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I hereby recommend that the thesis prepared under my supervision by William C. Roubush
entitled "A Measurement of the Diurnal Variation of the Potential Gradient and the Space Charge with a Correlation Between These Elements and the Meteorological Elements"
be accepted as fulfilling this part of the requirements for the degree of Doctor of Philosophy

Approved by:

Charles Harrison Dwight

D. A. Wells

"A MEASUREMENT of the DIURNAL VARIATION of the
POTENTIAL GRADIENT and the SPACE CHARGE with a CORRE-
LATION BETWEEN THESE ELEMENTS and the METEOROLOGICAL
ELEMENTS"

A dissertation submitted to the

Graduate School

of the University of Cincinnati

in partial fulfillment of the
requirements for the degree of

DOCTOR of PHILOSOPHY

1939

by

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INTRODUCTION

Certain manifestations of atmospheric electricity such as lightning, the aurora, and St. Elmo's fire have long been known, although not until recently understood. Much later it was discovered that everywhere and at all times there exists a permanent electrical potential difference between the earth and the upper atmosphere. This has led to the division of the subject of atmospheric electricity into two main classes, i.e., that which deals with what we call Normal Phenomena--fair weather phenomena--and that which deals with those phenomena associated with thunderstorms which we call Thunderstorm Phenomena. In this work we shall consider in detail only the former class. Under this class we deal with the following quantities:

1. The Potential Gradient
2. The Space Charge
3. The Conductivity of the Air
4. The Air-Earth Current

Of this group we deal directly with only the first and second. However, most of these atmospheric electric elements are so interrelated that we actually will make use of all of them.

The proof of the existence of the fair weather phenomena may be attributed to Le Monnier, who in July 1752 proved

that a tall insulated metallic conductor becomes electrified even when the sky is absolutely clear.

Franklin's kite experiment in 1752 may also be mentioned, although he was primarily interested in Thunderstorm Phenomena. Other important discoveries were:

1. The inauguration in 1757 by Beccaria of systematic and long continued observations of atmospheric electricity.
2. The invention by Lord Kelvin of the quadrant electrometer in 1855, and the water dropper about the same time.
3. The discovery by Linss 1887 that even the most perfectly insulated conductors lose their charges when exposed to the air, in a manner that shows the atmosphere itself to be a conductor of electricity.
4. The discovery in 1900 by C. T. R. Wilson, and also by H. Geitel, of spontaneous ionization in the atmosphere.
5. The discovery in 1902 independently by Rutherford, Cooke, and McLennon and Burton of a penetrating radiation in the lower atmosphere, presumably from radioactive substances near the surface of the earth.

6. The discovery in 1905 by Langevin of slow-moving, or large ions, in the atmosphere.
7. The discovery by Simpson in 1908 and 1909 that the electric charge on thunderstorm rain, and precipitation generally, is prevaillingly positive.
8. The discovery in 1913 by Kolhorster that an extremely hard or penetrating radiation exists in the atmosphere that comes from the outside.¹

The potential difference between the earth and the upper atmosphere is of the order of 1,000,000 volts. The direction of the field shows that the earth carries a negative charge, and the air a positive one. The negative charge density over the surface of the earth is of the order of 2.7×10^{-4} E. S. U. per cm.²---over the entire surface of the earth this amounts to about 500,000 coulombs.

POTENTIAL GRADIENT

The potential gradient--i.e., the change in potential per meter as we go up in the air--amounts on the average to about 100 volts per meter, and decreases rapidly with altitude. At 10 km, (about 5 miles) it is practically zero--

¹Humphreys, Physics of the Air

forcing us to the conclusion that in the first 10 km. of the atmosphere is contained a positive charge just equal to the negative charge on the earth. Thus, if we let

$$X = \text{downward electric force} = 4\pi\sigma$$

where

σ = negative surface charge on the earth

σ_1 = charge on column of air up to height (h),

then the potential gradient at the surface is given by

$$X = 4\pi\sigma$$

and that for any height (h) above the ground by

$$X = 4\pi(\sigma - \sigma_1).$$

Now at 10 km.

$$\sigma_1 \cong \sigma$$

and hence

$$X = 0.$$

The potential gradient at the earth's surface, especially over land areas, is continually varying. This is due largely to local meteorological conditions, and, in the case of cities, to air pollution, etc. While there are also well-marked annual and diurnal variations, it generally happens that over land areas the local effects either partially or completely hide the more general character of the variations. The potential gradient is also affected by the topography of the land. The presence of

trees, buildings, etc., alter the true value of the gradient by disturbing the equipotential surfaces.

CONDUCTION CURRENT

The conducting power of the air is due to the presence of free positive and negative ions which move under the action of the electric field. Their movement constitutes a conduction current, which, due to the direction of the field, is known as the air-earth current. The average value of this conduction current is of the order of 2×10^{-16} amp. per cm.², and is practically constant. Over the surface of the earth this amounts to a continuous current of 1,000 amperes tending to destroy the negative charge on the earth. In view of this, the origin and maintenance of the earth's charge constitute a serious problem in atmospheric electricity. Some of the theories formulated to account for this will be mentioned later on.

CONDUCTIVITY OF THE ATMOSPHERE

The conductivity of the atmosphere depends on three quantities, the number of ions (n), the charge on the ions (e), and the mobility of the ions (k). Thus in general the conductivity (λ) is given by the following expression:

$$\lambda = k e n.$$

The more exact expression for the conductivity takes into consideration the fact that there are in general three classes of ions. Classification is made according to mobilities. The mobility of an ion is defined as the velocity which it experiences in a unit field. Here we consider the mobility to mean the velocity in centimeters per second in a field of one volt per centimeter. Thus there are:

1. "Normal", "Small", or "Fast" ions formed by ejection of an electron from a gas molecule. Mobility 1.5 (cm. per sec. in a field of one volt per cm.).
2. "Large" or "Langevin" ions--probably are small ions attached to condensation nuclei. Mobility .0005 to .0003. About one-third of this type are electrically neutral.
3. "Intermediate" ions--occurring in times of low humidity. Mobility .1 to .01.²

The exact expression for the total conductivity is:

$$\lambda = \lambda_+ + \lambda_-$$

where λ_+ and λ_- are called
the polar conductivities, viz.,

$$\lambda_+ = (k_+ n_+ + K_+ N_+) e$$

$$\lambda_- = (k_- n_- + K_- N_-) e$$

²Hess, The Electrical Conductivity of the Air and Its Causes.

The capital letters refer to the large ions and the lower case letters to the small ions. In clear air over land and over the ocean most of the conductivity is due to the small ions, while near large cities, due to air pollution, a greater part of the conductivity is due to the larger ions. The usual value obtained for the conductivity is about 3×10^{-4} E.S.U. This value, when compared with the conductivity of copper (about 5×10^{18} E. S. U.), is almost inconceivably small--a column of air one inch long offers as much resistance to the passage of the electric current as a copper cable 30×10^{15} miles long, and of the same cross section. Nevertheless it is large enough to insure that in ten minutes 90% of the charge on the earth would be dissipated. It is evident from what follows that this is so.

The current (i) is given by the expression

$$i = - \frac{d\sigma}{dt} = X \lambda$$

where

$$\sigma = \frac{X}{4\pi} = \text{surface charge}$$

Putting in the value of σ we see that

$$\frac{dX}{X} = -4\pi\lambda dt$$

Whence

$$X = X_0 e^{-4\pi\lambda t}$$

Now if we put

$$\lambda = 3 \times 10^{-4} \text{ E. S.U.}$$

$$t = 10 \text{ min.} = 600 \text{ sec.}$$

we see that

$$X = \frac{1}{10} X_c$$

It is thus quite evident that there must be some other factors at work tending to counter-balance this loss of charge due to conduction. A few of the theories formulated to account for this will now be mentioned quite briefly.

1. Soil Respiration--Ebert has attempted to account for the negative charge on the earth, and a positive charge in air by his respiration theory. This theory states that during periods of low pressure or due to the suction of winds or to the action of sunlight positively-charged air from radioactive materials in the soil will be drawn out leaving negative ions which are more readily absorbed in soil capillaries.
2. Precipitation Theory--C. T. R. Wilson introduced a theory in which he assumed that rain drops carry down enough charge to maintain the earth's charge. He assumed that most rain carries a negative charge. However, all observers seem to find a preponderance of positive charge on rain with the ratio of positive to negative being about 2.4 to 1.
3. Lightning Flashes--Over the whole surface of the earth there are on the average about 100 flashes

of lightning per second. As the gradient during a thunderstorm is generally negative this constitutes a continuous addition of negative charge to the earth.

4. Point Discharges--C. T. R. Wilson pointed out that brush discharges from trees, houses, bushes, and even blades of grass during thunderstorms, when the fields are strong, and usually negative, would account for a large part of the negative charge on the earth.
5. Many other theories involving extremely penetrating radiations have also been set forth.

In the way of a summary of the above theories, and their relative effects, observations taken over a period of years by Wormell at Cambridge are quite interesting. Wormell³ gives an estimate of the annual "electrical balance sheet" of a square kilometer of ground.

Coulombs/sq.km./year		
By point discharge	gained	-100
By lightning	gained	-20
By atmospheric conduction	lost	-60
By precipitation	lost	-20
Net gain of negative charge on earth		-40

³Wormell, Proc. Roy. Soc. A, 115, p. 443 (1927)
Proc. Roy. Soc. A, 127-128, p. 567 (1930)

It thus seems possible that a combination of all of these factors perhaps may account for the maintenance of the earth's negative charge.

SPACE CHARGE

Space charge is defined as the net quantity of electricity (sum of positive and negative ions) per unit volume. It is generally a positive quantity, and amounts on the average to from .02 to .04 E.S.U./cubic meter. Many factors affect both its sign, and its magnitude. For example, during very humid weather just before a storm it often has a negative value. The presence in the air of smoke, dust, rain, snow, etc., affects the space charge markedly.

* * * * *

PRESENT PROBLEM

The present piece of research has as its aim, A Measurement of the Diurnal Variation of the Potential Gradient, and the Space Charge, with a Correlation Between These Elements and the Meteorological Elements.

The weather elements to be considered are the temperature, the relative humidity, the barometric pressure, and the wind velocity and direction. The pollution of the air by smoke etc. will also be considered.

Of course the most ideal location for atmospheric electricity measurements is a broad, flat field free from trees, buildings, etc., and completely removed from the disturbing influences of large cities. In that respect the present location is unfortunate--measurements being taken atop the Physics Building which is surrounded on three sides by other buildings and on the north by a heavily wooded area (see Fig. 1). In addition to this it is located on top of a hill, and in general in the path of the prevailing southwest winds which have already blown over the industrial sections of the city. It is true, nevertheless, that the measurements taken do at least represent in a qualitative, if not quantitative, way the variations in the potential gradient. It was found possible also to make several measurements in the way of determining a reduction factor. This work was done on the University Parking Lot some 0.3 of a mile to the east of the Physics Building. The location was not ideal by any means but was the only possible place that could be found within a radius of some two or three miles of the Physics Building. Our measurements were in themselves interesting but it is doubtful if their application as a reduction factor to the other measurements would have much significance. The method of determining the reduction factor will be discussed in detail later.

The general basis of all potential gradient measurements is the determination of the potential difference between the ground and an insulated conductor a known height above the ground or between two known points in air a known distance apart. The chief difficulty in such measurements is the problem of securing good insulation.

Measurements of the space charge involve merely the determination of the total charge in a known volume of air. The chief difficulty here, in addition to one of insulation, is to obtain an instrument sensitive enough to make the measurements.

EXPERIMENTAL SET-UP FOR PRESENT PROBLEM

Part of the apparatus was located on the roof of the Physics Building, and the remaining portion of it in a room immediately under the roof on the fifth floor of the building. As a matter of convenience, all of the apparatus on the roof will be described first.

POTENTIAL GRADIENT MEASUREMENTS

The insulated conductor was an aerial made of No. 18 bare copper wire 24 m. long. The aerial was held 10 m. above the roof by two wooden posts. The wire was supported at each end by a sulphur insulator (see Fig. 2). The

insulator consisted of a brass tube BT 10 cm. long and 3.5 cm. in diameter, with a brass rod BR embedded in sulphur S. PS was a protecting sleeve of metal which could be slid on and off--it served the purpose of protecting the sulphur from the weather, and had the advantage that it could be slid back when it was necessary to clean the sulphur surface. The aerial was connected to the small hole in the end of the rod BR. To the loop at the other end of the insulator was fastened a rope which ran through a pulley at the top of the supporting posts--thus making it possible to raise and lower the whole assembly. Two small ionium collectors were attached to the midpoint of the aerial, thus enabling it, through their ionizing action, to be brought to the potential of the surrounding layer of air in approximately 30 seconds. The lead-in ran from the aerial to a point about 6 m. from one of the supporting posts where it was connected to one end of an insulated conductor leading through the walls of a small cupola on top of the roof (see Fig. 3). The other end of this conductor was directly above the ceiling of the research room. The lead-in (see Fig. 4) consisted of a brass tube BT about 36 cm. long and 2.5 cm. in diameter, embedded in the wall W. BR was a brass rod threaded on each end to accommodate a knurled nut, and completely insulated from the brass tube

by sulphur plugs S. PS was a metal can which slipped over the rod, and protected the sulphur insulator where it was exposed to the weather on the outside of the wall. From the end of this rod the lead-in continued to the torsion-head of the electrometer.

SPACE CHARGE APPARATUS

The air intake for the space charge measurements consisted of several sections of 4 inch stovepipe projecting some 5 feet above the level of the roof (see Fig. 3). This intake led through the roof to the bottom of the Faraday pail (collecting system) inside. For part of the work, the end of the air intake was surrounded with a grounded wire cage. This was done to see what effect, if any, was caused by removal of the earth's field.

WEATHER INSTRUMENTS

Also on the roof was located a standard instrument shelter, housing a thermograph and a hygrometer (see Fig. 5). These instruments furnished a continuous daily record of the temperature, and the relative humidity.

APPARATUS INSIDE OF THE BUILDING

The experimental work was conducted in a photographically dark room 7.8 ft. by 9.5 ft., and 7.2 ft. high

located on the fifth floor of the Physics Building.

POTENTIAL GRADIENT MEASUREMENTS

Potential gradient measurements were made with a Dolzalek quadrant electrometer of fairly low sensitivity (3 volts/mm. at a scale distance of 59 cm.). The instrument was magnetically damped. The instrument, so damped, operated to give a much steadier deflection. The electrometer was connected heterostatically (see Fig. 6). One quadrant of the electrometer E_p was connected through a grid-leak GL to a 6 volt battery B, the negative side of which was grounded. The other quadrant was grounded. It was possible, by means of a knife switch KS (all parts of which were embedded in sulphur), to connect the needle of the electrometer to the calibrating batteries CB, to the aerial A, or to the ground through the grounding switch GS. (The purpose of the grid-leak was to prevent the burning out of the batteries or the electrometer suspension in case the needle accidentally touched one of the quadrants). At the beginning of each run, and occasionally, at the end, a calibration was made. During operation the electrometer was, of course, connected to the aerial. Measurements were made automatically, and were photographically recorded. Bromide paper 6 inches wide was fastened to the drum of a chronograph, the period of which was 24 hours. A flat vane on

the axle of the drum was made to throw off a switch, turning out the lamp at the end of each record, thus preventing superposition of two successive records.

SPACE CHARGE MEASUREMENTS

Space charge measurements were made after the manner suggested, and used by Obolensky⁴ and employed later by Dwight⁵. A Dolzalek electrometer of very high sensitivity (800mm. per volt at 62 cm. scale distance) was employed. The electrometer was connected heterostatically as shown (see Fig. 7). The needle of the electrometer E_q was connected through a grid-leak GL to a battery B of about 160 volts. One quadrant was grounded, and the other was connected to the Faraday pail (see Fig. 8), which consisted of a brass cylinder BT, 24 cm. long, and 10 cm. in diameter. The top of the pail was poured full of sulphur S, and was threaded on to the cylinder as shown at TJ. Inside of the pail was another hollow cylinder T which could be slid over a brass ring embedded in the sulphur and thus held in the position shown. This cylinder was tightly packed with steel wool, and was connected to the electrometer as shown. The electrometer connection could be unscrewed, allowing

⁴Obolensky, Ann. d. Phys., 4th ser., v. (77), p. 644 (1925).

⁵Dwight, "Thesis" (Atmospheric Electricity), University of Cincinnati Library (1931).

the inner cylinder to be removed for the purpose of cleaning the sulphur S. One end of the pail was connected to the air vent, and the other, by means of a rubber tube, to the aspirator. A gasmeter measured the volume of air aspirated. The clock in the main circuit controlled the length of time that air was drawn into the pail. The electrometer could also be connected (see Fig. 7), by means of the knife switch KS, to the calibrating battery CB, or, by means of the switch MS, to the ground. Recordings were made in the same manner as those of the potential gradient--both records, in fact, being made on the same strip of bromide paper. Light from two small lamps was focused, by means of small concave mirrors attached to the electrometer needles, on to the photographic paper. (To eliminate the presence of stray electric fields, all of the batteries were housed in boxes covered with grounded screen wire).

The theory for the space charge measurements is as follows: If v_t be the volume of air drawn through the pail in the time t , and d be the deflection of the electrometer of sensitivity s , the charge is given by the expression

$$q = \frac{c \times d}{s}$$

where c is the capacitance of the whole system, including the electrometer, Faraday pail, and connections. The space charge will then be given by

$$Q = \frac{q}{v_t} = \frac{c}{s} \times \frac{d}{v_t}$$

In practice the following values were found:

$$c = 148.8 \text{ cm.}$$

$$s = 800 \text{ mm. per volt}$$

$$v_t = 40 \text{ cubic feet}$$

$$t = 4 \text{ min. 42 sec.}$$

and remembering that

$$1 \text{ E.S.U.} = 300 \text{ volts}$$

$$1 \text{ cu. m.} = 55.5 \text{ cu. ft.}$$

The average value found for d will be used here to show a sample calculation.

$$d = 30.2 \text{ mm.}$$

Putting in the equation above these values the average value for Q is found to be .0165 E.S.U./cubic meter.

It was desired in the present set-up to obtain simultaneous, continuous, and automatic recordings of the potential gradient, and the space charge. This has been done to the following extent:

1. Records were made automatically on strips of solar bromide paper.
2. Records were taken continuously except for days having a rainy or stormy character, and except for Sundays.
3. By means of a system of magnetic relays, mercury

switches, and an electric clock, it was found possible to take potential gradient readings for 55 minutes, and space charge readings for 5 minutes of every hour.

DESCRIPTION OF OPERATION OF APPARATUS

The system operated as follows:

In normal operation the lamp for the potential gradient recording is turned on, and the aerial is connected to the needle of the electrometer. At approximately 28 minutes past each hour an electric clock operates a system of relays, and switches which do the following things:

1. Turns off the lamp for the potential gradient recordings.
2. Grounds the needle of the potential gradient electrometer.
3. Turns on the lamp for the space charge recording.
4. Removes the ground connection from the Faraday pail.
5. Turns on the electric motor operating the aspirator.

At approximately 28 minutes before each hour the lamp for the potential gradient recording is again turned on, and the ground is removed from the from the p. g. electro-

meter needle--the other lamp is shut off and the space charge apparatus is grounded. This set of operations is repeated each hour until at the end of the 24th hour the chronograph drum throws off a switch breaking the entire circuit.

The complete wiring diagram is shown in (Fig. 9). The most important part of the circuit is an electric clock equipped with a mercury cup at the bottom of the dial through which the long hour hand of the clock passes once each revolution, and, in passing, completes the circuit for the magnetic relay MR_1 . This relay operates four mercury switches, viz.:

1. Switch operating lamp for the space charge electrometer.
2. Switch operating magnetic relay MR_2 which in turn operates to remove the ground connection from the Faraday pail.
3. Switch operating magnetic relay MR_3 which turns off lamp for the p.g. electrometer, and at the same time grounds this instrument.
4. Switch operating magnetic relay MR_4 which in turn operates the mercury switch which operates the blower motor for the aspirator.

The two knife switches operated by the chronograph shut

off the potential gradient lamp, and break the main relay circuit at the end of every 24-hour period. The short-circuiting switches SC are placed in the circuits in order that any part of the set-up may be operated by itself whenever it is so desired--generally during calibration. For a picture of the apparatus, see Fig. 10.

The most difficult problem in this work, i.e., after the apparatus had been constructed, assembled and put in working order, was the problem of insulation. As has been previously mentioned, sulphur insulation was used throughout--sulphur when kept clean and dry being one of the best insulators known. It was thus necessary every day to clean each sulphur insulator with sandpaper. This was a very laborious process for there were eight such surfaces to be cleaned every day. Because of the fact that the sulphur insulation was apt to break down during damp weather, records taken at such times were necessarily discarded.

Records were made as continuously as was found possible, from the middle of April until the middle of December 1937, except during the month of September when no records were kept. Observations were not made on Sundays. As was mentioned before, simultaneous measurements of the meteorological elements were taken, consisting of daily records of the temperature, barometric pressure, and

relative humidity. Wind, i.e., the wind directions and velocities, were obtained from the records of the Abbe Observatory which is located at approximately the same elevation, and just a mile and a half to the north. In addition to these elements, the character of the day was always noted and recorded.

Two typical records of the electrical elements are shown (see Fig. 11). The record represented by heavy lines broken at regular intervals of one hour is the potential gradient record. The short lines extending cross-wise of the record at hourly intervals are records of the space charge. The maximum displacements of these lines were, by comparison with the calibration marks, seen at the top of the records, translated into actual values.

RESULTS

Records were obtained for 87 days during the period April 1937 to December 1937. Records taken on days during which there was more than a trace of precipitation were thrown out, and not counted. The records obtained include approximately 2,000 separate readings on the space charge, and a similar number for the potential gradient, for only hourly values were read from the continuous record of this element.

Since in the present work the purpose is primarily a correlation between the various elements the following procedure will be followed: In view of the topography of the region, and the necessarily unfortunate location of the observatory with regard to the accurate quantitative measurements of the potential gradient (this point has already been mentioned on page 12) it seems advisable for the present, at least, to consider the results as merely qualitative. Hence all graphs for this element will be plotted, for the purpose of convenience, in arbitrary units. Later on the procedure for the determination of a reduction factor will be described. At this later time the advisability of applying the factor so obtained to the whole series of observations will be discussed.

For the purpose of convenience in plotting graphs, etc., the values for the space charge will also be considered in arbitrary units. (In both cases these arbitrary values are really the actual displacements in cm. as taken from the daily records). It is to be understood, however, that in this latter case definite values can be assigned for the space charge.

A very comprehensive set of graphs has been plotted with all five of the elements, viz., potential gradient, space charge, temperature, relative humidity, and wind velocity being shown on one graph. The following graphs

were plotted:

1. Graph on which all of the records were averaged.
2. Graph on which only the observations for the most complete days were used.
3. Graph of a typical day for each month.
4. Graphs for three different periods of consecutive days.
5. Graph showing the annual variation of the elements.

In addition to these, as a preliminary analysis, a graph showing the variations of all of the elements for each individual day was prepared. This work has not been included in the present report since it occupies some 20 feet of graph paper, and since it is possible to draw more accurate conclusions from a number of records averaged together than from just a single day's record. A more complete description of the graphs will be given later.

GENERAL DISCUSSION OF RESULTS

SPACE CHARGE

In general, a maximum occurred in connection with a maximum of temperature, and wind velocity, and a minimum of relative humidity and potential gradient. There were 56 days on which a definite maximum occurred between the 15th and 17th hours.

A minimum in space charge occurred in connection with a minimum in temperature, and wind velocity, and a maximum of relative humidity. On 48 days a definite minimum in the space charge occurred around the 5th hour. The majority of the other days, during which observations were taken, and not included in the above classes, had no definite maxima or minima--a very few had them occurring at different times. It is believed, though that the type of day described above is characteristic of a typical day.

POTENTIAL GRADIENT

Of the 51 days with fairly complete records, 33 show a definite maximum between the 7th and 9th hours. Seven days have a maximum at about midnight, 5 of these occurring in connection with a northeast wind. Nine days have a maximum at about the 18th or 19th hour. These seem to occur when there is no marked variation in temperature or relative humidity.

Minima in the potential gradient seem to occur in mid-afternoon.

DISCUSSION OF THE GRAPHS

Graph 1. (Average of all records for 1937) (See Fig. 12)

The maximum value of the space charge occurs at 15 h. 30 m., that of the temperature at 15 h., and that of the

wind velocity at 14 h. The minimum value of the space charge occurs at 4 h. 50 m., that of the temperature at 5 h., and that of the wind velocity between 3 h. and 5 h. It seems then that there is a close correlation among these three elements. Ebert's Soil Respiration theory, where-by more positive ions are sucked out of the ground by the action of winds, sunlight (period of highest temperature), and during periods of low barometric pressure, would probably account for it. The diurnal variation of the barometric pressure is such that a maximum occurs at 10 h. and 22 h., and a minimum at 4 h. and 16 h. A possible explanation of the occurrence of a high space charge during the time of low relative humidity is that during such times there is a smaller number of slow negative ions and consequently a relatively greater number of positive ions. In the morning a minimum space charge occurs with a maximum relative humidity because water particles, and perhaps smoke particles, act as nuclei more readily for negative than for positive ions (greater mobility). This reasoning assumes in general that space charge is due to the large or Langevin ions. This is true because in polluted air the number of large ions greatly outnumber the small ions. The large ions also are quite frequently multiply-charged--a number of small ions being grouped in clusters about a condensation nucleus.

The variation of the potential gradient, which has a maximum occurring at the 8th hour, and a minimum during the afternoon, can be explained quite readily on the basis of the various factors affecting the conductivity of the air.

Let us remember that in general the conductivity λ is given by the expression

$$\lambda = k n e$$

and also that the air-earth current (i) is very approximately constant

$$i = X \lambda$$

Hence to account for a maximum gradient we need merely show that a minimum conductivity exists. An increase in relative humidity means an increase in the number of slow or Langevin ions, formed by the union of small ions with condensation nuclei. This increase in ions of low mobility means a low conductivity and hence a large value for the potential gradient. Less important, but nevertheless factors in the right direction, are the minima of the temperature, and the wind velocity, and their consequent reduction in the ionic mobilities.

We have shown that a variation in the conductivity will satisfactorily account for the observed variation in the potential gradient. It is now necessary to account for the change in the conductivity of the air throughout the day. This can be done on the basis of the variation in the

amount of atmospheric pollution, i.e., smoke, dust, etc. Whipple⁶, working at the Kew Observatory, has shown that by considering the two factors, (1) the times of the maximum production of smoke, and (2) the variation throughout the day of the stability of the air, that a satisfactory explanation for the total amount of pollution, and the way in which it affects the potential gradient, can be given. The variation in the amount and time of smoke pollution, etc., here is essentially the same as in the case cited above. It is believed therefore that the assumption made by Whipple will apply equally well to the present case. Whipple shows, (see Fig. 13) that a maximum in the amount of pollution exists about the 8th hour in the morning due to the increased amount of smoke production, and to the fairly stable condition (little wind, and generally stagnant condition of the air) of the atmosphere at this time. Later in the day although the production of smoke continues, the stability of the air is much lower--the effect of the wind and the convection currents being to disperse the smoke particles. Consequently, the total amount of pollution decreases. This then would satisfactorily account for the early morning minimum in the potential gradient, followed by a maximum around the 8th hour, and

⁶Whipple, Q.J.R. Met. Soc. 55, p. 351-360, (1929).

then a subsequent decrease during the afternoon. Whipple found that another maximum, i.e., a secondary maximum, in the potential gradient occurs about the 18th hour that could be accounted for by assuming an increase in the stability of the atmosphere towards evening while the rate of production of smoke is still fairly high. In the present observations such a maximum was found on quite a number of the daily records, and is evident on most of the graphs representing typical days for each month--the maximum occurring, however, several hours later. When all of the results are averaged and plotted the existence of this secondary maximum is not evident--the graph showing in general only a single daily maximum. It is quite possible to account for this on the basis that local conditions hide the more general variations of the potential gradient. For example, the nonexistence of a second maximum around the 18th or the 20th hour can probably be explained on the following basis: As a general rule the stability of the atmosphere increases after sundown. This is due to the absence of convection currents, etc. Now in the present case where the observations were taken on top of the Physics Building it is quite reasonable to suppose that radiations from the building exist long after dark, thus preventing a stagnation of the air, with, as we have seen, a consequent increase in the potential gradient. Another and possibly

important factor, is that during the summer months the blowers of the ventilating system of the Physics Building are operated only at night between the hours of 10 p.m. and 6 a.m. This would be equivalent, part of the time at least, to a building radiation, since these ventilators open directly on to the roof.

Graph--(Average of the Most Compete Records) (See Fig. 14)

This graph represents the average results for a group of selected days. The usual meaning attached to a selected day is one on which no negative gradient occurs. Here, however, owing to the fact that so few days were found with a negative gradient, we mean instead, those days during which the weather conditions were up to a certain standard--i.e., days on which not more than a trace of precipitation was recorded. In this graph all of the elements have the same general characteristics, and bear the same relation to each other, as in the first graph. The results herein depicted probably are the more accurate because they represent the average of a large number of records taken under the most ideal conditions of weather, etc.

Graph--(Typical Day for Each Month) (See Figs. 15 to 22)

The following graphs are plots of all of the elements for eight typical days--one day being selected from each month of observation. The day selected was, in general,

one of a series of successive fair days, i.e., from a meteorological standpoint. Single days were selected in the belief that by direct comparison of all of the various elements at any one time it would be possible to obtain some definite sort of correlation among these elements, i. e., for example, it might be possible to see just how the potential gradient is affected by changes in the space charge, temperature, relative humidity, wind velocity and direction, air pollution, etc.

As a matter of general interest a wind rose has been included for each month to show the percentage of time that the wind blows from the direction indicated by the arrows.

In discussing, and in attempting to explain these graphs we will make use of the following procedure. We assume in the first place that the potential gradient varies throughout the day in accordance with a world wide 24-hour wave, and perhaps in addition with a smaller 12-hour wave. Further, we assume that local conditions can and do account to a great extent for many modifications and irregularities which exist. In the present work we try to explain the diurnal variation of the potential gradient and of the space charge on the basis of all of the factors which might affect them.

The possible effect of air pollution has been considered in the following way. A chart has been prepared (see Fig. 23) showing the location of the dirtiest parts of the city with respect to the University where the observations were taken. Accordingly we should expect that a wind blowing from the southwest quarter (the prevailing direction here) would contain a great deal more smoke, dust, etc., than a wind from the north.

The effect of an increase in wind velocity is to increase the general turbulent condition of the atmosphere with, as we have shown (see Fig. 13), a general reduction in the magnitude of the potential gradient, and (due to soil respiration) a general increase in the space charge.

If we refer now to the graph (a typical day for April, Fig. 15) we see that: (1) the potential gradient has a maximum value at the 8th hour, and a secondary maximum at the 22nd hour; with a minimum occurring between the 12th and the 19th hours; (2) the space charge has a maximum at the 14.5th hour, and secondary minima at 11.5, 1.5, and 18.5; with a minimum value at the 22.5th hour, and a secondary minimum at the 3.5th hour.

The morning maximum in the gradient occurs simultaneously with a shift in the wind from the northeast to the south. Reference to Fig. 23 shows that such a wind shift could quite feasibly account for an increase in the

gradient. During the middle of the day the gradient is low (see Fig. 13) in spite of the fact that the wind continues from the south and west quarters. The gradual increase in the gradient to a secondary maximum at the 22nd hour occurs simultaneously with a wind shift from the northwest to the northeast (a direction for which we would expect the gradient to be higher). In general the space charge curve seems to follow that of the wind velocity and the temperature so that variations in this element may possibly be ascribed to soil respiration.

Such a discussion could be carried out for each of these eight monthly graphs--however, since such discussions would for the most part be almost identical, this will not be done, but instead a summary of each record will be given.

April (see Fig. 15)

<u>Elements</u>	<u>Time of occurrence of max. and min.</u>			
	Max.	Sec. Max.	Min.	Sec. Min.
Potential Grad.	8	22	12-19	.....
Space Charge	14.5	11.5, 1.5, 18.5	22.5	3.5

May (see Fig. 16)

Potential Grad.	6	9, 23, 17, 1	3	21, 13
Space Charge	18.5	.....	4.5	.....

June (see Fig. 17)

Potential Grad.	8	4, 23, 17	13, 19, 6	3
Space Charge	13.5-16.5	....	5	.....

<u>Elements</u>	<u>Time of occurrence of max. and min.</u>			
	Max.	Sec. Max	Min.	Sec. Min.
	<u>July</u> (see Fig. 18)			
Potential Grad.	6	2	23-24	12-14,3
Space Charge	11.5	14.5,17.5	1.5,3.5	6.5,8.5
	<u>August</u> (see Fig. 19)			
Potential Grad.	6	20-21,23,12,16	1	9-10,13,17,22
Space Charge	14.5	3.5	2.5,1.5	.....
	<u>October</u> (see Fig. 20)			
Potential Grad.	7	3,21	24	13-14,22-23,4-5
Space Charge	16.5-17.5	21.5	20.5	15.5
	<u>November</u> (see Fig. 21)			
Potential Grad.	7	5,21-22	24	16-19
Space Charge	12.5	17.5,6.5,22.5	0.5	21.5
	<u>December</u> (see Fig. 22)			
Potential Grad.	7	23	3	18-19,24-1
Space Charge	....	....	....	.....

Close inspection of the above summary will reveal the fact that in general the results are fairly consistent--the times for the various maxima and minima differing only slightly throughout.

In addition to the graphs so far discussed four other

graphs were plotted.

Graph (see Fig. 24) representing the average of the results for the period May 14-28, 1937.

Graph (see Fig. 25) representing the average of the results for the period July 22-24, 1937.

Graph (see Fig. 26) representing the average of the results for the period August 17-25, 1937.

Graph (see Fig. 27) representing the annual variation of the elements.

In the way of a summary of all of the graphs and especially of those representing a large number of observations, the following facts are recorded.

SUMMARY

<u>Elements</u>	<u>Time of Max.</u>	<u>Time of Min.</u>
Potential Gradient	8 h.	12 h. to 16 h.
Space Charge	15 h. 30 m.	4 h. 30 m.
Temperature	15 h.	5 h.
Relative Humidity	6 h.	15 h.
Wind Velocity	14 h.	3 h. to 5 h.

In addition to the 8 o'clock maximum of the potential gradient a secondary maximum of very much smaller amplitude sometimes occurs around the 23rd hour. In general however, the single daily maximum seems to be the most characteristic.

The above results for the potential gradient agree quite well with the results found elsewhere by other observers. For example, Swann⁷ has found maxima at the 8th and 21st hours, with a minimum at the 4th and 14th hours for the summer months, and for the winter months a maximum at the 10th, and 19th hours. Dwight⁵, at the University of Cincinnati, found a maximum at the 21st and 9th hour with a minimum during the early morning hours.

The times found for the occurrence of the maximum and the minimum of the space charge do not agree very well with those found by other observers elsewhere. However, this element is known to vary greatly with different localities, and with local conditions. For part of the work, as illustrated in Fig. 3b, the air intake for the space charge measurements was surrounded with a grounded wire cage. This was done for the purpose of eliminating the presence, and possible effect of the earth's field. For this set-up

⁷Swann, J. Franklin Insti., Vol. 188, Nov. 1919

⁵Dwight, "Thesis" (Atmospheric Electricity), University of Cincinnati Library (1931).

the ions drawn into the Faraday pail were those which drifted into the wire cage. The results obtained here seemed to show that when the action of the earth's field was removed the magnitude, and the variation from the mean value of the space charge were reduced slightly. A number of observations were also taken with a drying agent inserted at the bottom of the Faraday pail. The results (slightly higher space charge) emphasize the probable correctness of the relation between the space charge and the relative humidity as found in the present observations, and illustrated quite well in Fig. 14.

In consideration of the above facts, and also of the fact that the space charge electrometer and system was found to be practically leak free, it is felt that the results obtained here for the space charge do accurately represent the existing conditions.

DATA

Data for just one of the graphs (see Fig. 12) are given below. The potential gradient readings are recorded for the even hour, and the space charge for the intervening half hours. The potential gradient is given in arbitrary units, each of which equals approximately 30 volts (see page 44). The space charge is also given in arbitrary units each one of which equals 0.0055 E.S.U./cubic meter.

The temperature is given in degrees Fahrenheit, the relative humidity in percent, and the wind velocity in miles per hour.

A short description of each of the figures, pictures, graphs, etc., follows at the end of this paper.

Data (For graph--average of all records)

<u>Hour</u>	<u>Pot. Grad.</u>	<u>No. Obs.</u>	<u>Sp. Ch.</u>	<u>No. Obs.</u>	<u>Temp.</u>	<u>Rel. Hum.</u>	<u>Wind Vel.</u>
0. 0.5	1.24	51	2.7	51	63.9	79.7	5.4
1 1.5	1.52	51	2.52	51	62.4	81.7	5.2
2 2.5	1.28	49	2.43	51	61.6	83.3	5.3
3 3.5	1.39	49	2.43	50	60.8	84.7	4.9
4 4.5	1.65	48	1.96	48	60.1	85.6	5.0
5 5.5	1.54	48	2.38	47	59.5	86.9	4.9
6 6.5	1.86	49	2.43	46	59.3	87.0	5.3
7 7.5	2.04	44	2.50	45	61.8	84.6	5.3
8 8.5	2.41	44	2.57	44	64.1	78.4	5.7
9 9.5	2.25	43	2.75	43	67.8	73.2	5.9
10 10.5	1.34	45	3.03	50	70.3	66.7	6.5
11 11.5	1.10	51	3.29	52	72.6	62.8	6.9
12 12.5	0.93	50	3.81	50	73.8	58.8	7.2
13 13.5	1.00	49	3.80	43	75.0	56.4	7.4

Data (continued).

<u>Hour</u>	<u>Pot. Grad.</u>	<u>No. Obs.</u>	<u>Sp. Ch.</u>	<u>No. Obs.</u>	<u>Temp.</u>	<u>Rel. Hum.</u>	<u>Wind Vel.</u>
14 14.5	0.99	47	3.80	47	75.6	54.9	7.6
15 15.5	1.06	54	3.94	48	76.2	53.3	7.5
16 16.5	0.96	55	3.80	49	75.7	53.5	7.5
m17 17.5	1.12	57	3.80	54	74.5	55.2	7.4
18 18.5	1.06	55	3.70	54	73.3	57.3	7.0
19 19.5	1.21	58	3.86	54	70.7	61.3	6.4
20 20.5	1.06	53	3.13	55	68.9	66.5	5.4
21 21.5	1.17	55	2.84	54	67.4	70.9	5.5
22 22.5	1.00	53	2.84	52	66.0	74.4	5.1
23 23.5	1.20	51	2.75	53	64.7	77.3	5.2

Average	1.35	3.02
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DETERMINATION of a REDUCTION FACTOR

The need for the determination of a reduction factor has previously been cited (see page 12). The University Parking Lot was finally selected as the most suitable spot to make the measurements. The location of the lot is approximately 0.3 of a mile east of the Physics Building on the north side of University Avenue. The lot has a cinder surface, and is bordered, on three sides by houses, and on the north side by a deep gully. The dimensions of the field are approximately 450 ft. by 150 ft. Three points P_1 , P_2 , P_3 (see Fig. 28) were selected for making the measurements. Three positions were chosen to see what effect if any, the bordering houses and gully had on the potential gradient (see Fig. 29).

Method of Measurement

A sensitive gold-leaf electroscope was used (see Fig. 30) to measure the potential gradient--the deflections of the leaf being read from some distance away by means of a telescope, (see Fig. 31). The collecting system consisted of an ionium collector held 1 meter above the ground by means of an insulated support. A calibration of the electroscope was made for each of the three points at which potential gradient measurements were taken. The heights of the houses bordering the lot were determined

by means of a sextant.

Results

Calibration curves were made for the electroscope, and from them the following values were obtained for the potential gradient at the points P_1 , P_2 , P_3 :

Position P_1 ---111 volts/meter

Position P_2 --- 93 volts/meter

Position P_3 ---56.5 volts/meter

Observations taken at the same time but on top of the Physics Building with the permanent apparatus seemed to indicate a much lower value. The factor in this case apparently was of the order of 2.

Further observations were made on the same site for a whole day, during which readings were taken every 15 minutes. The results of this work not only confirmed the results mentioned above but also that the diurnal variation was of the same general character as that which had been found by means of the permanent apparatus.

Three points P_1 , P_2 , P_3 , were selected to make observations for the reason that we wished to determine whether or not the houses bordering the Parking Lot had any effect on the equipotential lines or layers. Observations showed that there was a difference, i.e., the farther the points of observations were removed from the

bordering houses the higher was the reading for the potential gradient. It would seem then that even the measurements taken here did not represent the true value of the potential gradient. Nevertheless it did show that qualitatively the observations were correct.

The best that we can do then is to say that the exact value of the potential gradient cannot be determined here. All things considered, however, it seems safe to say that the average value of the gradient would appear to be somewhat higher than the value of 111 volts/meter found above.

In conclusion we can report that the results seem to indicate that the variations of the local conditions, viz., the temperature, wind velocity and direction, relative humidity, barometric pressure, air pollution, etc., are the main factors which apparently determine the general characteristics of the diurnal variations of the space charge and of the potential gradient--the net results being in general a single daily maximum and minimum for these elements.

Description of Drawings, Graphs, and Pictures

FIG. 1

Plat of the University campus showing the location of the Physics Building with respect to the other buildings.

FIG. 2

Type of insulator used to support the aerial for the potential gradient measurements. The insulator consists of a brass tube BT filled with sulphur S which has embedded in it a brass rod BR to which the aerial is fastened. A metal sleeve FS which is free to slide makes it possible to clean the sulphur surface quite easily.

FIG. 3a

View on top of the roof of the Physics Building, showing the air intake for the space charge measurements. Just to the right of the intake pipe the object seen projecting through the wall is the lead-in for the potential gradient, as is described in Fig. 4. In the background may be seen the instrument shelter, and the ventilators.

FIG. 3b

Air intake for the space charge measurements, surrounded with a grounded wire cage.

FIG. 4

View showing how the collector wire is insulated as it is brought from the aerial outside of the building to the research room on the inside of the building. BT is a brass tube embedded in the wall of the building W. The metal rod BR is insulated at each end by a sulphur insulator S. PS is a protecting sleeve of metal for the insulator exposed to the weather.

FIG. 5

Weather-instrument shelter loaned by the Weather Bureau, housing the hygrograph and the thermograph.

FIG. 6

Wiring diagram for the potential gradient apparatus.

FIG. 7

Wiring diagram for the space charge apparatus.

FIG. 8

Diagram of the Faraday pail used as the collecting system for the space charge. It consists of two concentric cylinders BT and T, insulated from each other by means of the sulphur S. The inner cylinder is packed with steel wool so that when a stream of air is drawn through the system the wool will remove any charge which the air may have, regardless of the type of ions.

FIG. 9

Complete wiring diagram for all of the apparatus used.

FIG. 10a

Inside of the research room showing the two electrometers, the chronograph and drum carrying the sensitized paper, the Faraday pail, the air intake, the master clock, numerous switches, etc.

FIG. 10b

Aspirator and gasmeter used in connection with the space charge measurements.

FIG. 11

An example of the type of photographic records obtained. The heavy continuous line represents the potential gradient and the broken lines the space charge.

FIG. 12

Graph of all of the elements, representing the average of all of the results obtained over the whole period of observation.

FIG. 13

Graph showing the diurnal variation of air pollution, assumed due to the combined effect of smoke production, and the stability (absence of convection currents, etc.) of the air.

FIG. 14

Graph representing the average of the results for a

group of meteorologically selected days throughout the whole period of observation.

FIG. 15 to 22 (inclusive)

Graphs illustrating the variations for all of the elements for a typical day for each month. In addition to a wind rose for the whole month, the hourly directions for the particular day under consideration have been indicated by means of small white arrows drawn along the curve representing the wind velocity.

FIG. 23

Chart showing the location with respect to the University of the regions or parts of the city which are most apt to pollute the atmosphere.

FIG. 24

Graph of the results for the period May 14-28, 1937.

FIG. 25

Graph of the results for the period July 22-24, 1937.

FIG. 26

Graph of the results for the period August 17-25, 1937.

FIG. 27

Graph of the annual variations of the elements.

FIG. 28

Diagram of the University Parking Lot where experiments were conducted for the determination of a reduction factor.

FIG. 29

Picture of the Parking Lot, showing the spot at which observations were made.

FIG. 30

Diagram of the apparatus used for the determination of a reduction factor. E is a sensitive gold-leaf electroscope equipped with a scale as shown. I is the ionium collector, supported by means of a sulphur insulator exactly one meter above the electroscope.

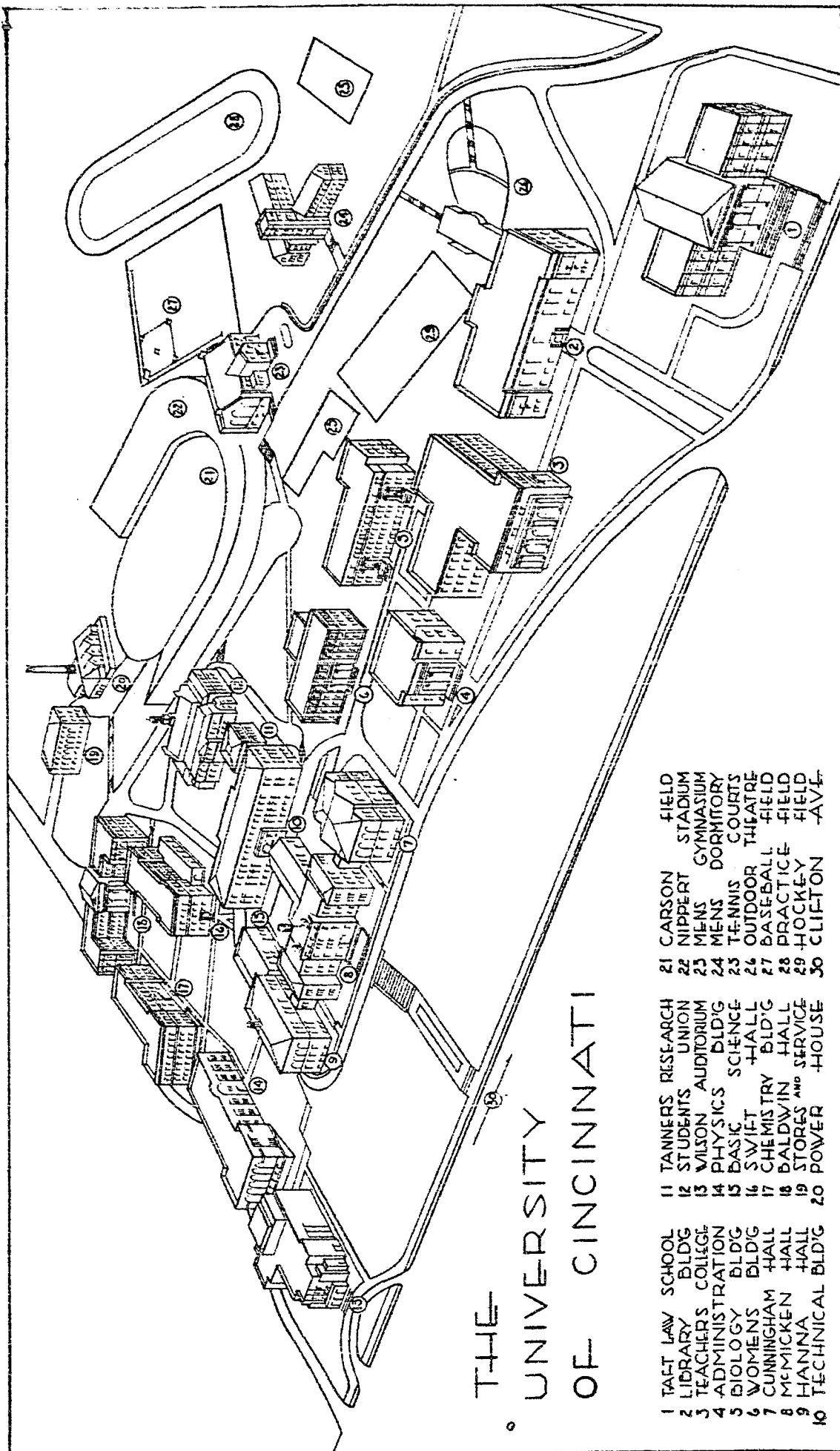
FIG. 31

View of the apparatus used for the determination of a reduction factor. Readings, i.e., deflections of the electroscope, were made by means of a periscope arrangement and a telescope.

* * * * *

ACKNOWLEDGEMENTS

The writer wishes to express his thanks to Professor C. H. Dwight for his constant interest in the problem and to the other members of the Staff for timely suggestions.



THE UNIVERSITY OF CINCINNATI

- | | | |
|---------------------|-----------------------|--------------------|
| 1 TAYLOR LAW SCHOOL | 11 TANNERS RESEARCH | 21 CARSON FIELD |
| 2 LIBRARY BLDG | 12 STUDENTS UNION | 22 NIPPERT STADIUM |
| 3 TEACHERS COLLEGE | 13 WILSON AUDITORIUM | 23 MENS GYMNASIUM |
| 4 ADMINISTRATION | 14 PHYSICS BLDG | 24 MENS DORMITORY |
| 5 BIOLOGY BLDG | 15 BASIC SCIENCE | 25 TENNIS COURTS |
| 6 WOMENS BLDG | 16 SWIFT HALL | 26 OUTDOOR THEATRE |
| 7 CUNNINGHAM HALL | 17 CHEMISTRY BLDG | 27 BASEBALL FIELD |
| 8 McMICKEN HALL | 18 BALDWIN HALL | 28 PRACTICE FIELD |
| 9 HANNA HALL | 19 STORES AND SERVICE | 29 HOCKEY FIELD |
| 10 TECHNICAL BLDG | 20 POWER HOUSE | 30 CLIFTON AVE. |

FIG. 1

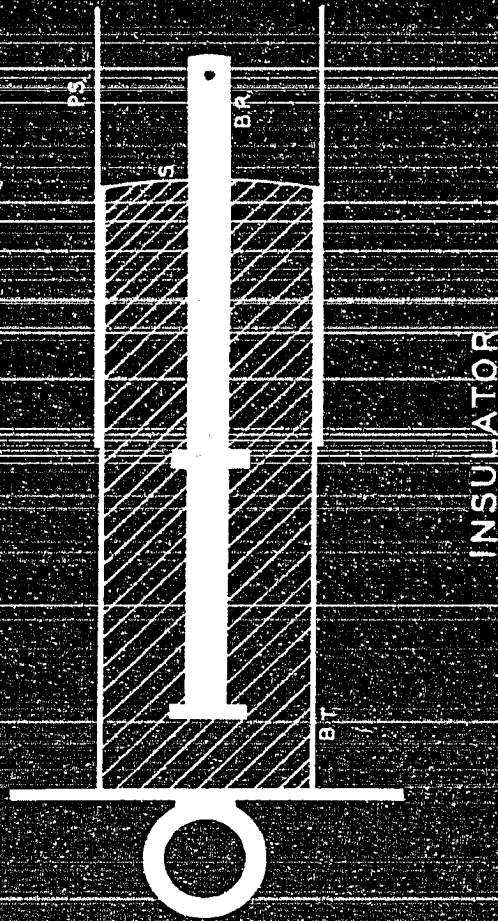


FIG. 2

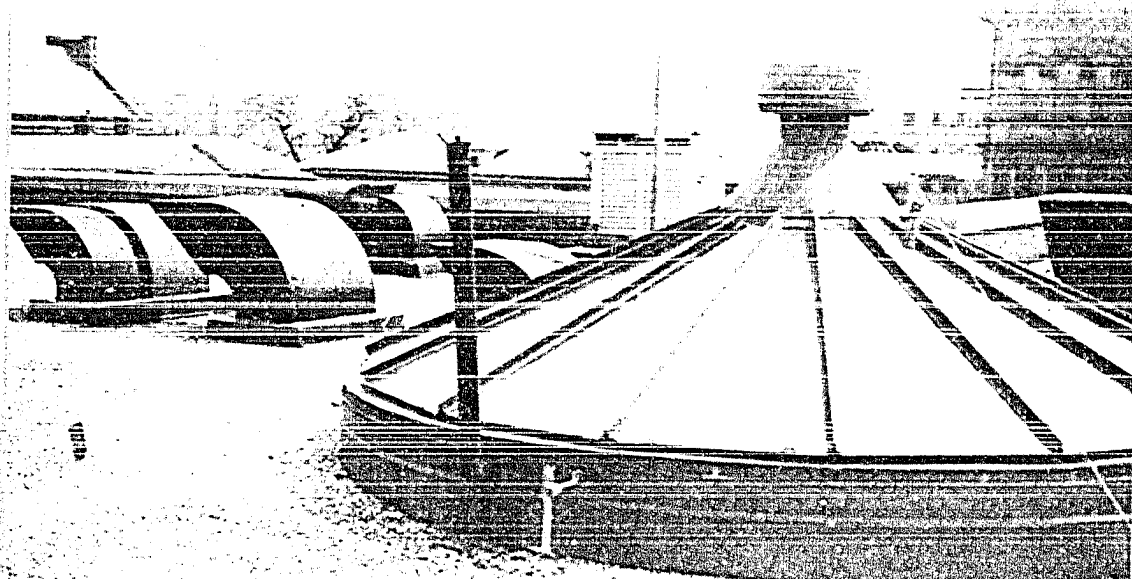


FIG. 3a

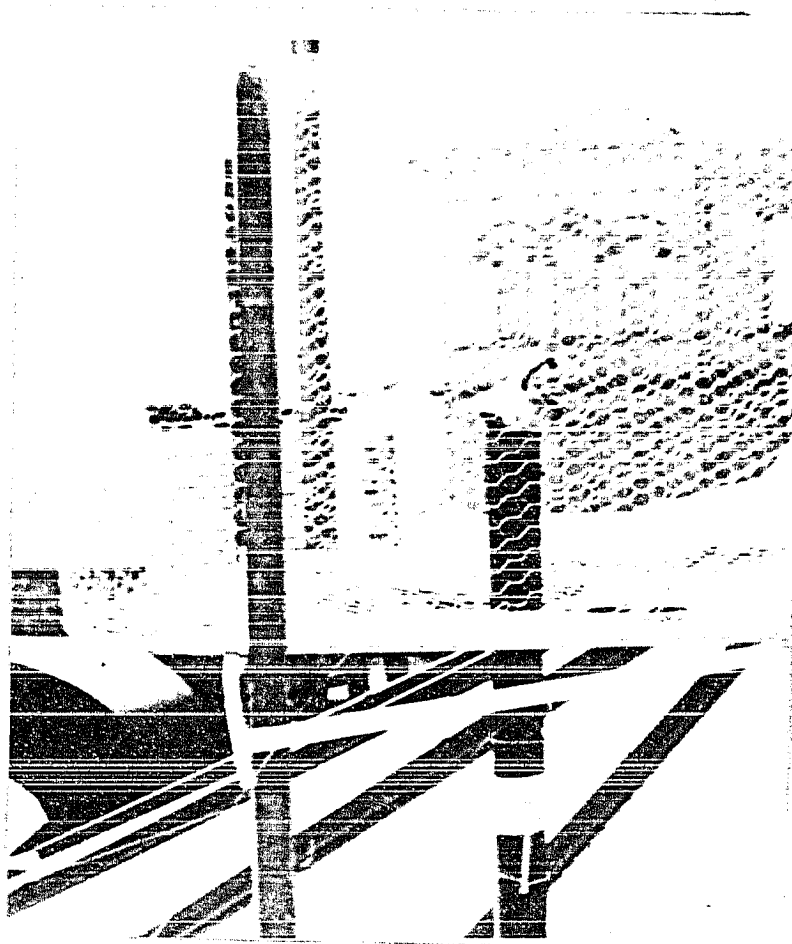


FIG. 3b

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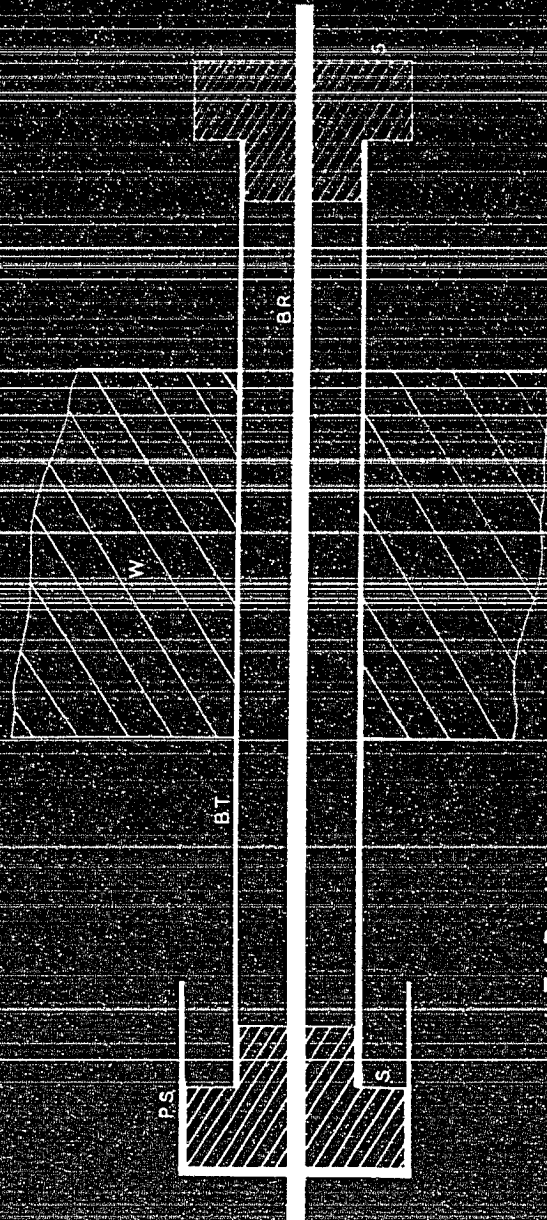


FIG. 4

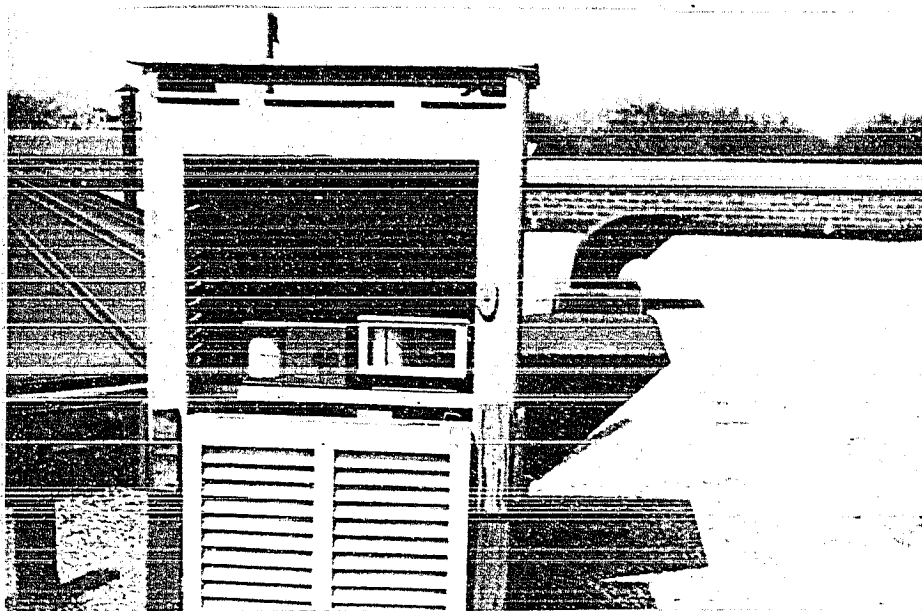
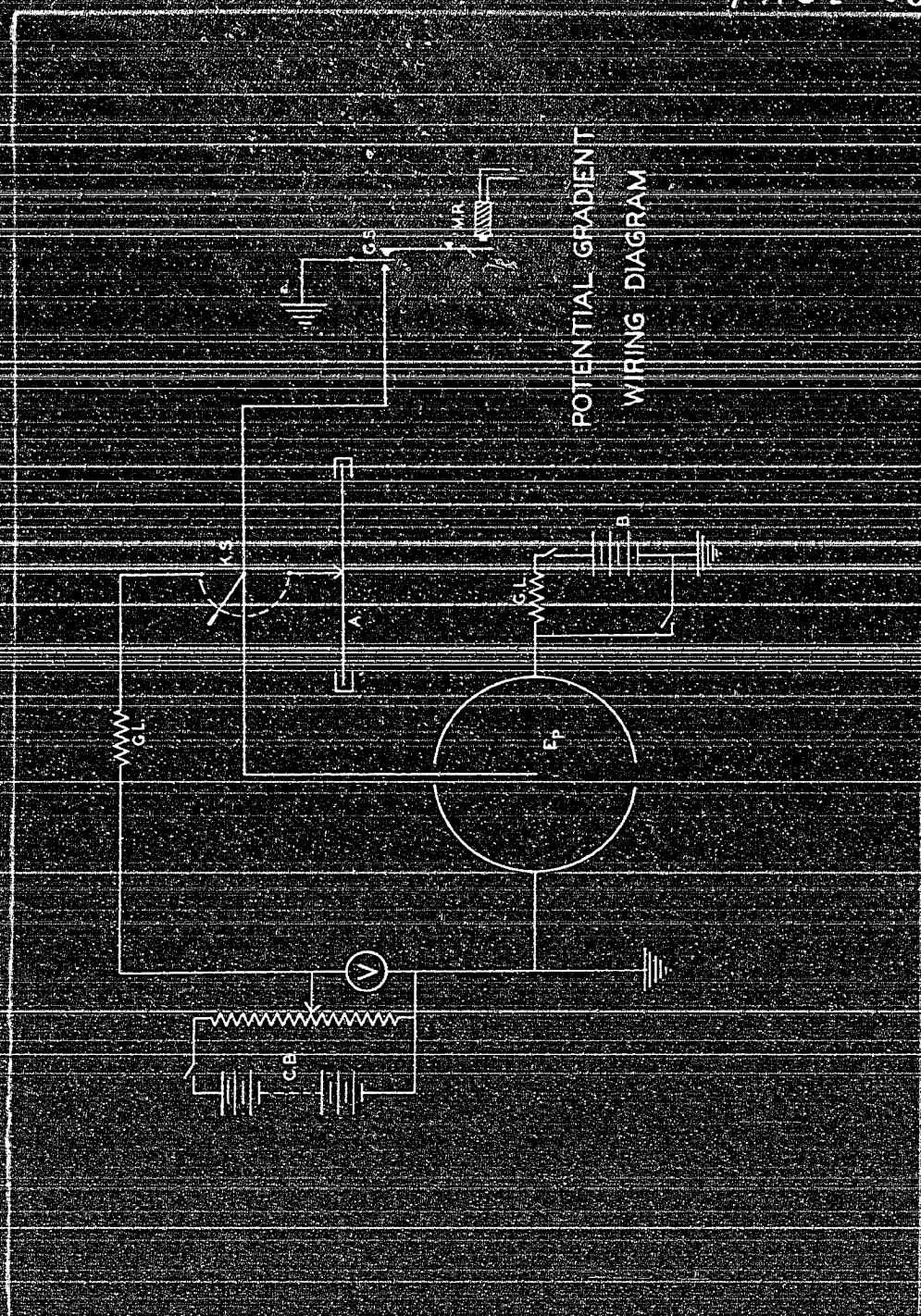


FIG. 5



6
6
1

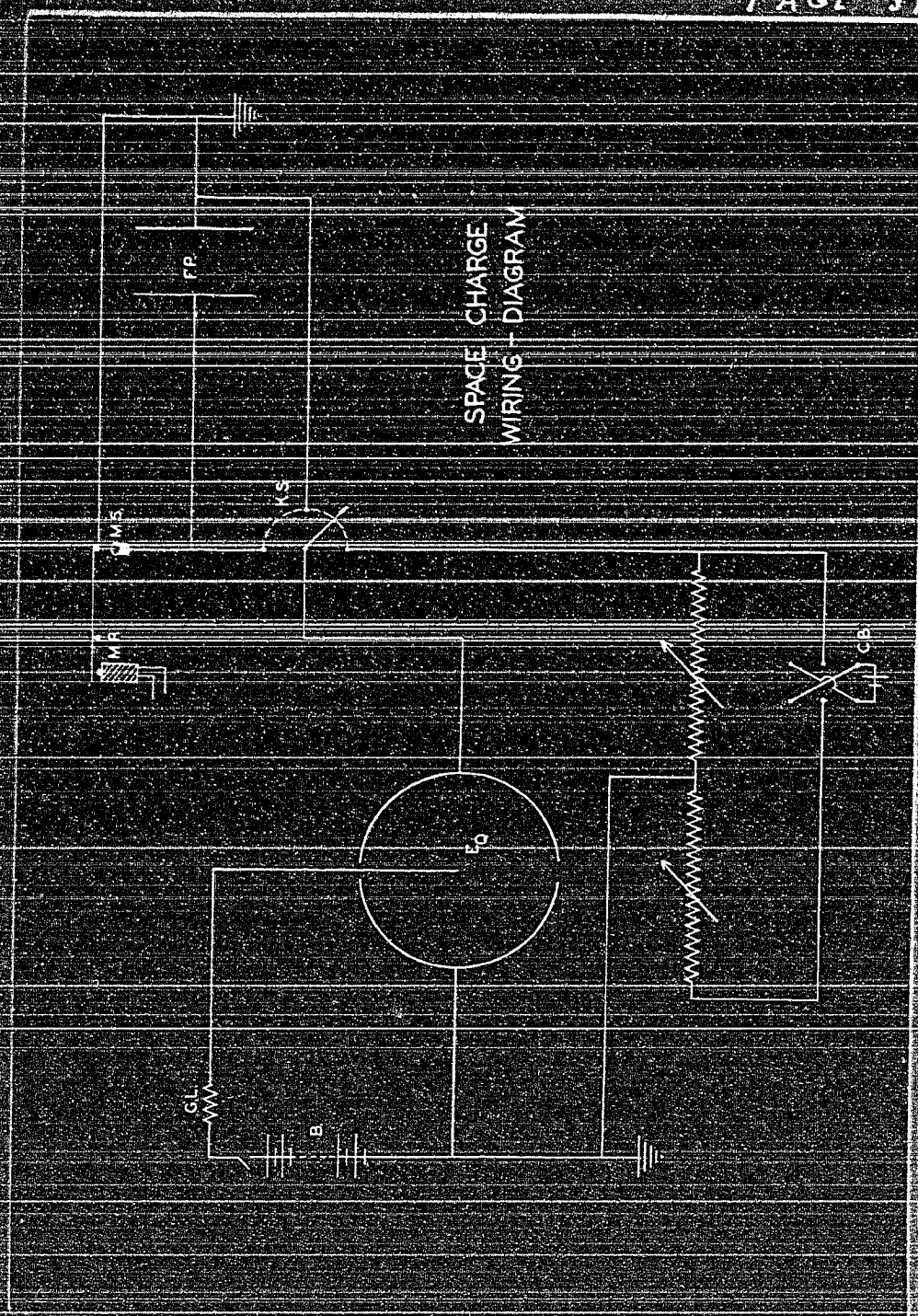


FIG. 7

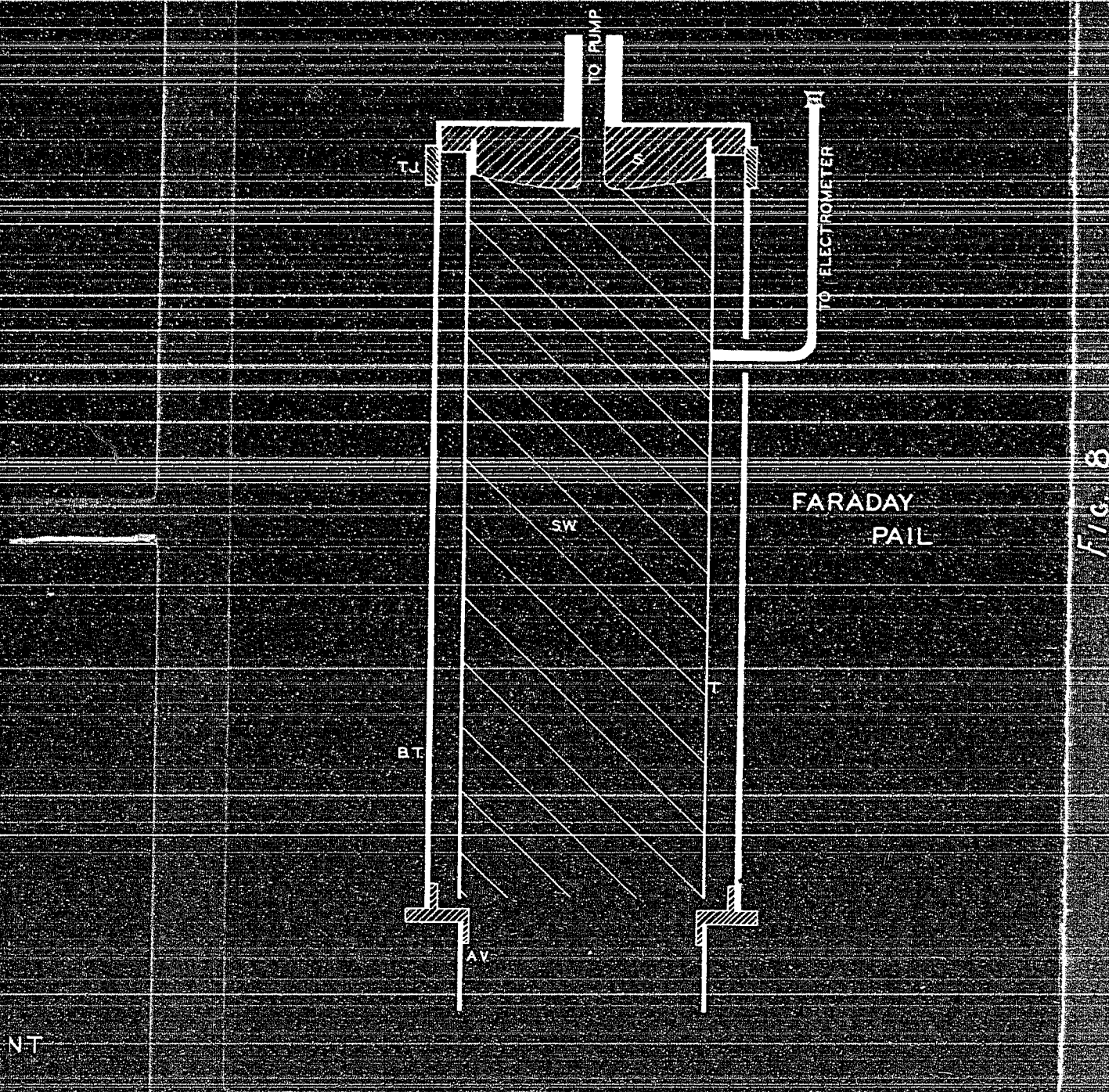
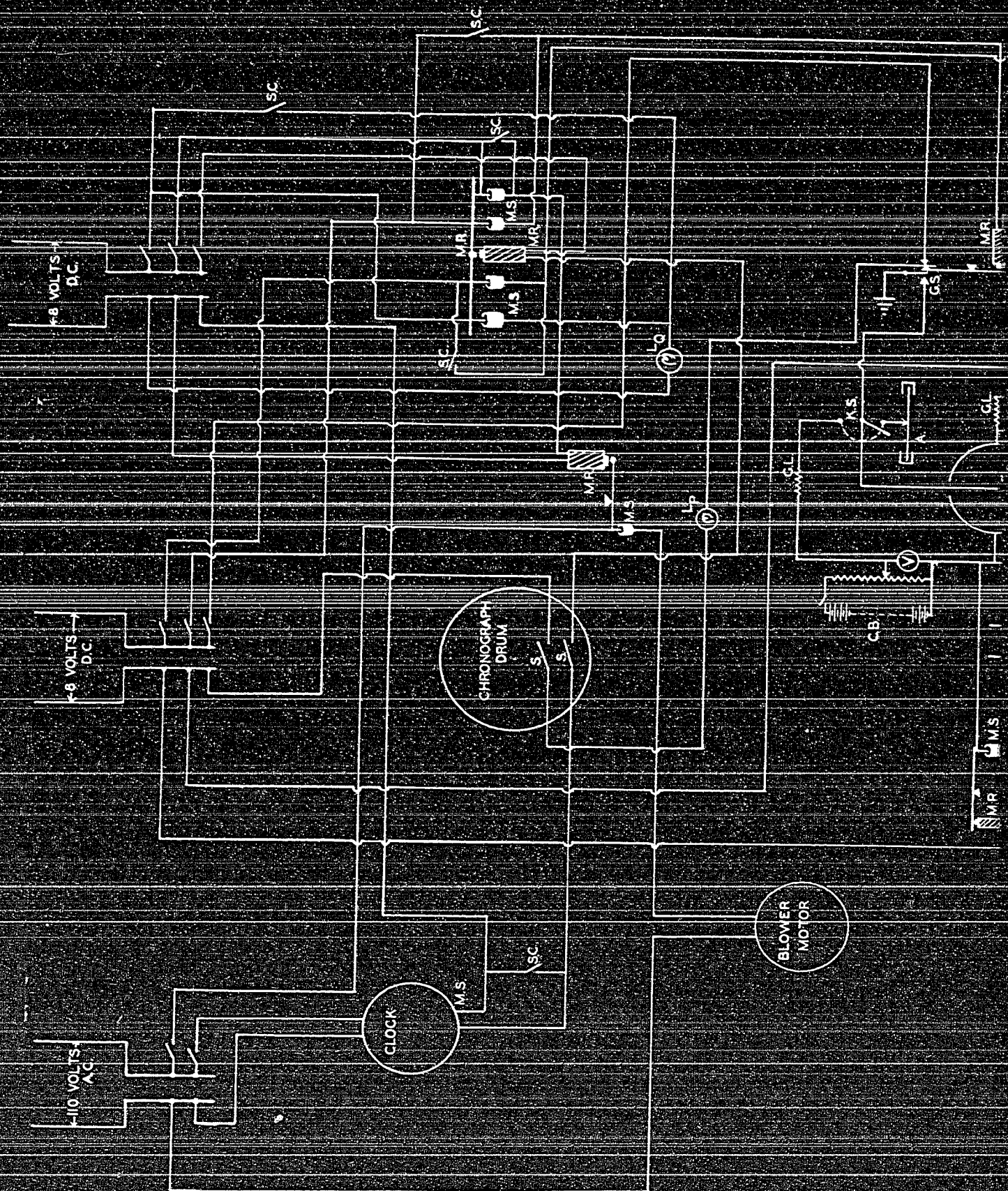
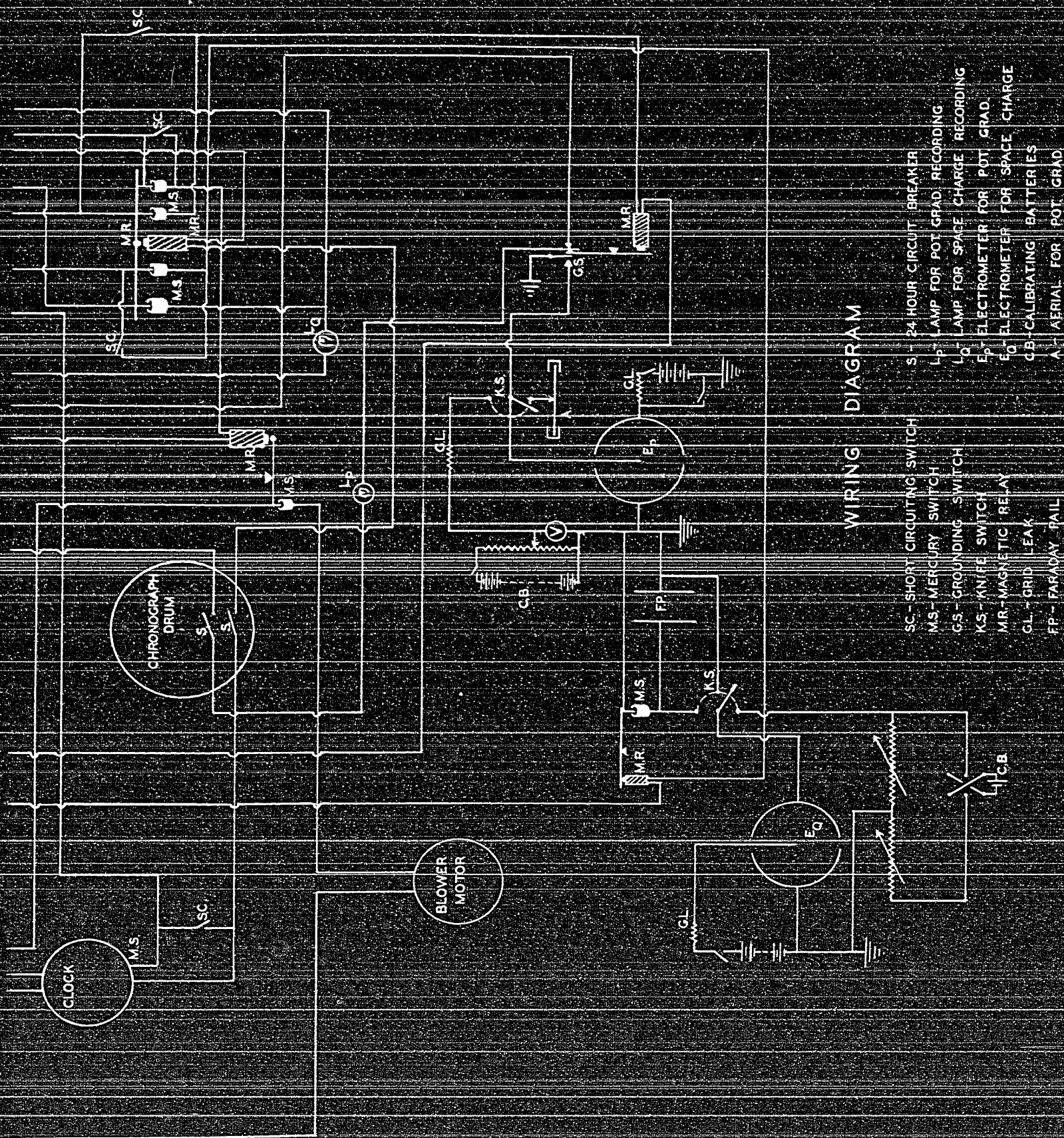


FIG. 8

NT





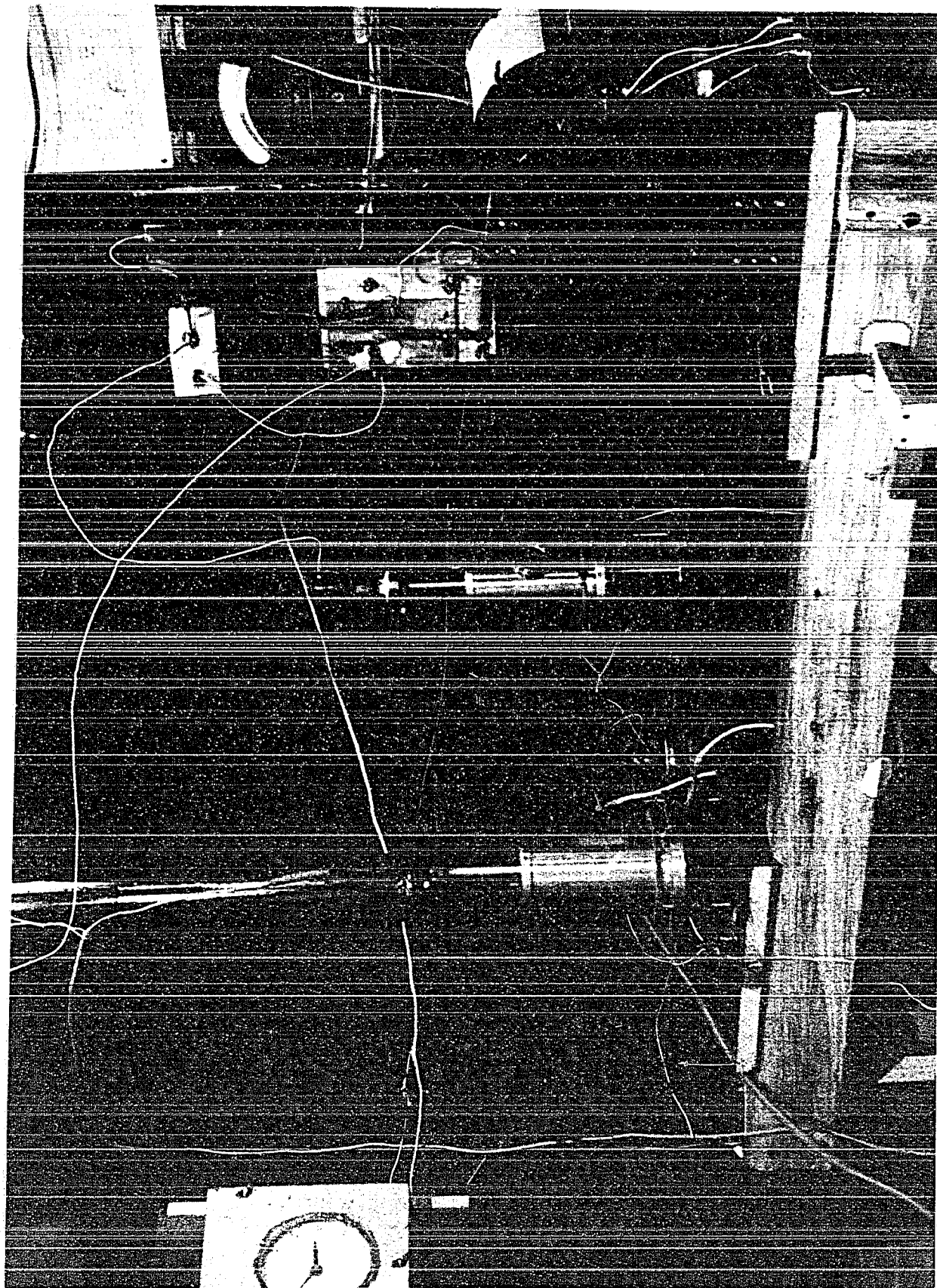


FIG. 10a

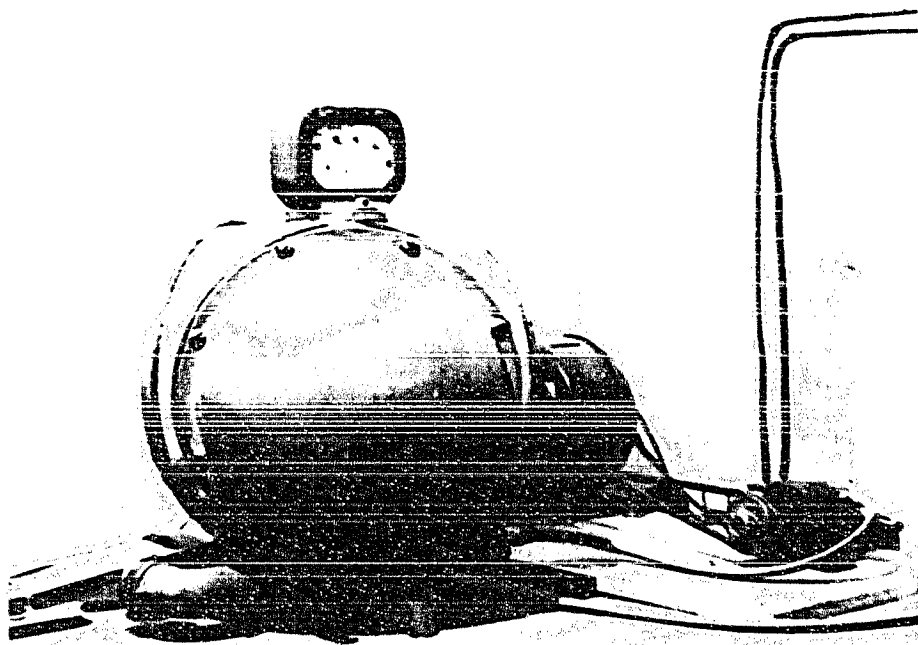
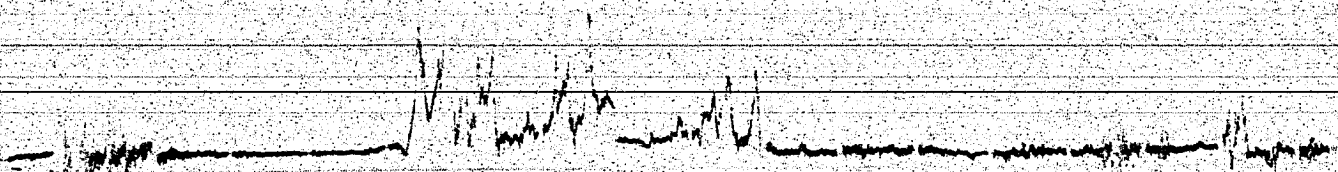
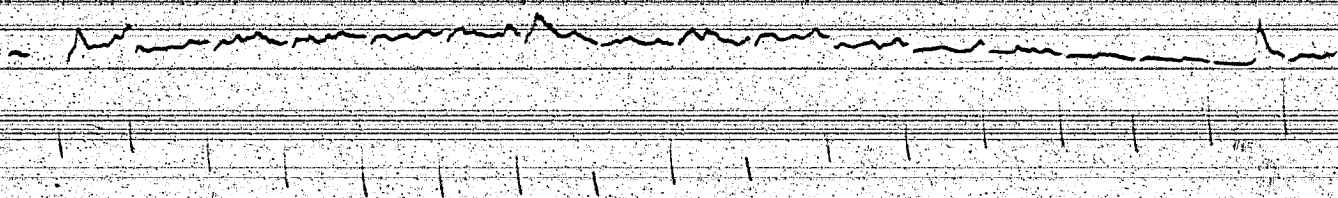
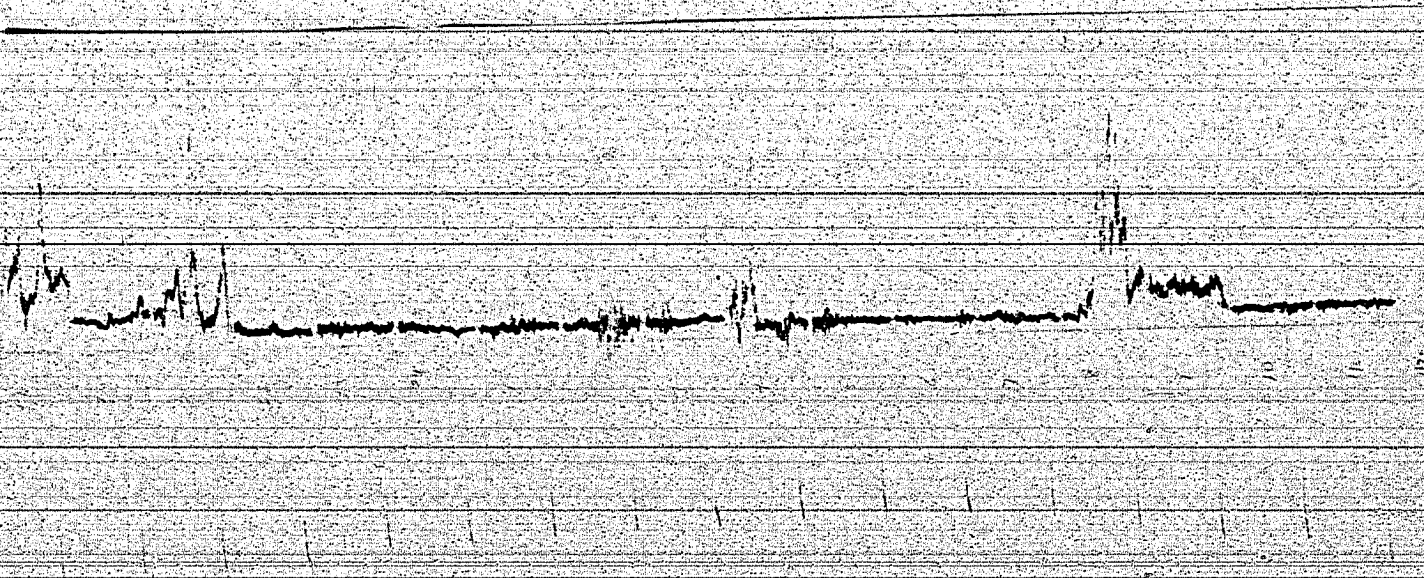
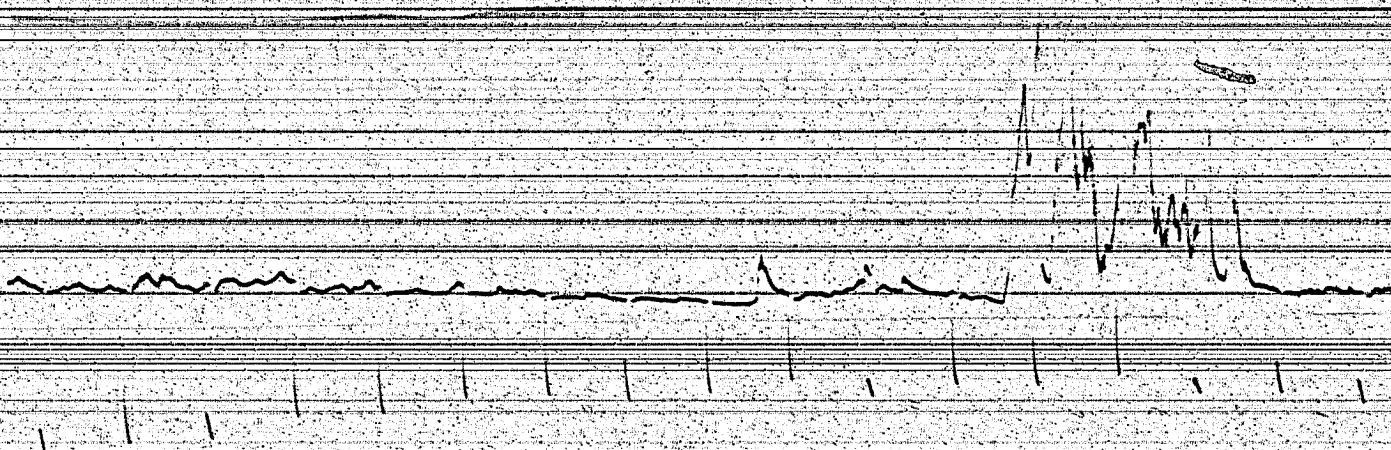


FIG. 10b





Handwritten signature or text.

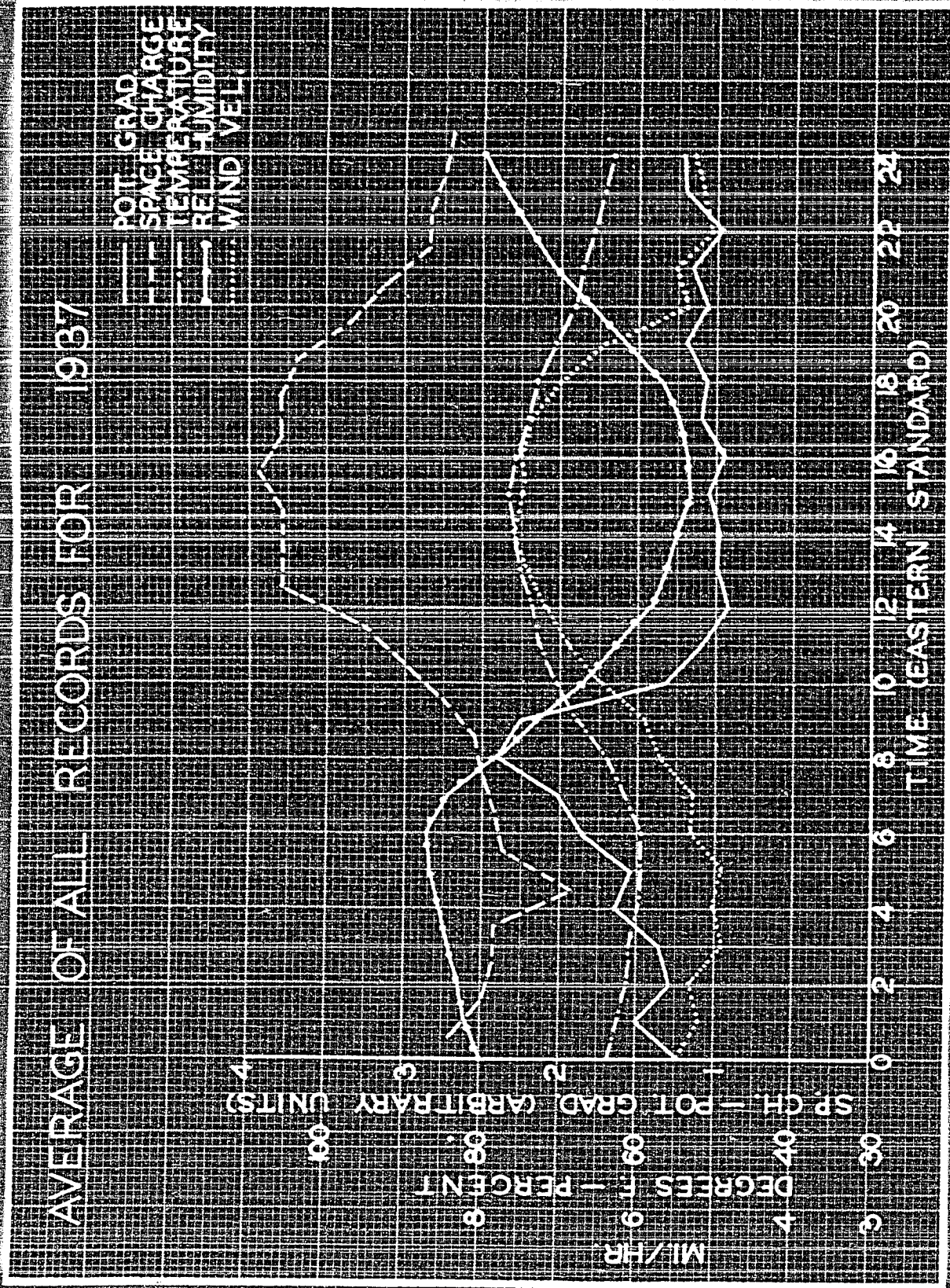


Fig 12

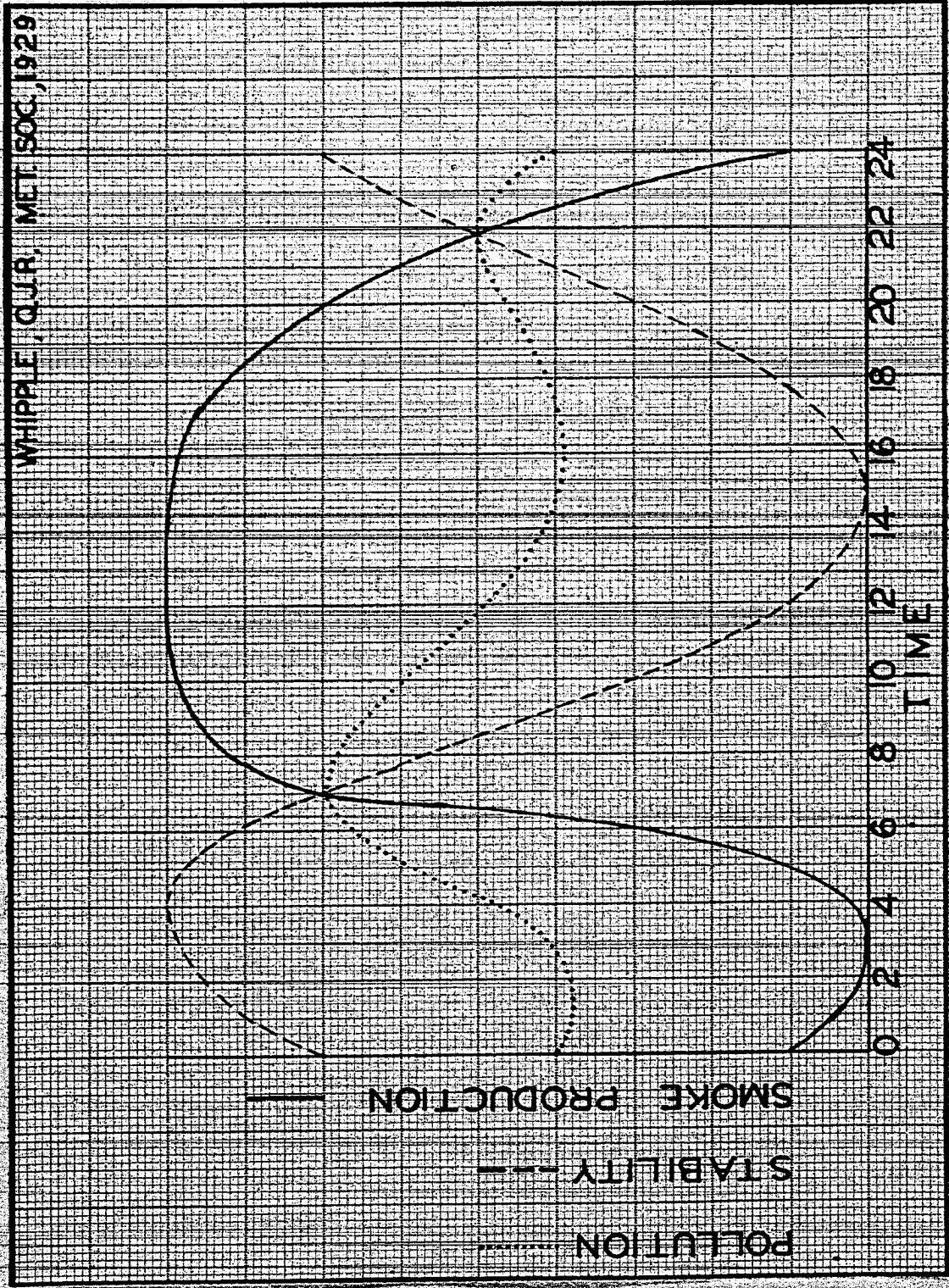


FIG. 13

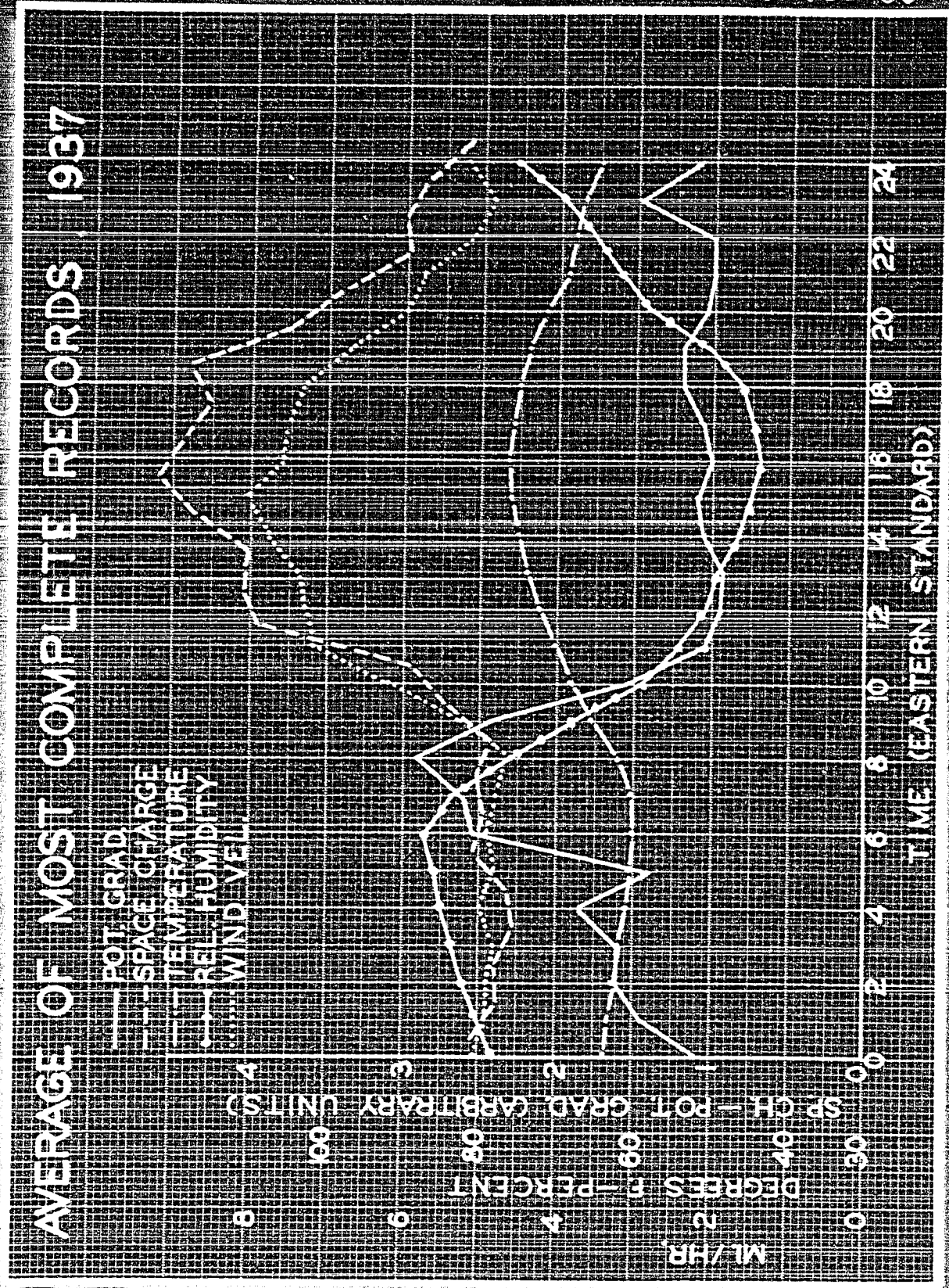


FIG. 14

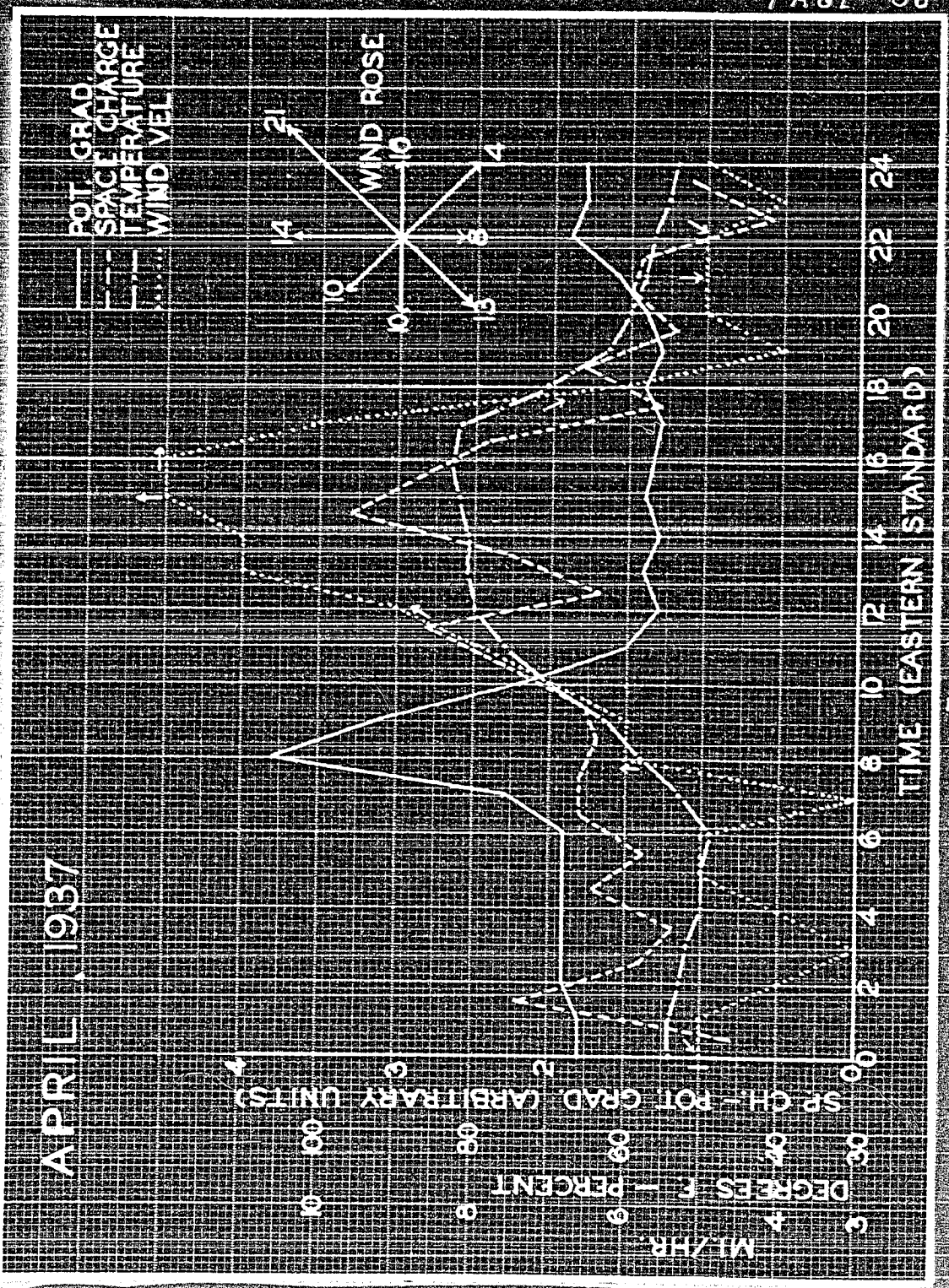
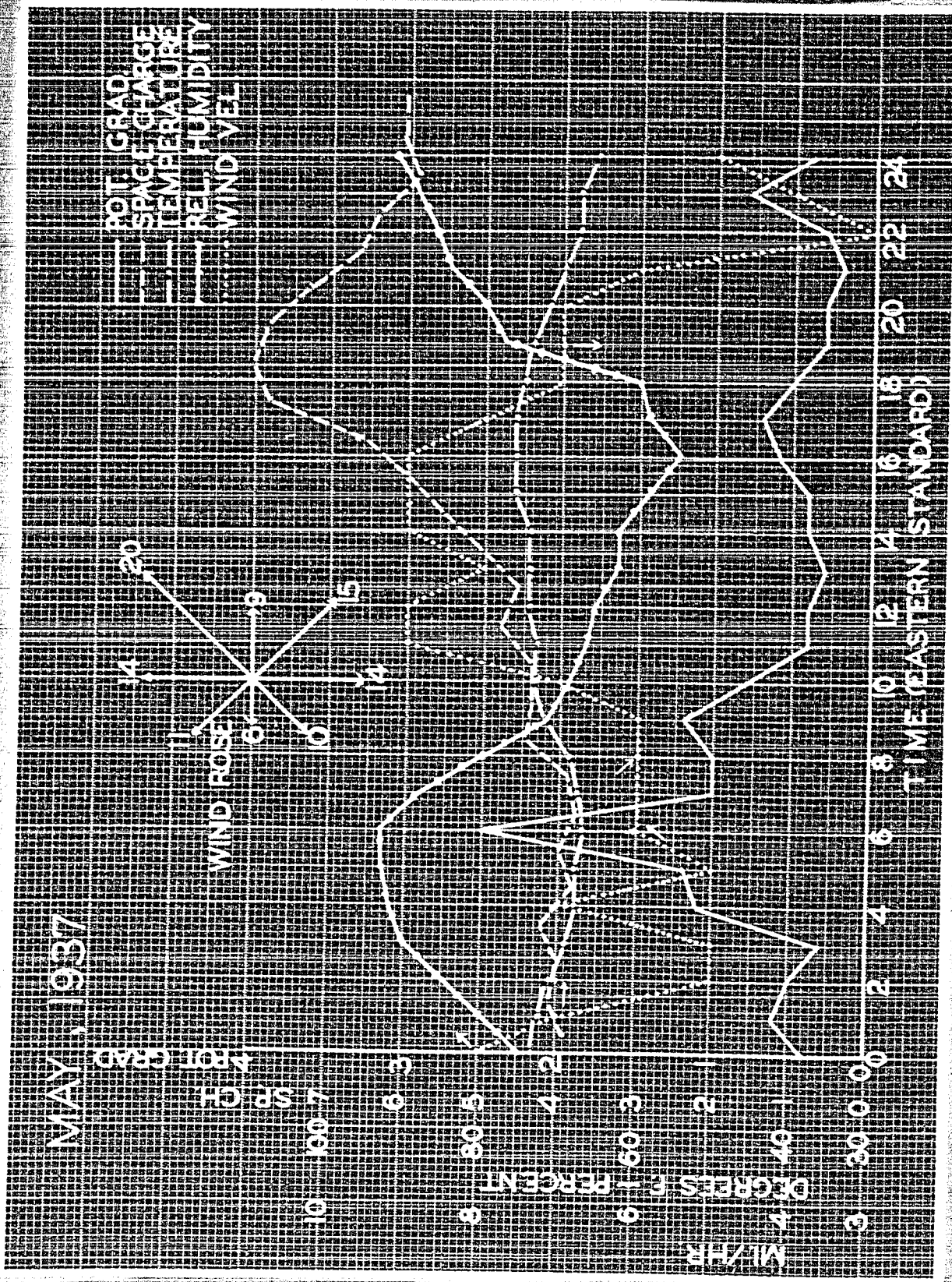


FIG. 15



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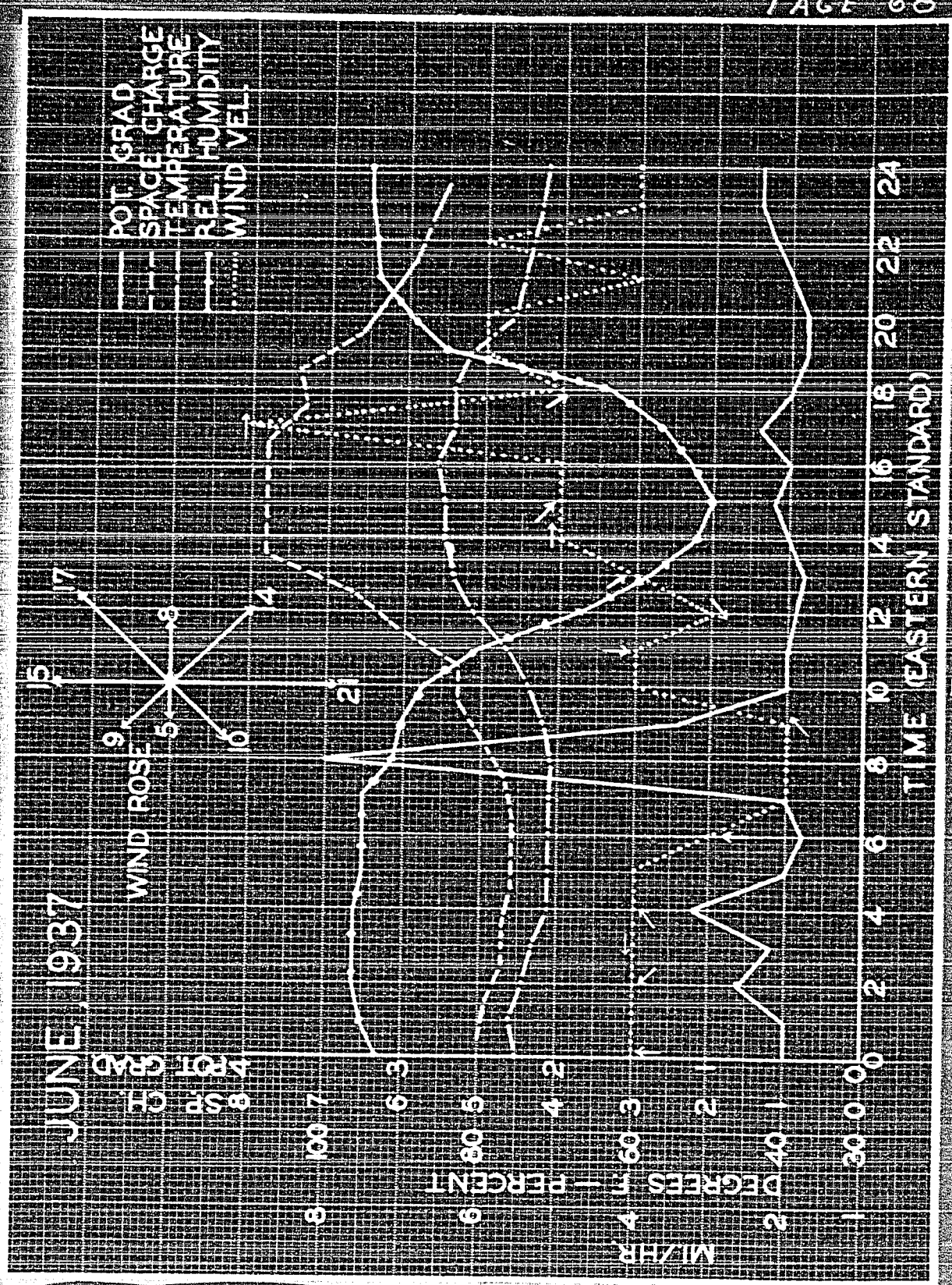
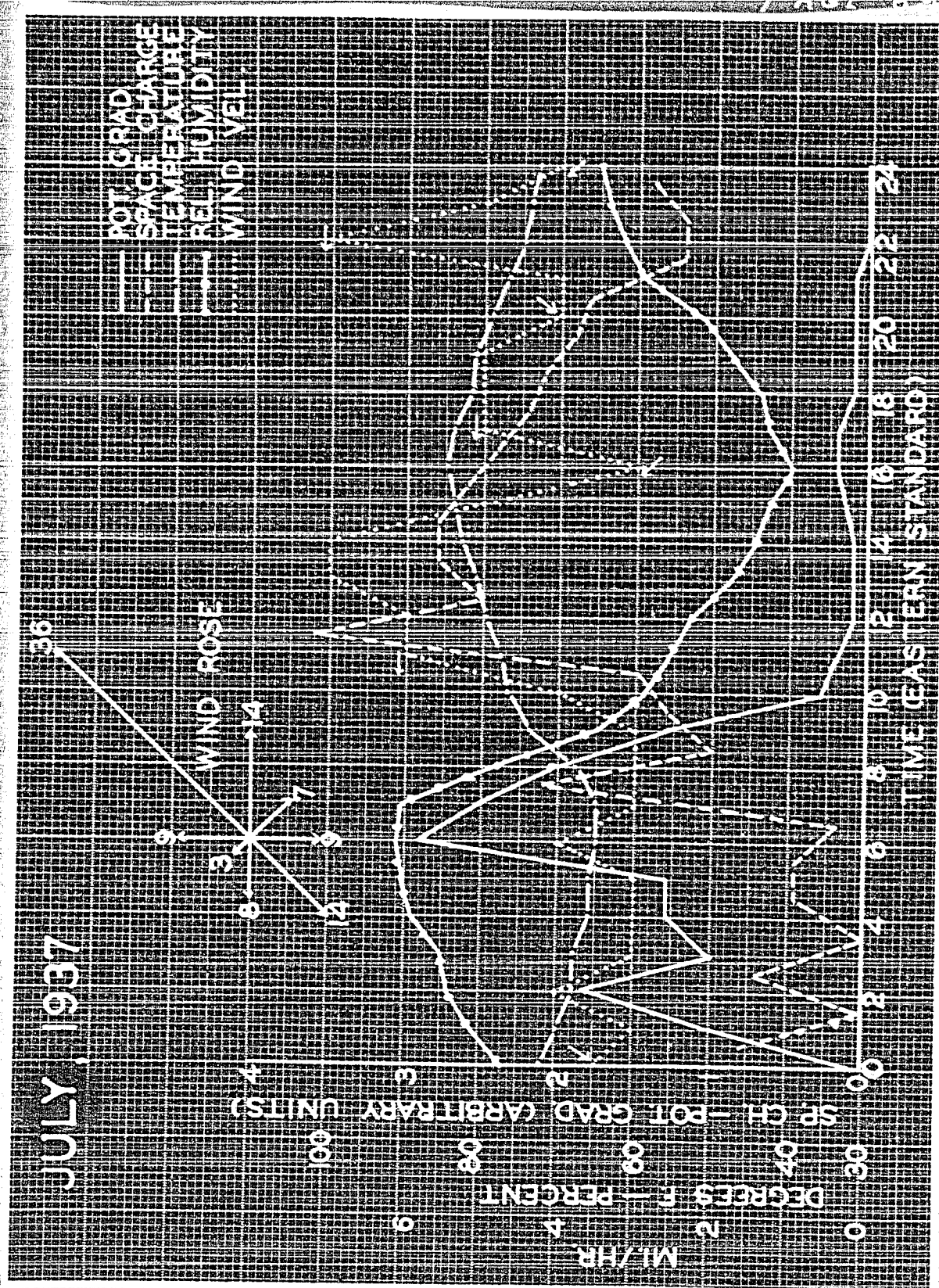


FIG. 17



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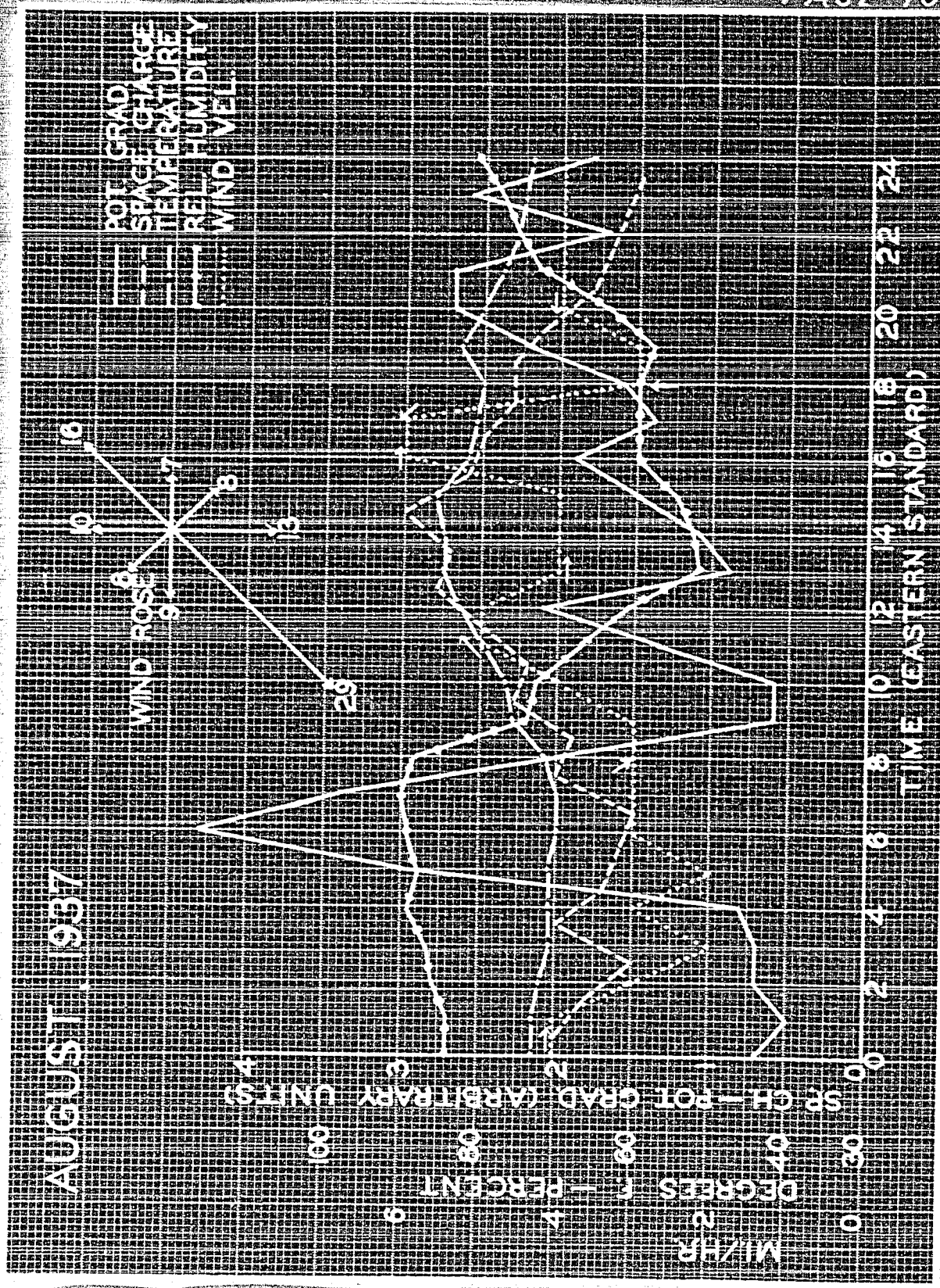
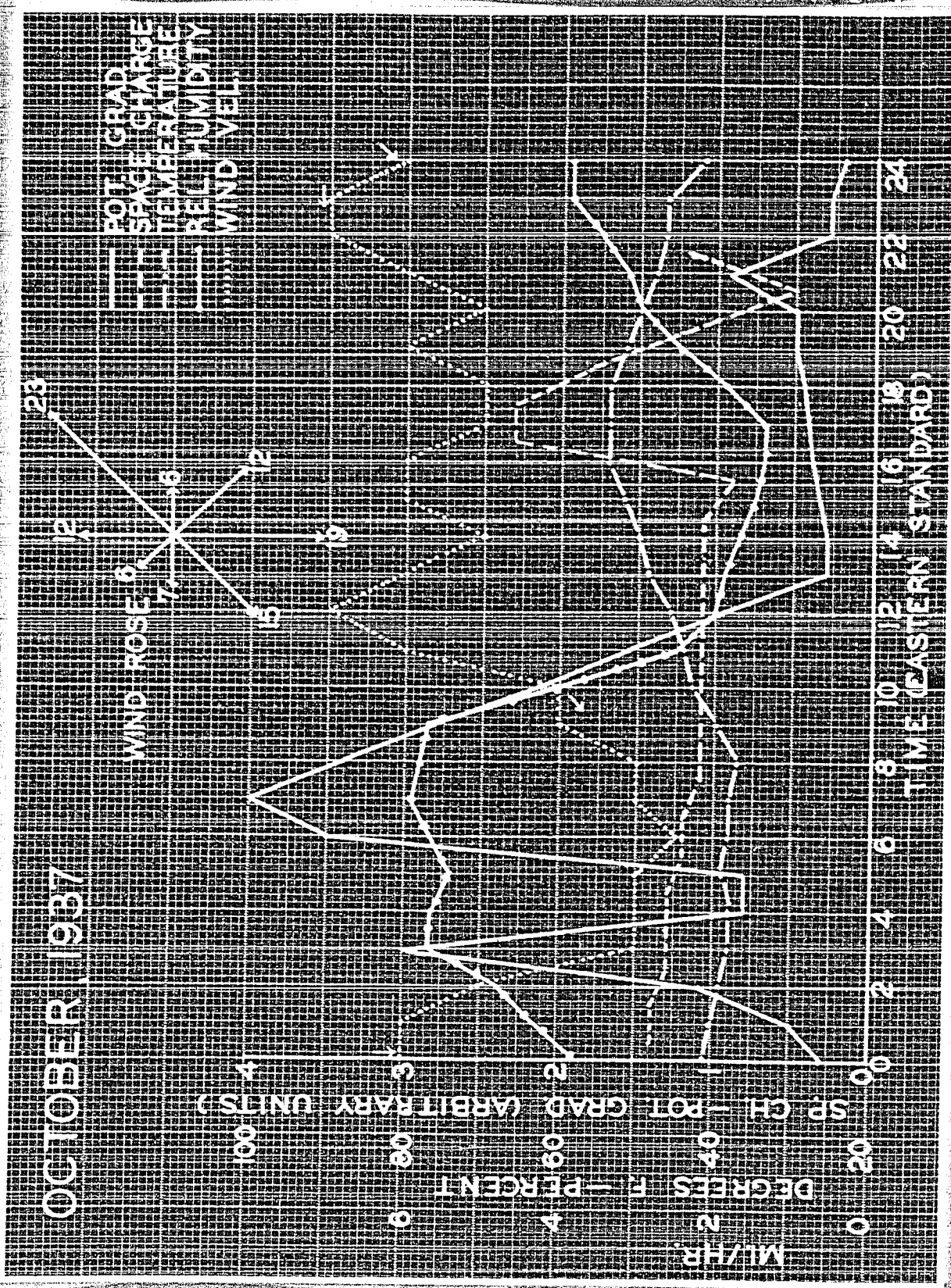
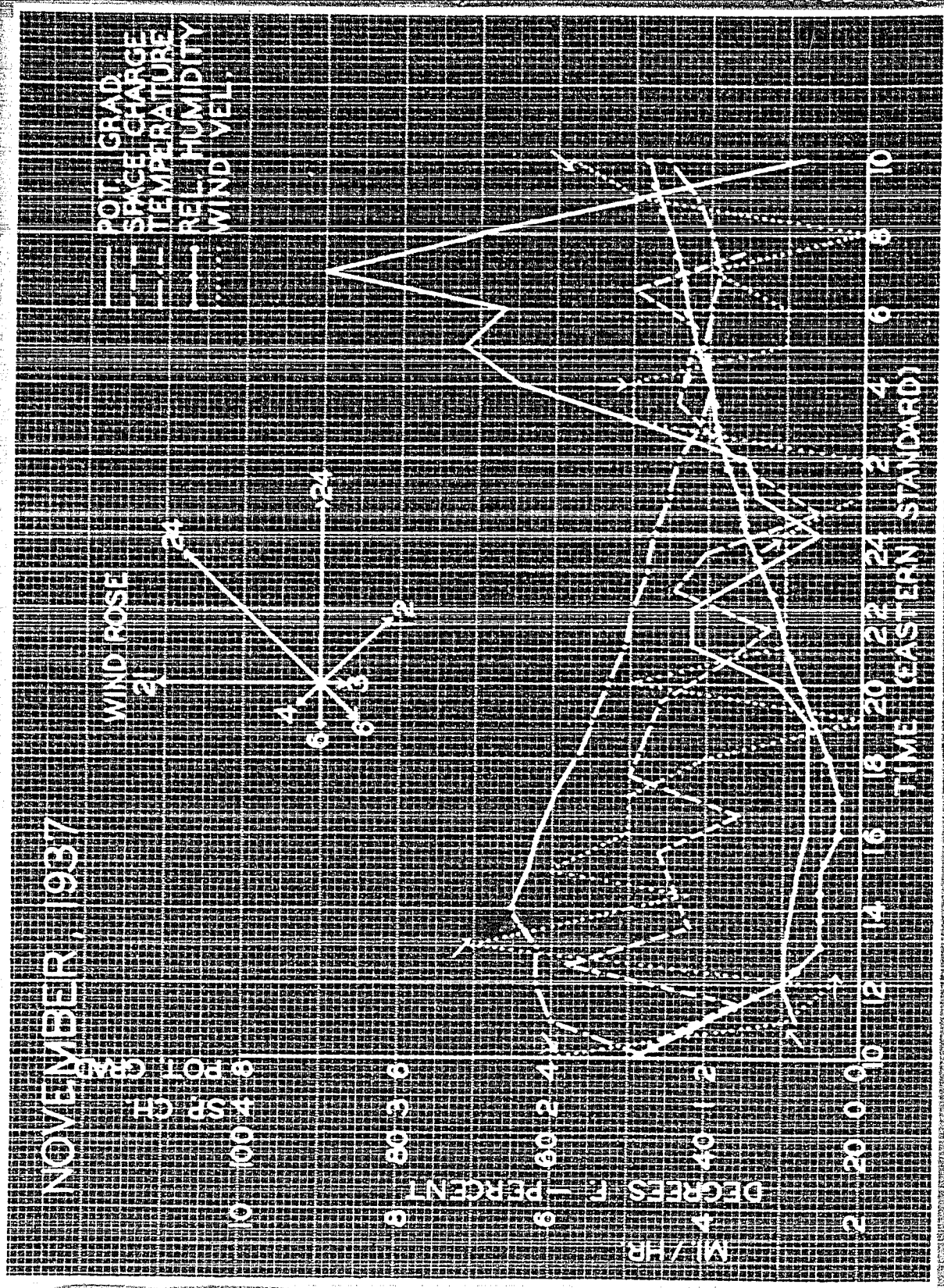


Fig 19



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7/10, 2/

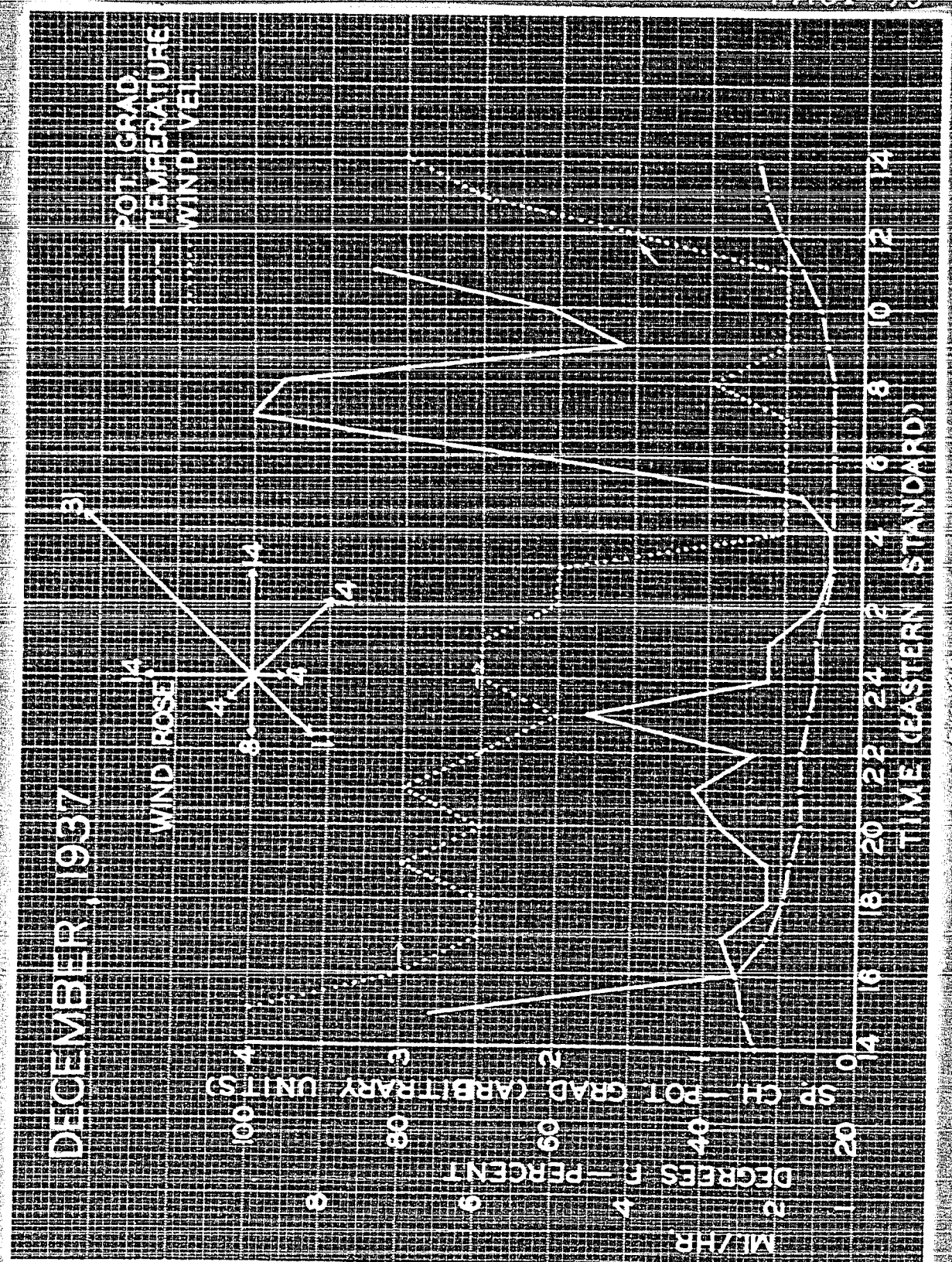


FIG. 22

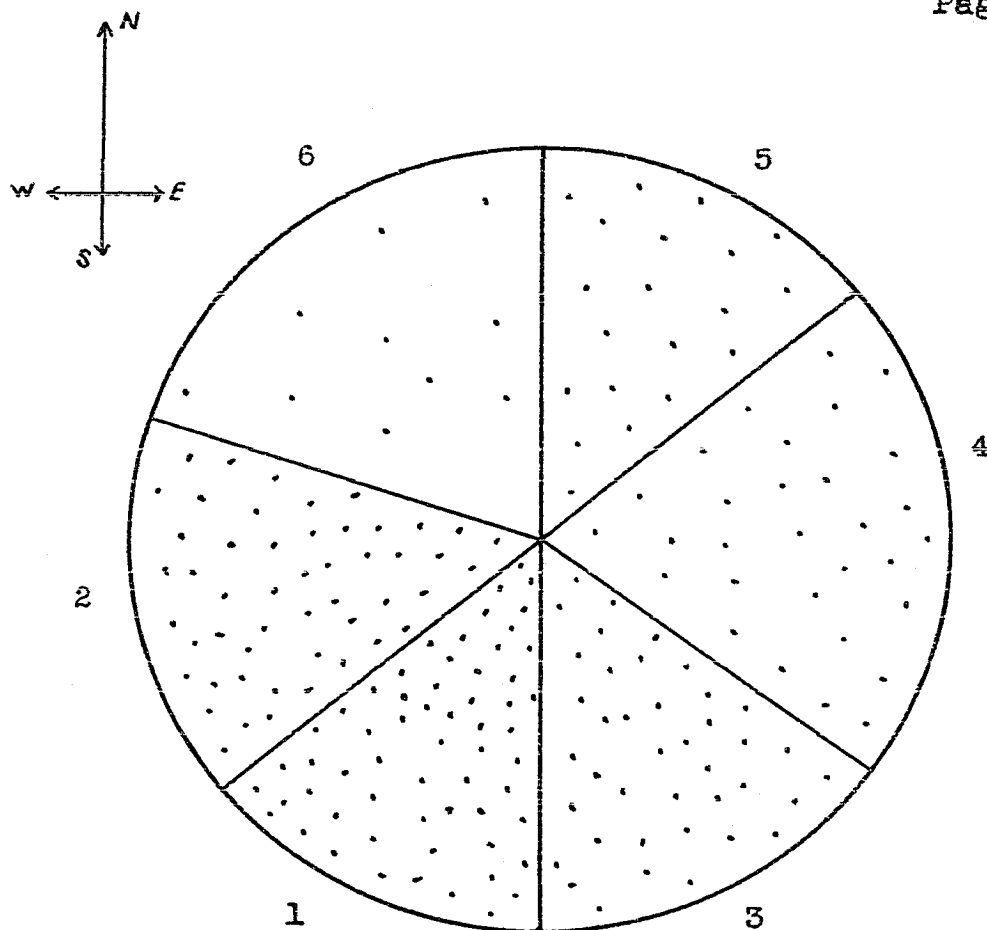


Fig 23

Chart showing regions from which we would expect winds to carry the most smoke, soot, and dust. (1 is the region which produces the most dirt.)

The Physics Building is located at the center of the circle.

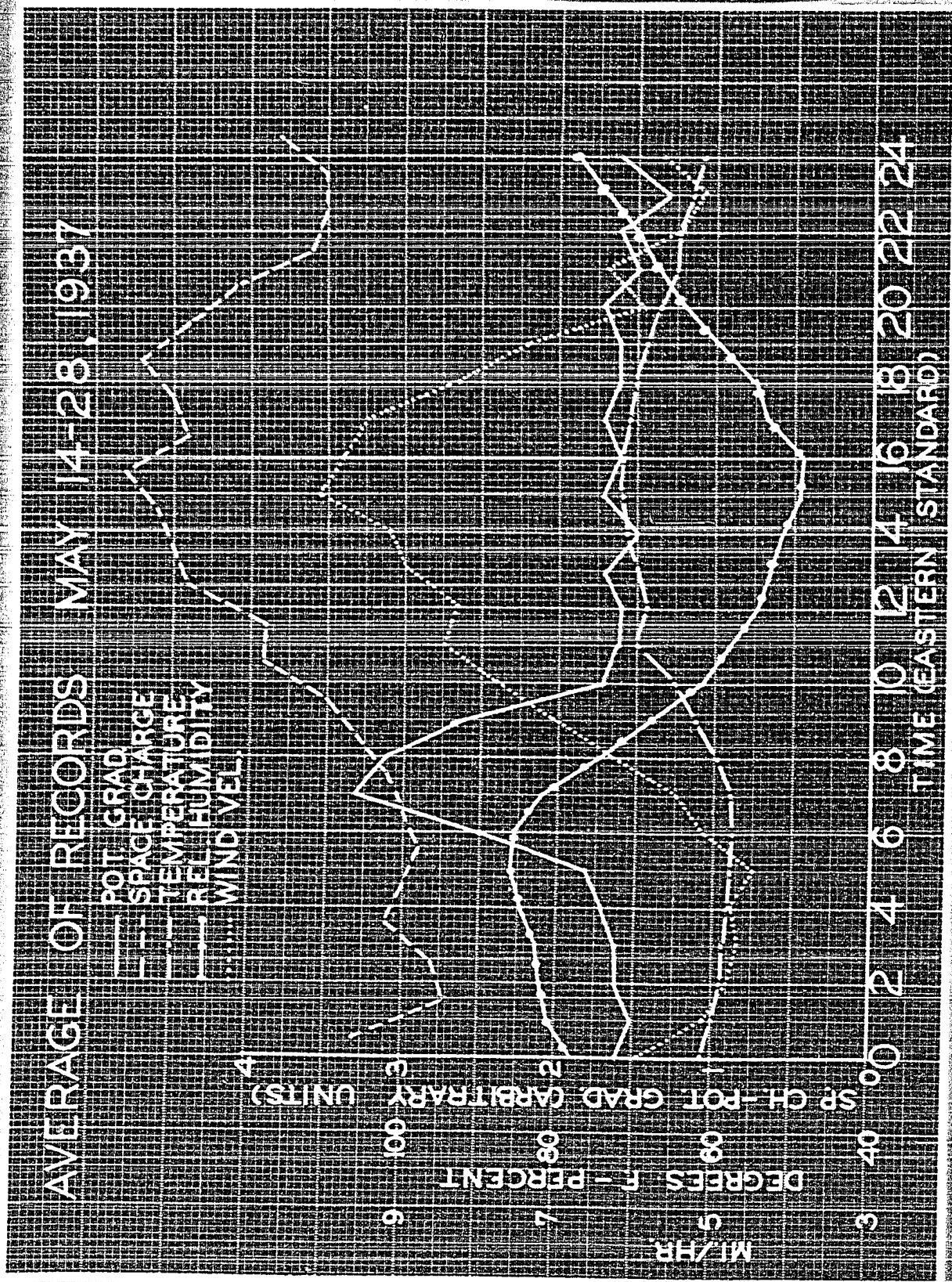


FIG. 24

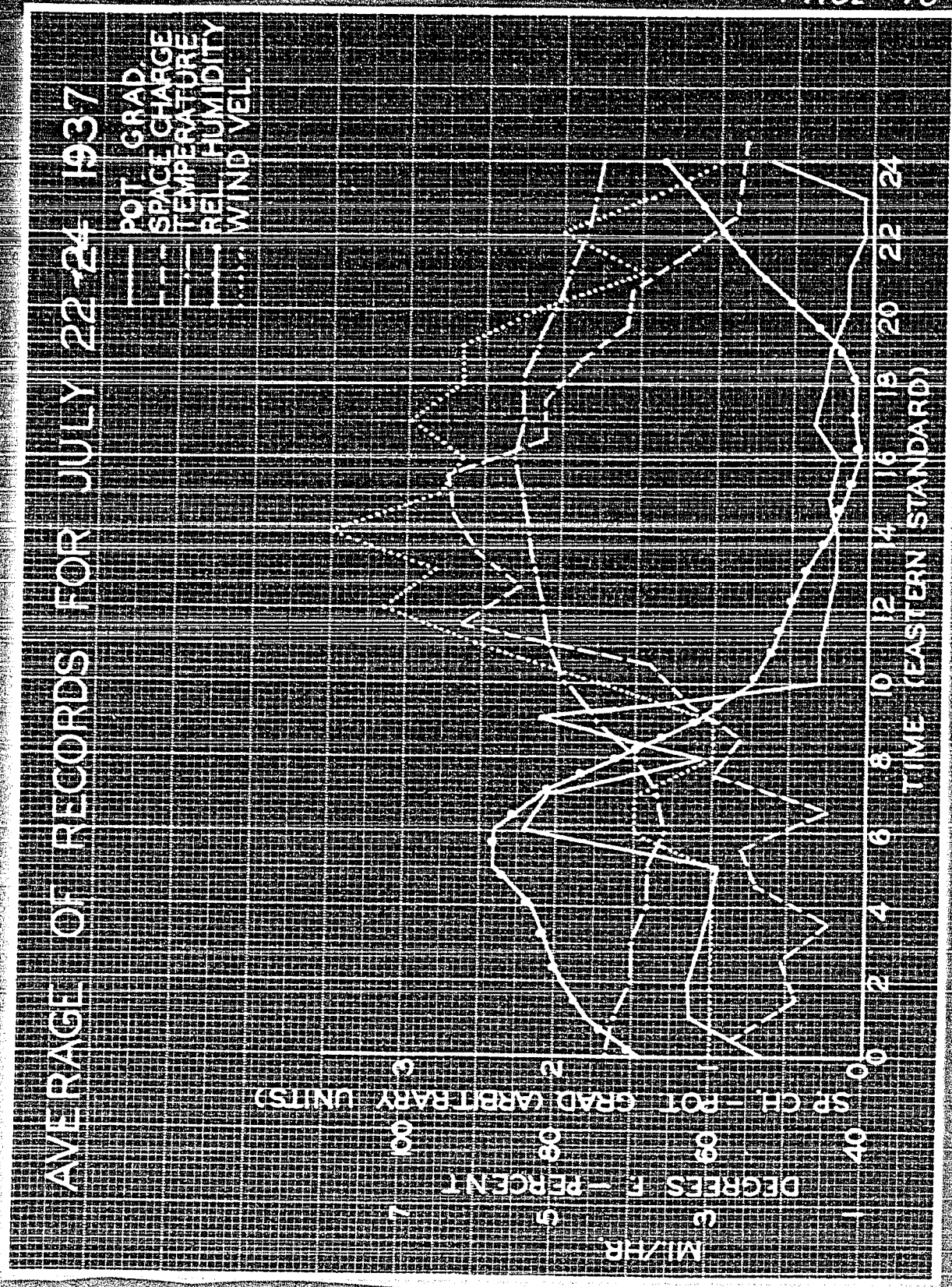


FIG. 25

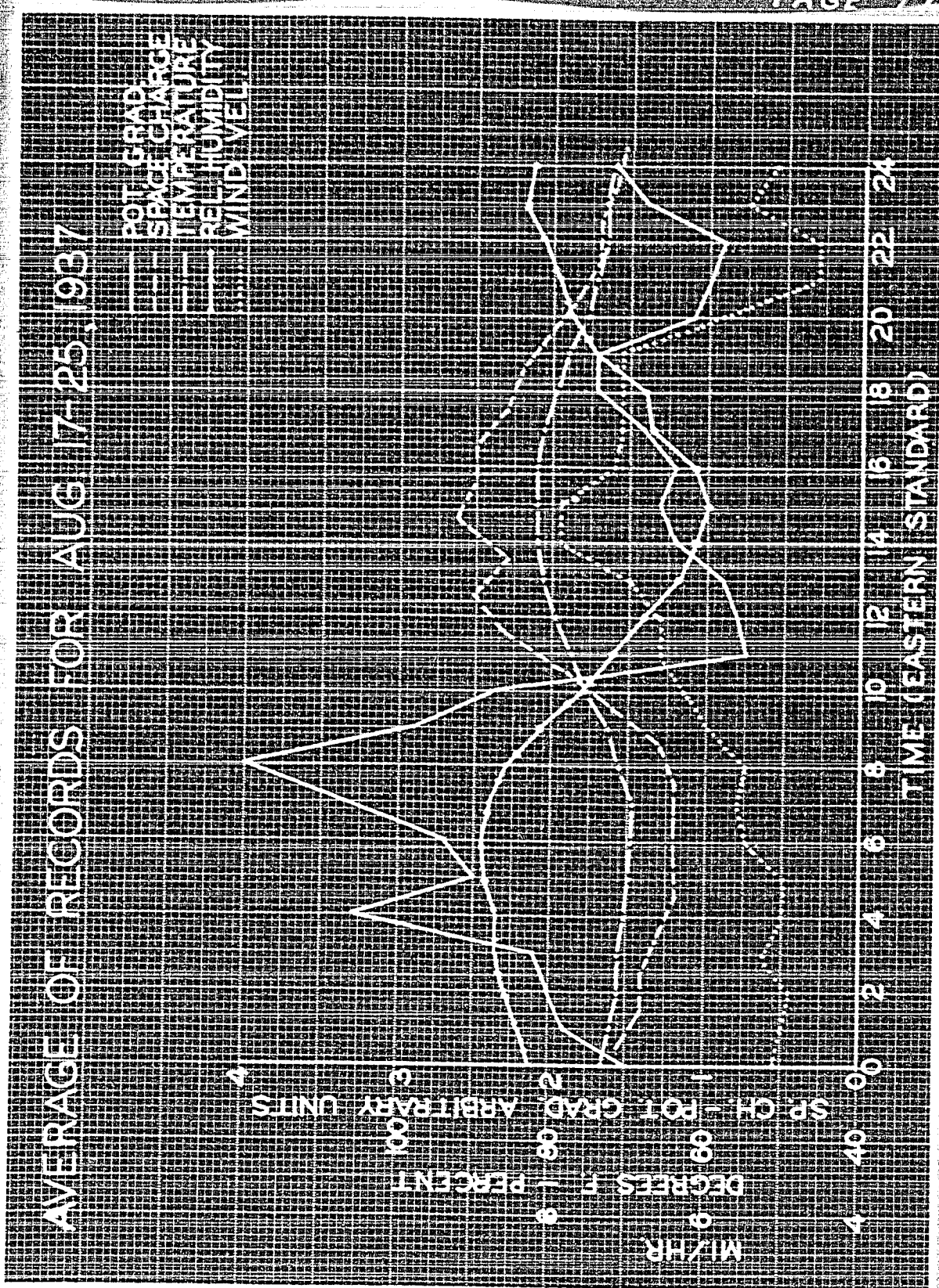


FIG. 26

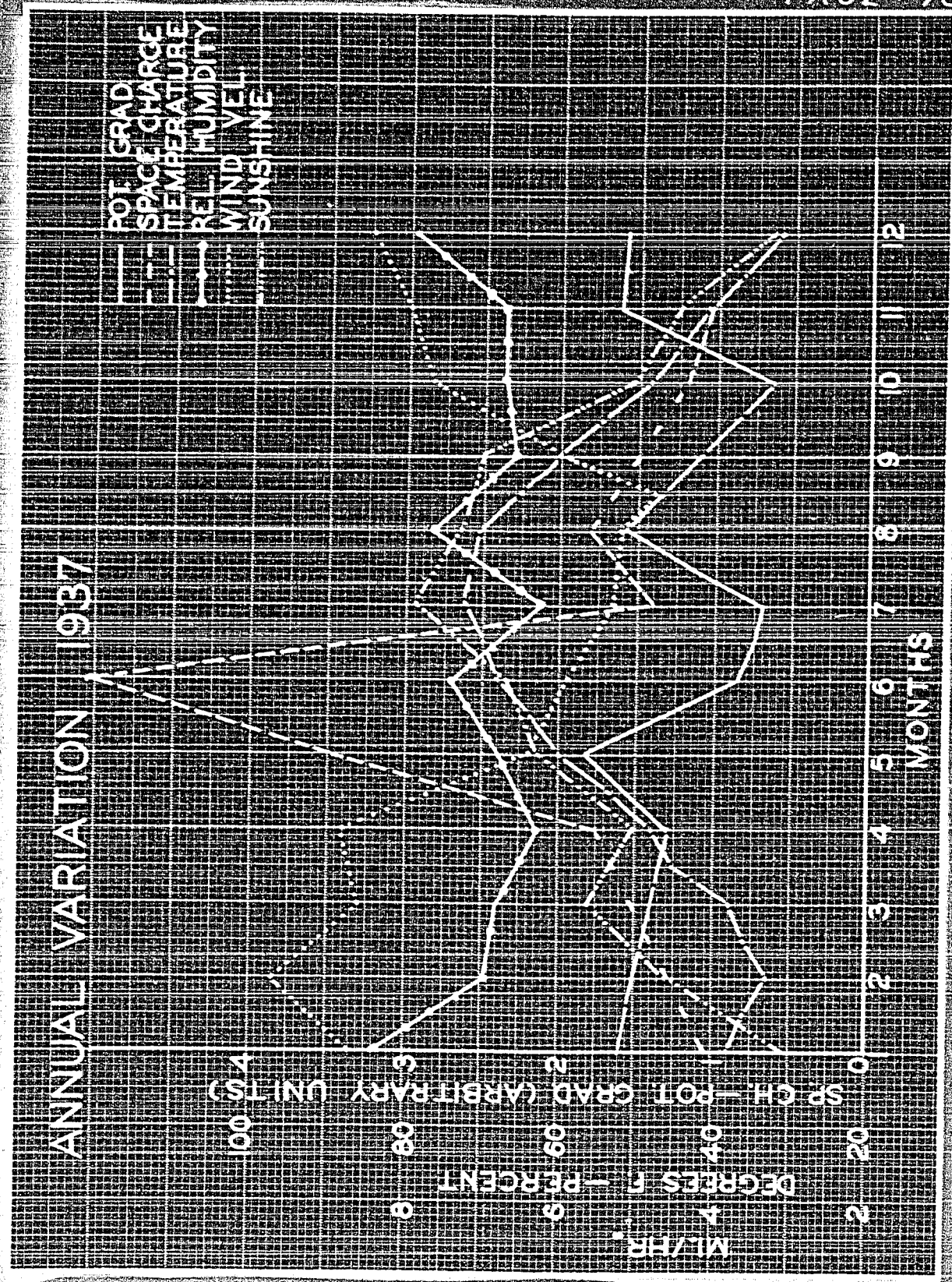


FIG. 27

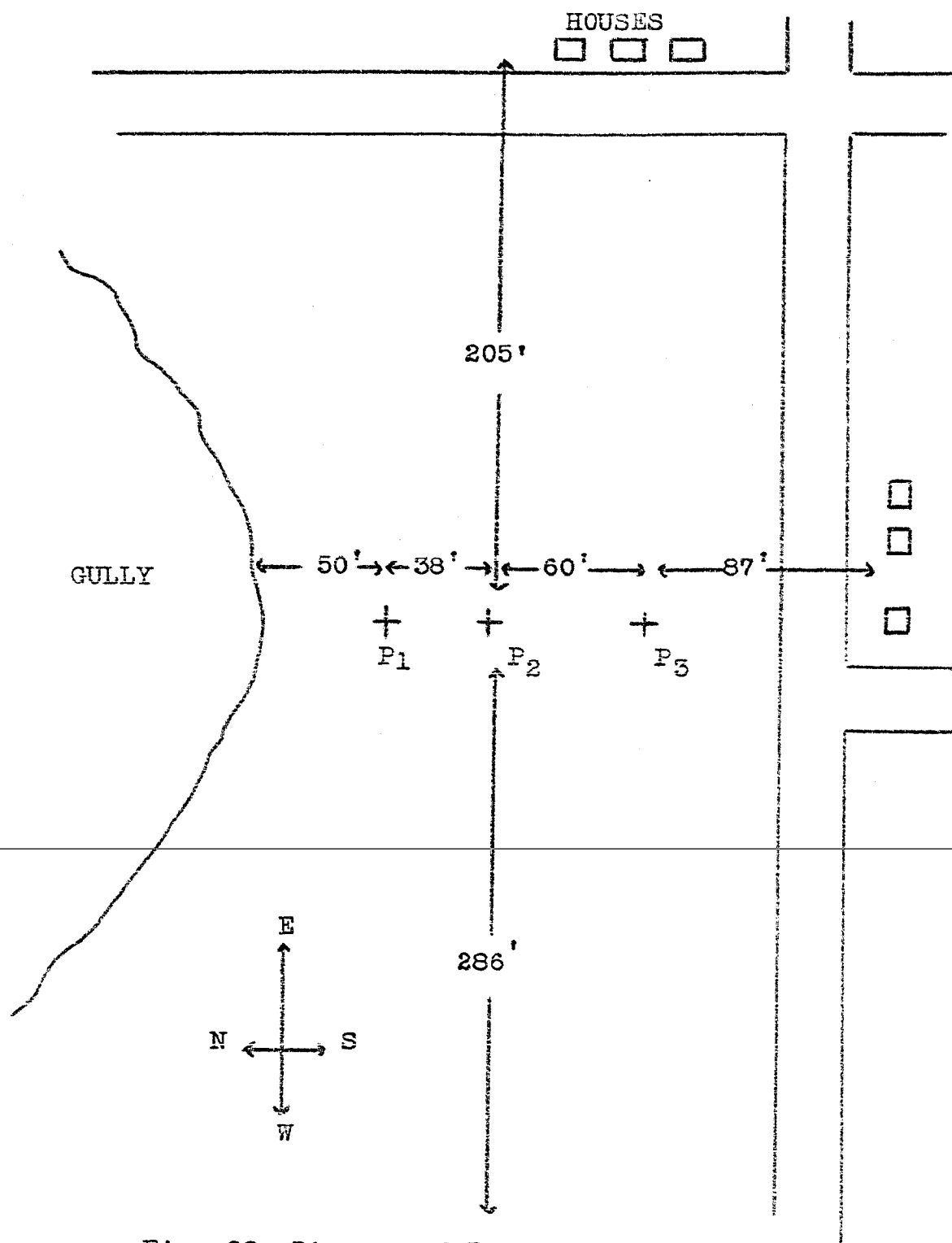


Fig. 28 Diagram of Parking Lot

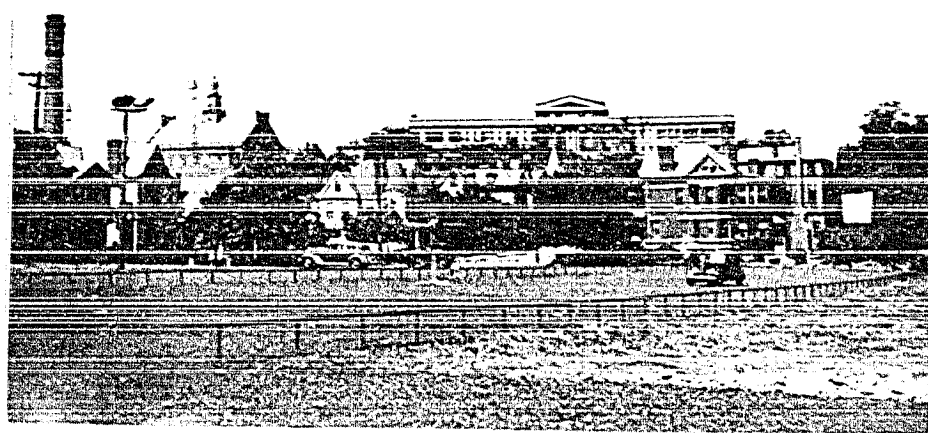
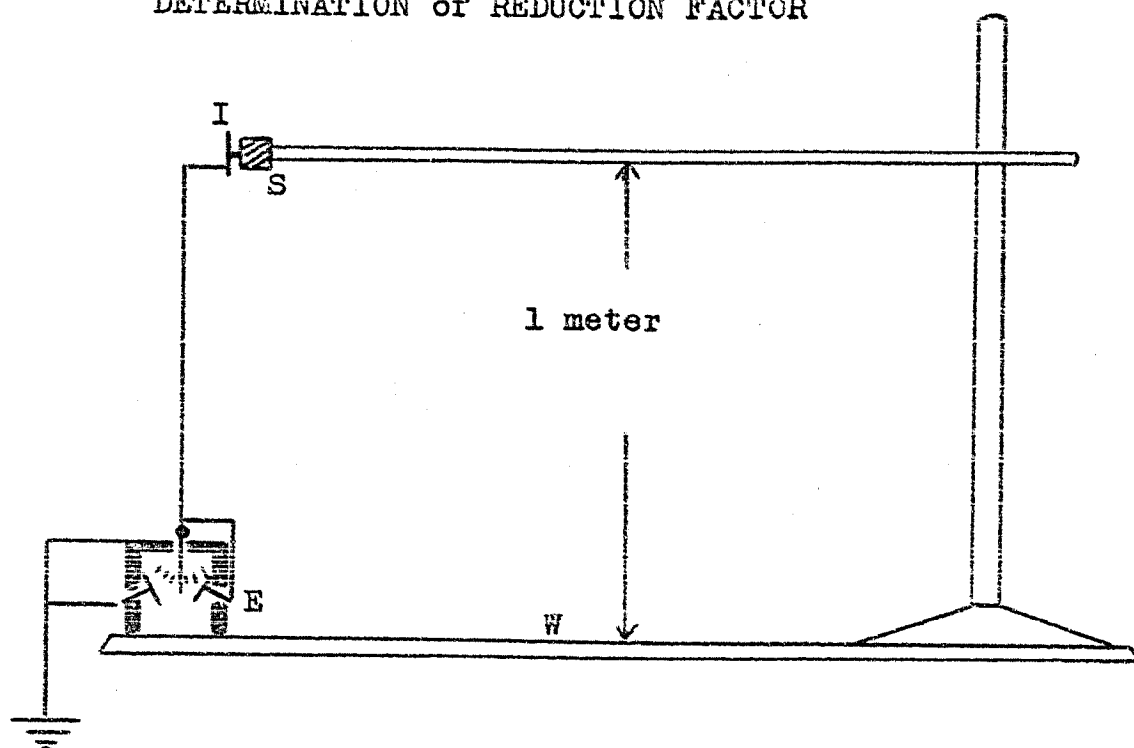


FIG. 29

DIAGRAM of APPARATUS
for
DETERMINATION of REDUCTION FACTOR



- I - Ionium Collector
- S - Sulphur Insulator
- E - Electroscope
- W - Wooden Base

Fig. 30

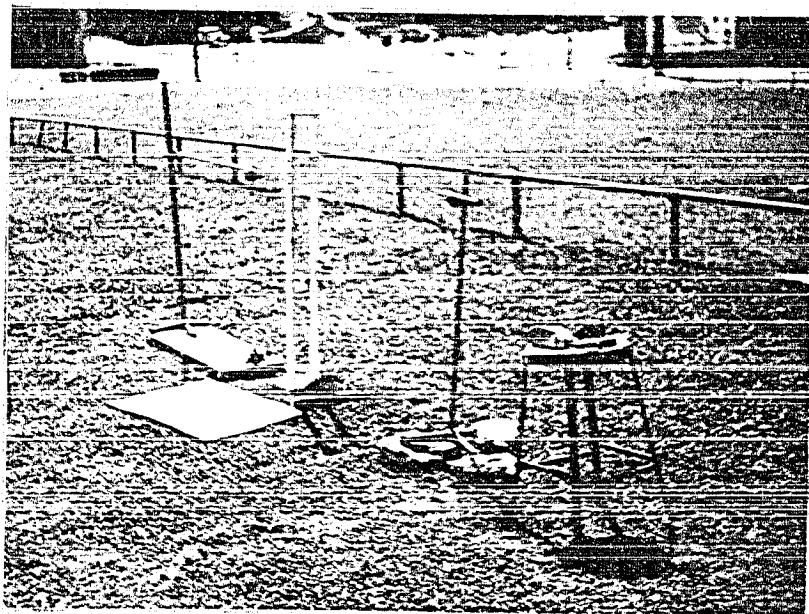


FIG. 31