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12 August 1938

NRL Report No.S-1466

NAVY DEPARTMENT
BUREAU OF ENGINEERING

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Report on

Absorption Coefficients
of Sound in Sea Water

NAVAL RESEARCH LABORATORY
ANACOSTIA STATION
WASHINGTON, D.C.

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ABSTRACT

Absorption Coefficients

During the period 5 February to 24 March 1938, the USS SEMMES and S-20 operated in the South Atlantic and Caribbean Sea. They made some 40 approach runs during which the intensity of the received signal was measured on 17.6, 23.6 and 30 Kcs. for ranges between 500 yards and about 10,000 yards. After each run the temperature of the water was measured from the surface to 120 feet with an accuracy of 0.01° or better.

Thirty five plates of range-intensity and temperature-depth curves are included showing wide deviations from the theoretical formulae but a fairly definite correlation between the form of the range-intensity curves and the temperature gradients.

An adequate explanation is given for the "afternoon" effect phenomena.

The loss coefficient, α , which includes all the factors which reduce the intensity of the sound signal in water, may be simply expressed in decibels per kilo-yard for normal curves where the temperature gradient is small and uniform and frequency is expressed in Kc.

The average value of α for normal curves increases with the frequency according to the empirical formula

$$\alpha = .0040 f^2 + .161 f.$$

The major conclusion is that the path of the sound beam, determined largely by the temperature gradients but complicated by reflection, refraction and scattering, is the dominant factor in determining the intensity of the received signal.

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TABLE OF CONTENTS

SUBJECT

1. Theory.	1
2. Practice.	2
(a) Reflection.	2
(b) Refraction.	2
(c) Scattering.	2
3. Experimental Procedure.	3
4. Experimental Results on Absorption Coefficients . . .	5
5. Summary.	7
6. Conclusions.	7

APPENDICES

Range-Intensity vs. Frequency, 5 Feb. 1938-1920-2018, Run #3. .	Plate 1
Range-Intensity vs. Frequency, 6 Feb. 1938-0803-0903, Run #4. .	Plate 2
Range-Intensity vs. Frequency, 6 Feb. 1938-1111-1155, Run #5. .	Plate 3
Range-Intensity vs. Frequency, 6 Feb. 1938-1237-1337, Run #6. .	Plate 4
Range-Intensity vs. Frequency, 14 Feb. 1938-1546-1625, Run #8. .	Plate 5
Range-Intensity vs. Frequency, 9 Feb. 1938-1748-1907, Run #9. .	Plate 6
Range-Intensity vs. Frequency, 14 Feb. 1938-1950-2047, Run #10. .	Plate 7
Range-Intensity vs. Frequency, 14 Feb. 1938-2126-2220, Run #11. .	Plate 8
Range-Intensity vs. Frequency, 15 Feb. 1938-0030-0123, Run #12. .	Plate 9
Range-Intensity vs. Frequency, 15 Feb. 1938-0205-0308, Run #13. .	Plate 10
Range-Intensity vs. Frequency, 15 Feb. 1938-0429-0524, Run #14. .	Plate 11
Range-Intensity vs. Frequency, 15 Feb. 1938-0558-0650, Run #15. .	Plate 12
Range-Intensity vs. Frequency, 15 Feb. 1938-0801-0851, Run #16. .	Plate 13
Range-Intensity vs. Frequency, 15 Feb. 1938-0929-1033, Run #17. .	Plate 14
Range-Intensity vs. Frequency, 15 Feb. 1938-1146-1236, Run #18. .	Plate 15
Range-Intensity vs. Frequency, 15 Feb. 1938-1355-1433, Run #19. .	Plate 16
Range-Intensity vs. Frequency, 4 Mar. 1938-1337-1444, Run #20. .	Plate 17
Range-Intensity vs. Frequency, 4 Mar. 1938-1545-1646, Run #21. .	Plate 18
Range-Intensity vs. Frequency, 4 Mar. 1938-1759-1910, Run #22. .	Plate 19
Range-Intensity vs. Frequency, 9 Mar. 1938-1900-1950, Run #23. .	Plate 20
Range-Intensity vs. Frequency, 9 Mar. 1938-2117-2215, Run #24. .	Plate 21
Range-Intensity vs. Frequency, 9-10 Mar. 1938-2342-0050, Run #25. .	Plate 22
Range-Intensity vs. Frequency, 10 Mar. 1938-0218-0312, Run #26. .	Plate 23
Range-Intensity vs. Frequency, 10 Mar. 1938-0430-0540, Run #27. .	Plate 24
Range-Intensity vs. Frequency, 10 Mar. 1938-0643-0737, Run #28. .	Plate 25
Range-Intensity vs. Frequency, 10 Mar. 1938-0837-0932, Run #29. .	Plate 26
Range-Intensity vs. Frequency, 10 Mar. 1938-1024-1130, Run #30. .	Plate 27
Range-Intensity vs. Frequency, 10 Mar. 1938-1225-1324, Run #31. .	Plate 28
Range-Intensity vs. Frequency, 10 Mar. 1938-1400-1450, Run #32. .	Plate 29
Range-Intensity vs. Frequency, 10 Mar. 1938-1543-1626, Run #33. .	Plate 30
Range-Intensity vs. Frequency, 10 Mar. 1938-1744-1905, Run #34. .	Plate 31
Range-Intensity vs. Frequency, 10 Mar. 1938-2015-2125, Run #35. .	Plate 32
Range-Intensity vs. Frequency, 15 Mar. 1938-1434-1535, Run #36. .	Plate 33
Temperature vs. Depth, 9-10 Mar. 1938, Gonaives Gulf Area . . .	Plate 34
Temperature vs. Depth, 15-16 Mar. 1938, Guantanamo Bay Area . .	Plate 35
Variation of α with Frequency, α in db per Kiloyard, f in Kilocycles, $\alpha = .0040f^2 + .161f$	Plate 36

ABSORPTION COEFFICIENTS

1. Theory

For sound waves propagated in an infinite, homogeneous medium, the relation between the intensity and the range is given by the formula -

$$\frac{I_r}{I_o} = \left(\frac{R_o}{R}\right)^n 10^{-\alpha(R - R_o)} \quad (1)$$

(Reference (1))

where I_o and I_r are the intensities at the ranges R_o and R respectively, α is the absorption coefficient, and n is an exponent determined by the type of propagation. For spherical waves, or for plane waves in a conical beam, n is equal to 2 from simple geometry. It is also possible to calculate α for a given medium from the numerical values of the velocity of sound, the coefficient of viscosity, the density and the frequency, (Reference (2)), but this value is about 0.1% of the experimental values.

If a series of measurements of the intensity at known ranges are made, it is possible to evaluate the constants of this equation. Intensities are commonly measured in decibels above a specified level. By definition

$$-db = 10 \log \frac{I}{I_o},$$

therefore

$$db_1 - db_2 = 10 \log \frac{I_1}{I_2}.$$

By taking the logarithms of both sides of equation (1) and eliminating I_o and R_o from the simultaneous equations, we may write -

$$\frac{db_1 - db_2}{10(R_2 - R_1)} = n \frac{\log \frac{R_2}{R_1}}{R_2 - R_1} + \alpha \quad (2)$$

Reference (1) - NRL Report S-1204 of 16 October 1935.

Reference (2) - "A Textbook of Sound" by Wood, pp. 317-335.

This is the form of the simple linear equation $y = ax + b$ for which a is the slope of the line and b the intercept on the y axis. By plotting decibel differences against the logarithms of the range ratio the values of n and a may be found (Reference (3)).

2. Practice

When measurements are made between two surface ships in open water, the assumption of an infinite homogeneous medium in which the above formulae are valid no longer meets the actual conditions.

(a) Reflection.

Due to the shallow submergence of the transmitting and receiving units, the upper portion of a conical beam soon suffers reflection at the air-water surface. This reflection is with change of phase. Similarly, the lower portion of the beam may be reflected from the bottom, or from any surface where there is a rapid change in the ρc product. This reflection is without change of phase. Multiple reflections are possible at the longer ranges or in shallow water.

(b) Refraction.

The temperature of the water is seldom uniform over any considerable range of depths, generally, though not always, being higher at the surface and decreasing with depth. Since the velocity of sound increases nearly 2 yards per second per degree Fahrenheit, the bending due to the temperature gradient may be considerable and even cause the sound beam to pass below the detector on the receiving ship.

The velocity of sound increases with the depth due to the increase in pressure and salinity, and this tends to bend the ray upward. The net refraction effect will be the algebraic sum of the temperature gradient and the depth and salinity effects, (Reference (4)).

(c) Scattering.

Neither the air-water surface, the water-earth surface, nor a thermocline boundary surface, is smooth or level for supersonic waves so the reflected beam will always be somewhat scattered. Also turbulence absorbs, reflects, and scatters sound as may be noted in the diffuse echo from the wake of a ship. Turbulence may also be caused by the wind as shown by Langmuir (Reference (5)). He shows

Reference (3) - "Underwater Sound Investigations in Northern Waters," August 1937, BuEng. file 368 (1-28-W6).

Reference (4) - "Velocity of Sound in Sea Water," U.S. Coast & Geodetic Survey, Sp. Pub. No. 108.

Reference (5) - "Surface Motion of Water Induced by Wind," Science, Vol. 87, No. 2250, February 11, 1938.

signal intensities on the S-20's receiver at a definite sensitivity expressed as microvolts input for standard output. This sensitivity was maintained constant by frequent checks with a standard signal generator. However, absorption coefficients are based on the slopes of the curves and not the absolute values of the intensities so the results of this report are not dependent on the accuracy of the zero levels.

After each range run eleven temperature readings were made between the surface and 120 feet. A platinum resistance thermometer and a high grade bridge were used to measure temperatures in terms of resistance. The accuracy of the temperature readings was limited by the galvanometer. The low sensitivity galvanometer used prior to February 18 was good to $\pm 0.1^\circ \text{C}$. Afterwards a better galvanometer was used which was sensitive to 0.001°C ., but the accuracy was usually limited to $\pm 0.005^\circ \text{C}$. due to the roll of the ship making the exact balance point uncertain. The thermometer was calibrated at the ice point and by comparison with three good Laboratory thermometers over the temperature range from 20 to 25°C . and over a period of days. The absolute values of the temperatures are considered good to $\pm 0.1^\circ \text{C}$. and the variations with depth to $\pm 0.005^\circ \text{C}$.

Temperature Gradients.

Plate 34 shows a series of curves of temperatures vs. depths taken at approximately 2-hour intervals for some 36 hours. The previously observed "afternoon effect" is shown in curves 10 to 13 and is correlated with the wind, sea and sun conditions. The outstanding points are: On a calm day with a bright sun there is a rapid heating of the water at the surface and a gradual but less marked heating at greater depths reaching a maximum about 1700. During the early evening, with increasing wind, the surface layers cools and a small inverse gradient appears at 1700. Between 2000 and 0600 with winds up to 28 knots the temperature is uniform within $.01^\circ \text{C}$. down to 120 feet and the lowest temperatures of the series are found. The next morning the cycle starts to repeat.

The explanation of this cycle is as follows: The sun light falling on the water is largely absorbed and transformed into heat. Ninety per cent of the visible light will be absorbed in the first 125 feet and ninety-nine per cent will be absorbed at a depth of 250 feet for a logarithmic absorption coefficient of 0.008 (Reference (6)) which is a probable value for this area. The infra-red light, containing about one-third of the total energy of the sunlight, will be completely absorbed in the first few inches. This explains the relatively high temperature of the shallow surface layer when the sea is calm as there is then little stirring action by the wind and convection or diffusion effects are small.

Reference (6) - Stephenson JOSA, August 1934, Vol. 24, pp. 220-1.

If the weather continues calm, the warm layer will cool slowly at night due to radiation to the atmosphere at the surface and to a small convection to the colder water below. If a strong wind arises vertical currents are set up (Reference (5)) which thoroughly mix the water as shown by curves 5, 6 and 7, where the temperature is uniform with 0.01°C . for 120 feet. The mixing evidently extended to depths greater than 120 feet since the minimum temperatures were obtained at 0800 at the end of the period of high wind indicating that the warm surface water was mixed with the colder water from considerably below 120 feet.

In Plate 35 the sea was not so calm in the afternoon nor was the wind so strong at night so the warm layer did not get so hot nor was the mixing so thorough at night.

The temperature vs. depth curves throughout this report are plotted to a large temperature scale, one small division equals 0.01°C ., to show the differences actually measured. Without precise temperature measuring equipment, no gradient would have been found in a majority of cases in the Guantanamo area.

4. Experimental Results on Absorption Coefficients

Some 38 range-intensity runs were made altogether. The data are plotted in Plates 1 to 33 showing the effects of range, frequency, temperature gradients, wind, sea, and sunlight on the sound transmission.

The curves may be arranged in three general groups where there is a definite correlation between the type of transmission curve and the temperature gradient.

In Group I where the temperature gradient is zero or slightly negative, a single straight line comes the nearest going through all the points beyond 1000 yards, though there may be irregular but somewhat cyclical variations impressed on this line. The loss coefficient is given in db/yard for each frequency. Obviously, for this type of curve the loss factor is numerically so much more important than the $\left(\frac{R_0}{R}\right)^n$ factor that $n = 0$ after the first 1000 yards. The general method was not designed for accurate measurements at ranges under 500 yards as the longer ranges were considered more important for practical service. The irregular variations from the straight line are due to minor reflection, refraction or scattering effects.

Group II shows three runs, Plates 1, 19 and 33, that have fairly definite breaks in the curves with high absorption in the first 3500 yards and half to a third this value at the longer ranges. This occurs where there is a small positive gradient in both upper and lower layers of water.

Group III, Plates 27 to 30, shows the effect of a large gradient

in the first 20 feet and a smaller but considerable gradient down to 120 feet. The sea is always calm with little wind and the sun is bright. The Type III range-intensity curves are characterized by large positive values of α that are 10 times the normal for the first 1500 yards, then become zero and negative and finally positive again. There is definite evidence of reinforcement in the 4 to 6 kiloyard range as this point is 10 to 15 db higher than for a run with normal α .

There is a transition from Types I to II to III and a definite correlation with the temperature gradient.

The loss coefficients for all the runs where an average value was obtainable were averaged for each frequency and are shown in the following table. Comparable runs from February 1937 at 24.5 kilocycles are also shown.

Frequency kc	α in <u>db</u> <u>kiloyard</u>	α/f	Average Deviation from Mean	Number of Runs
17.6	4.06	.231	$\pm 20\%$	26
23.6	6.00	.255	$\pm 20\%$	26
30.0	8.44	.281	$\pm 10\%$	13
24.5	5.6	.229	Feb. 1937	7

If the quantity α/f is plotted against frequency, Plate 36, a straight line is obtained of the form $\alpha/f = mf + b$ where m and b are constants which may be evaluated from the data to give the empirical equation -

$$\alpha = .0040 f^2 + .161 f$$

where α is the decibel loss per 1000 yards and f is the frequency in kilocycles. This means that in addition to the classical absorption term based on the viscosity of the medium and proportional to the square of the frequency, there is another term proportional to the first power of the frequency. This first power term is 30% of the total loss at 10 kilocycles, 66% at 20 kilocycles and 57% at 30 kilocycles.

Calculating from the formula the α for 24.5 kilocycles used in February 1937, the value is 6.3 compared with 5.6 observed, a difference of 12% that is within the mean variation.

SUMMARY

Some 38 range-intensity runs at 17.6, 23.6 and 30 kilocycles were made in the South Atlantic and Caribbean area during February and March 1938, and accurate temperature measurements from the surface to 120 feet depth were made after each run, a total of 48 thermal stations.

A brief theoretical discussion and a description of the experimental technique are given.

The data and derived results are presented in the form of curves on a total of 36 plates.

An Empirical formula is derived for the decibel loss per thousand yards as a function of frequency. An adequate explanation is given for the occurrence of the "afternoon effect" on a bright, calm afternoon and for its complete disappearance on a windy night.

The path of the sound beam, determined largely by temperature gradients, is shown to be the major factor in determining the intensity of the direct signal.

Definite conclusions are drawn on numerous phases of the problem on absorption coefficients.

CONCLUSIONS

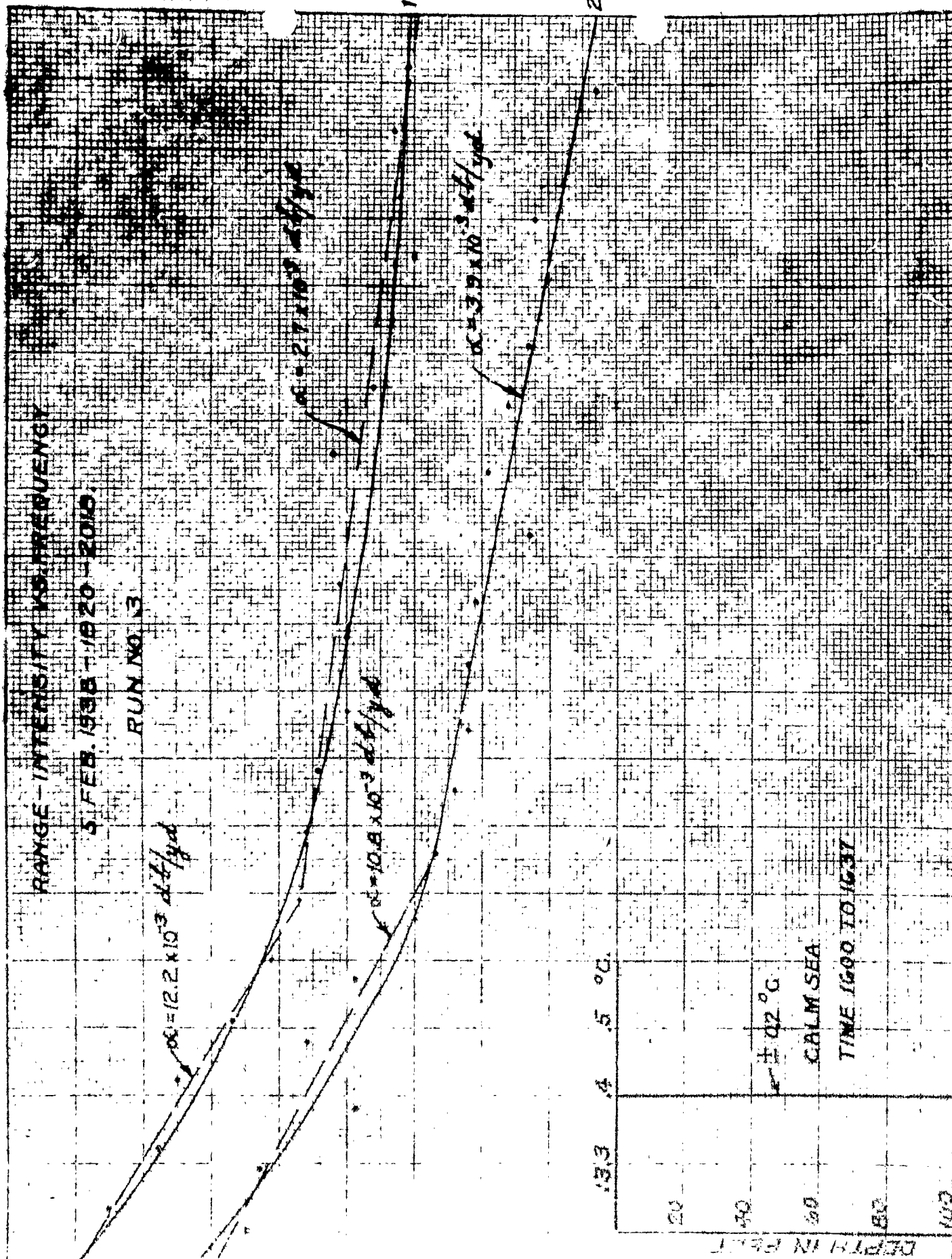
(a) The theoretical formula, based on the assumption of an infinite homogeneous medium, does not adequately express the law for the propagation of the sound beam in water under normal service conditions because the beam is subject to refraction, reflection and scattering effects.

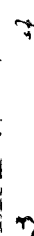
(b) Beyond the first thousand yards and when the temperature gradient is small, a straight line gives the best average fit for the points on a normal range-intensity curve. Therefore, the loss coefficient, α , which includes all the factors which reduce the signal intensity in the water, may be simply expressed in decibels per yard.

(c) The range-intensity data consistently and conclusively show that the decibel loss in intensity per yard in range increases with the frequency. For the conditions in the area studied the average values may be expressed by the empirical formula -

$$\alpha = .0040 f^2 + .161f$$

Single determinations of α under different conditions may vary $\pm 50\%$ from the average value, and the mean deviation is $\pm 20\%$.



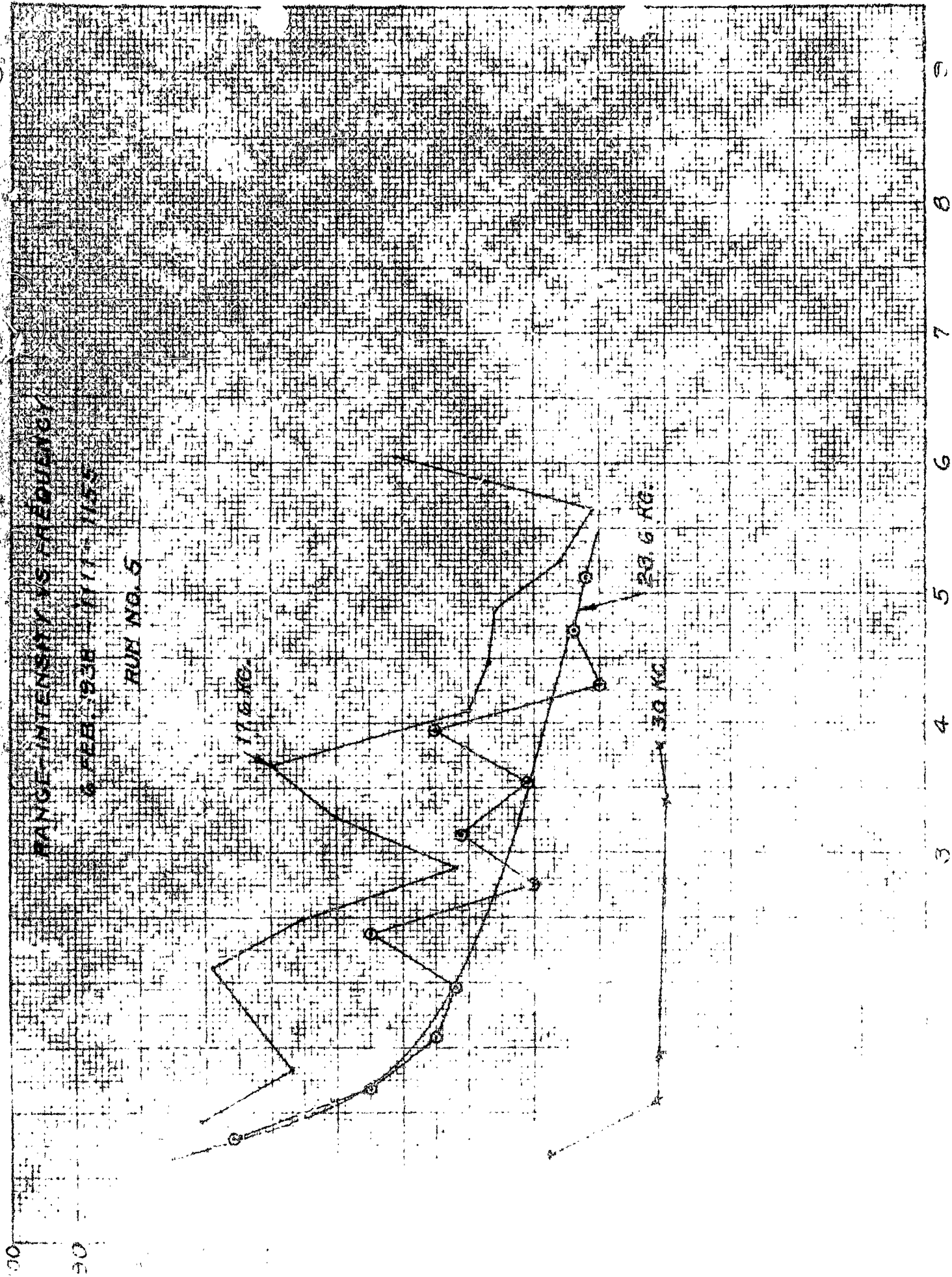


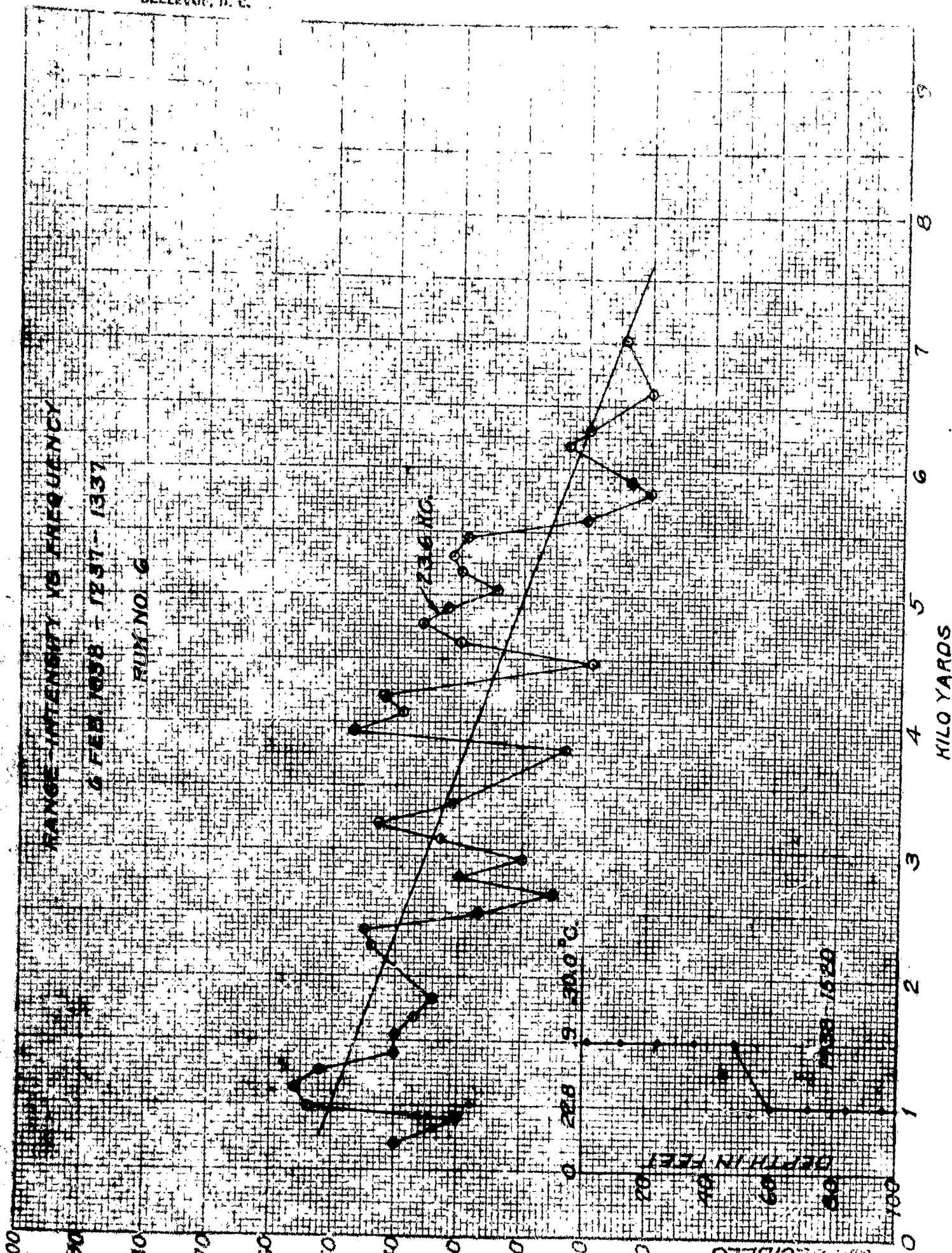
N. R. L. 34

RANGE-INTENSITY VS. FREQUENCY

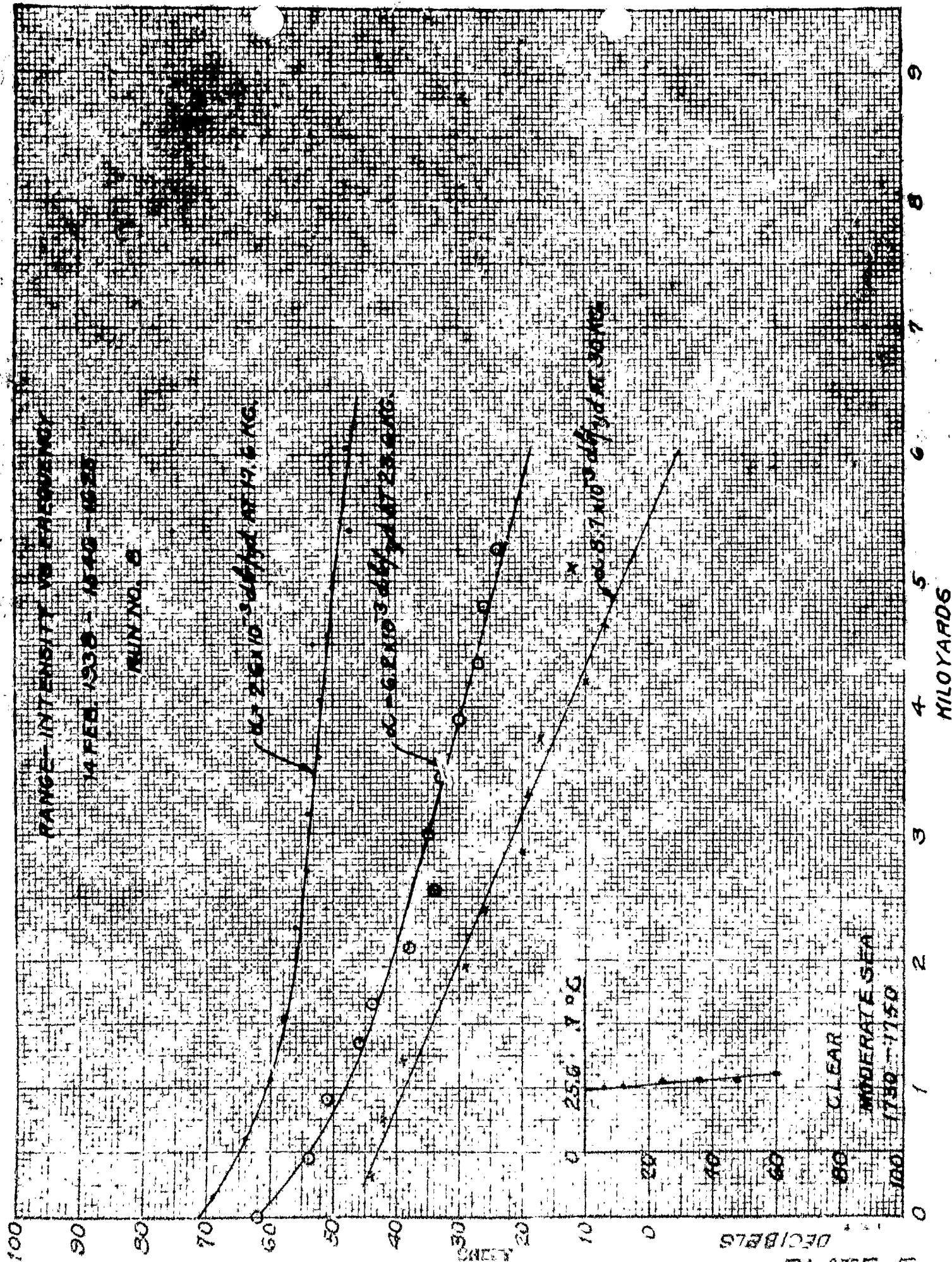
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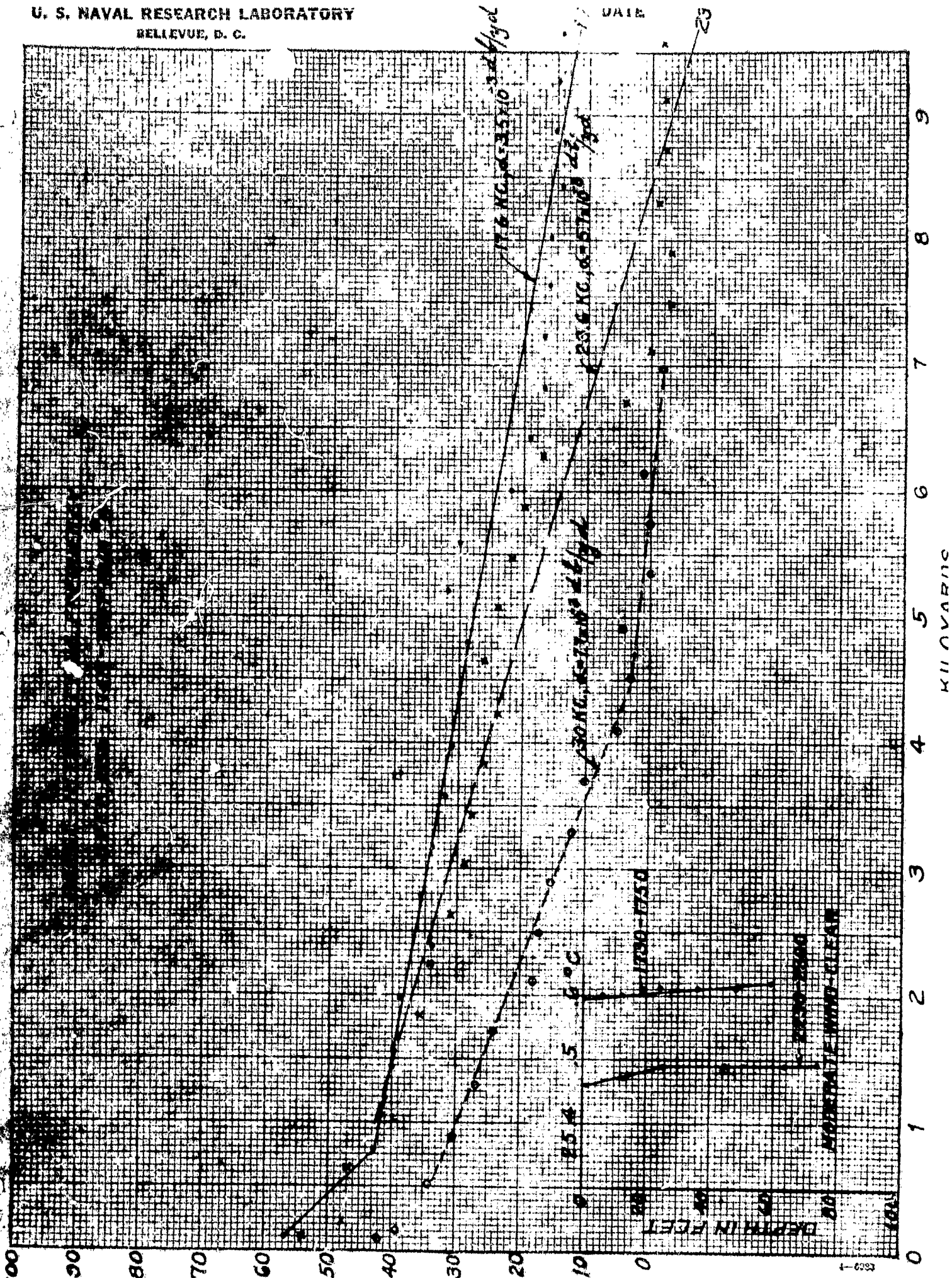
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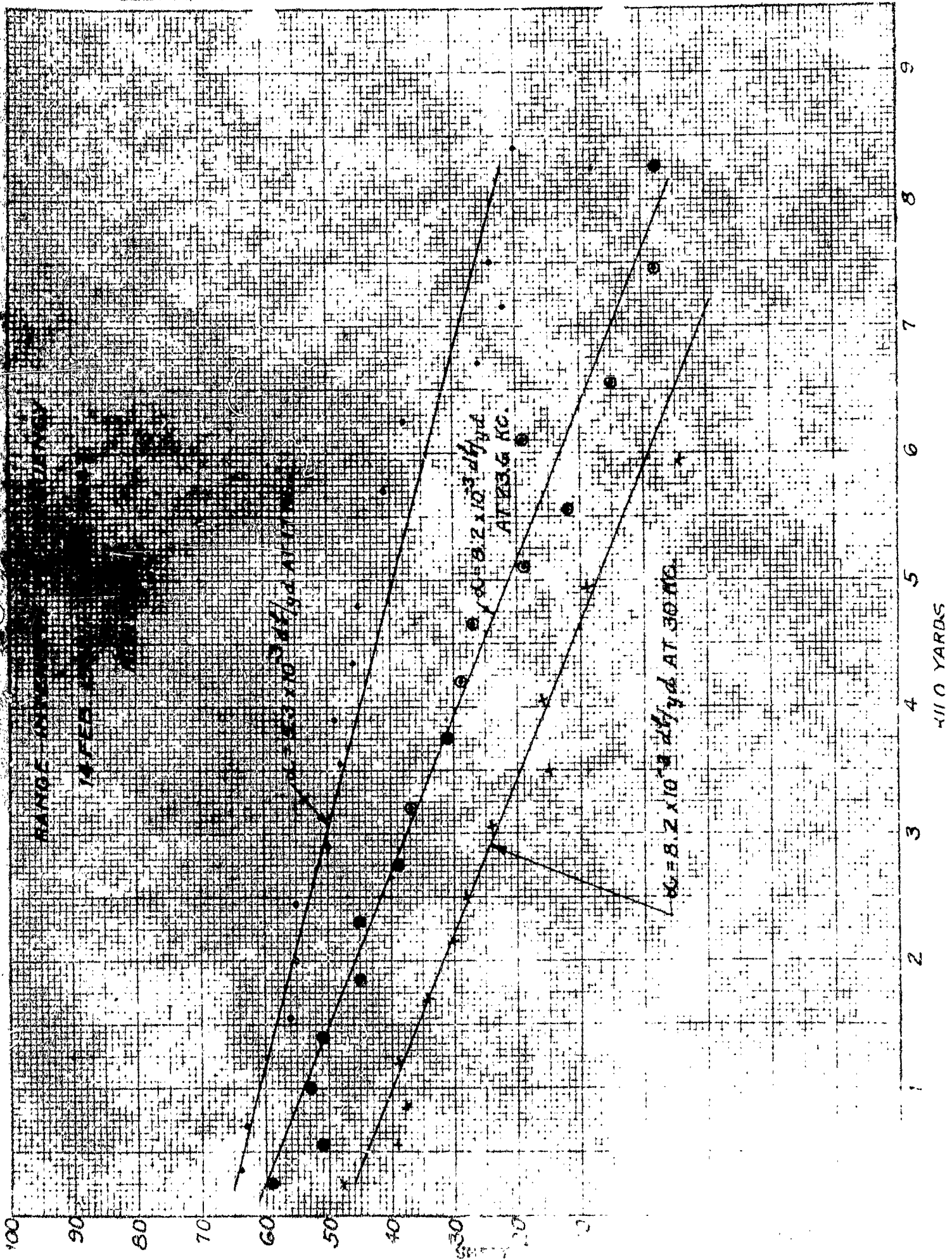


8-603 N. R. L. 34





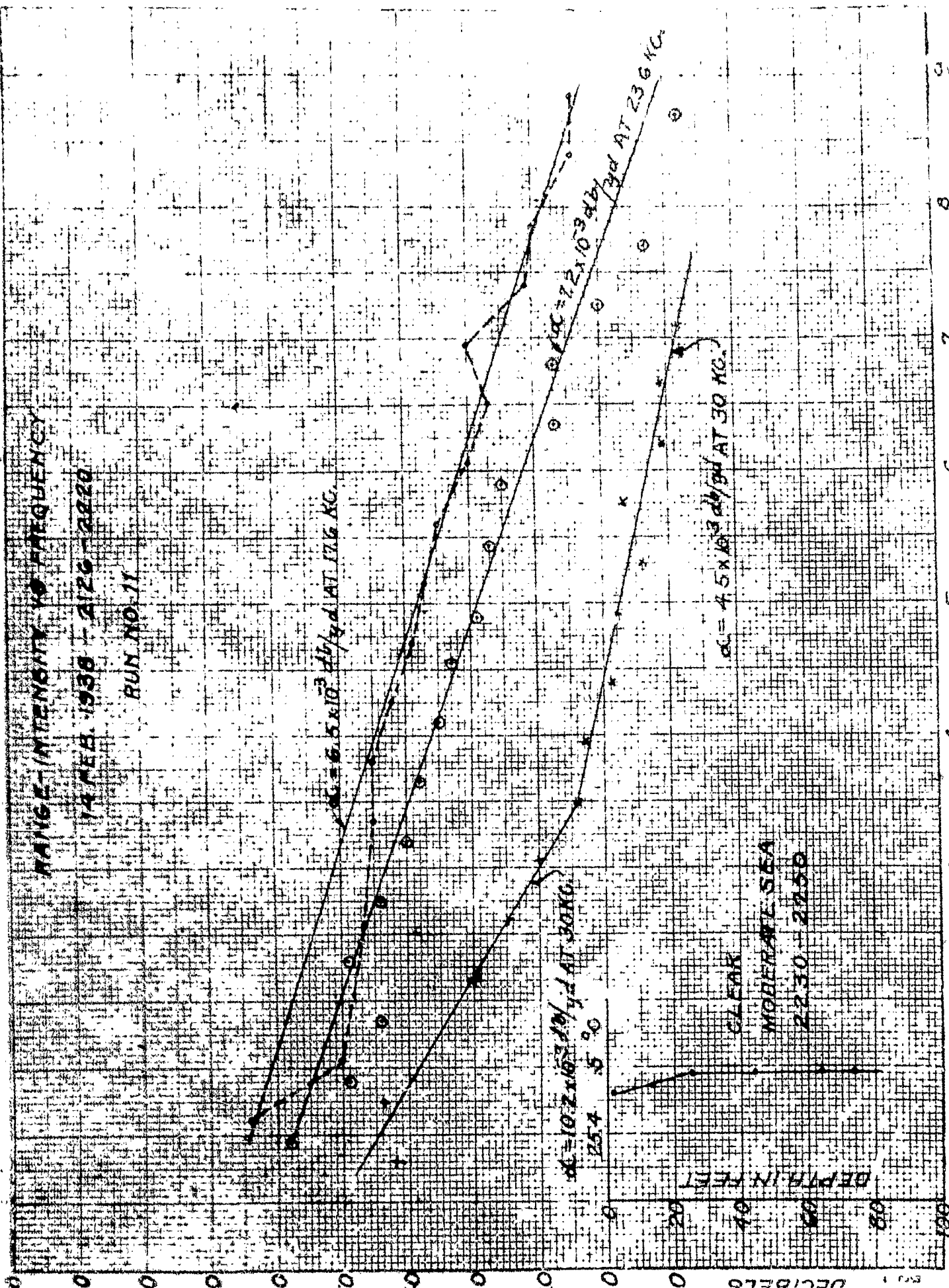
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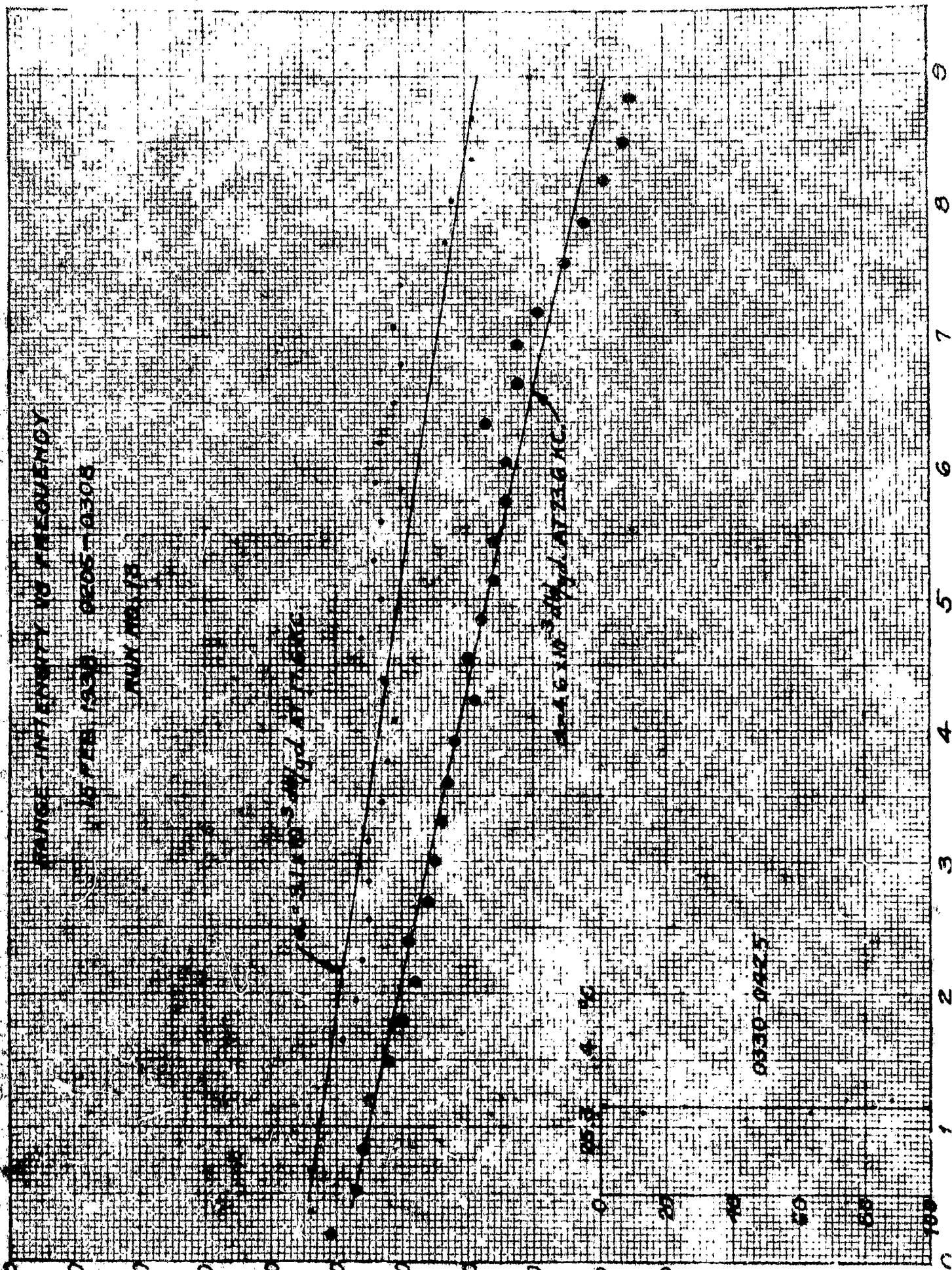
RANGE-INTENSITY vs. FREQUENCY

14 FEB. 1938 - 2120 - 2220

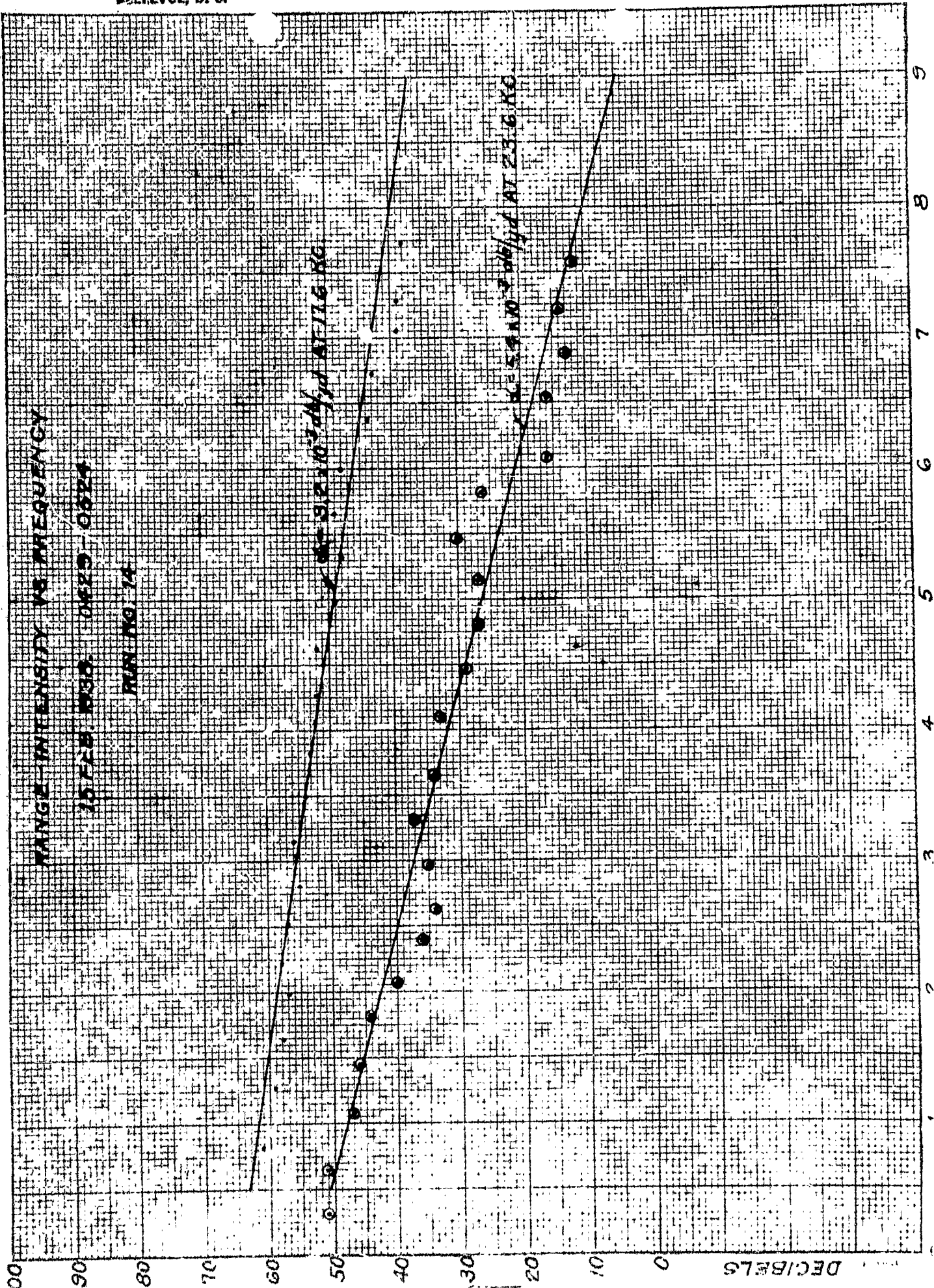
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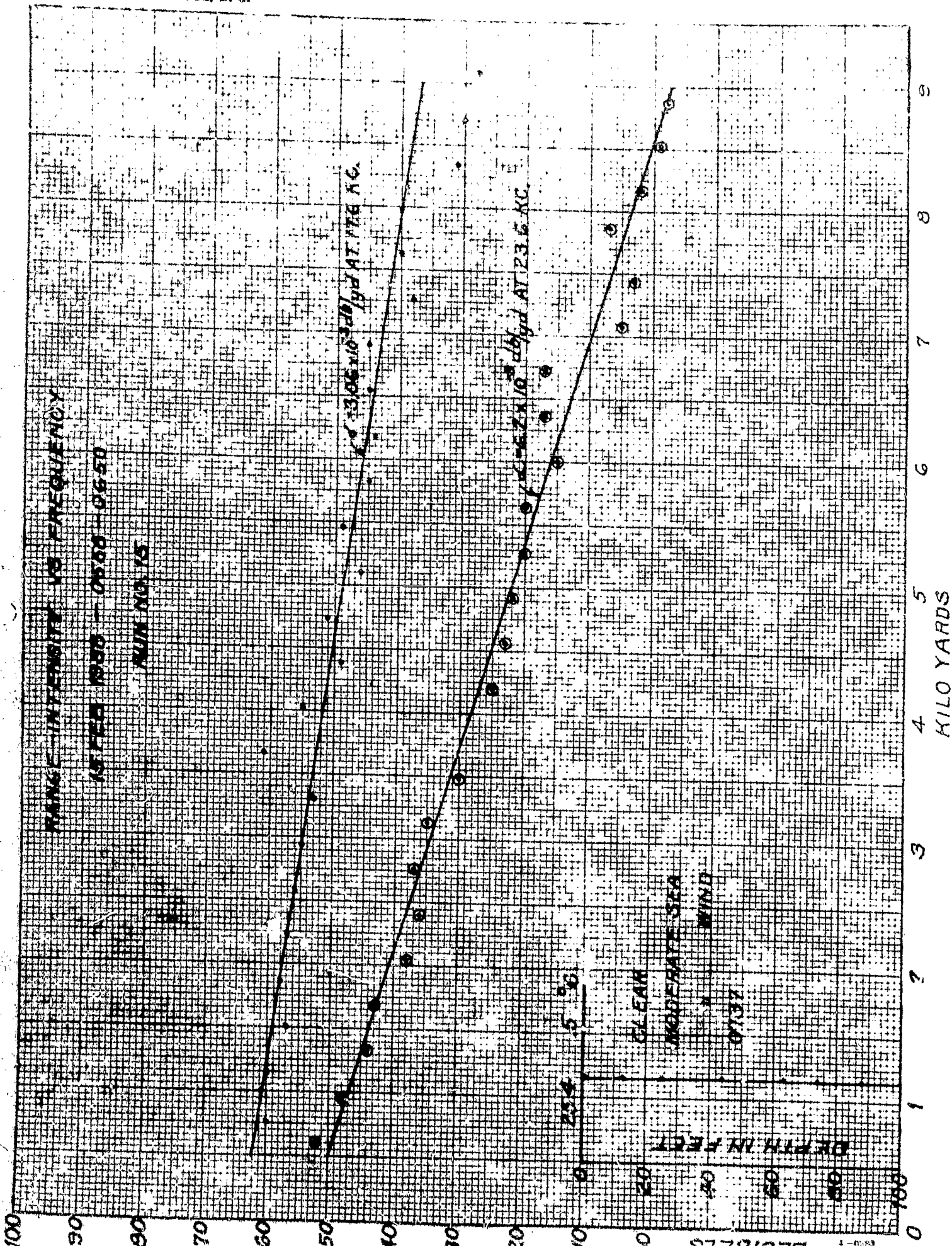
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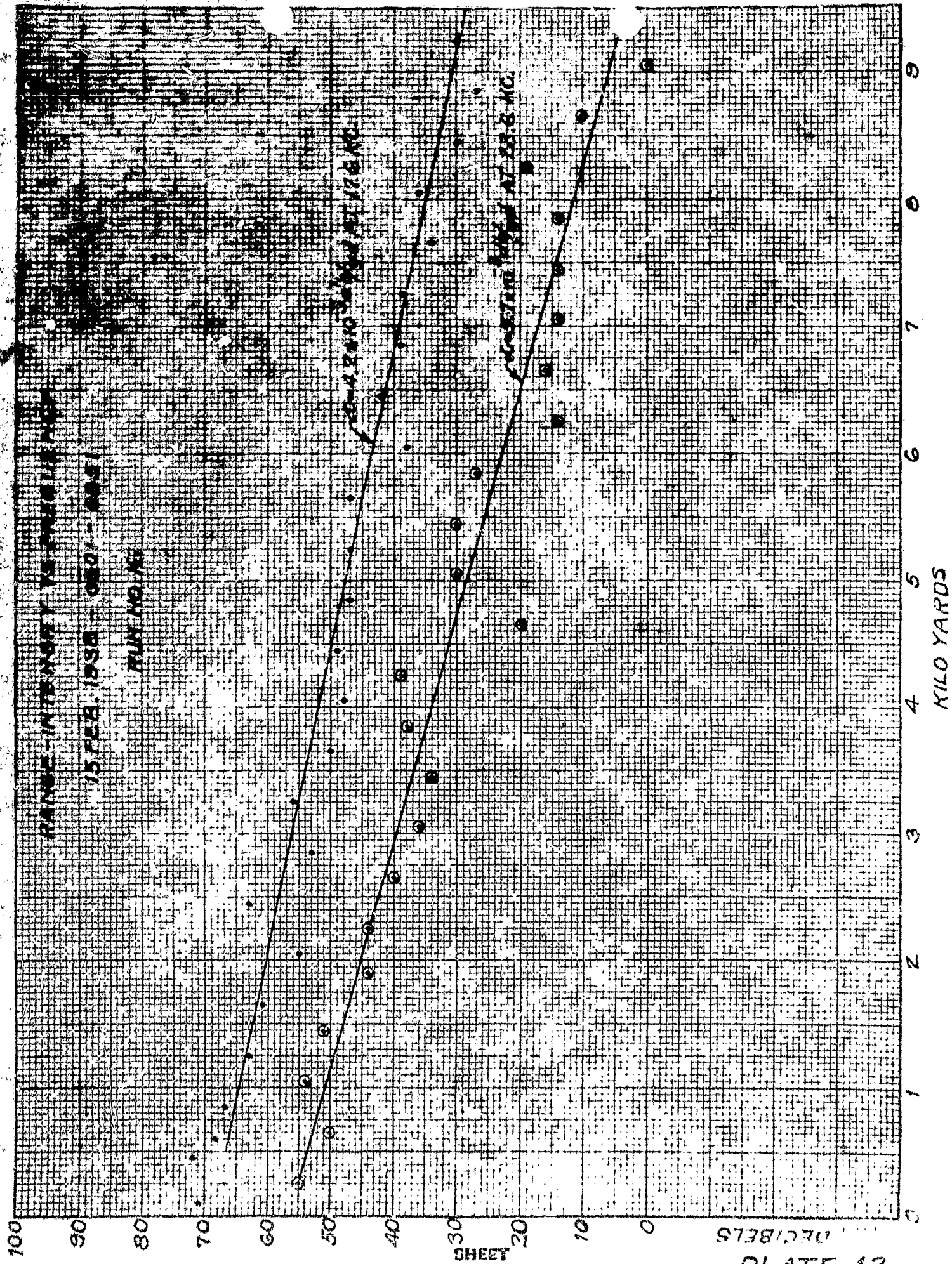


10-53 N R L 34

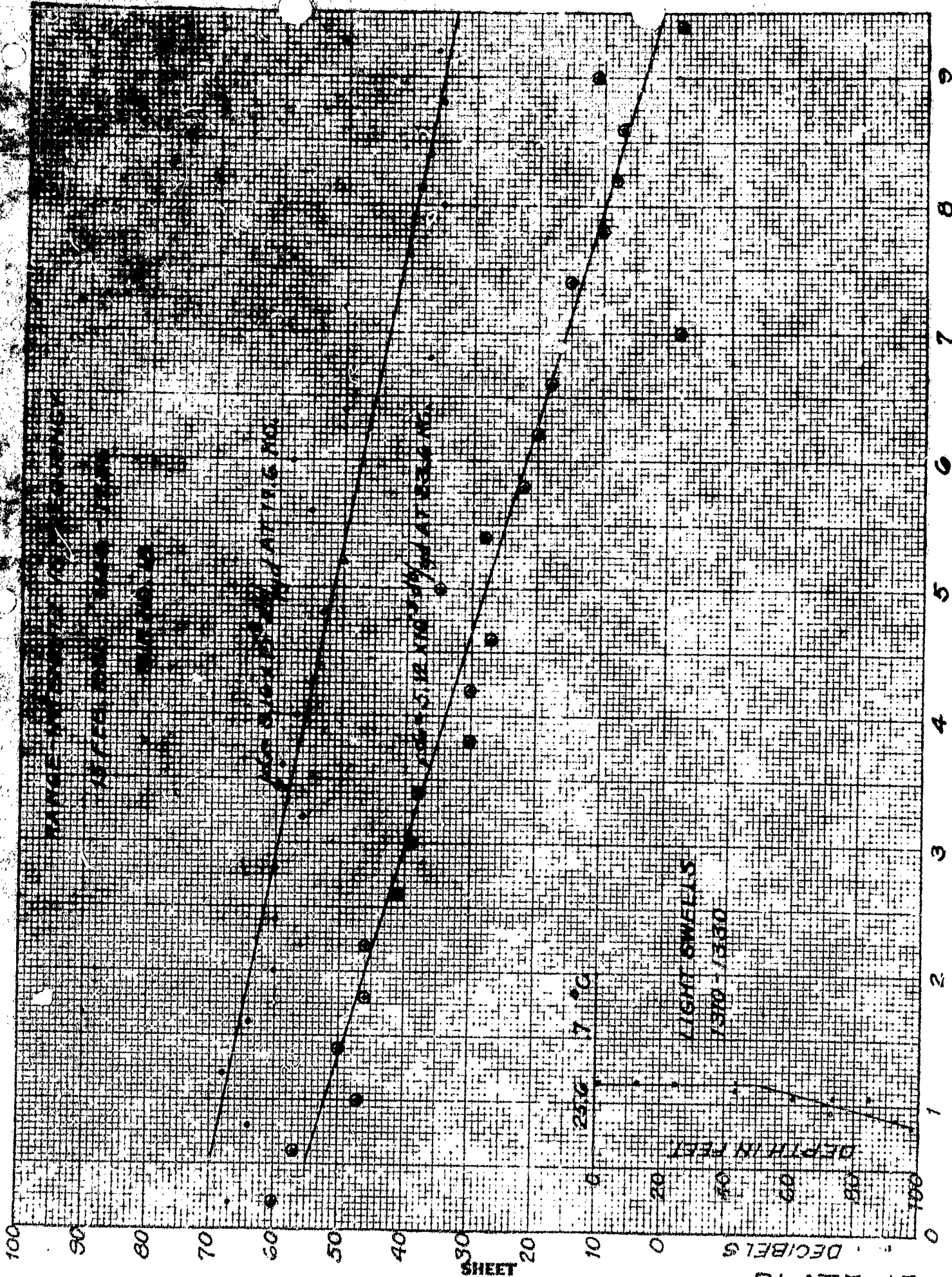


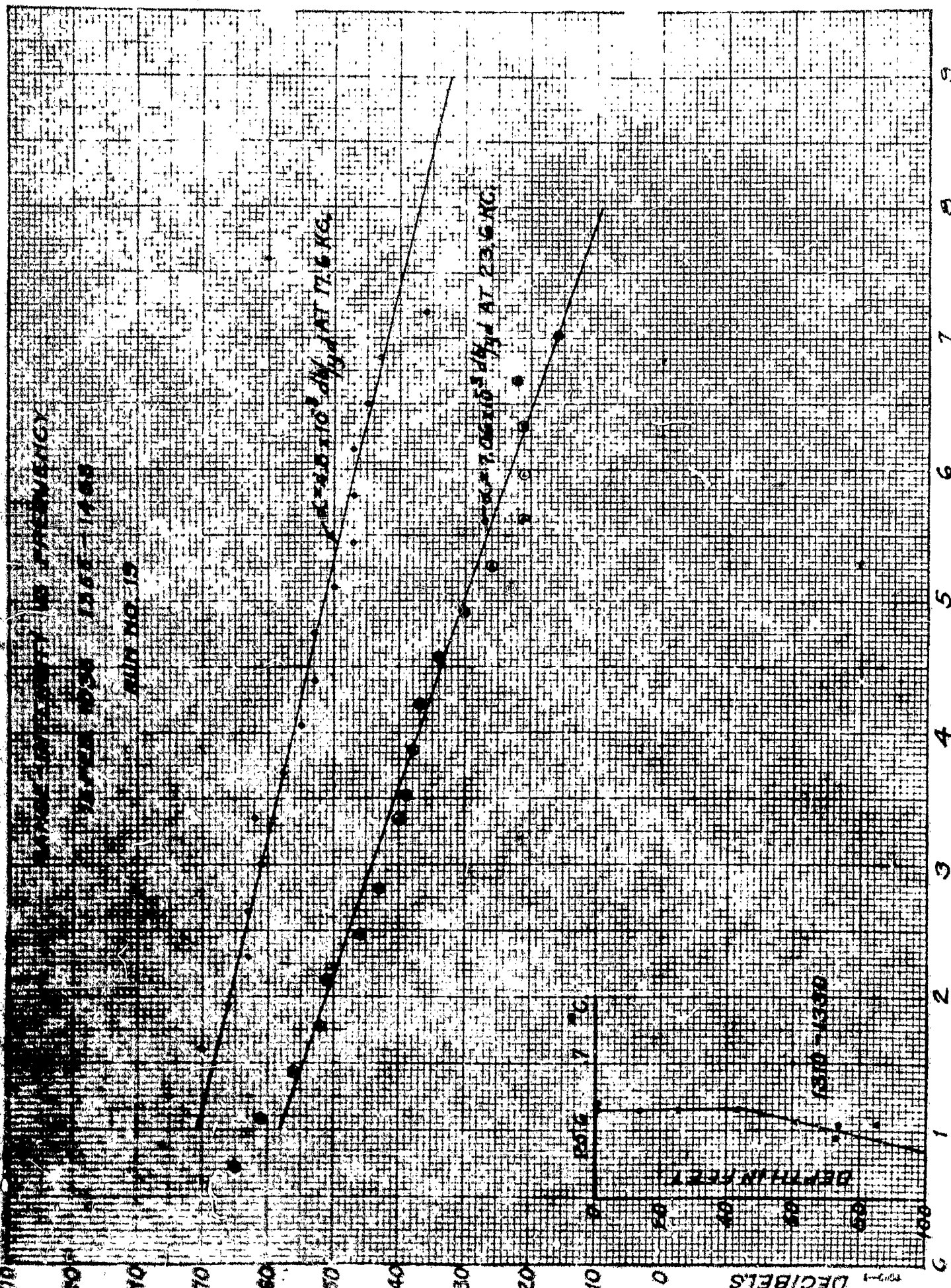
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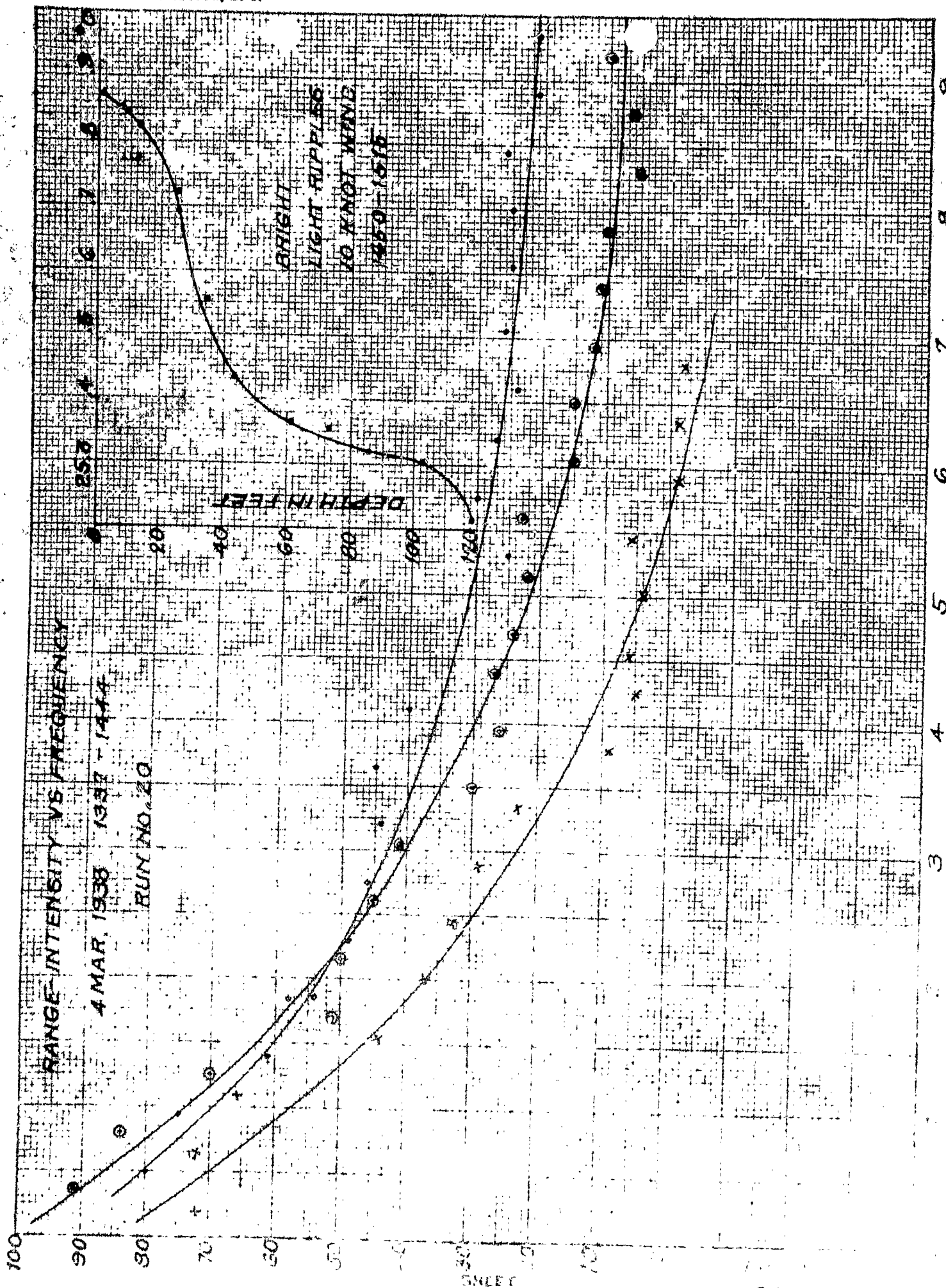


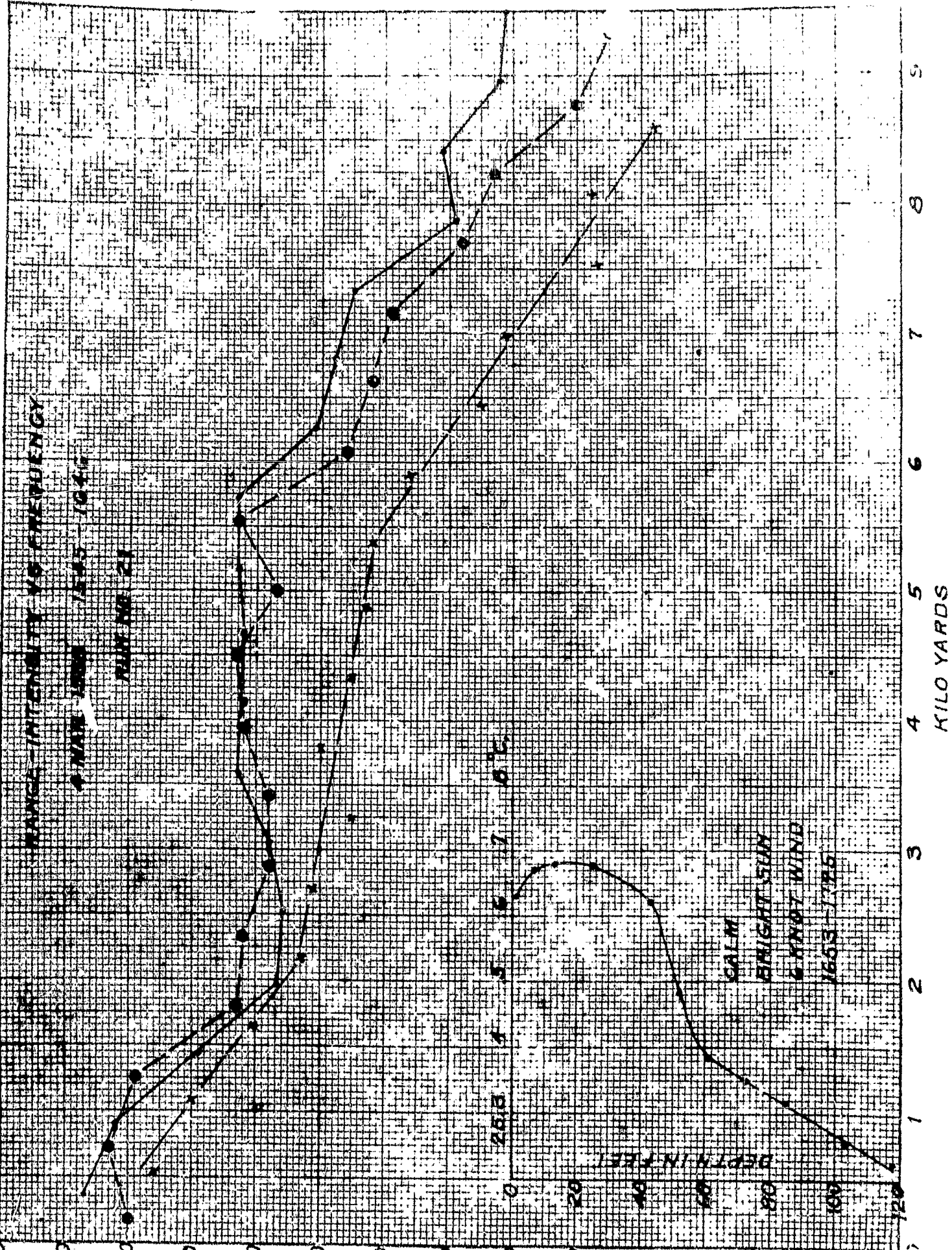
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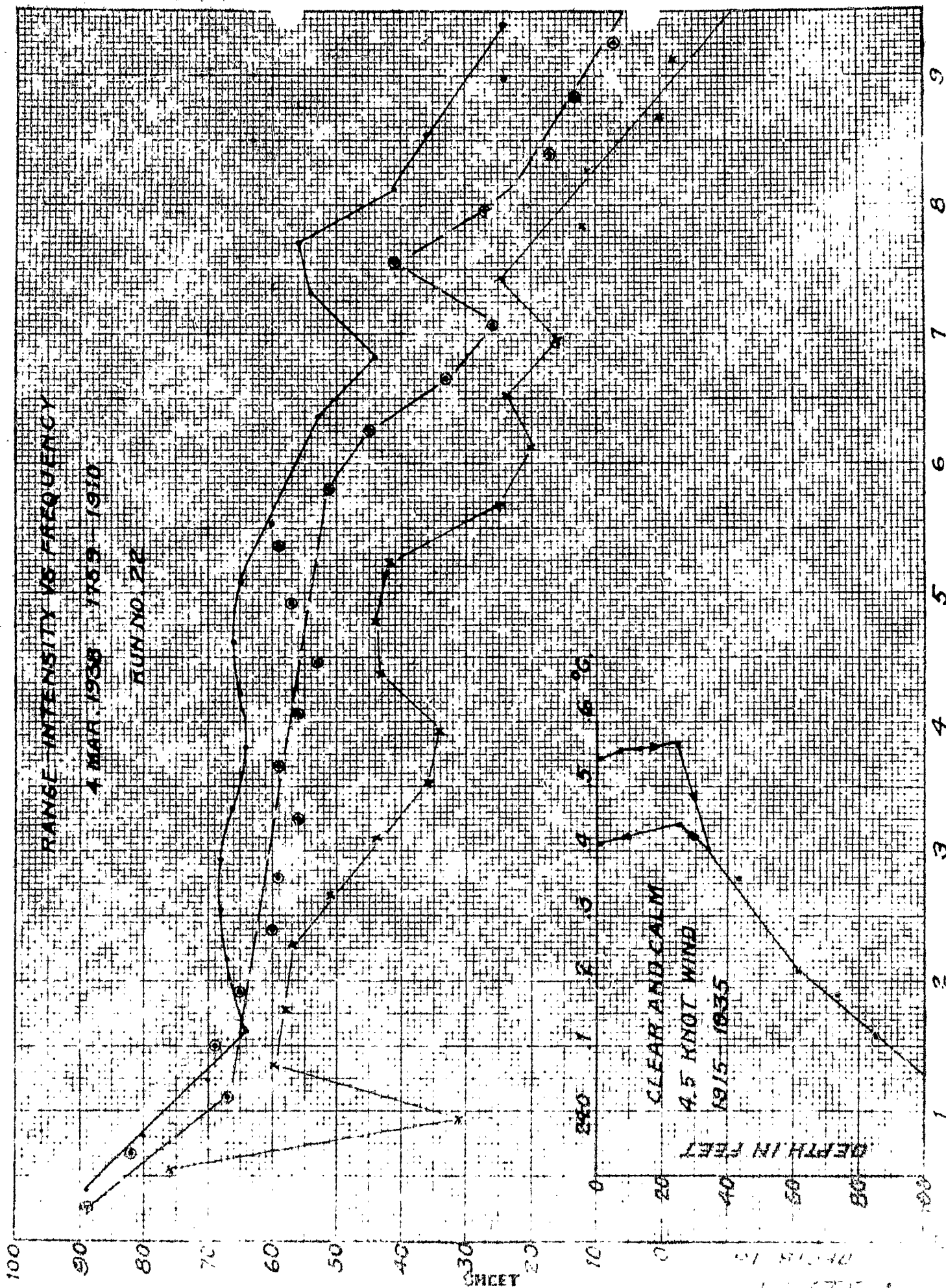


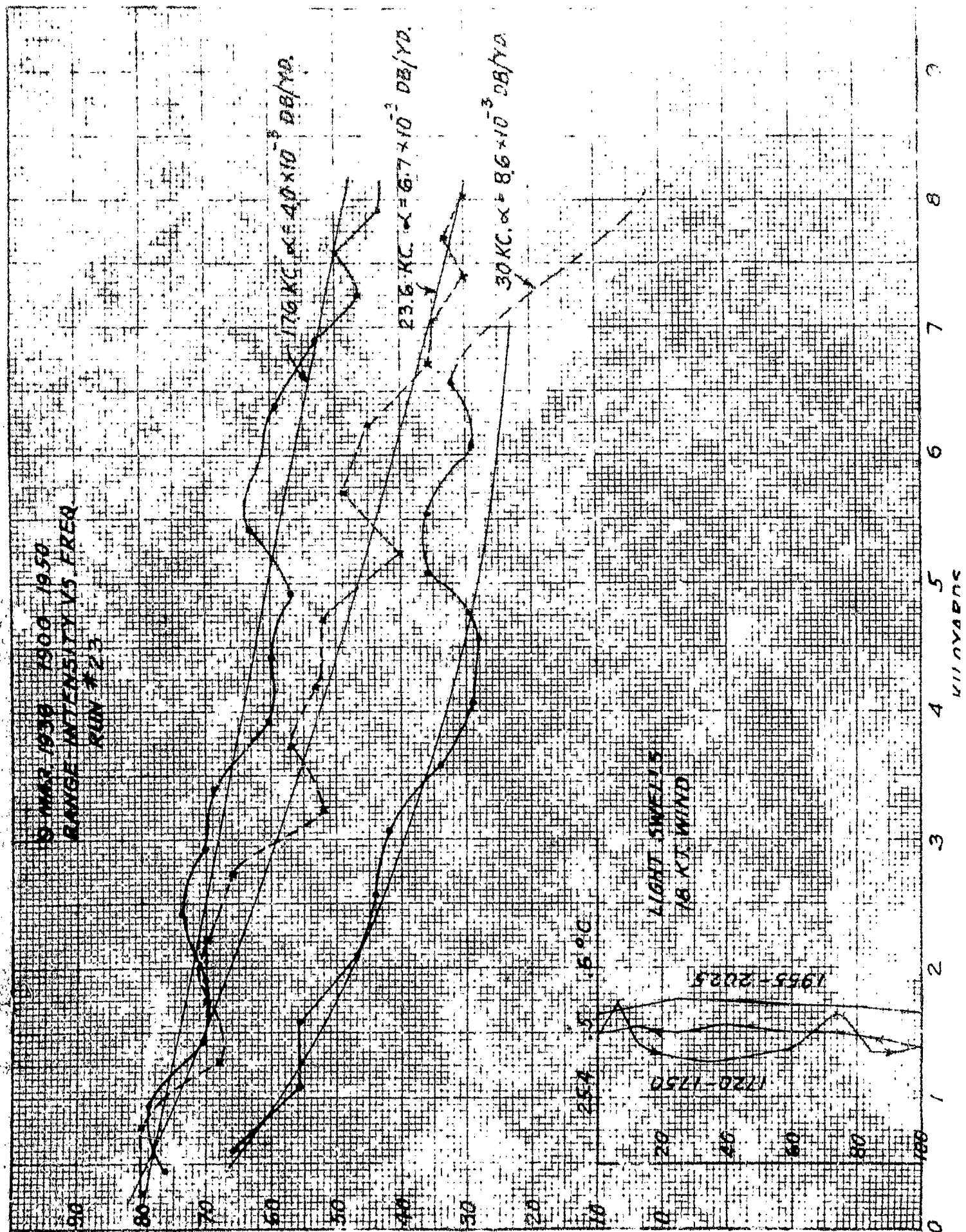


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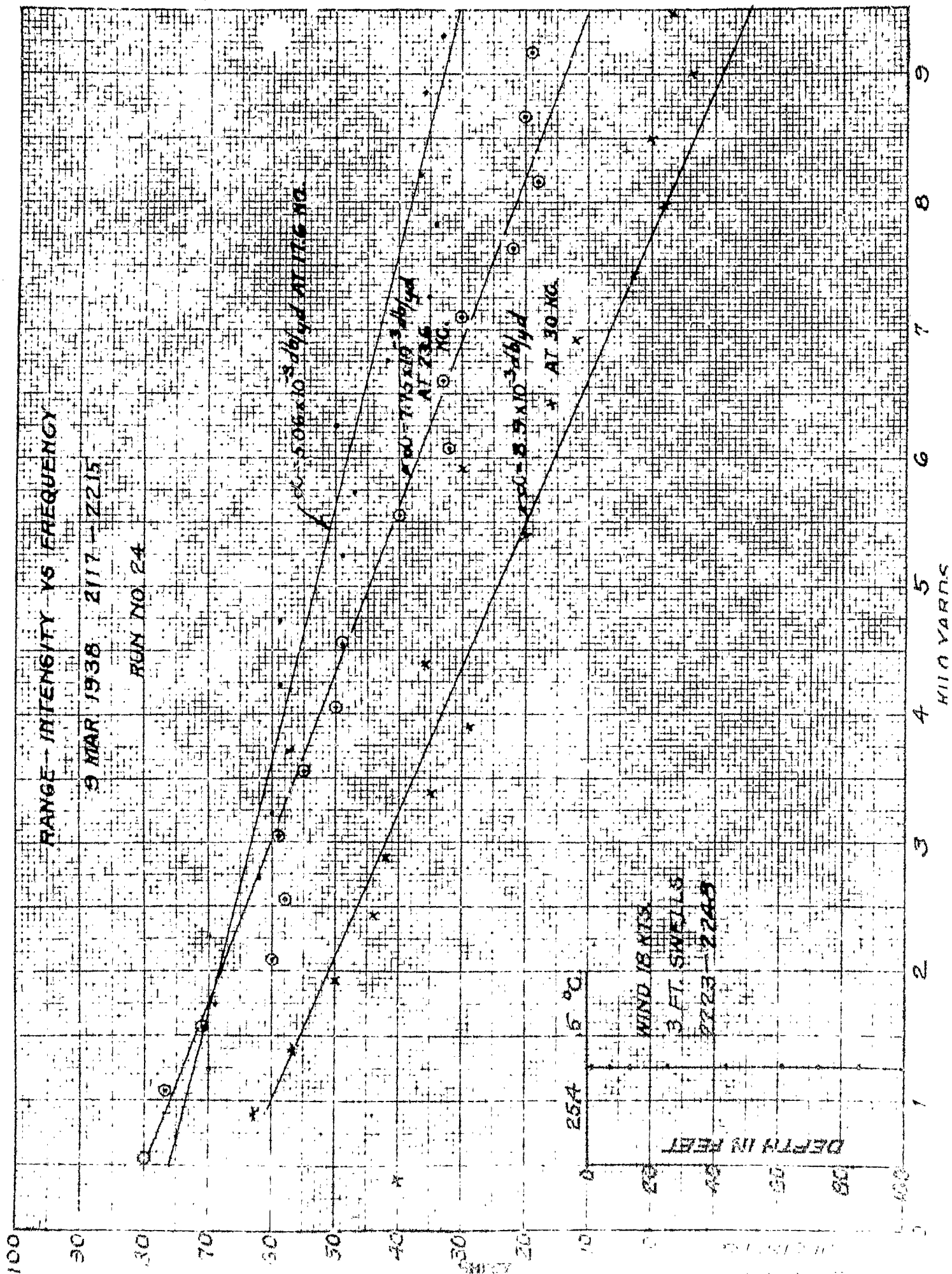






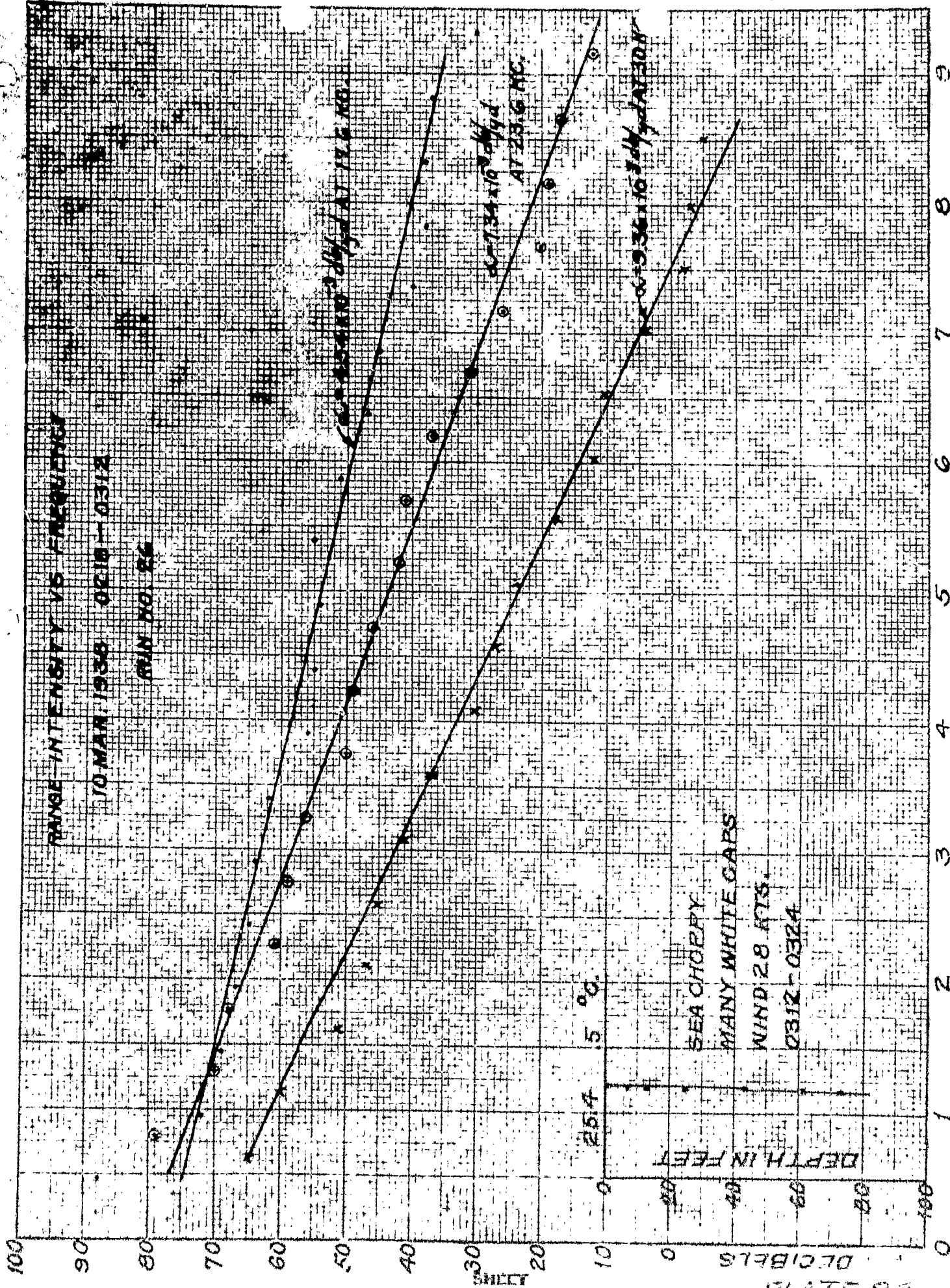


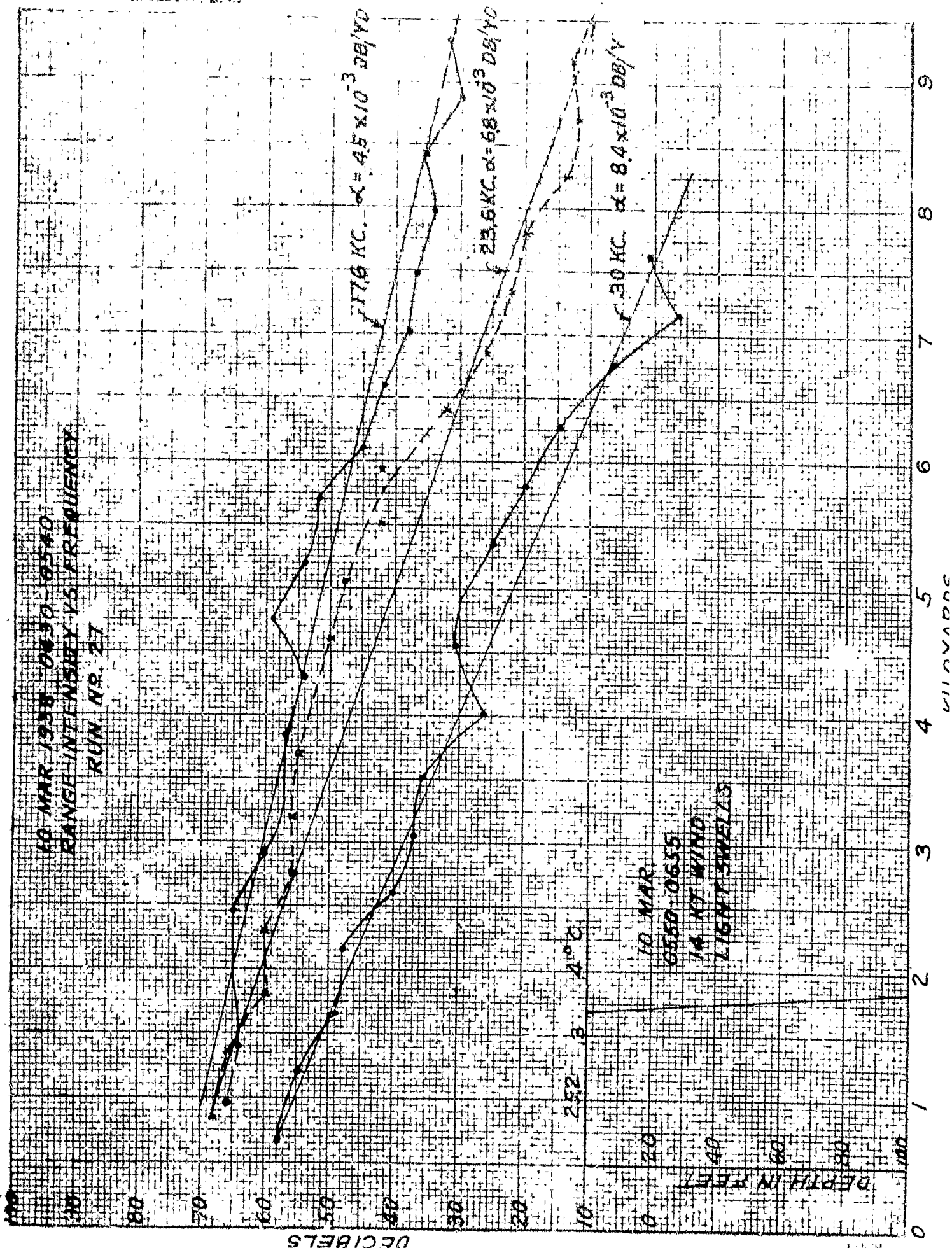
3 N. R. I. 34

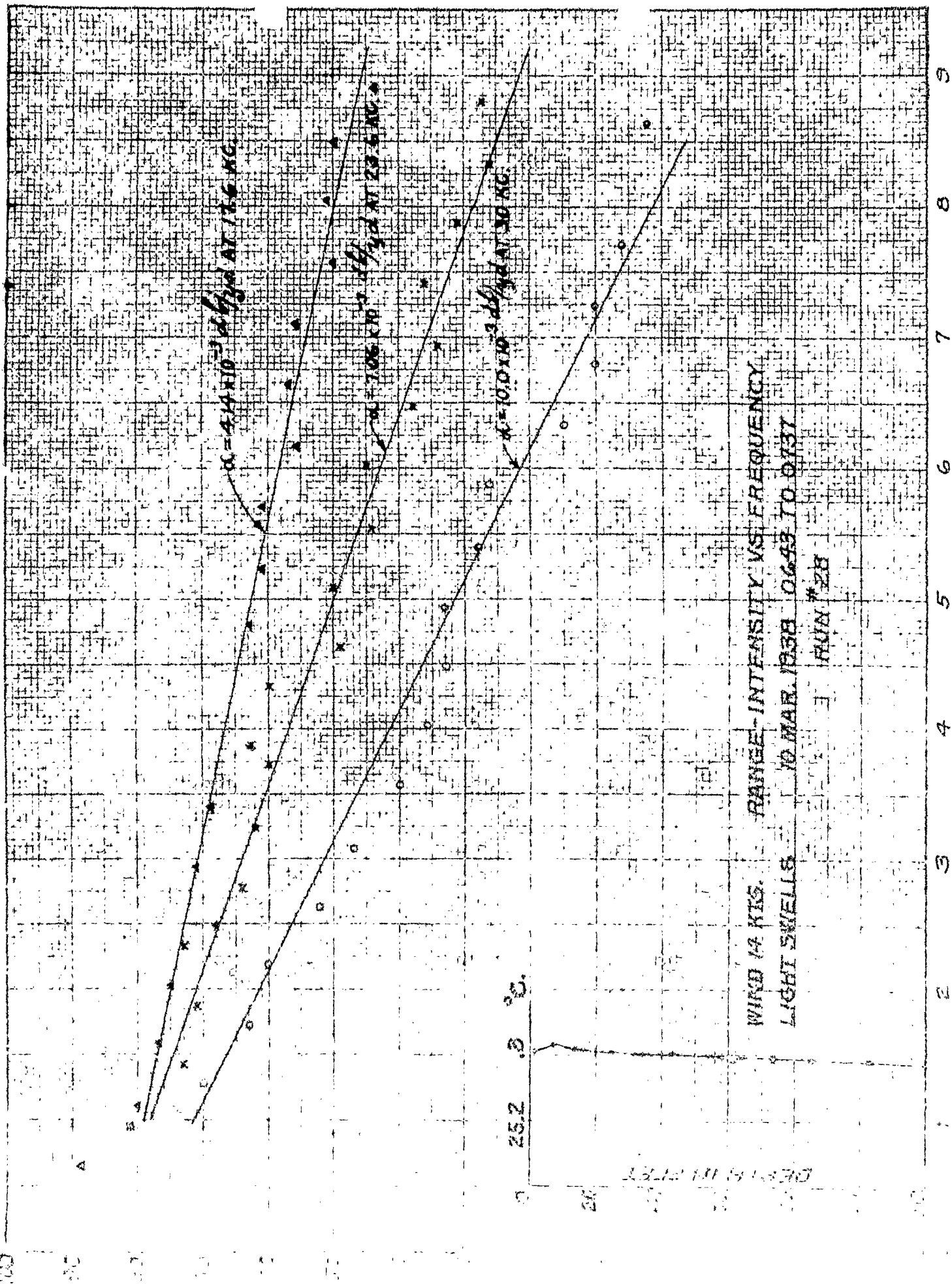




1-3 N.K.L.S.







RANGE-INTENSITY VS FREQUENCY

10 MAR. 1938 0837-0932

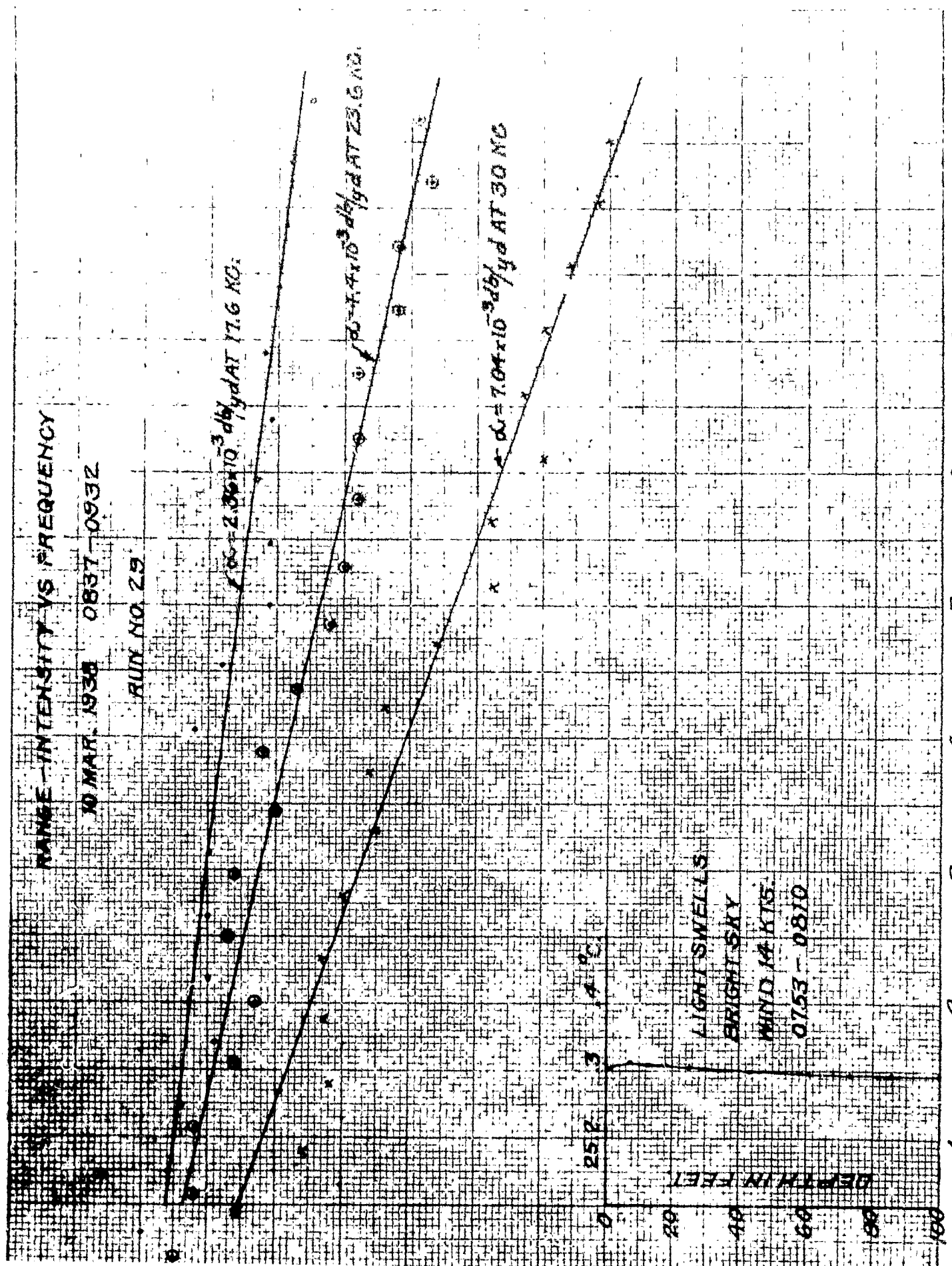
RUN NO. 29

$$I_{00} = 2.36 \times 10^{-3} \frac{d^4}{y} \text{ AT } 17.6 \text{ KC.}$$

$$I_{00} = 1.4 \times 10^{-3} \frac{d^4}{y} \text{ AT } 23.6 \text{ KC.}$$

$$I_{00} = 7.04 \times 10^{-3} \frac{d^4}{y} \text{ AT } 30 \text{ KC.}$$

LIGHT SWELLS
BRIGHT SKY
WIND 14 KTS
0753 - 0810



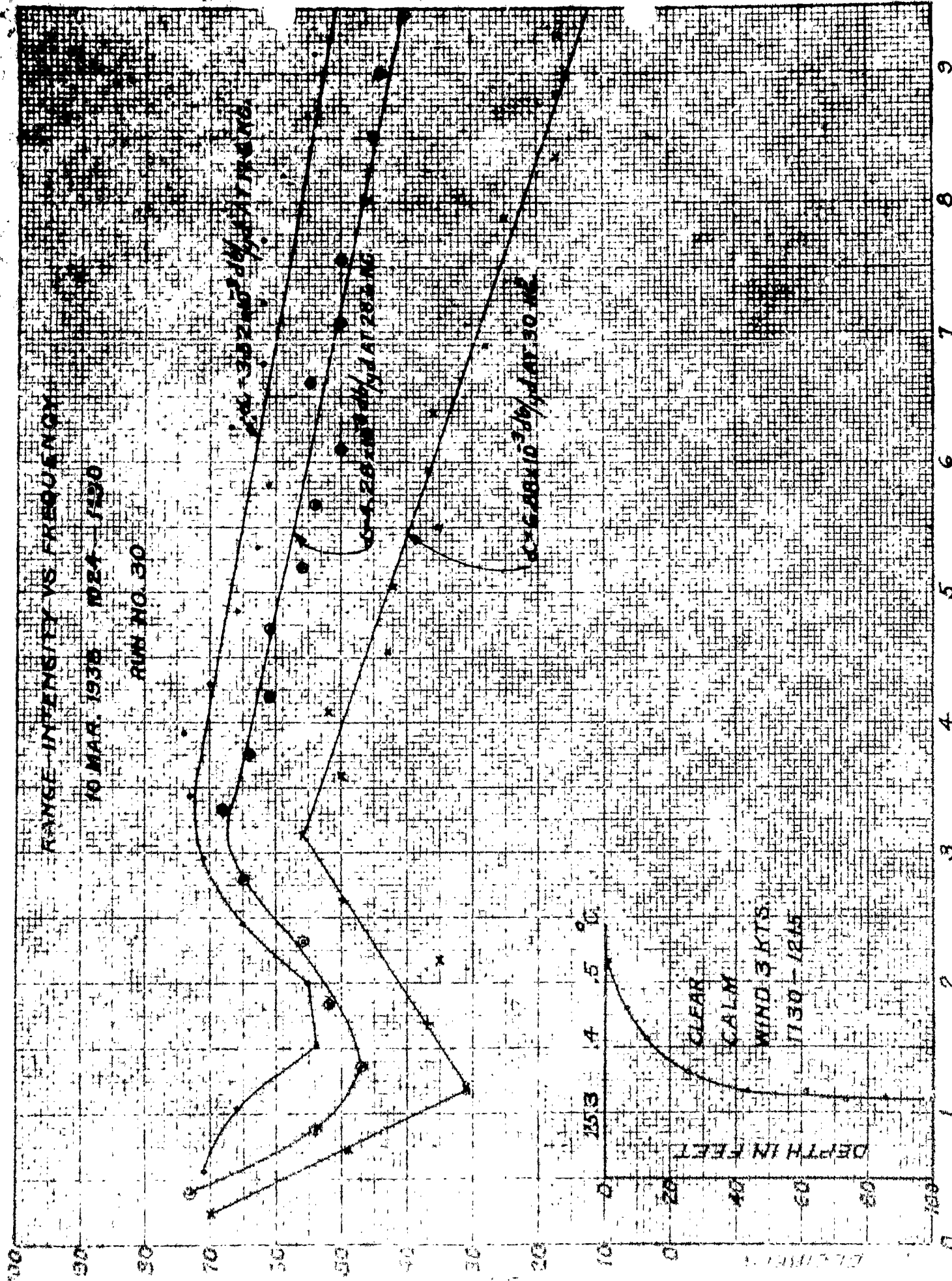
U. S. NAVY

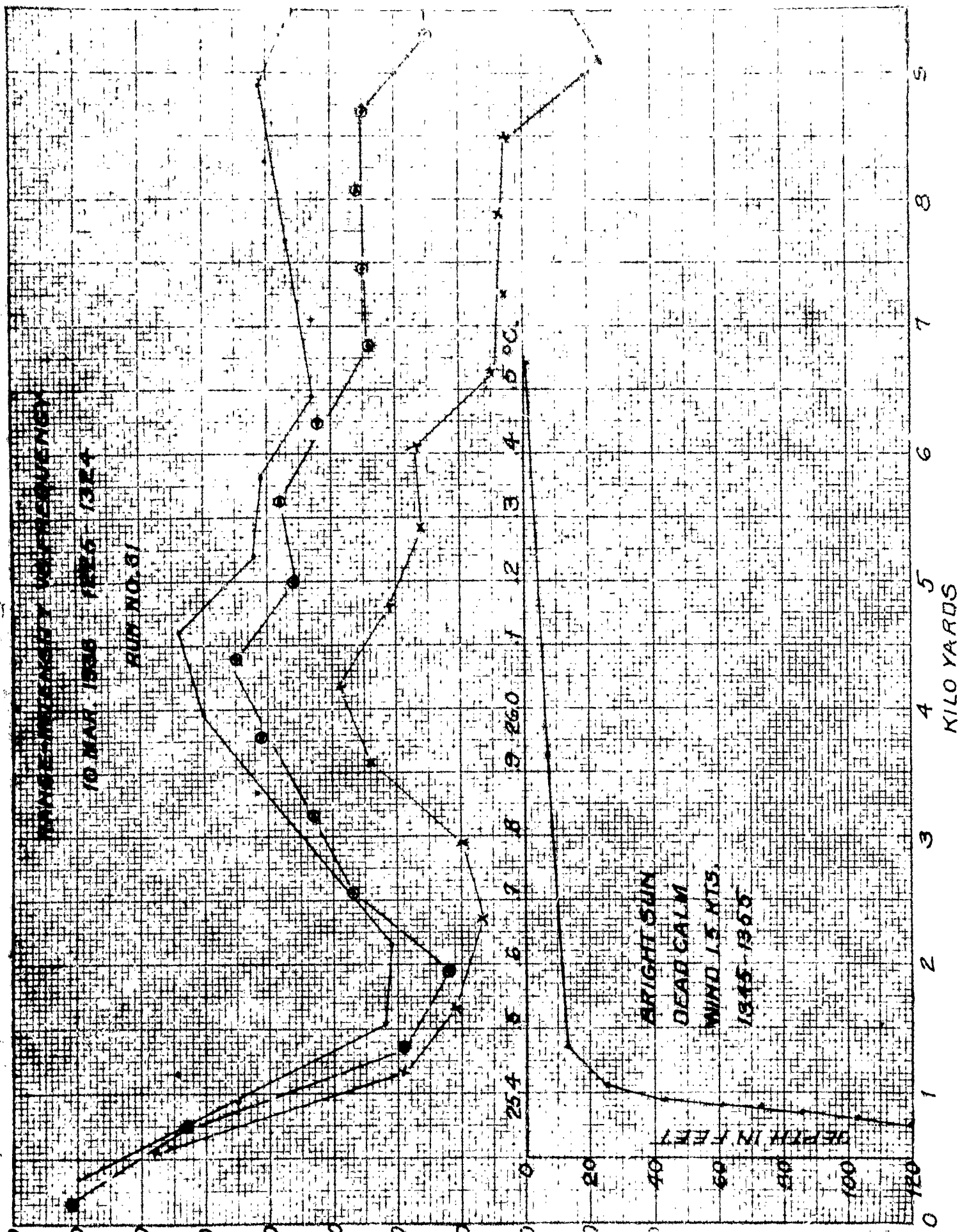
10 MAR 1938

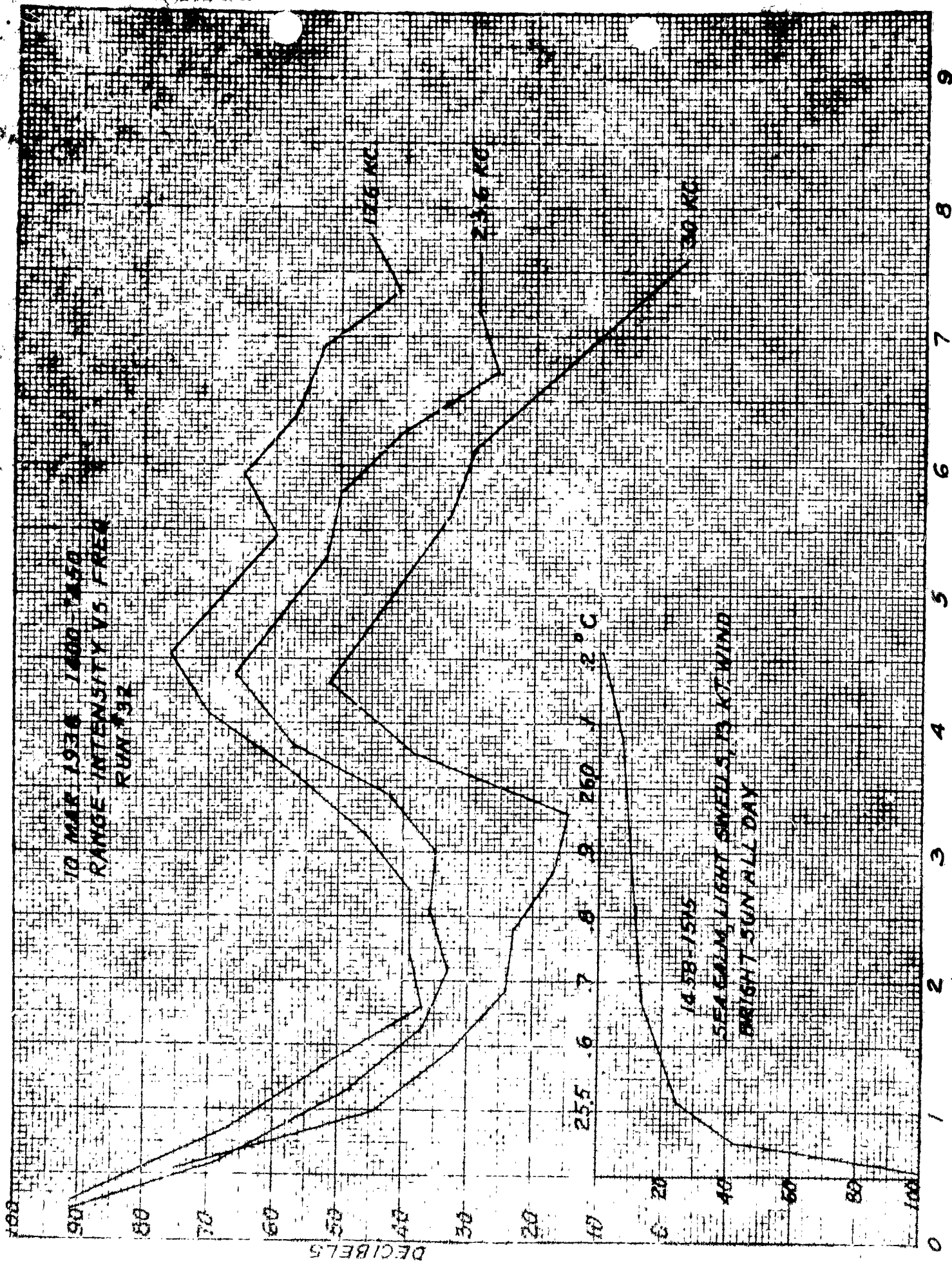
RANGE INTENSITY VS. FREQUENCY

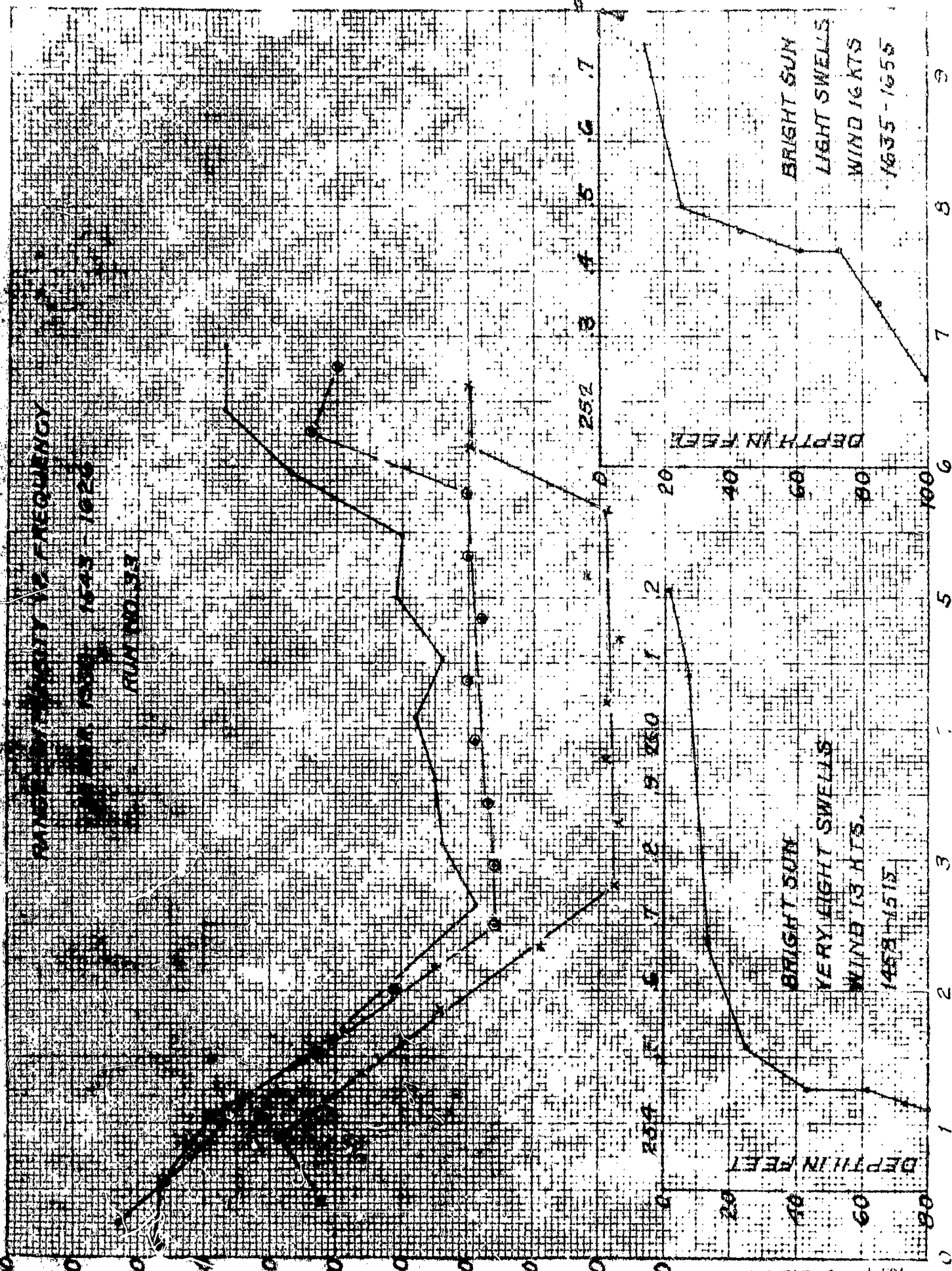
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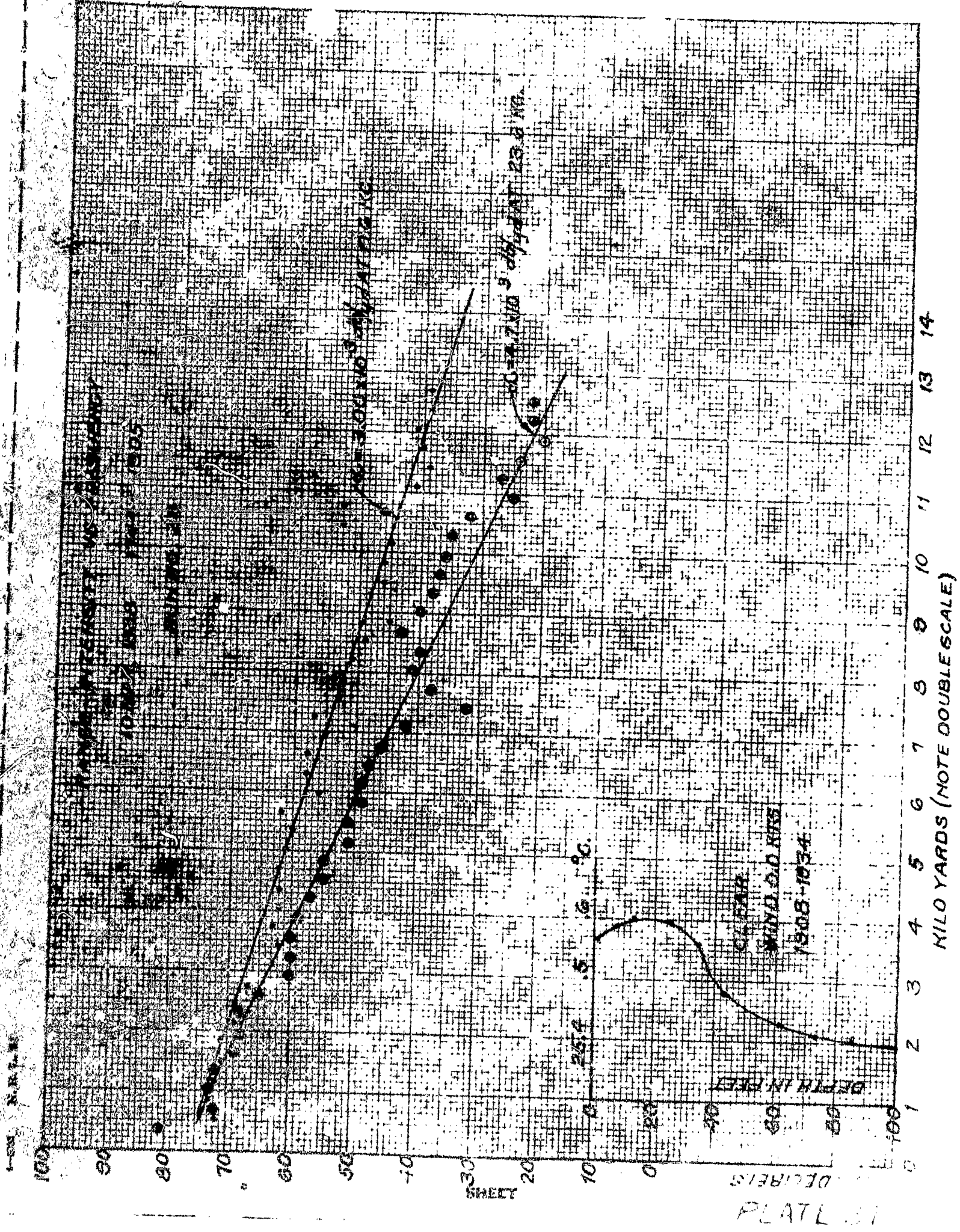
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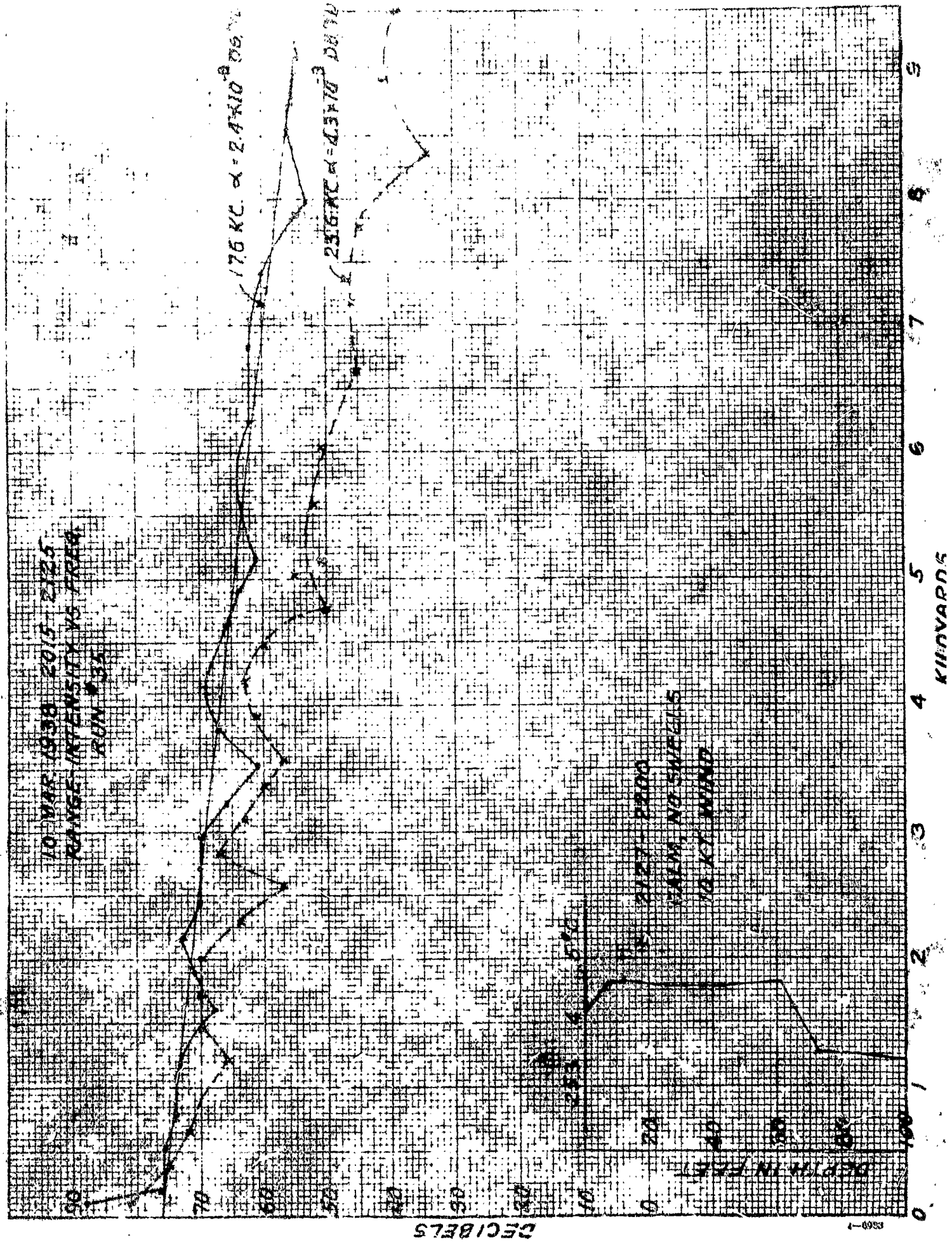


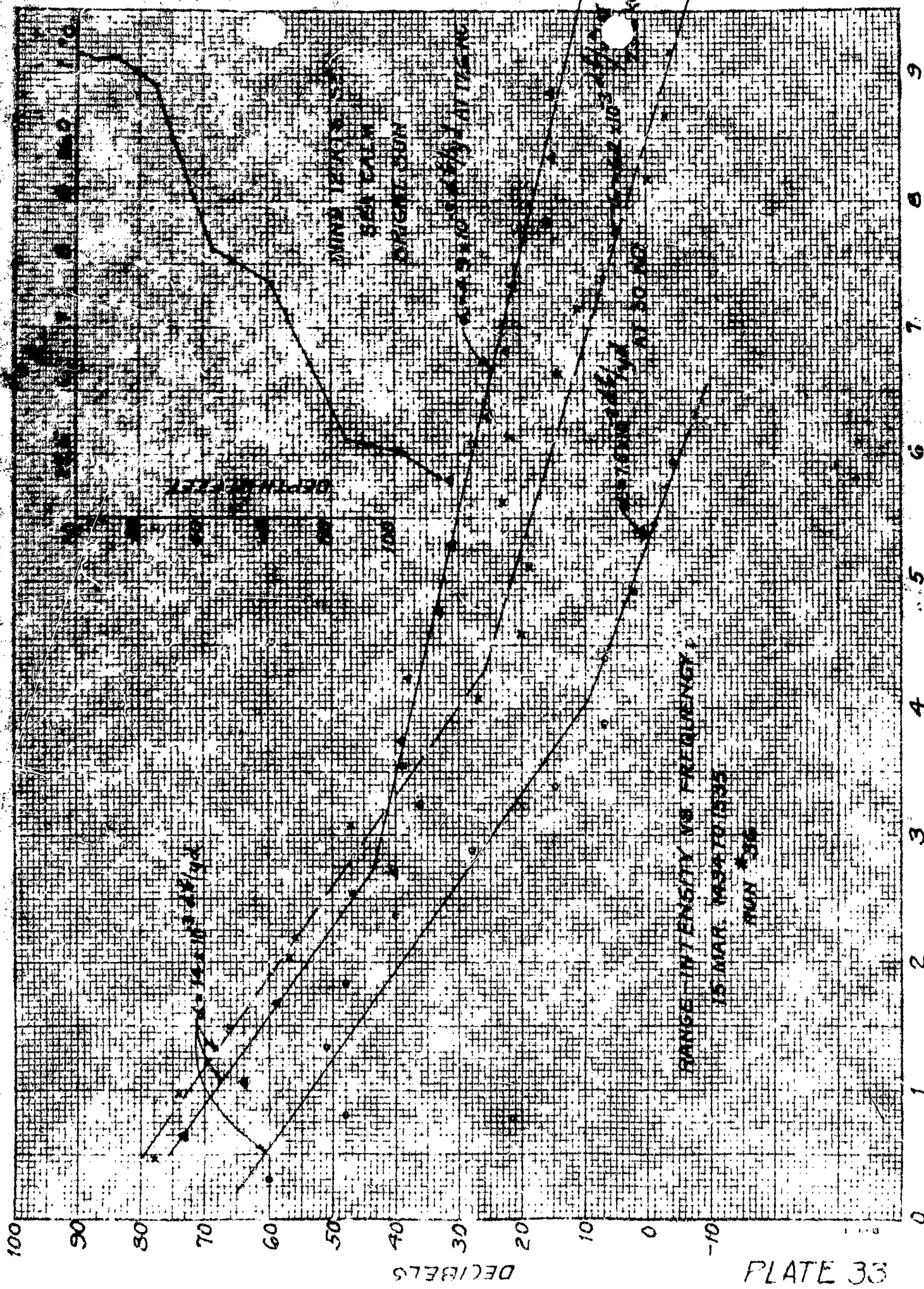




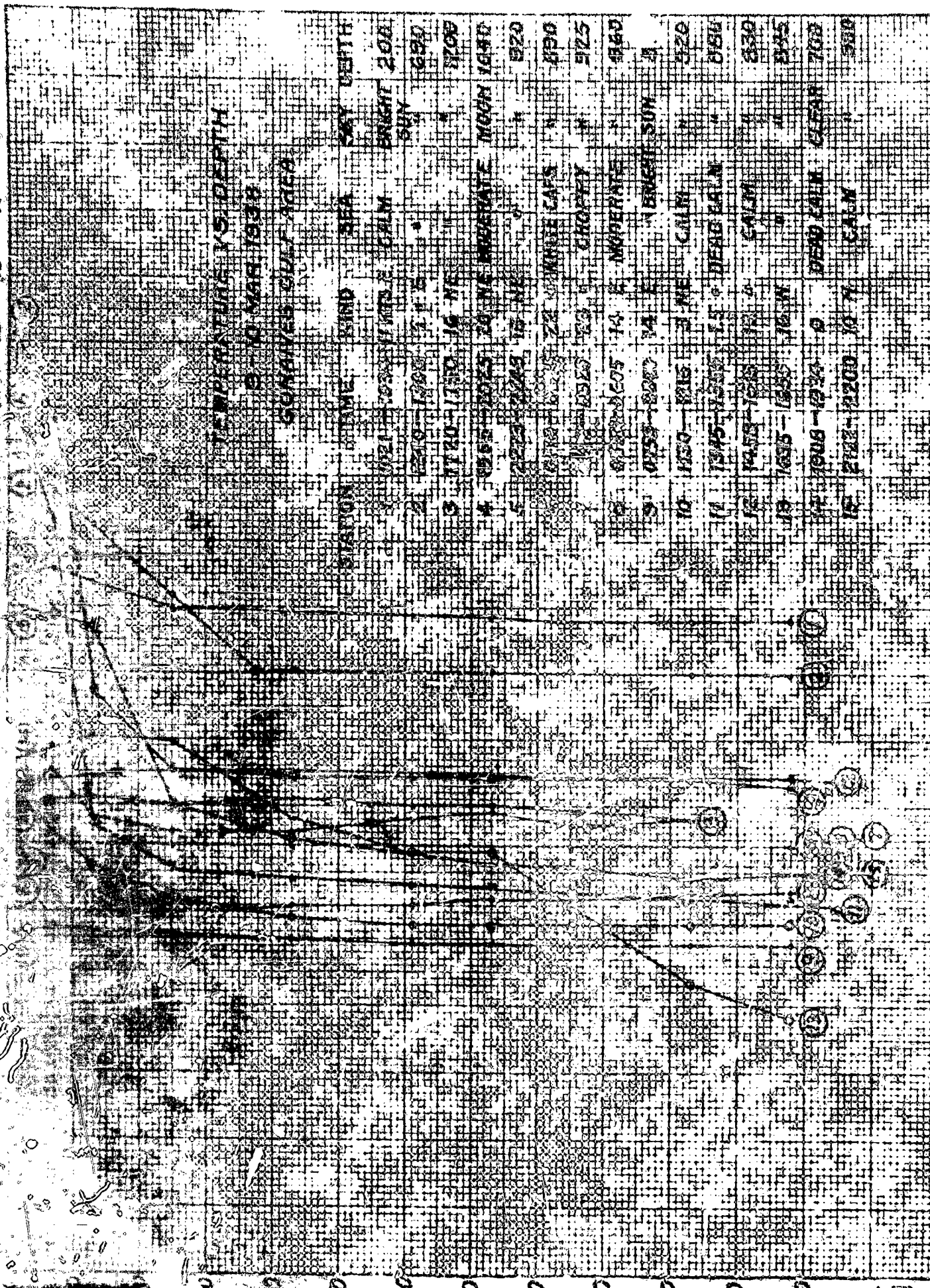








1 2 3 4 5 6



R. L. 84

25.0 1 2 3 4 5 6 7 8

0 10 20 30 40 50 60 70 80 90 100 110 120

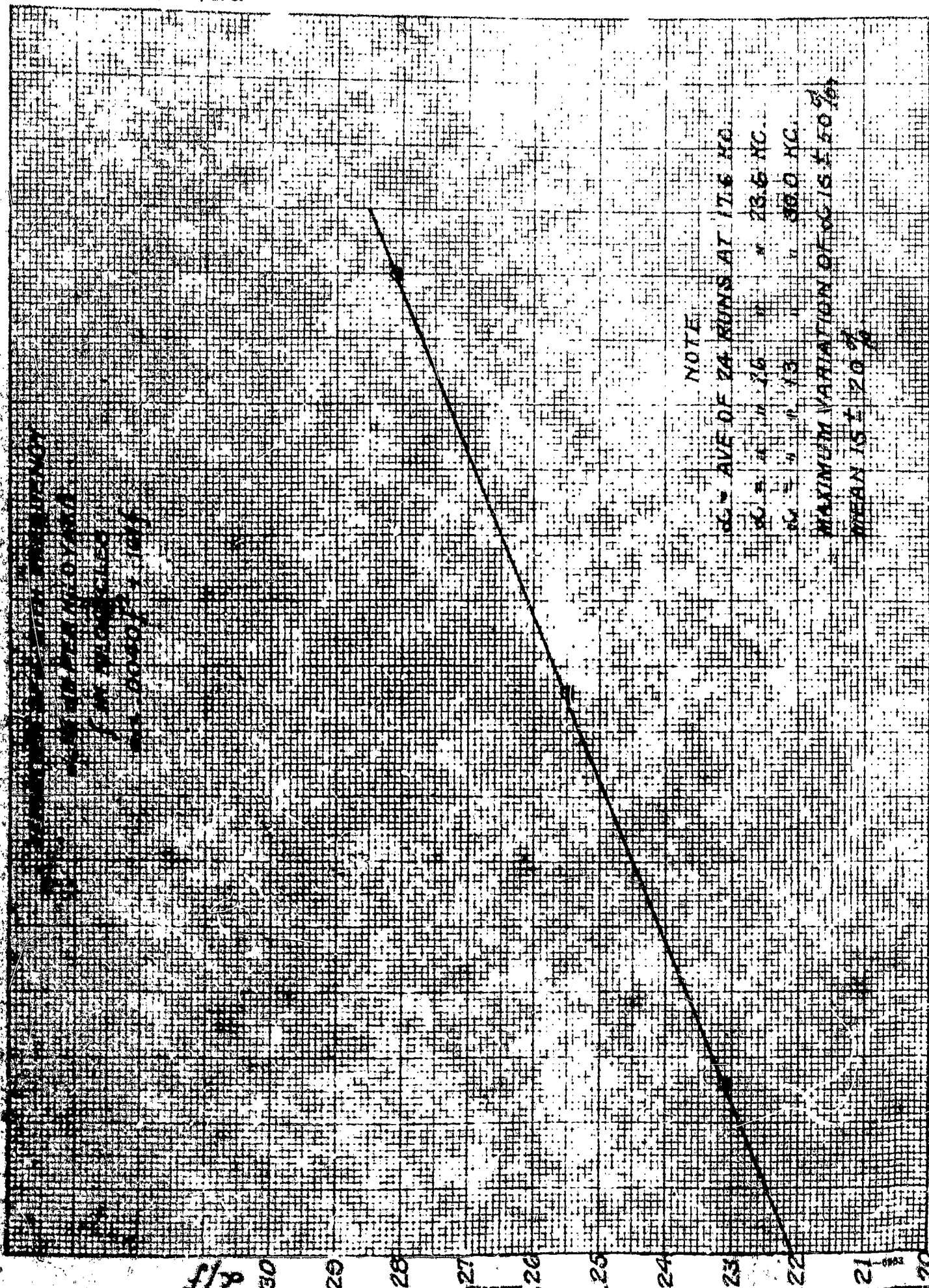
DEPTH IN FEET

FLAT



STATION TIME TEMPERATURE SEA SWAY DEPTH
1 5:45-10:11 12.1 12.1 12.1 12.1 12.1
2 17:45-18:05 12.1 12.1 12.1 12.1 12.1
3 19:05-19:15 12.1 12.1 12.1 12.1 12.1
4 19:15-19:25 12.1 12.1 12.1 12.1 12.1
5 19:25-19:35 12.1 12.1 12.1 12.1 12.1

① ② ③ ④ ⑤



15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30

UNITED STATES GOVERNMENT
memorandum

7103/141

DATE: 21 November 1996

FROM: Burton G. Hurdle (Code 7103)

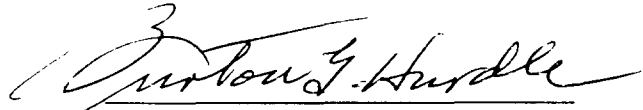
SUBJECT: REVIEW OF REF. (a) FOR DECLASSIFICATION

TO: Code 1221.1

VIA: Code 7100

REF: (a) NRL Report #S-1466 by E.B. Stephenson, 12 Aug 1938

1. Reference (a) reports a series of measurements of acoustic absorption in the ocean at frequencies of 17.6, 23.6, and 30 kcs in the South Atlantic and Caribbean Sea between 5 February and 24 March 1938.
2. The technology and equipment of reference (a) have long been superseded. The current value of this report is historical.
3. Based on the above, it is recommended that reference (a) be released with no restrictions.


BURTON G. HURDLE
Acoustics Division

CONCUR:


EDWARD R. FRANCHI 11/22/96
Superintendent Date
Acoustics Division

25/1

STI-ATI-208 582

Naval Research Lab, Washington, D.C.

ABSORPTION COEFFICIENTS OF SOUND IN SEA WATER,

by E.B. Stephenson. 12 Aug 38. 7p, illus. (Rpt No. S-1466)

DIV: Physics (25) 20
SEC: Acoustics (1) 1

SUBJECT HEADINGS (OVER)

Waves, Sound - Absorption

Acoustics Underwater
Water Sea

(Copies obtainable from ASTIA-DSC)

Acoustic Absorption

25/1

251950

AD-B870 412

U *Auth: DOD DIR 5200.9, 26 Nov 58*
(also per NRL Rept, Jul 1962)