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UNITED STATES AIR FORCE
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GEOPHYSICS

Final Report Part II

"Study of Atmospheric Conductivity", AFOAT-1 Project Number W/62/N/AMC

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Conducted by

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Introduction

For the past 14 months, members of the Atmospheric Physics Laboratory of the Air Force Cambridge Research Laboratory have been investigating selected problems in atmospheric electricity. Emphasis has been placed on problems particularly suitable for experimental investigation with aircraft. Some of this work is an extension of work previously carried on by members of the Department of Terrestrial Magnetism, Carnegie Institution, Washington, D. C. Much time has been spent procuring equipment and developing techniques for the measurement of various atmospheric electric parameters with aircraft.

The main purpose of the present work has been to extend the measurement and interpretation of the electrical conductivity of the atmosphere. Its variation with altitude and time of day has been measured over widely separated areas. As will be shown on the following pages, the conductivity at an arbitrary point in the atmosphere is a function of the ion concentration, charge, and mobility, It is, therefore, indirectly a function of all parameters which affect these three, such as temperature, pressure, ion production, water content etc. An attempt has been made to correlate the measured conductivity with the existing meteorological conditions. In addition, the effect on conductivity of varying both positive and negative charge on the surface of an aircraft has been determined. This is necessary for the absolute measurement of atmospheric electric parameters involving ion densities.

Definitions

The total electrical conductivity of the atmosphere for positive ions is defined

$$\lambda_+ = e \sum_{i=0}^{m} n_i K_i \qquad (1)$$

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where n_i is the ion concentration, k_i the mobility of the ith type of positive ion and e is the charge per ion. $\sum_{i=0}^{m}$ indicates a summation of the conductivities for the different types of positive ions present. Similarly for negative ions

$$\lambda_- = e \sum_{i=0}^{m} n_{-i} \, k_{-i}$$

Measurements of the mobility of ions in the atmosphere have shown that to a good approximation, the ions can be divided into three groups; small, intermediate and large. The above equations can then be simplified to

$$(2) \qquad \lambda_+ = e \sum_{i=0}^{3} n_i \, k_i \qquad \lambda_- = e \sum_{i=0}^{3} n_{-i} \, k_{-i}$$

It is generally assumed that the small ions consist of about one to three air molecules which have lost or gained one more electron than is necessary for the group to remain neutral. Their average mobilities have been measured in the laboratory to be approximately 1.6 for positive and 2.2 cm/sec per volt/cm for negative at room temperature and pressure. The intermediate ions have a mobility one tenth to one hundredth that of the small ions. It has been found that their mobility varies with vapor pressure, decreasing as the vapor pressure is increased. The large ion is made up of an aggregate of many molecules and exists as water vapor, dust or smoke particles. It has a mobility about one five-thousandth that of the small ion. The charge of each of these three types of ions has been measured to be one elementary charge per ion.

In cities the large ion content is greater than that of small ions. In Washington D.C. the large ion concentration has been found to be of the order of thirty times that of the small ion. The small ion content was measured to be approximately 200 ions per c.c.[1] The intermediate

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ion content at the same location was found to be one tenth that of the large ion.[2] These ratios are lower in the country and at higher altitudes where there is less pollution of the air. The large and intermediate ion contribution to the total conductivity is much smaller than that of small ions, however, because of their much lower mobilities. In Washington for example, the large ion contribution was determined to be 5% of the total conductivity. Therefore the positive or negative small ion conductivity gives a good approximation to the total polar conductivity in the atmosphere.

This paper is largely concerned with the measurement and interpretation of the polar conductivity of small ions in the lower atmosphere. This will be denoted by $\lambda_+ = n_+ K_+ e$ for small positive ions, $\lambda_- = n_- K_- e$ for small negative ions. Here n_+ is the positive small ion concentration, n_- the same for small negative ions. K_+ and K_- represent the average mobility for positive and negative small ions respectively. The ion concentration will depend on all factors which control the rate of production and loss of ions in the atmosphere. The ion mobility varies inversely with air density.[3] From the equation of state the air density ρ is proportional to P/T where P is the air pressure and T the absolute temperature. Therefore the ion mobility will vary as T/P.

General Background

Total conductivity measurements over widely separated areas at the earth's surface give results varying from $.4 \times 10^{-4}$ to 5×10^{-4} sec^{-1} in electrostatic units. The conductivity generally increases with distance from cities or other areas which are sources of air pollution. Continuous

(1) Terr. Mag. 39, p115 (1934)
(2) Terr. Mag. 40, 425-431 (1935)
(3) Loeb, Kinetic Theory of Gases p 565

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measurements throughout the year show a maximum in summer and minimum in winter. This can be partly attributed to the increase in ion mobility with increasing temperature in summer. Continuous daily records of conductivity show a diurnal variation with a maximum in the morning.[4] The exact time of the maximum varies with the place at which the measurements are obtained. Gish[5] has suggested that the morning maximum is largely due to diminished air pollution that is, a decrease in large ion content. Measurements at Huancayo by W.D. Parkinson[6] do show an increase in small ion content and a minimum in large and intermediate ion concentration at the time of the conductivity maximum. This is in agreement with the theory of ion-balance in the atmosphere. The amplitude of both the annual and diurnal variation of conductivity differ widely at different places. Measurements on the experimental ship, the Carnegie, show a diurnal variation of small amplitude over the ocean. The conductivity varies gradually during the day from a minimum in the afternoon to a maximum in the morning, the magnitude of the variation amounting to about 4% of the mean. This supports the hypothesis that cosmic radiation is the primary ionizer at sea.

Plane and balloon measurements show an increase of conductivity with altitude. The order of mangitude of this increase is shown in Figure I. The maximum altitude at which conductivity measurements are available was reached by the Explorer II balloon.[7] These results show an increase with altitude up to 18 km. when both positive and negative conductivity begin to decrease. The increase in conductivity is associated with the increase in rate of ion formation due to the variation in cosmic ray intensity with

(4) Journal of the Washington Academy of Sciences 36 325-328 (1946)
(5) Terrestrial Magnetism and Electricity (Dover Press) p. 198
(6) Terrestrial Mag 53 305-317 (1948)
(7) Terrestrial Magnetism and Electricity (Dover Press) p 205

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height. It is also associated with an increase in mobility. The plot of altitude vs T/P, Figure 2, indicates the contribution of mobility to the conductivity. An almost linear increase is shown below 10 km with a much more rapid increase above this height. The temperature and pressure values used are for a standard atmosphere.[8] The decrease at high altitudes could be due to a decrease in ion concentration resulting from a decrease in cosmic ray intensity which occurs at about 13 km[9]. It could also be caused by the introduction of nuclei at these altitudes or to instrument limitations. Since this is the result of only one flight, further measurements are necessary before definite conclusions can be reached about the nature of this decrease.

In fog, clouds (not thunderclouds) and haze the conductivity is generally found to decrease. The electrical conductivity in clouds (not thunderclouds) has been investigated experimentally and theoretically by Pluvinage[10]. He found it to be of the order of 10 less than in a cloudless atmosphere. Others have found almost no change in conductivity.

Theory of Measurement

The conductivity apparatus used in the present experiments is based on an instrument first used by Gerdien.[11] The apparatus consists of two concentric cylinders through which an air sample is drawn (Figure 3). A potential difference is applied between cylinders a and b. The charge collected on the central cylinder is measured with a sensitive electrometer. The value of the potential applied between the cylinders is arbitrary with

(8) G. Grimminger, Project Rand Report p 35, Nov 1948
(9) Terrestrial Magnetism and Electricity (Dover Press) p 177
(10) Annales de Geophysique 2 March and June, 1946
(11) Terr. Mag. 10, 65-79 (1905)

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the restriction that it must be less than the initial saturation voltage for a given air flow. At saturation all ions in a given volume of air are being collected and the instrument operates as an ion counter. Thus, initial saturation voltage is that voltage above which all ions in the air stream are being collected.

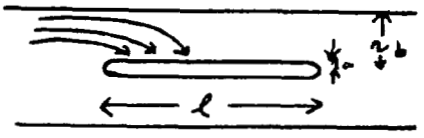
From the Gerdien theory, the ions which are drawn to the central cylinder come from a region bounded by a cylindrical surface. The cross-sectional area of this surface is inversely proportional to the velocity of the air stream, and directly proportional to the potential difference between the inner and outer cylinder and to the mobility of the ions measured. The radius of this cylinder r_0 can be expressed

$$r_0^2 - r_a^2 = 4cVK/U$$

This is obtained in the following manner: Ions of mobility k travelling in the air stream parallel to the axis of the cylinder are attracted to the central cylinder when they come under the influence of the electric field E. They will then have a velocity component v perpendicular to the direction of the air stream.

(3) $$v = KE$$

where E, the field inside the chamber at a distance r from the inner cylinder, is equal to $V/r \log r_b/r_a$. V is the potential between the cylinders, r_b the radius of the outer cylinder and r_a is the radius of the inner cylinder.



Integrating equation 3 between the limits r_a and r_0, one obtains

(4) $$r_0^2 = 2KVt/\log \frac{r_b}{r_a} + r_a^2$$

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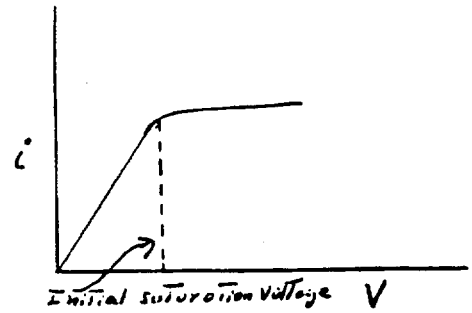
The time τ for a particle of velocity u to just travel to the end of the inner cylinder and not beyond is $t = l/u$. Substituting this in equation 4

$$r_0^2 = 2KVl/u \log \frac{r_b}{r_a} + r_a^2$$

Now $1/2 \log \frac{r_b}{r_a}$ is the capacity C of a cylindrical condenser of length l, therefore

(5) $$r_0^2 = 4KVC/u + r_a^2$$

This equation enables one to adjust V, for a fixed air velocity so that r_0 is less than the radius of the outer cylinder of the chamber. Then the instrument measures conductivity. The range for which a proportional relation exists between the measured current and the potential difference applied to the cylinders can be determined more exactly by measuring i, the current to the electrometer as the potential difference V between the cylinders is increased. The result is a curve of the form:



Swann[12] has shown that a charged body with the shape of the central cylinder of the Gerdien conductivity chamber if immersed in air of sufficient velocity loses its charge at a rate

$$-\frac{dQ}{dt} = 4\pi C V \lambda$$

The rate of loss of charge of the inner cylinder equals the total charge arriving at the inner cylinder per second. This condition can be expressed

(6) $$-\frac{dQ}{dt} = Wne$$

(12) Terr. Mag. 19, 81-92 (1914)

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where n is the ion concentration, and e is the charge per ion. W is that part of the volume of air per second flowing through the chamber from which all ions are brought to the central cylinder.

$$W = \pi(r_o^2 - r_a^2)U$$

r_o is the radius of the cylinder from which all ions arrive at the central collector, U is the velocity of the air stream. Substituting for r_o, the expression given by equation 5 one obtains

$$W = 4\pi K V C$$

Using this value for W in equation 6

$$-\frac{dQ}{dt} = 4\pi K V C n e$$

but $\lambda = neK$,

therefore

$$-\frac{dQ}{dt} = 4\pi C V \lambda \qquad (7)$$

It has been found more accurate to use the measured rather than computed value for C in equation 7. The rate at which charge is lost by the central cylinder $\frac{dQ}{dt}$ is measured with an electrometer. The polar conductivity is then obtained from equation 7, which shows that for constant potential V between the cylinders the current varies directly with conductivity and is independent of air velocity.

Swann[13] has investigated the theoretical limitations of this method for measuring conductivity. An experimental investigation of sources of error using a Gerdien type chamber has been made by Hewlett[14]. From his experiments it was found that non-uniformity of air flowing the conductivity chamber effectively increased the cylindrical surface from which all ions are brought to the central collector. The ions collected by the supporting rod of the central

(13) Terr. Mag. 19, 205-219 (1914)
(14) Terr. Mag. 19, 219-233 (1914)

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cylinder were found to have a negligible effect on conductivity. Changing the type of air intake had an effect which could be eliminated by reducing the potential on the cylinder. These experiments also showed that induced charge on the outer cylinder had no affect on ions collected of the same sign as the induced charge but that the conductivity of ions of opposite sign to the induced charge was decreased.

Present Equipment

A block diagram of the experimental setup in the B-17 aircraft which was used for the experiments under discussion is shown in Figure 4. Air enters the conductivity chamber by means of a four inch diameter intake tube which extends three feet in front of the aircraft (Figure 5). The chamber and recording apparatus are located in the nose of the plane. Ions entering the chamber are drawn toward the central cylinder by the electric field produced by a 45 volt battery placed across the inner and outer cylinders of the chamber. For the velocities of air flow in the chamber, approximately equal to the speed of the plane, this voltage is well below that required for saturation of the instrument. In order to measure the conductivity due to both positive and negative ions, a reversing switch was supplied to change the polarity of the central probe. The charge collected is measured with a vibrating reed electrometer[15] which is placed across a high resistance in series with the central cylinder. For a resistance of 10^{11} ohms the electrometer measures currents of the order of 10^{-15} to 10^{-9} amperes. A Brown recorder in the output of the electrometer gives a continuous record of current variations. The air passing through the chamber flows into an output tube which is connected to an opening in the side of the aircraft.

(15) Review of Scientific Instruments 18, 298 (1947)

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Figures 3, 6, and 7 show views of the conductivity chamber and electrometer. The outer cylinder is 18" long with a 2" radius, the inner cylinder is 9" long with a 3/8" radius. As is shown in these figures the electrometer has two components, a pre-amplifier which is attached directly to the conductivity chamber and an amplifier. The location of the apparatus in the aircraft is shown in Figures 8, 9, and 10. The position of the chamber, pre-amplifier and output tube is indicated in Figure 8. The pre-amplifier and conductivity chamber are inverted and installed with shock mounts to reduce to a minimum the effects of plane vibration. Figure 9 is a view of part of the intake tube and its relation to the conductivity chamber. The black knob on the side of the pre-amplifier is a switch for shorting the electrometer input in order to zero the instrument. The Brown recorder is shown in Figure 10.

Experimental

Altitude v.s. Conductivity

(a) Results with "Chinese Hat and Shell Type" Intake

The first results of measurements of small ion conductivity in fair weather are shown in Figure 11. The conductivity is found to increase with increase in altitude. As was indicated earlier, this is to be expected since the ionization due to increase in cosmic ray intensity varies in this manner therefore the conductivity λ = nek should also increase. The method of measurement is as described above except that the input to the conductivity chamber was shaped like a chinese hat (Figure 12). Air was drawn into the chamber with a root blower. The purpose of this type of input was to reduce the amount of water entering the chamber when the aircraft passed through rain or clouds. Water in the conductivity chamber breaks down electrometer insulation. In addition, water drops impinging on the walls of the chamber at high velocities break up

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creating many new ions so that true conductivity is no longer measured.

The values obtained were an order of magnitude smaller than the results of earlier workers[7]. The discrepancy was found to decrease with increasing altitude.

In order to cut down any turbulence introduced using the "chinese hat" type intake and still keep out large water drops, a shell-like intake was made (Figure 13). This projected three feet in front of the aircraft. Six holes with ¼" inch diameter were placed equidistantly around the periphery of the shell. The results in fair weather are shown on Figure 14. Again the values obtained were found to differ from earlier measurements by about a factor of 10. The error decreased with increasing altitude.

A summary of the results of variation in conductivity with altitude in fair weather with both types of intake are shown on Figure 15. An important point to note is that at a given altitude the conductivity does not vary, except for small daily fluctuations, over widely separated areas. The data was taken on the east coast and in southern California. This is an eight degree difference in latitude. These curves also show that at a given altitude the positive and negative small ion conductivity are the same. Both types of intake were unsuccessful in eliminating water drops. They also cut down the air flow to such an extent that too few ions entered the conductivity chamber. Allowing the air to flow freely into the chamber resulted in conductivity measurements of the order of magnitude obtained by earlier workers.

(b) Results with Free Air Flow

The results of measurements of conductivity as a function of altitude with no constriction at the input to the conductivity chamber are shown on Figures 1, 16 and 17. A rapid increase with altitude is shown. The data

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was obtained from January to March 1950. The curve on Figure 1 gives the average of the fair weather data for positive conductivity. At a given altitude there is found very little variation in λ_+ from day to day in fair weather. The curve on Figure 16 gives the same results for small negative ion conductivity. The data for positive and negative ions are summarized on Figure 17. Within the accuracy of the experiment $\lambda_+ = \lambda_-$ at a given altitude. The day to day fluctuations in λ_+ and λ_- at a given altitude for seven different flights are summarized in the following table.

Table 1

Altitude (feet)	λ Average $\times 10^4$ (sec^{-1})	$\Delta\lambda \times 10^4$ (sec^{-1})	% Variation	Temp. Change °C
5,000	1.4	0.62	43	3
10,000	2.0	0.70	35	2
15,000	3.4	0.71	20	4
20,000	5.3	0.65	12	3
25,000	7.5	0.62	8	3
30,000	10.0	1.10	11	5
35,000	13.0	1.70	13	-

$\Delta\lambda$ is the variation of conductivity from the average value for a given altitude. This shows a decrease in the percentage day to day variation with increase in altitude. Much of this variation is undoubtedly due to actual changes in conductivity. This is in part indicated by the temperature fluctuations at a given altitude since the conductivity as was indicated earlier varies directly as the temperature.

These experiments were carried out in the northern part of New England and from MacDill Air Force Base, Florida. The results show that the variation in conductivity with altitude is the same at both places. The values of conductivity obtained in these experiments vary by an average factor of 1.7 from the Explorer II data. This ratio increases from a value of 1.4 at 5,000 feet

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to a value of approximately 1.9 at 30,000 feet.

Diurnal Variation in Conductivity

Continuous measurements of conductivity at the earth's surface indicate a daily variation with a maximum in the early morning and minimum in the afternoon[4]. The exact time of the maximum and minimum and the magnitude of the variation change considerably with position and season. This variation is attributed to the observed daily change in small ion density and the corresponding inverse change in large and intermediate ion concentrations. The rate of formation of ions is found to vary in much the same manner as the small ion density[6], with a maximum in the early morning. This is consistent with theory which shows that the small ion density varies approximately as the square root of the rate of production[16].

These are the most important factors controlling the daily variation in conductivity over land. The increase in the rate of production of ions at night at the earth's surface could be due to the accumulation of radioactive matter from the soil below the level of temperature inversion. In the morning this is dispersed by vertical convection currents. Therefore any variation which occurs above the level of temperature inversion will be largely due to the upward movement of ions which will begin with the vertical winds in the morning. Data on the daily variation in λ with altitude should thus give information of interest to meteorologists on the vertical velocities of these currents, for the variation in λ at a given altitude due to this mixing will occur at earlier times the greater the velocity. Two flights with aircraft were made at 10,000 feet throughout the morning hours. On both flights a decrease in λ was observed near sunrise. This only indicates that diurnal changes in λ can be detected above the level of temperature inversion. Further

(16) Terrestrial Magnetism and Electricity, (Dover Press) p 207

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information concerning this phenomena cannot be obtained until balloon measurements are made and correlated with ground station data. This laboratory hopes to continue this investigation in the near future. These measurements will have to be made over an area where the magnitude of the daily variation is large.

Conductivity in Clouds (not Thunderclouds) Haze, and Mist

When discussing the departures of positive and negative conductivity in clouds, haze and mist from the values obtained in fair weather one must distinguish the effect of charge accumulated on aircraft and the change in ion concentration in the precipitation. The effect of positive and negative charge on the surface of an aircraft on conductivity has been investigated by members of this laboratory. The experimental results were discussed in the first part of this report. It was found that a negative field on the surface of the aircraft linearly decreased the negative conductivity. Positive field had no influence on negative conductivity. Similarly positive conductivity was affected only by positive field on the aircraft, etc. In mist, stable clouds and haze, the aircraft was always found to be charged negatively. This is in agreement with the results of Ross Gunn[17] in clouds.

This discussion of the results obtained in clouds and mist includes the data of seven flights with aircraft. No consistent results were obtained. The measured conductivity sometimes increased, sometimes decreased when the aircraft passed through precipitation. In some cases, it was not affected. These results merely indicate the necessity for further measurements with instruments which will at least qualitatively give relative humidity or density of the mist, and possibly some idea of drop size.

(17) Journal of Applied Physics 19, 481-484 (1948)

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During four flights the conductivity was found to increase up to twenty times its fair weather value at a given altitude. During three flights, the conductivity was found to decrease to approximately one third of its value on clear days. At times during some of these flights the conductivity was not affected when flying through mist or clouds. The values given above are corrected for charge on the plane surface. Considering the cases where the conductivity decreased, during one flight the decrease could be attributed to charge on the plane, in another no data was obtained on the field at the plane surface. In the third case after applying the correction for charge on the aircraft the conductivity was still lower than its normal value. During the flights where an increase was found, there were instances when the conductivity should be essentially zero after the correction for charge on the plane was applied and yet the conductivity was approximately twenty times its fair weather value. This increase may be due to an increase of ionization caused by the break up of water drops on the walls of the conductivity chamber rather than a real increase in ion concentration. Thus the results obtained are too erratic to arrive at any conclusion at this time as to the true conductivity in clouds or mist. More experiments are planned where data on the nature of the mist or cloud will also be obtained.

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(2) Terr. Mag. 40, 425-431 (1935)

(3) Loeb, Kinetic Theory of Gases p 565

(4) Journal of the Washington Academy of Sciences 36 325-328 (1946)

(5) Terrestrial Magnetism and Electricity (Dover Press) p. 198

(6) Terrestrial Mag 53 305-317 (1948)

(7) Terrestrial Magnetism and Electricity (Dover Press) p 205

(8) G. Grimminger, Project Rand Report p 35, Nov 1948

(9) Terrestrial Magnetism and Electricity (Dover Press) p 177

(10) Annales de Geophysique 2 March and June 1946

(11) Terr. Mag. 10, 65-79 (1905)

(12) Terr. Mag. 19, 81-92 (1914)

(13) Terr. Mag. 19,205-219 (1914)

(14) Terr.Mag.19,219-233 (1914)

(15) Review of Scientific Instruments 18, 298 (1947)

(16) Terrestrial Magnetism and Electricity, (Dover Press) p 207

(17) Journal of Applied Physics 19, 481-484 (1948)

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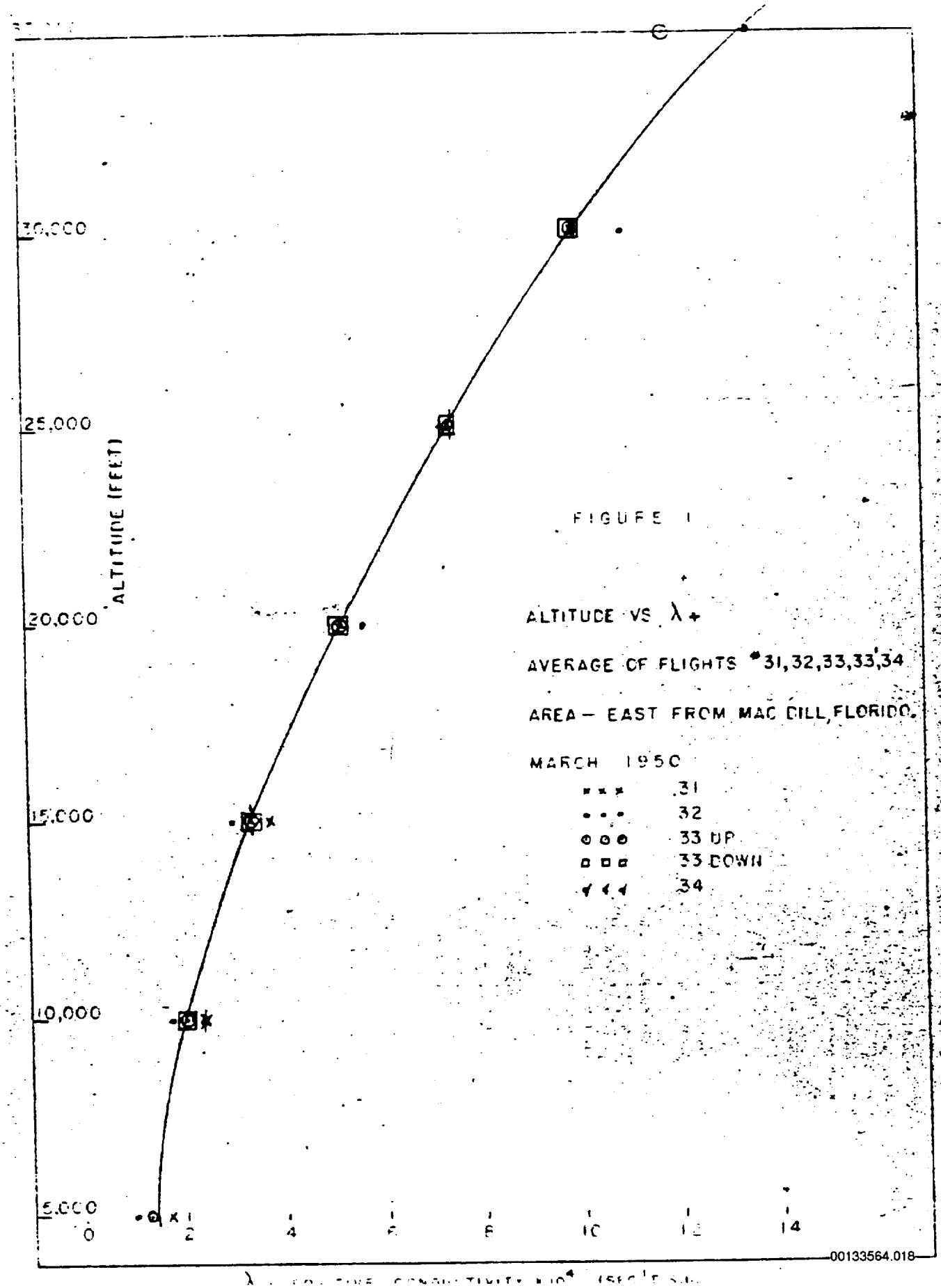

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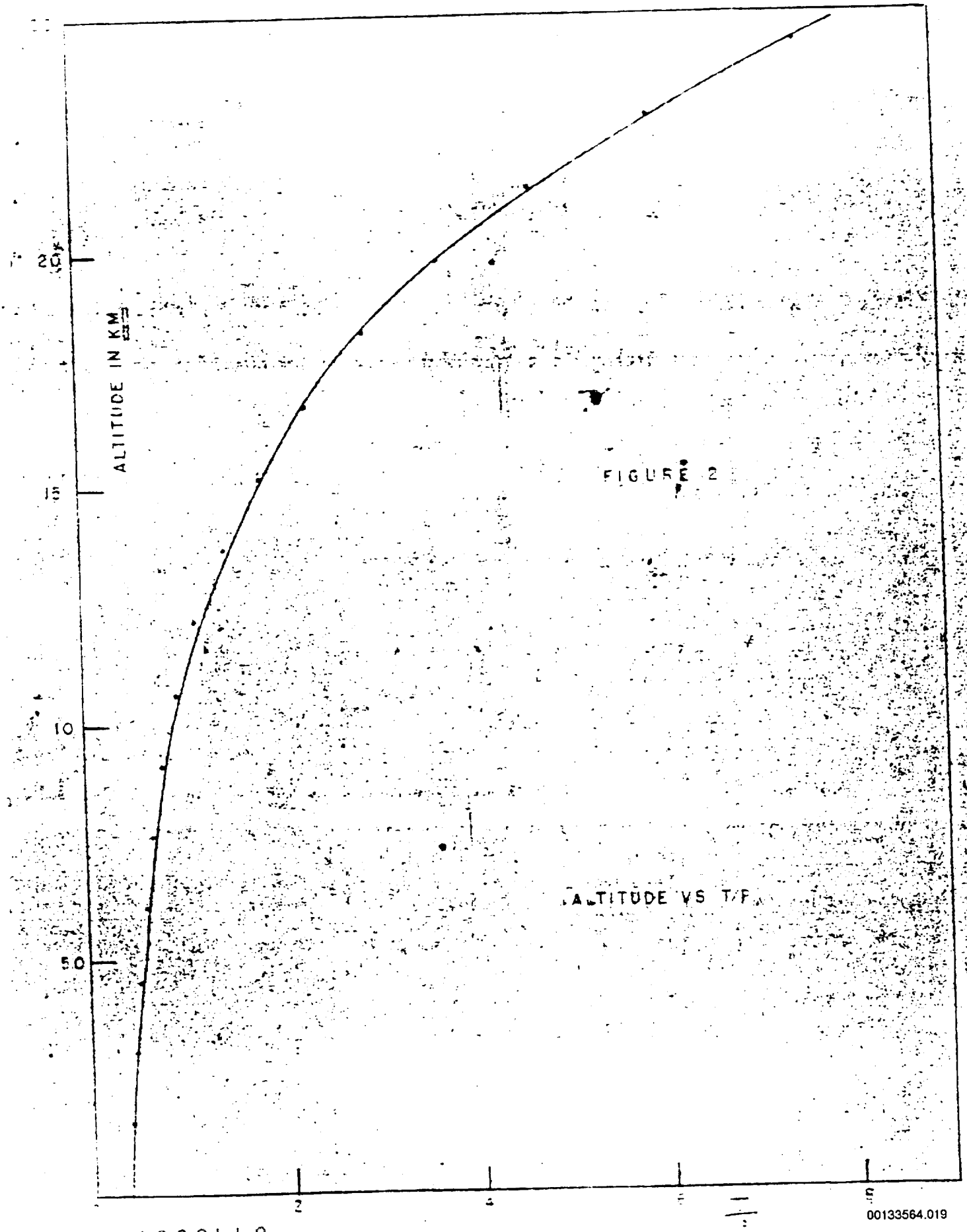

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FIGURE 3

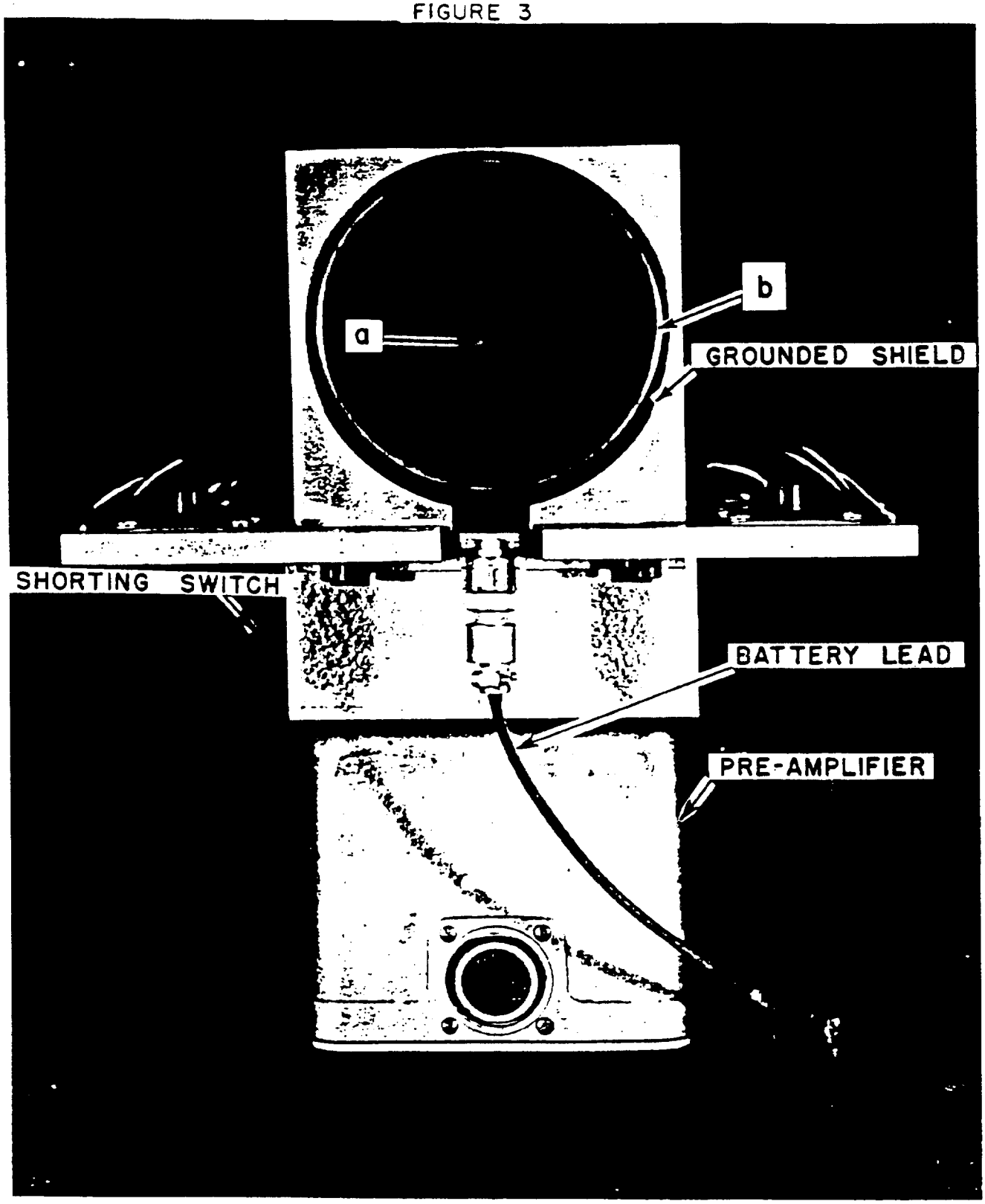

FIGURE 10

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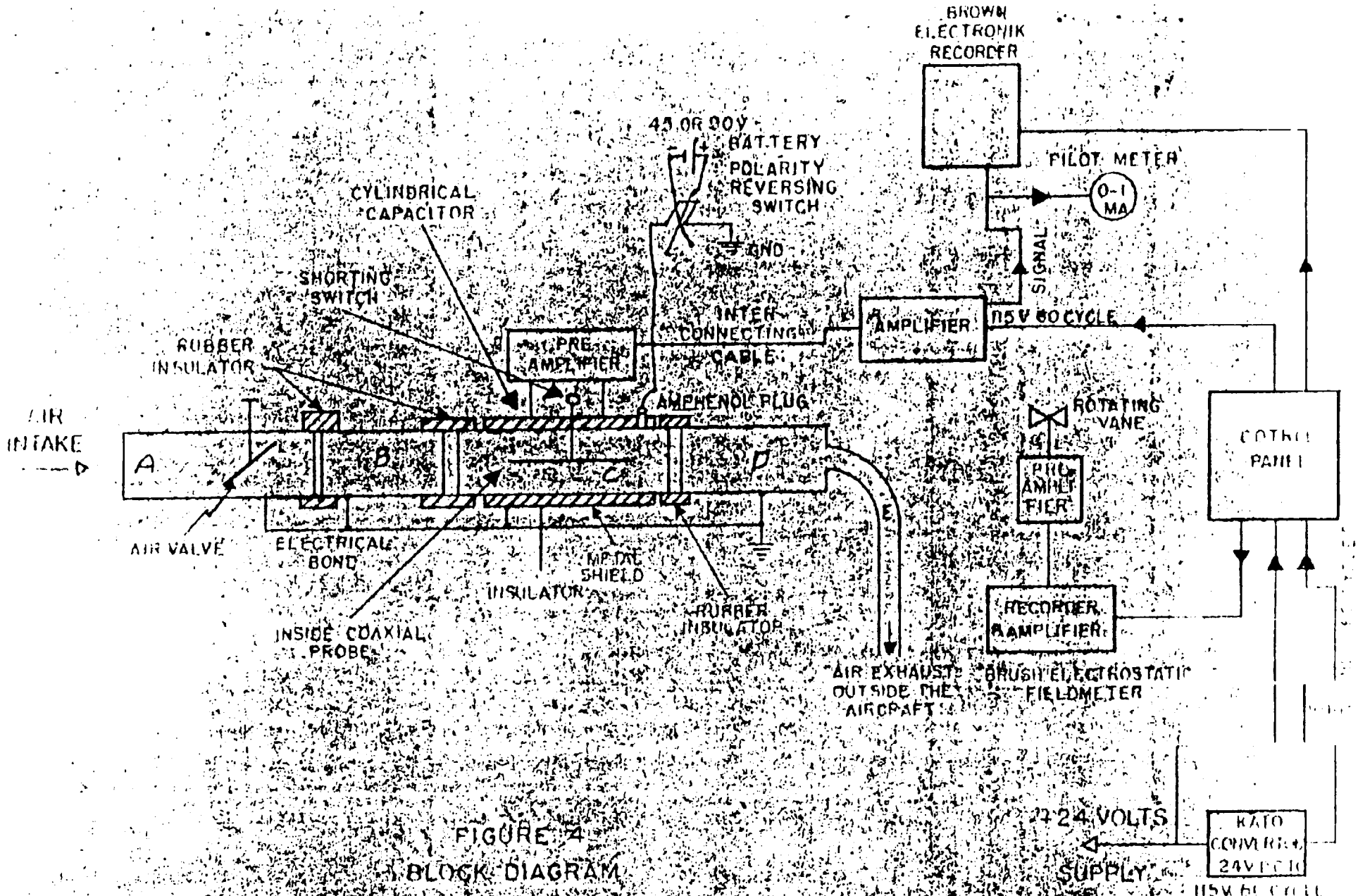

FIGURE 4
BLOCK DIAGRAM

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FIGURE 5

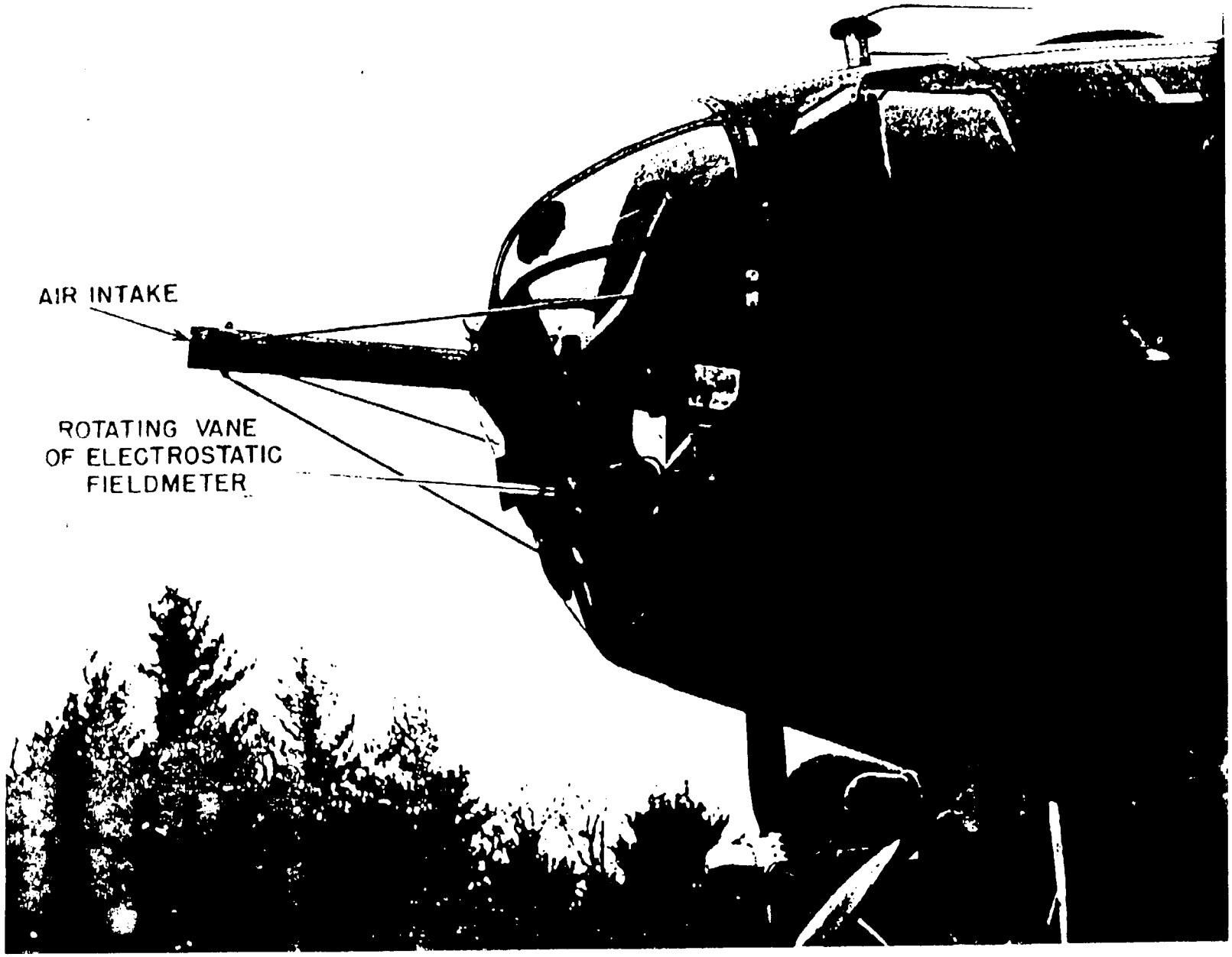

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FIGURE 6

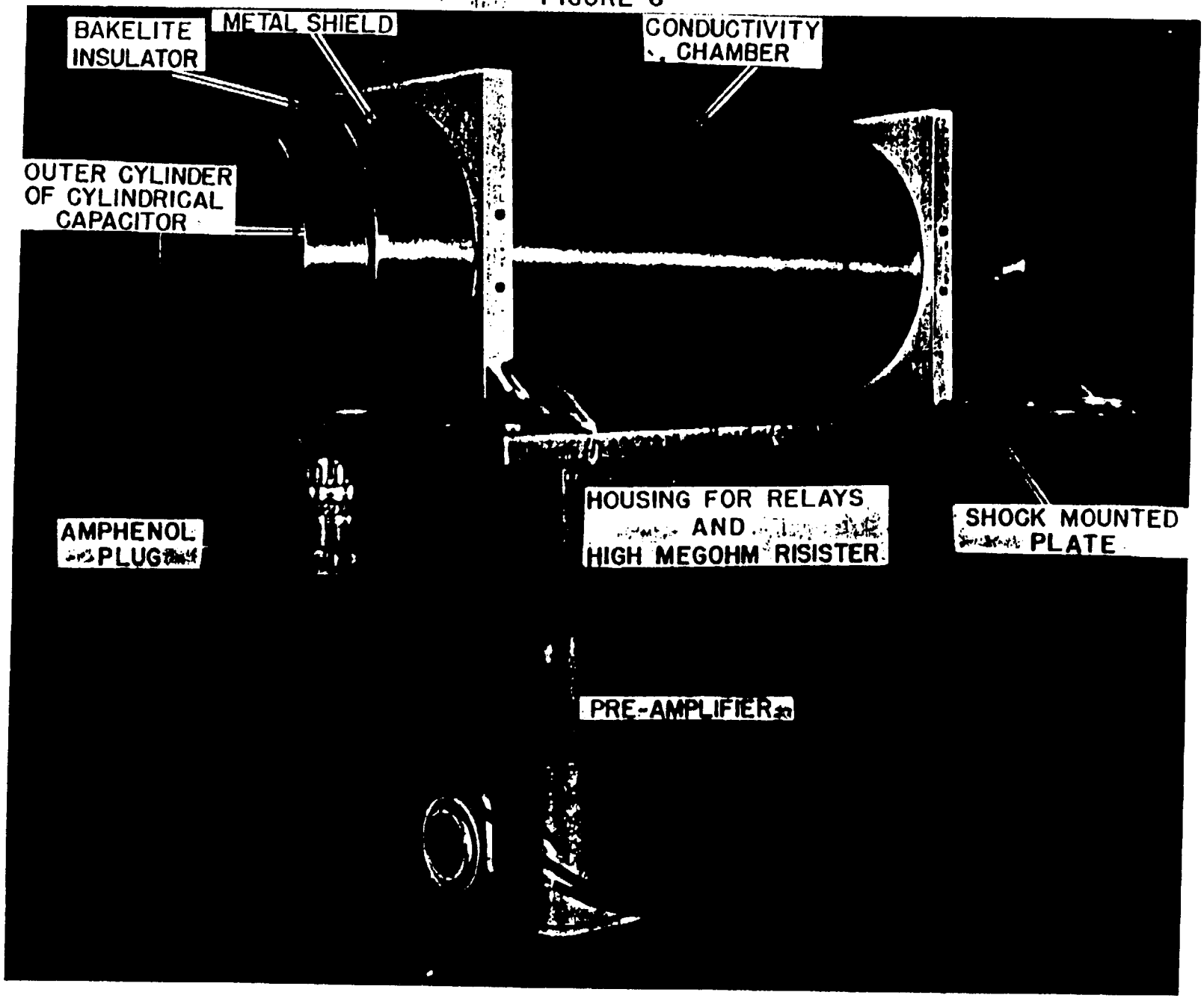

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FIGURE 7

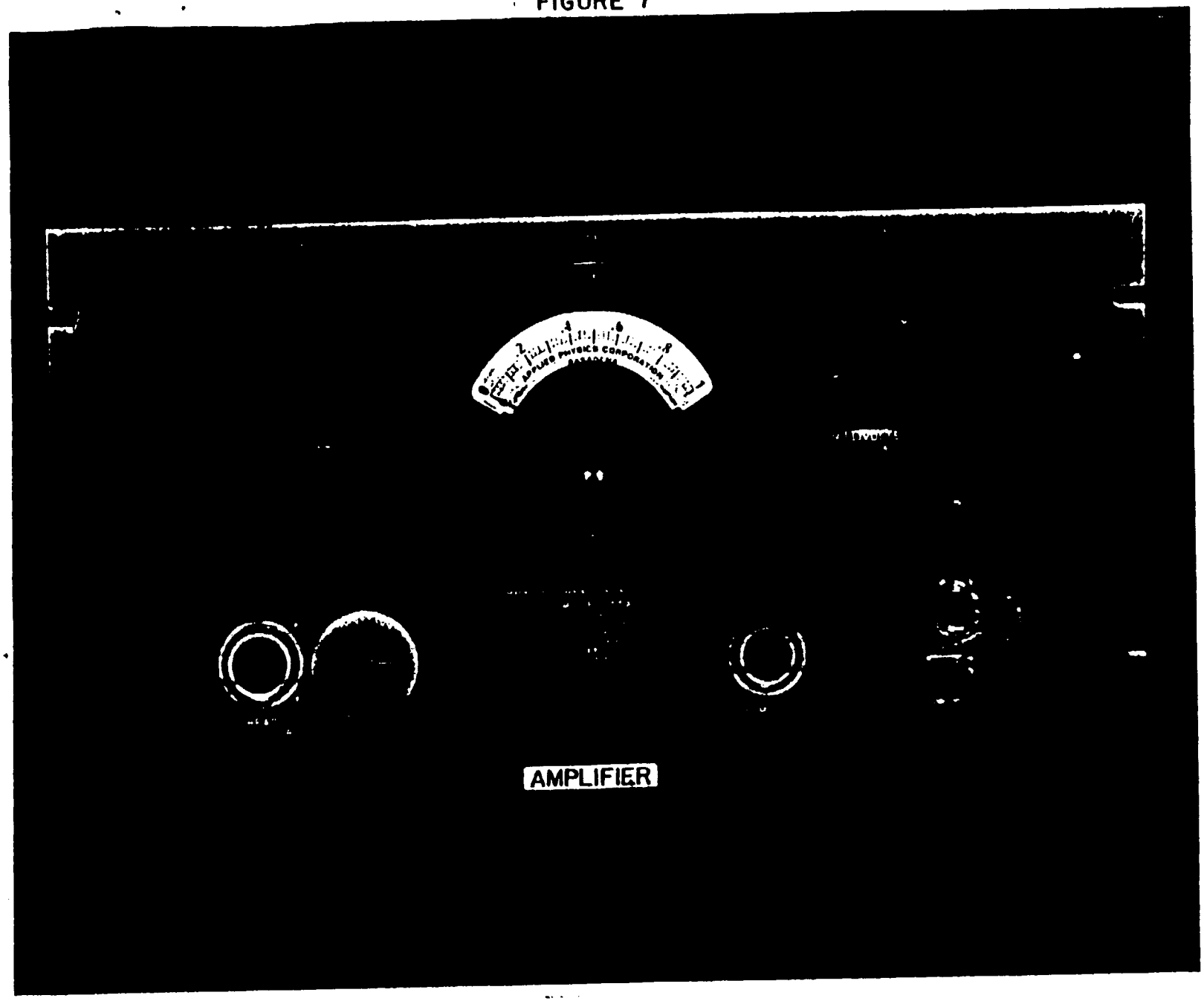

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FIGURE 8

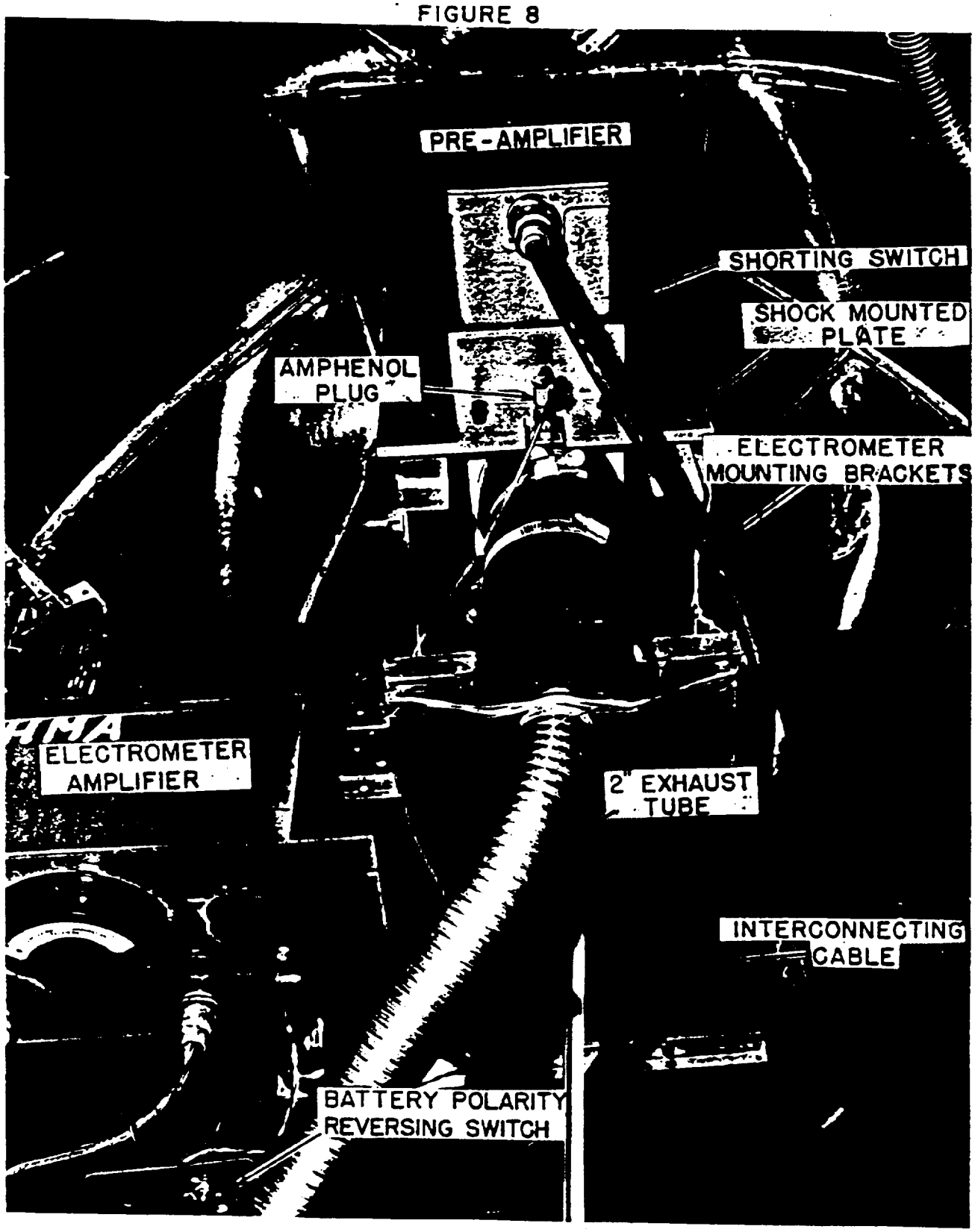

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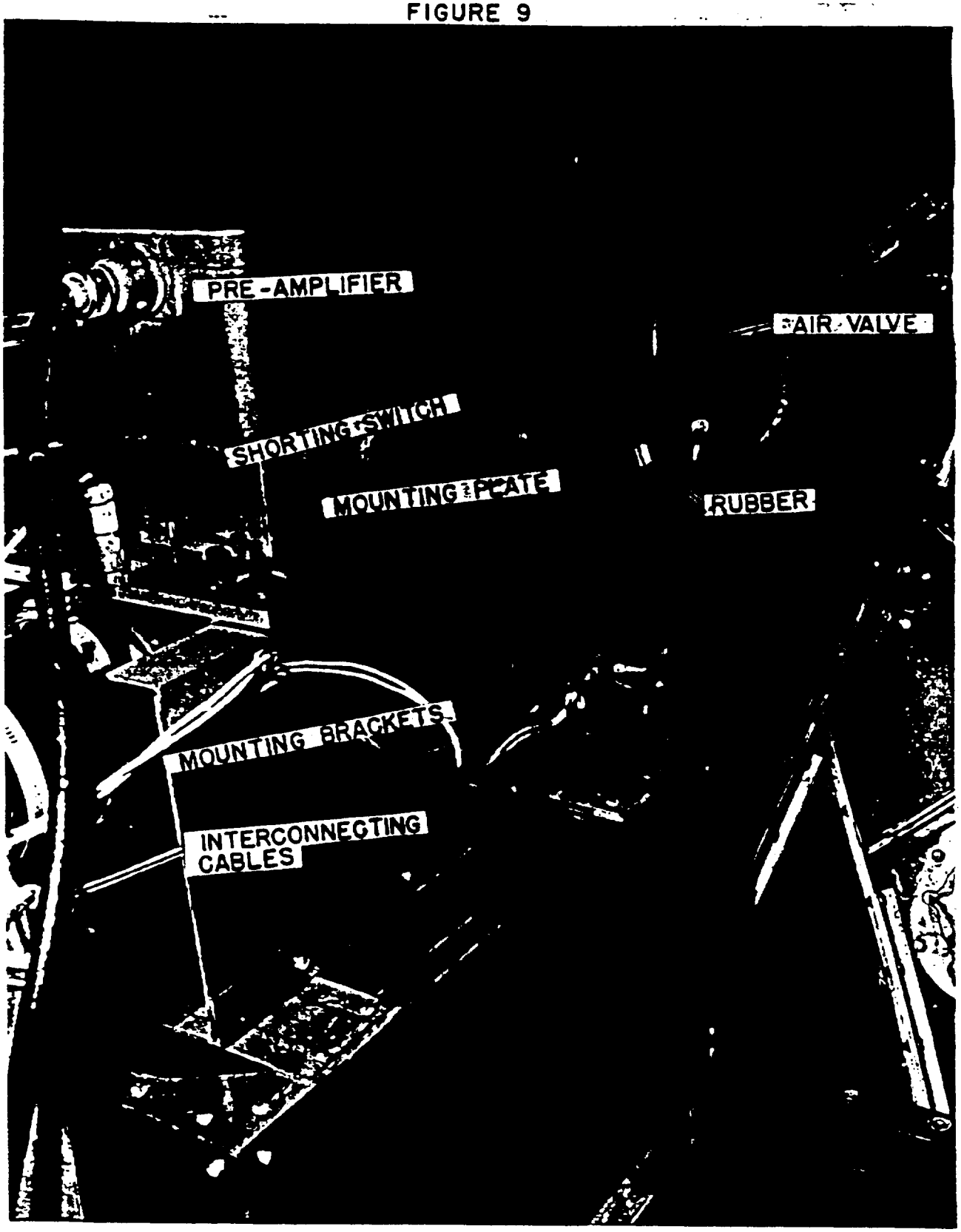
FIGURE 9

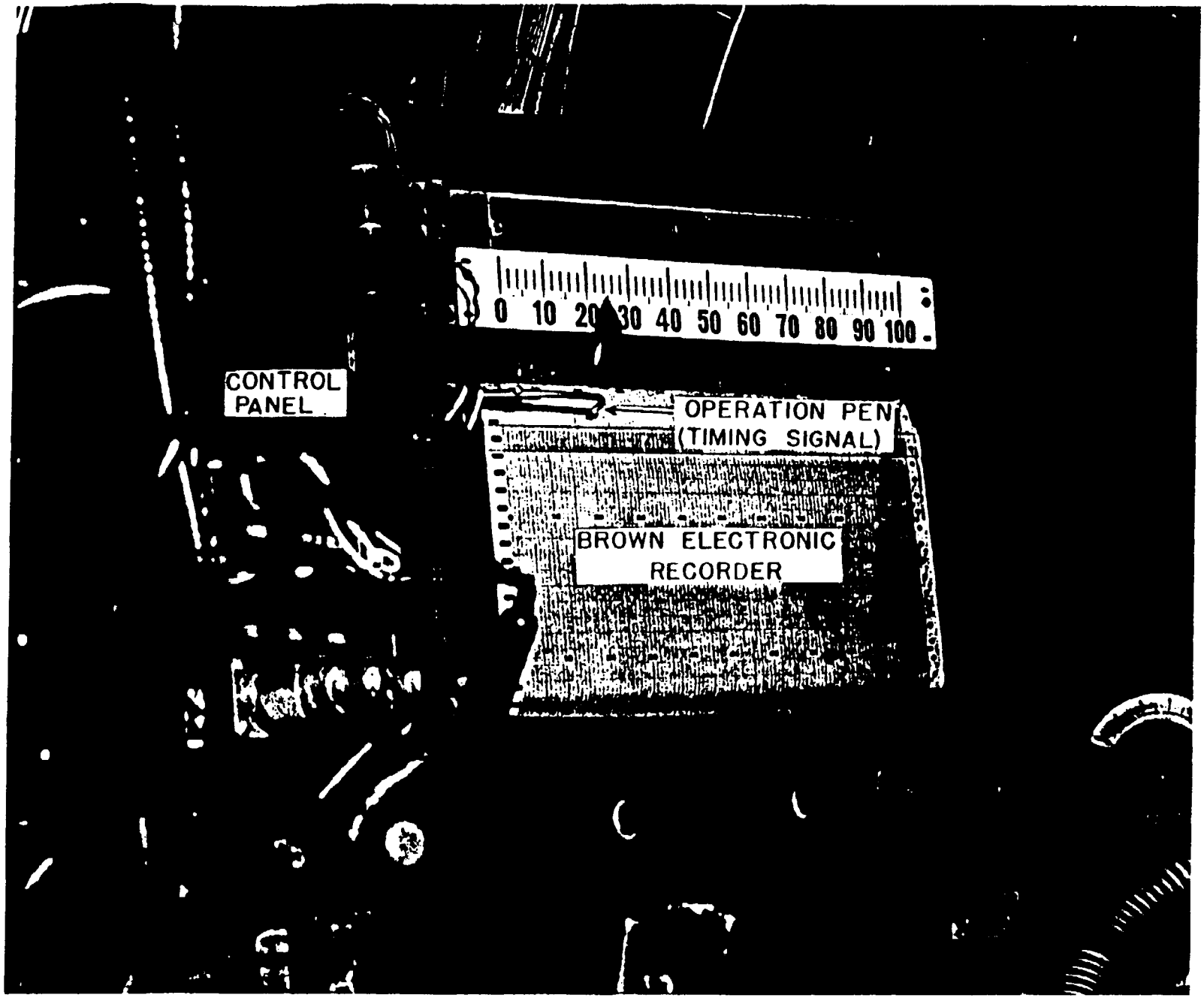


00133564.026

1092675

LANL

FIGURE 10



1092676

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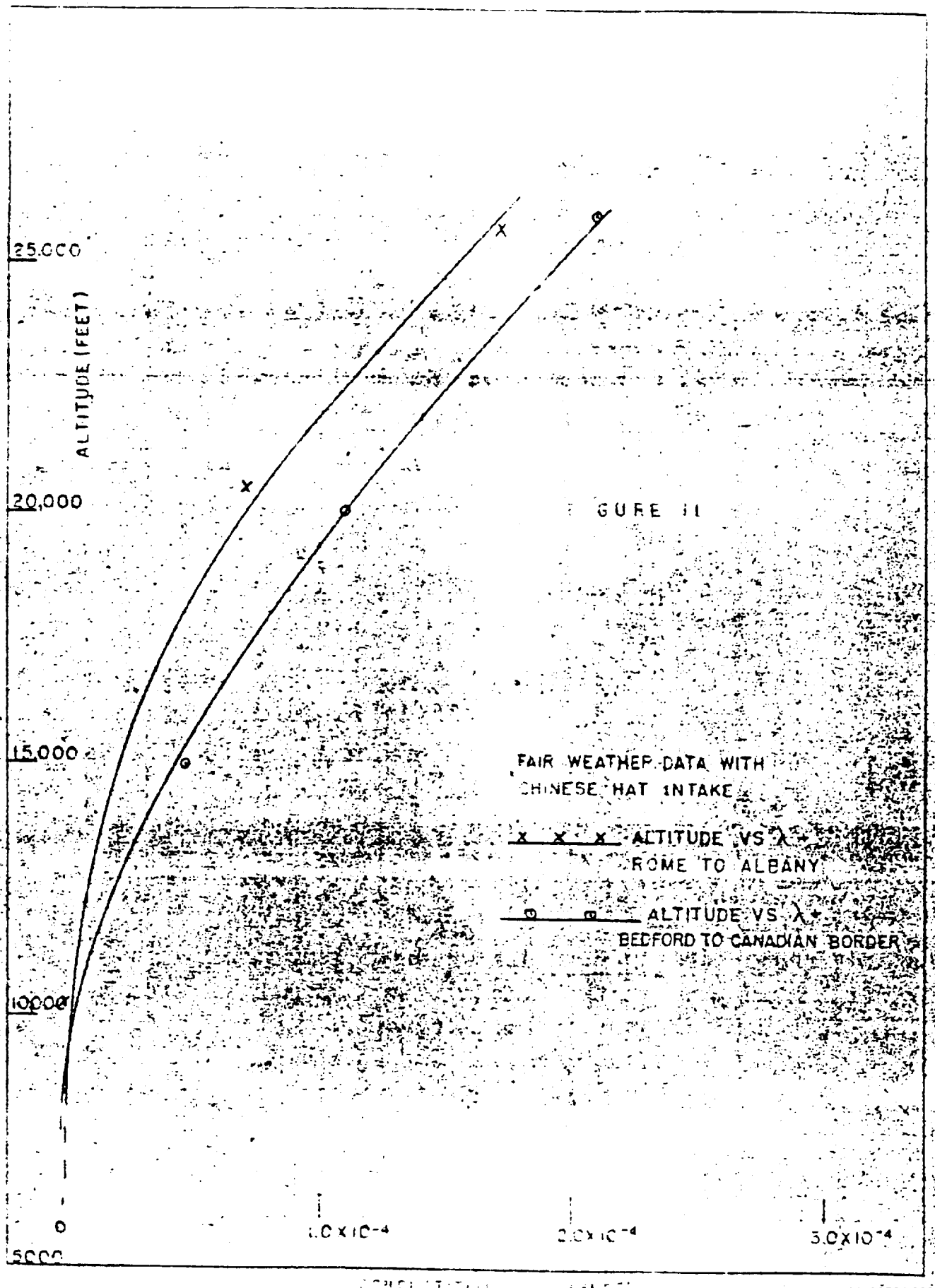

FIGURE 11

00133564.028

1092677

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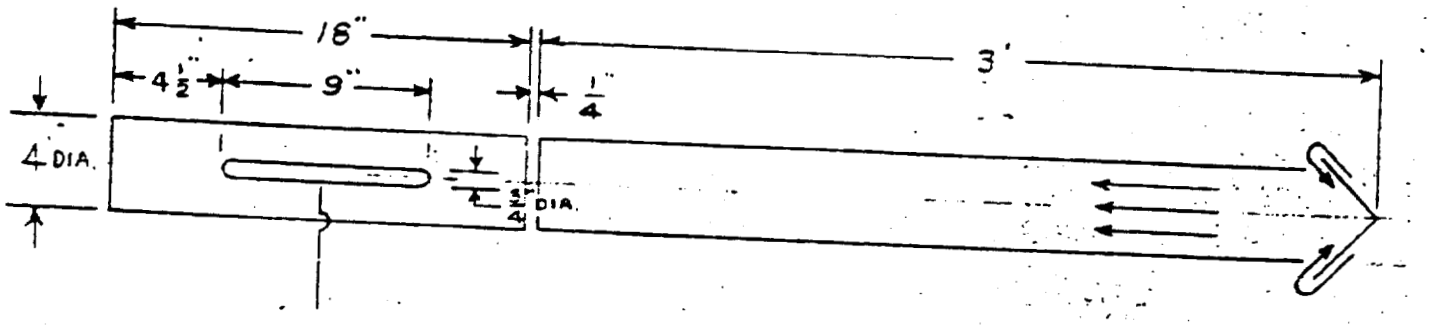

FIGURE 12

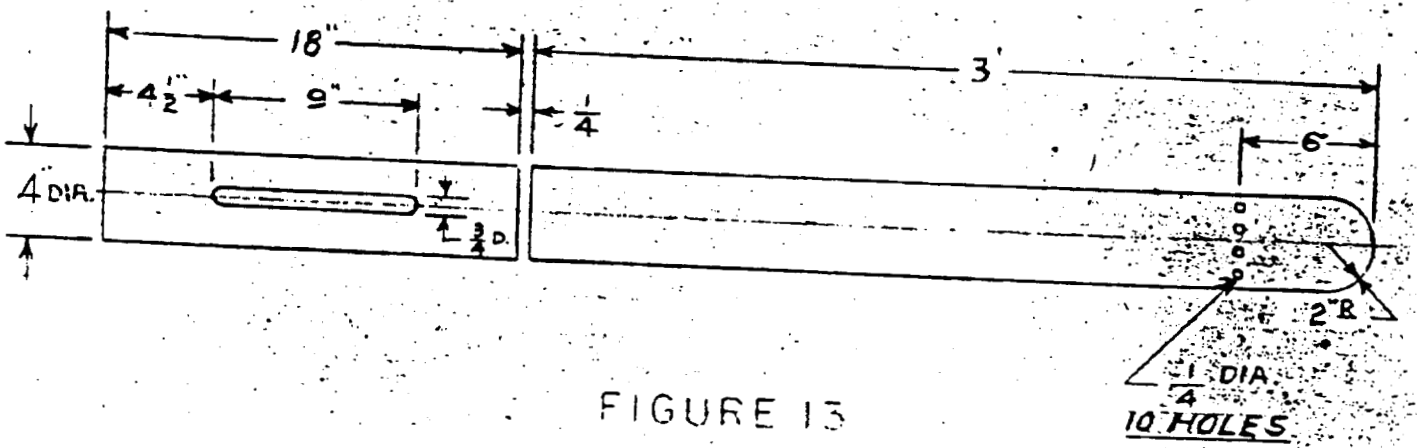

FIGURE 13

00133564.029

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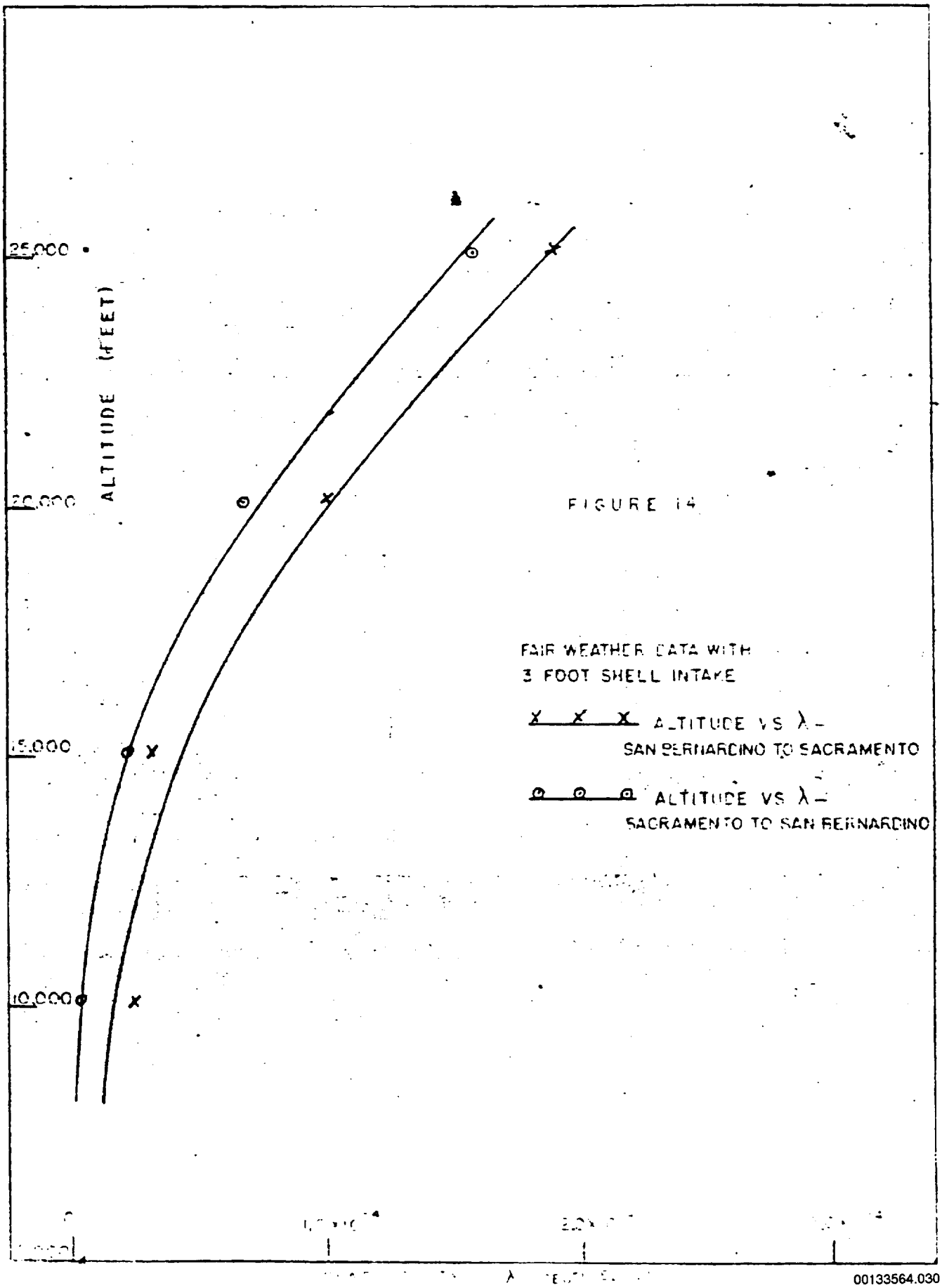

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1092679

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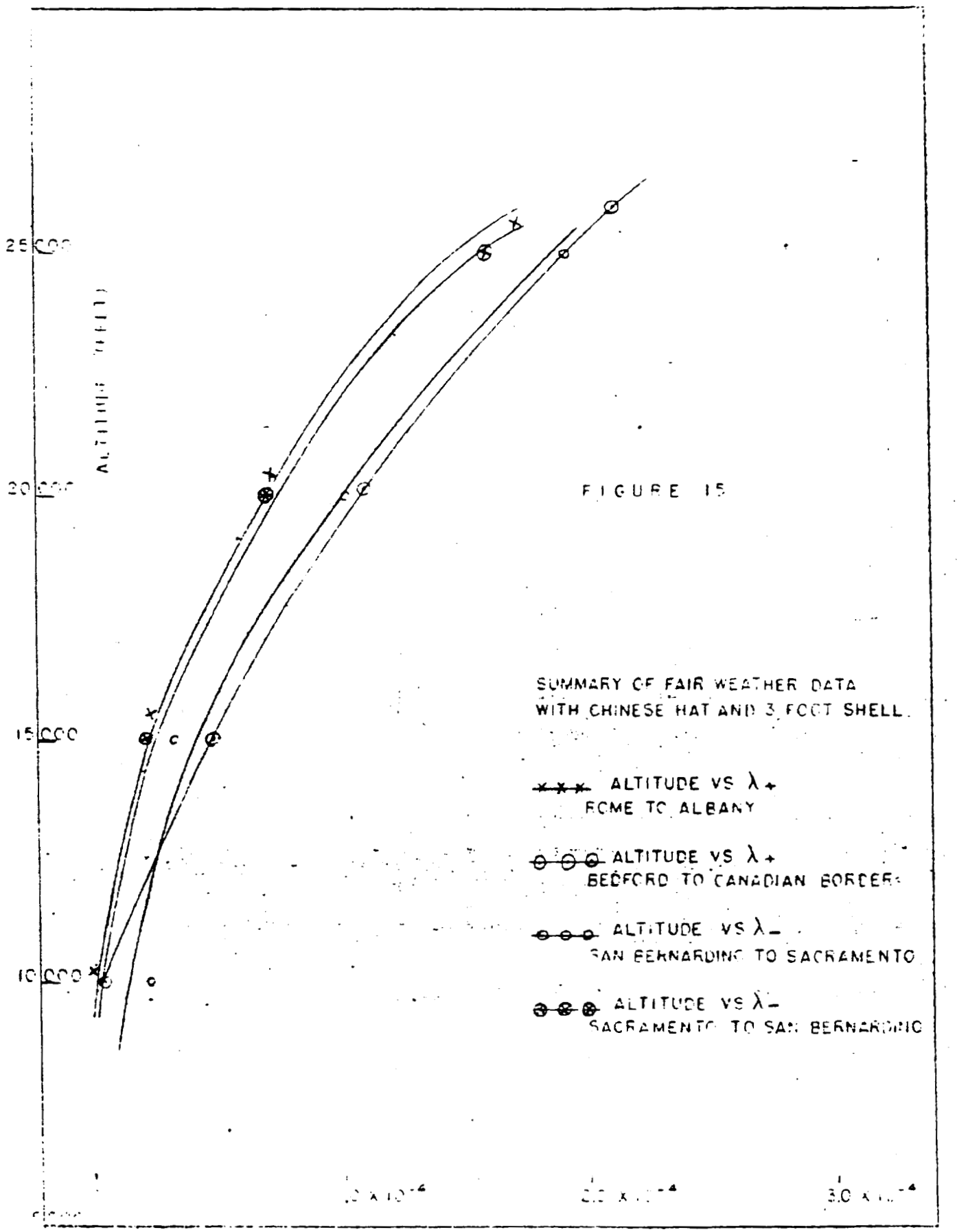

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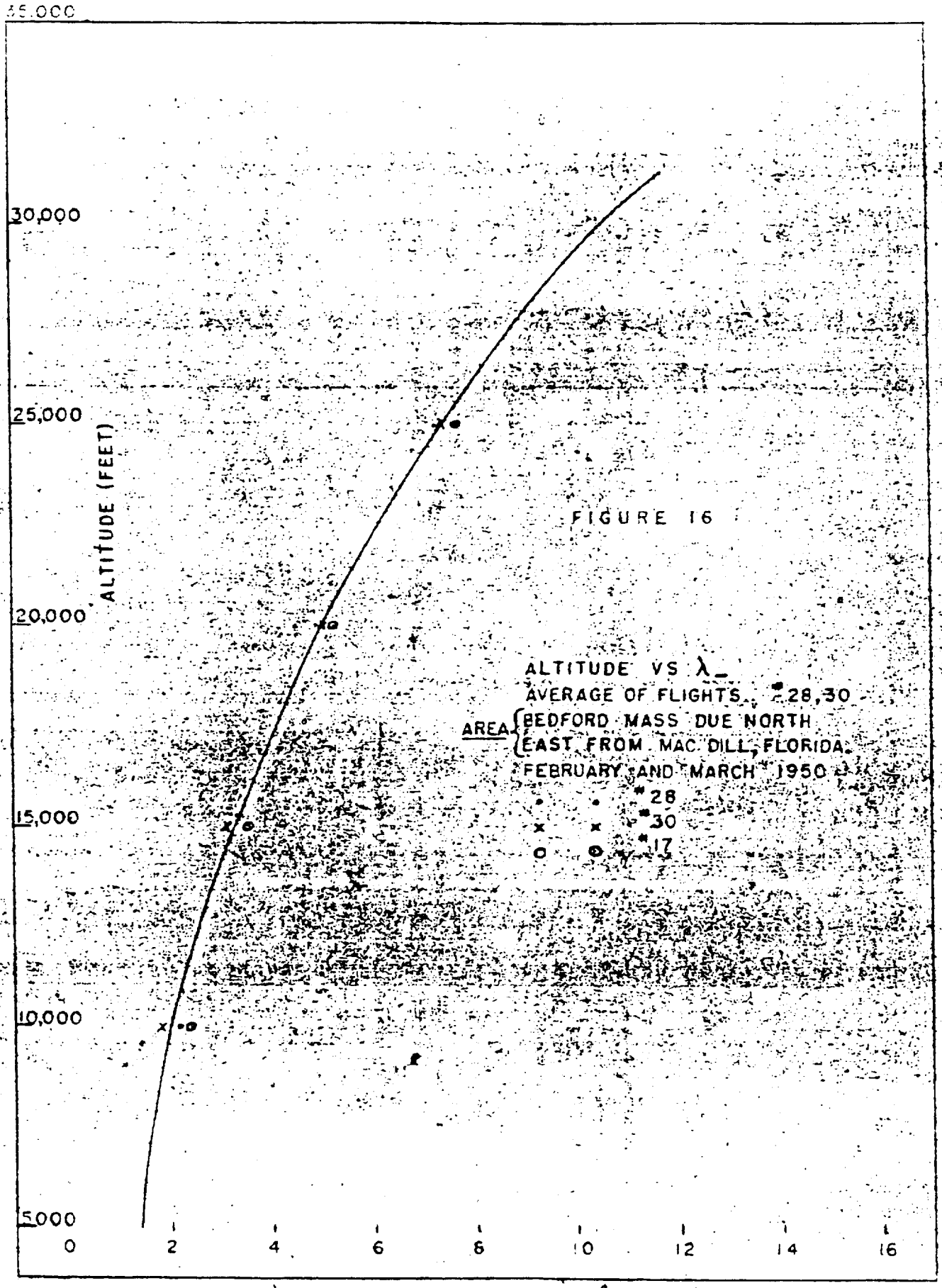

FIGURE 16

1092681

00133564.032

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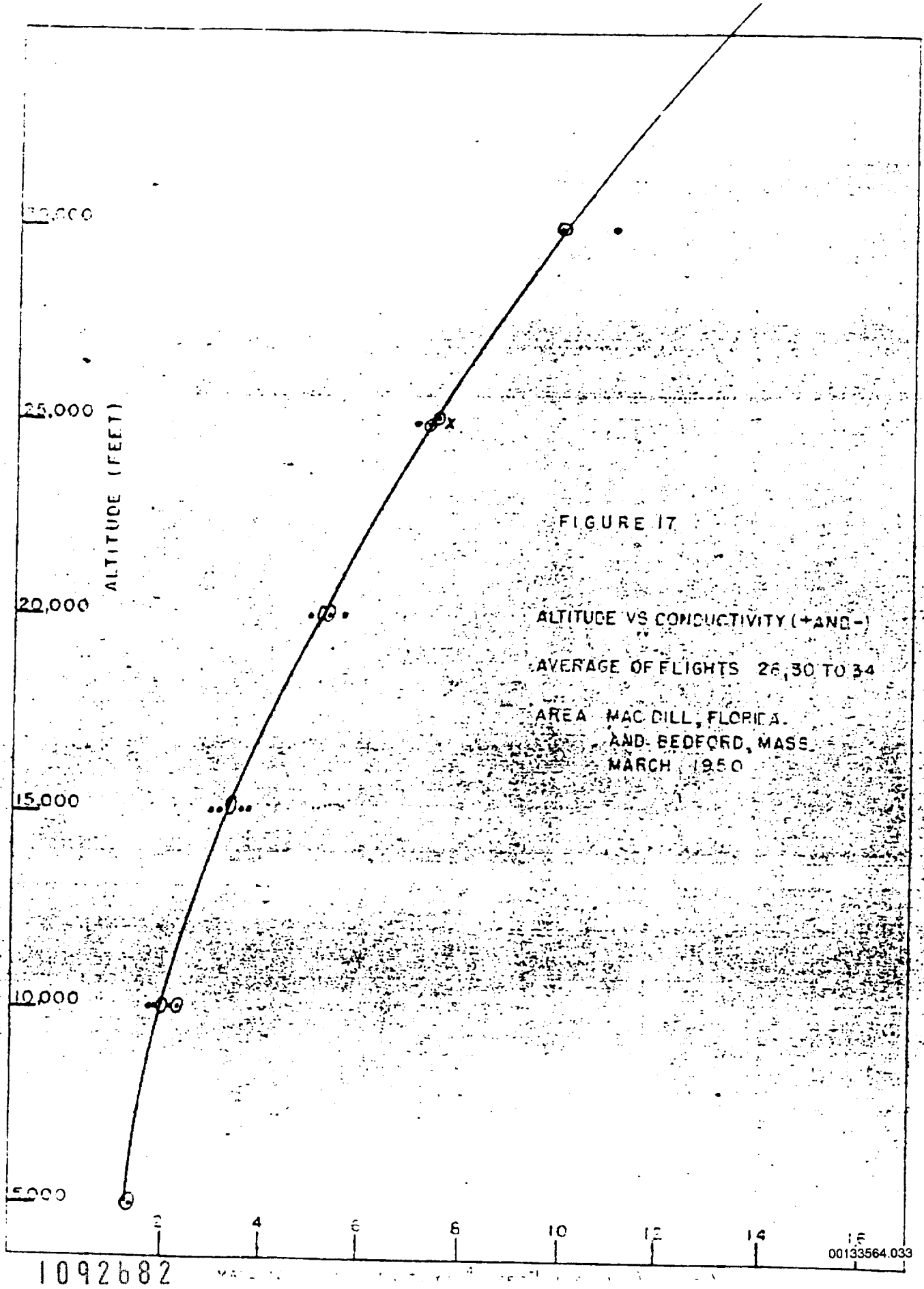

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