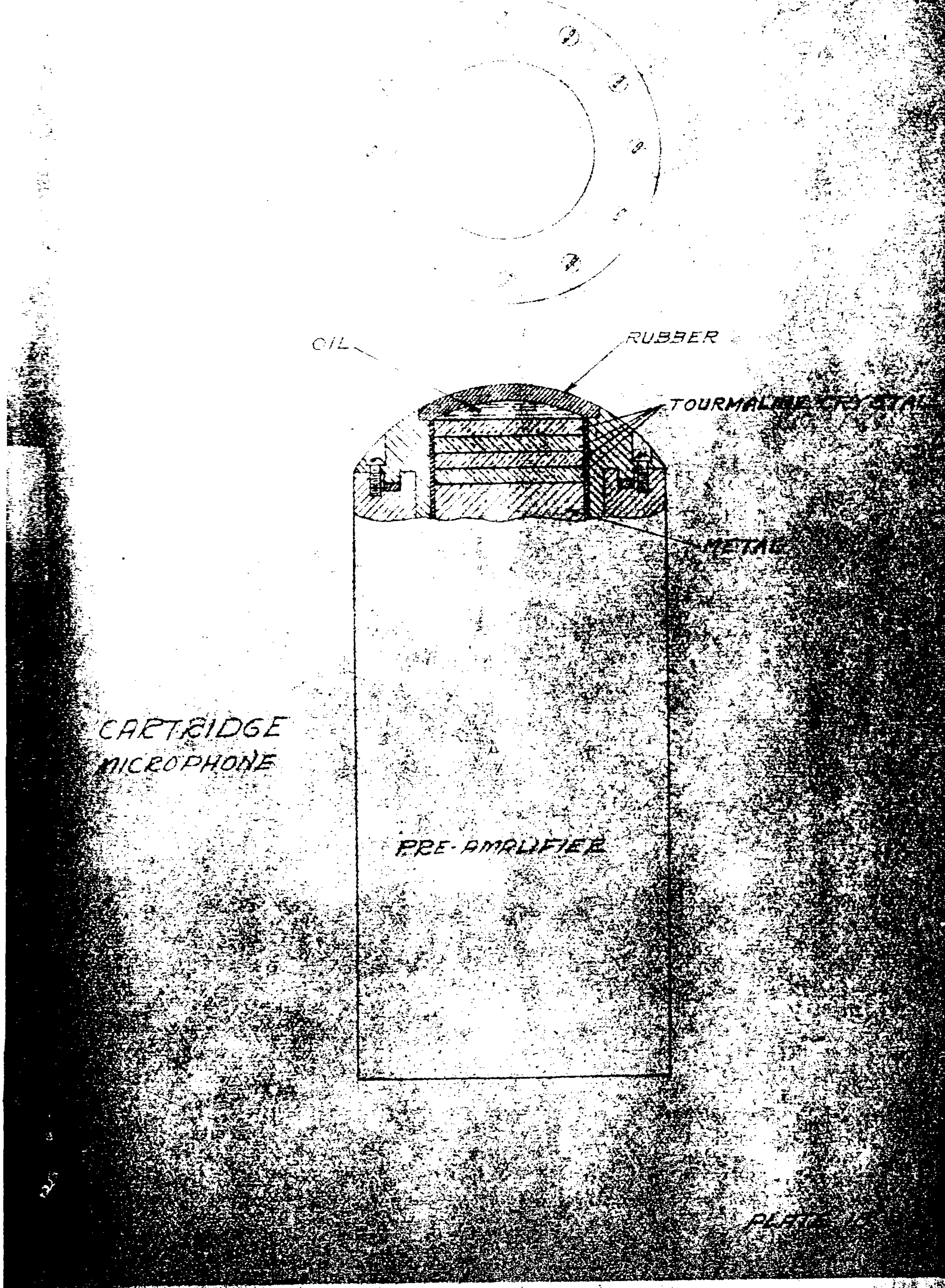
UNCLASSIFIED





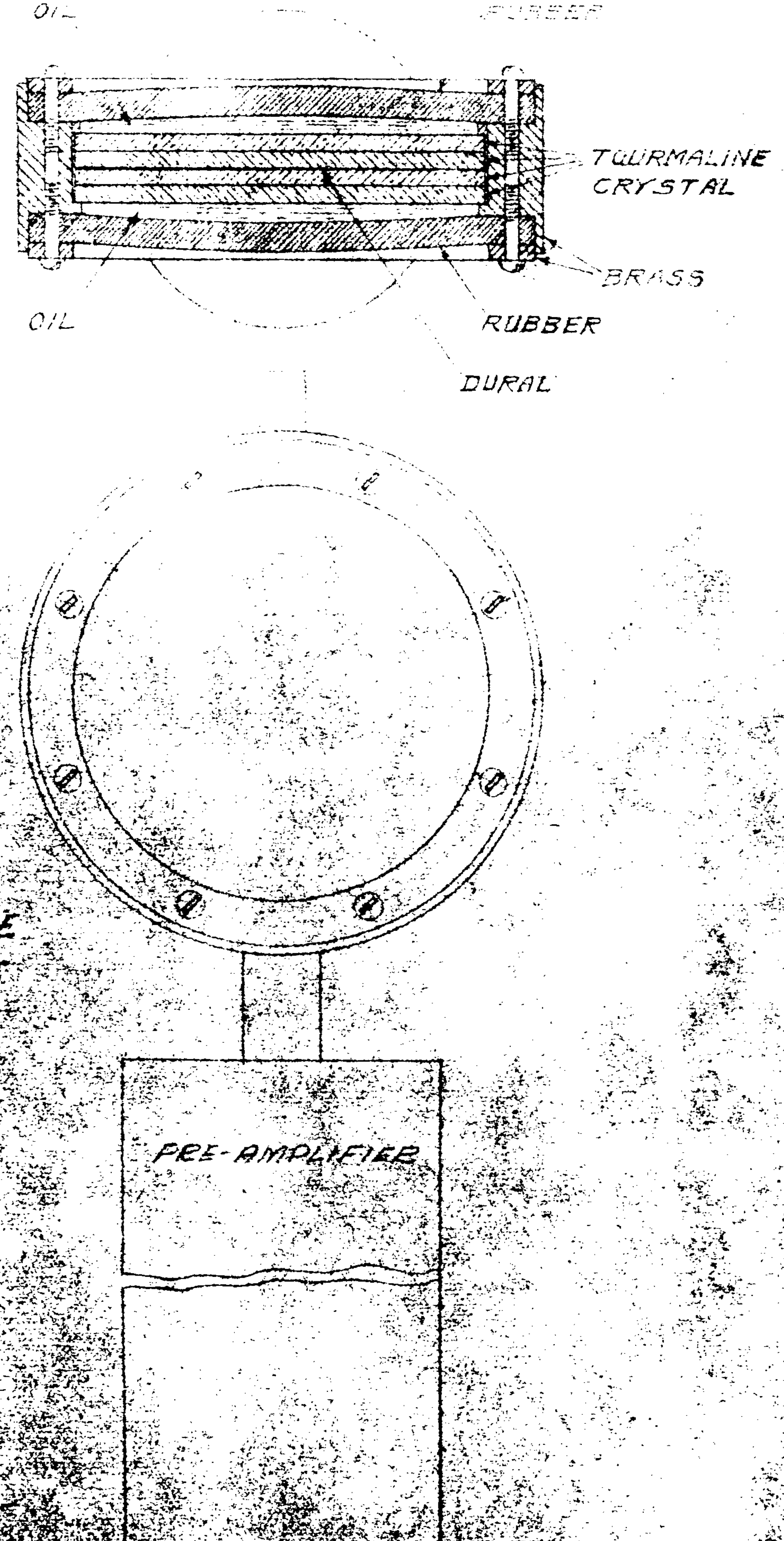
...IEX*
...ROPHONE

PLATE 17



UNCLASSIFIED

UNCLASSIFIED



ATCH CASE
MICROPHONE

PLATE 19

C_1 - [illegible] 600 V
C_2 - [illegible] "

- CRYSTAL MICROPHONE
T_1 - U.T.C. - O8
V_1 + V_2 - 6SC7

PLATE 20

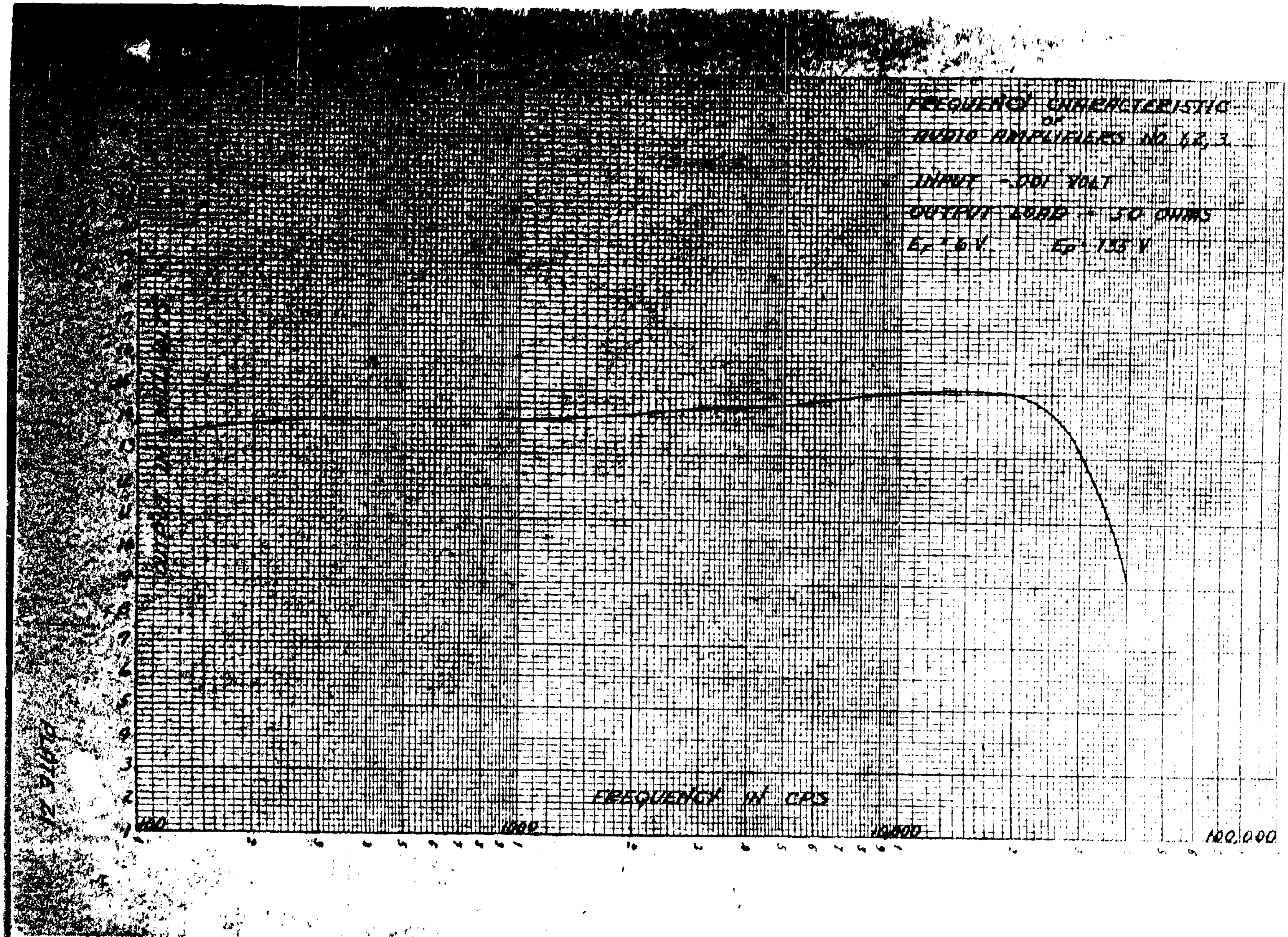

FREQUENCY CHARACTERISTIC
OF
AUDIO AMPLIFIERS NO 1,2,3
INPUT - .001 VOLT
OUTPUT LOAD - 50 OHMS
Ef = 6 V.   Ep = 135 V
FREQUENCY IN CPS
100
1000
10,000
100,000

PLATE 21

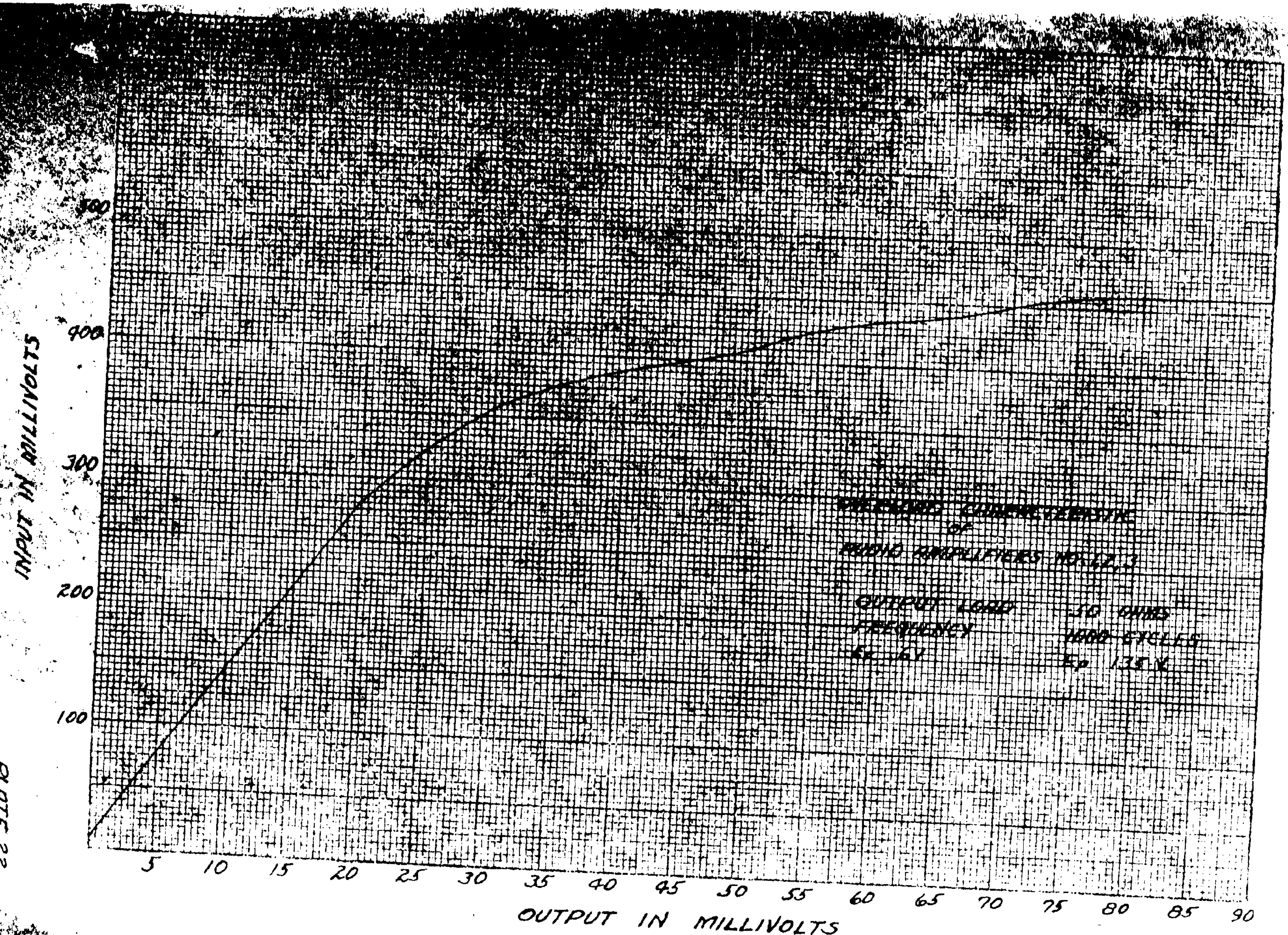


PLATE 22

UNCLASSIFIED

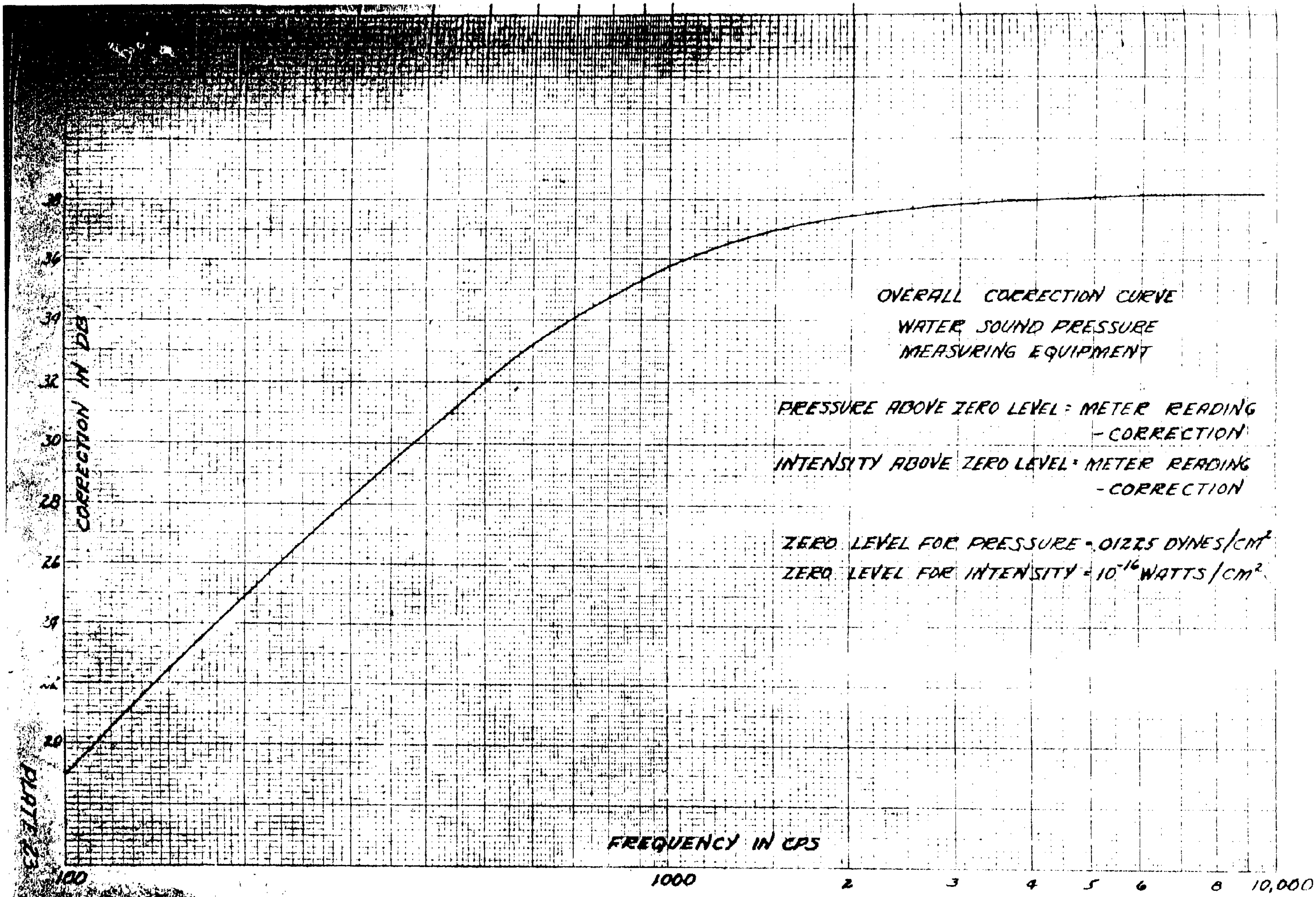


PLATE 23

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