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THE RELATION BETWEEN PRECIPITATION CURRENT, POTENTIAL GRADIENT, AND RATE OF PRECIPITATION

by

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THE RELATION BETWEEN PRECIPITATION CURRENT, POTENTIAL GRADIENT AND RATE OF PRECIPITATION.

ABSTRACT.

An account is given of the measurement of total air-earth current density under conditions of nimbo-stratus precipitation. The apparatus used was that developed by Adamson (1958) employing an exposed collecting surface with compensation for displacement currents. Simultaneous measurements of the potential gradient F and the rate of rainfall r were carried out and an attempt made to correlate the current density I with the variation of F and r, with particular reference to the results of Chalmers (1956) who established the empirical relationship $I = -a(F - C)$ where a and C are positive constants.

In addition the precipitation current was measured with a shielded receiver of the type used by earlier workers (e.g. Scrase 1938) in order to compare results obtained with those of the exposed type.

To measure the rate of rainfall an entirely electrical method was devised and constructed which combined simplicity in design with efficiency of operation.

Continuous recording was made over periods of several hours duration and a statistical analysis of large numbers of results was carried out.

The results in rain of the 1957-58 Winter showed good agreement with Chalmers' formula, and the gradient, a, was found to increase in magnitude with increasing rate of rainfall. Results for snow were less conclusive but showed fair agreement whilst those for sleet showed electrical effects intermediate between snow and rain.

A wider divergence from linearity was found in the results of the 1958 summer.

The differences found between the currents measured by the shielded and exposed collectors are discussed in terms of the results of Smith (1955) and the effects of splashing and of conduction current.

Particular interest was found in the frequent occurrence of the "mirror image" effect often showing a definite time-delay not found by previous workers.

PREFACE.

The rationalised M.K.S. system of units is used throughout the work, being most suitable for the formulae of Atmospheric Electricity.

To avoid confusion, instead of "field" the term "potential gradient" is used. This is positive when the atmospheric potential increases with height and is opposite in sign to the electrostatic field.

Chapters and paragraphs are numbered and references made in the usual way. It has been necessary to include only a small number of equations in the text and where cross references have been made they are numbered according to the paragraph in which they appear. Usually it has been more convenient to requote the equation.

The symbol "$\mu\mu$A", denotes "amp.x 10^{-12}".

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CHAPTER I

GENERAL INTRODUCTION

1.1. The Atmospheric Potential Gradient

The classical experiments of Franklin (1752) and D'Alibard (1752) first established the existence of electrostatic charge in thunderclouds accounting for the similarity of the lightning discharge and electric sparks produced in the laboratory. In the same year Lemmonier (1752) demonstrated that electrical effects in the atmosphere exist not only in thunderstorms but also in fair weather conditions. By using a stretched wire as an insulated collector which slowly attained the potential of its surroundings, he demonstrated that the air just above the earth's surface was at a positive potential with respect to the earth. Further work showed an increase of potential with height corresponding to a negatively charged earth with a positive charge located somewhere above. It is now well established, notably from balloon measurements (Chalmers 1957, p.136) that the potential gradient decreases with increasing height until at 10 km. it has a value less than 1% of that at ground level, the associated positive space charge distribution being given by Poisson's equation

$$-\rho = \varepsilon_0 \frac{d^2V}{dh^2} = \varepsilon_0 \frac{dF}{dh}$$

where ρ is the volume density of charge in C.m^{-1}. and V and F the potential and potential gradient at height h respectively.

At a height of some 50 to 60 km. the air may be considered to be perfectly conducting from the point of view of atmospheric electricity and above this lie the various conducting layers known in radio work as the ionosphere. This term may be extended to include the lower levels (50-60 km.), sometimes referred to as the electrosphere or equalising layer; the study of atmospheric electricity is confined to that region between this layer and the earth which are considered together as comprising a spherical condenser with the atmosphere itself as the "dielectric". The electrosphere is at an average potential of + 2·9 x 10^5 volts above earth, and the electrostatic potential gradient set up between it and the earth's surface is of fundamental importance in the physics of the lower atmosphere. Since the curvature of the earth is negligible compared to the distance between these two conducting spheres, the lines of force at the earth's surface may be taken as vertical so that the bound charge on the earth has a surface density given by

$$-\sigma = \varepsilon_0 F \qquad (C.m^{-2}).$$

1.2. The Air-Earth Conduction Current.

Owing to the presence of ionising radiation in the atmosphere, produced by (i) cosmic rays, (ii) radioactive matter in the earth, and (iii) radioactive gases in the air emanating from the earth's crust, the air is partly ionised and has therefore a low but finite conductivity, (average value for land stations $1{\cdot}8 \times 10^{-14}\text{ohms}^{-1}.\text{m}^{-1}$, Chalmers 1957 p.286). The concentration and distribution of ions in the atmosphere have been the subject of extensive study, a synopsis of which is found in Chalmer's 1957 volume, p.55.

The ions produced move under the influence of the electric field and so act as the carriers of a vertical current. Thus an ionic conduction current flows between the electrosphere and earth tending to neutralise the charge on the earth's surface. By convention, a vertical current is described as positive when it carries positive charge downwards and negative charge upwards; the air-earth conduction current has been found to have an average value in fine weather of about $2 \times 10^{-12}\text{A.m}^{-2}$. As Linss (1887) first pointed out this would bring about a neutralisation of the earth's charge in a period as short as 10 mins. and equalise the potentials of earth and electrosphere. How this potential difference is in fact maintained at a more or less constant value, has been one of the fundamental problems in atmospheric electricity.

1.3. The Maintenance of the Earth's Negative Charge.

It is now generally agreed that the earth's surface receives an excess of negative charge in stormy weather (e.g. Schonland 1928, and Wormell 1927 and 1930) which balances the positive charge brought down in fine weather. Thus, at any time, considering the earth-electrosphere system as a whole, there exists a state of dynamic equilibrium in which a positive current flows to the earth in fine weather regions and a negative charge is transferred to the earth in those areas experiencing storms, a positive charge also being carried to the electrosphere in these stormy areas. The most important mechanisms by which negative charge is brought to the earth are (i) point-discharge currents from natural and artificial points and (ii) lightning discharges.

The world-wide thunderstorm activity has been estimated as being of the order of 44,000 per day (Schonland 1953) and this is at a maxmimum at about 1900 hours G.M.T. at which time a maximum also occurs in the potential difference between earth and electrosphere. This has been arrived at by observing the diurnal variation in potential gradient in regions of the earth where local effects due to pollution etc. are negligible. (Whipple 1929; Whipple and Scrase 1936).

1.4. Charge Separation.

The essential part played by thunderstorms in maintaining the electrical conditions of the atmosphere raised the question of the process or processes by which charge separation takes place in the cumulo-nimbus cloud. The alti-electrograph balloon observations of Simpson, Scrase and Robinson (1937) and (1940), well supported by the many measurements of potential gradient below thunderclouds indicate fairly definitly that the thundercloud has a large negative charge in the base with a corresponding positive charge at the top of the cloud. In addition a smaller positive charge is found to reside where the temperature is at or above the freezing point in the base of most and possibly all cumulo-nimbus clouds.

Numerous theories of charge separation have been put forward and the reader is referred to Chalmers (1957) Chapter 12 for a summary of these, and also to Chalmers (1958). Since there are little or no electrical effects in non-raining clouds it has seemed reasonable to connect the electrical phenomena with the processes of precipitation. The theories may be divided into (i) those in which existing ions of each sign are preferentially attached to heavier or lighter particles which are separated by acquiring different velocities due to gravity and convection currents; (ii) these in which charge is actually generated by ice impact, effects of glazing, etc. and (iii) more recent theories relying solely on convection currents (Vonnegut 1955). In addition, a recent theory of Moore, Vonnegut and Emslie (1959) claims that it is the electrification which is the cause and not the result of the precipitation since the latter is known to carry out of the cloud very little of the charge present.

1.5. Precipitation Current and the Nimbo-Stratus Cloud.

The electrical activity associated with the nimbo-stratus cloud is considerably less than that of the cumulo-nimbus type, for instance typical values of precipitation current and potential gradient measured at the ground in nimbo-stratus conditions are 4 x 10^{-12}A.m^{-2} and -180 V.m^{-1} respectively (Chalmers 1956), whilst for the thundercloud both those values could be of the order of 100 times greater. Although the nimbo-stratus condition of steady continuous rain occur much more frequently especially in temperate climates, it has received little attention until recently compared to the work done in thundery weather.

The principle of the "quasistatic state" (Chalmers 1957 p.25) may be usefully applied to"nimbo-stratus weather" where conditions are reasonably steady. This is a useful concept in Atmospheric Electricity and is applicable when the time of duration of any changes in the electrical conditions are long compared to the relaxation time of the atmosphere. The important results are that the laws of electrostatics still apply (despite the fact that currents are flowing in the atmosphere-) and that the total vertical current density does not vary with height. The nimbo-stratus cloud usually associated with the warm front of a depression is of very considerable horizontal extent and fairly slow-moving. The steady continuous rainfall from such clouds may be of several hours duration and the meteorological conditions vary neither greatly nor rapidly.

If it can be assumed then, that the conditions prevailing in thisweather approximate to the "steady" or quasistatic state then it follows that if the vertical current received by an isolated portion of the earth's surface can be measured then the current inside the cloud is also known (Chalmers 1956).

Now the earth can receive charge in four known ways, by (i) conduction current (ii) precipitation current (iii) point-discharge (iv) lightning, but in nimbo-stratus conditions the picture is simplified since (iv) is absent, whilst (iii) is not usually present and may be eliminated if measurements are confined to times when the potential gradient at the ground remains fairly small. A "safe" figure appears to be ± 500 $V.m^{-1}$ particularly with regard to the results of Maund (1958) and Milner (1958) where no appreciable discharge could be detected from trees even when the potential gradient rose to as much as ten times this value.

By making measurements at the ground it has been hoped to obtain results which may assist in showing where the rain obtains its charge, what process of charge separation occurs in the cloud, and whether this can be "extrapolated" to the more violent cumulo-nimbus cloud. Chalmers (1956 and 1959) concludes that a similar process of separation occurs in both the thundercloud and the nimbo-stratus snow cloud where the snow receives a negative charge with the positive charge rising in the air, and that a second process possibly connected with melting occurs in steady rain giving the usually observed positive precipitation current and negative potential gradient at the ground. This latter effect, whilst much smaller than the former process in the thundercloud may account for the small positive concentration of charge in the base of the thundercloud.

Chalmers (1956) measured the total vertical current density and the potential gradient at the earth's surface during continuous rain and snow obtaining an inverse statistically linear relationship between the two quantities and the research described in this volume may be considered as a continuation and extension of this work.

CHAPTER 2.

MEASUREMENT OF PRECIPITATION CURRENT

2.1. Methods and Results of Previous Workers.

(a) Early Work. The measurement of the charge on precipitation can be made simply by setting up an insulated collector flush with the earth's surface and measuring the charge received with some form of electrometer. This immediately involves the problem of "displacement currents". If a collector of area A is exposed to the atmospheric potential gradient F then it will have a charge induced upon it of opposite sign to the potential gradient and given by the equation

$$\sigma = \varepsilon_0 F$$

where σ is the surface density of charge in $C.m^{-2}$. If there is now a change in the value of F then this "bound charge" will also change and the measuring instrument will record a displacement current equal to $A\frac{d\sigma}{dt} = -\varepsilon_0 A \frac{dF}{dt}$ amps, indistinguishable from the air-earth current being measured.

This difficulty has resulted in making all experiments to measure precipitation current capable of being divided into two main classes: (i) those in which the collector is shielded from the earth's field and (ii) those where an exposed collector is used and the displacement current is in some way subtracted from the measured current, or in some cases simply neglected.

Care has usually been taken to minimise spurious effects due to splashing at the ground; Lenard (1892) found that drops became positively charged on splashing, the corresponding negative charge being given to the air.

The relative merits and faults of the shielded collector are discussed more fully in Chapter 4, and the exposed collector is to be preferred but it is with the former type of receiver that the great majority of the earlier measurements were made.

Elster and Geitel (1888) were the first to use this method, measuring with an electrometer the quantity of rain-charge collected over periods of between 5 seconds and 2 minutes and making observations by eye. Gerdien (1903) attempted to measure not the charge but the actual current density, connecting his collector to earth through a high resistance of 10^{12} ohms which shunted the electrometer. This method was open to criticism due to the lack of reliable insulation at that time.

Both these investigations found an excess of negative charge on rain contrary to almost all later results, but some evidence of an inverse relationship between precipitation current and potential gradient was indicated. Also, snow was found to be negatively charged.

Weiss (1906) appears to be the first to use a completely exposed receiver. He used a wire brush as a collector in an attempt to eliminate any splashing effects but this introduced the possibility of point discharge in high potential gradients and did not represent a natural surface. Kohlrausch (1909) used a similar method, but shielded the brush from the field; his results however tended to agree with those of Weiss, both finding an excess of positive charge on rain.

Kähler (1908) and Schindelhauer (1913) using shielded collectors and Benndorf electrometers both found a positive excess but found no connection with the variations of potential gradient, Kähler noting a frequent variation in sign of potential gradient without any corresponding changes in precipitation current. Schindelhauer observed a seasonal variation, the relative frequency of positive rain being greater in Winter.

Simpson (1909) made extensive measurements at Simla, India, of precipitation current, recording continuously and measuring charge received in two minute intervals. He found a definite positive excess, this predominance increasing as the rate of rainfall increased, but his results were mainly in thundery weather.

Baldit (1911) took measurements every 15 seconds noticing that longer intervals would miss rapid variations in charge and sign. In contrast Berndt (1912) measured the charge collected over 5 minute intervals. Both found a predominance of positive charge in rain.

Benndorf (1910) found that the charge/time and potential gradient/time graphs were frequently inverse curves, and was thus the first to observe the "mirror image effect" which will be further discussed in a later chapter.

Herath (1914) used an exposed collector in the form of a large sheet of cloth (25 m^2. in area), insulated and connected directly through a sensitive galvanometer to earth; a photographic method was used to record the current density. Currents of the order of $10^{-11} A.m^{-2}$ were recorded and it was found that in "landregen" or nimbo-stratus rain, the current was invariably positive. However, Herath's collecting surface was not "natural" with regard to splashing and no compensation for displacement current was made.

McClelland and Nolan (1912), McClelland and Gilmour (1920), Marwick (1930), and Scrase (1938) measured the charge carried on a definite quantity of rain using a "tilting bucket" device, finding that the greatest current tends to occur with the greatest rate of rainfall.

Schonland (1928), (chiefly in thunderstorms) using a capillary electrometer, and Chalmers and Little (1940 and 1947) simulated natural conditions by using exposed collectors covered with turf and surrounded by similar guard rings. Wilson (1916) had suggested that the effects of splashing would in these circumstances approach those of natural conditions. Again, no displacement current compensation was made in either case.

<u>(b) Recent Results for Rain.</u> Simpson (1949) at Kew, using the

same apparatus as Scr~~e~~ase (1938) but with less shielding, obtained definite evidence of an inverse relationship between precipitation current and potential gradient especially in high potential gradient. The rain current was related to the point discharge current and the rate of rainfall by any of three empirical formulae

$$j/I_p = -2{\cdot}0 \times 10^{-4}\, R^{0{\cdot}57}$$

$$j/I_p = \frac{-1}{5{\cdot}5 \times 10^{2}}\left(1 - e^{-0{\cdot}058\, R}\right) \text{ and}$$

$$j/I_p = -\frac{1}{400}\left(\frac{R}{R+20}\right)$$

where j and I_p are rain current in $A.m^{-2}$ and point discharge in amps respectively and R is the rate of rainfall in m.m. per hour.

This has been explained in terms of the fa~~l~~lling rain capturing point discharge ions (Chalmers 1951).

Simpson also found that his results in low potential gradients could be represented by the formula

$$q = -4.8 \times 10^{-8}\,(F - 400)$$

where q is the charge in $C.m^{-3}$ and F is the potential gradient.

This may be expressed in terms of j the actual rain current in $A.m^{-2}$ and R the rate of rainfall in m.m./hour thus:

$$j = -1.33 \times 10^{-14}\,(F - 400)\,R$$

Simpson also found the "mirror image" effect, as did Stockill and Chalmers (in1956), noting wave-like patterns in both potential gradient and rain current traces, with periods of the order of 15 to 20 secs. (see Chapter 8).

At Durham, Chalmers (1956) used a completely exposed collector, and, employing continuous recording, measured the charge collected every 4½ mins. with a simple electronic circuit. From simultaneous potential gradient measurements the mean displacement current over each period could be calculated and then subtracted from the average current received by the collector in that period. All measurements were taken in nimbostratus conditions. A statistical analysis of the results for rain (recorded on 31 different days) yielded a linear relation between total air-earth current density I ($A.m^{-2}$) and potential gradient F ($V.m^{-1}$), viz:

$$I = -1\cdot18 \times 10^{-14} (F - 150)$$

A marked similarity is seen, between this equation and that of Simpson especially if the value $R \doteq 1$ (a typical value in continuous rain) is substituted in Simpson's equation. The most obvious divergence between the two is the value of F when $I = 0$. Simpson suggested that the 400 in his equation might represent the normal fair weather potential gradient at Kew so that is proportional to the deviation from this value. This view is supported by Chalmers' work since the normal value of the fair weather potential gradient at Durham is of the order of 150 Vm^{-1}, or less.

It should be noted here that any method employing an exposed collector measures the total air-earth current, i.e. both precipitation and conduction currents, whilst the shielded collectors record only the former. However, Simpson's collecting surface was only partly shielded and must be classed as being intermediate between the two types.

(c) Results for Snow. Chalmers (1956) also obtained a similar linear law for snow finding a similar gradient for the I/F graph, to that for rain, but a very different intercept:

$$I = -0{\cdot}92 \times 10^{-14} (F + 425),$$

using the same notation as before.

For a further discussion of the results of Chalmers (1956) reference may be made to Chalmers (1959).

Simpson (1949) with only a few results, found the occurrence of positive potential gradient and negative snow current the most usual. This agrees with the earlier work of Elster and Geitel (1888), Kahler (1908), Schindelhauer (1913), McClelland and Nolan (1913), and McClelland and Gilmour (1920) who all found a negative excess. However, Weiss (1906), Marwick (1930), Gschwend (1927), Simpson (1909), and Chalmers and Pasquill (1938) found the snow-charge more often positive than negative. In these earlier experiments no distinction was drawn between quietly falling snow (more common in nimbo-stratus conditions) and more turbulent fall; Chalmers and Little (1947) found a negative charge on the former and a positive charge on the latter on the average.

(d) Summary. In conclusion, the general inverse relation of potential gradient, and rain current, in doubt throughout the various experiments and diverse techniques of the early workers, now seems well established for the conditions of the nimbo-stratus cloud, by the recent results of Simpson and Chalmers. The added complications of point discharge, which provides an additional source of charge to the rain, are excluded when only low potential gradients occur thereby simplifying any discussion concerning the origin of the charge on precipitation. Further extensive work on precipitation current in steady rain was considered desirable particularly if an exposed collector in conjunction with modern equipment were used. Simultaneous rate of rainfall measurements were also required especially with regard to single-drop observations where drops of different sizes have been found to have charges of different sign and magnitude e.g. Smith (1955) found the larger drops to be of the same sign as the potential gradient whilst the smaller drops were of opposite sign.

2.2. Adamson's Apparatus.

(a) Compensation for Displacement Current. The use of a completely exposed collecting surface for air-earth current measurement necessarily involves some kind of compensation or allowance for the effects of displacement current. The receiver used by the author's predecessors at Durham comprised such an exposed collector in the form of a hemispherical copper bowl mounted on polystyrene insultation and connected to an input resistor of the order of

10^{10} ohms. The current received was detected by an electrometer valve and a direct-coupled amplifier of high stability employing negative feedback and acting as an impedance changer. This was developed by Kay (1950) who also furnished the amplifier with specially constructed H.T. and heater supplies.

Adamson (1958) modified the d.c amplifier, and his particular contribution was to provide an electronic means of compensating for displacement currents. A full description of this appears in Adamson's thesis and it is here proposed merely to summarise the apparatus and method used.

By this method, the output from a potential gradient measuring machine, after rectification and smoothing, is differentiated by a capacitance-resistance circuit and the resultant voltage applied to one grid of a double tetrode electrometer valve having a common cathode (Ferranti DBM 4A), whilst the other grid receives the signal from the air-earth current collector. The difference between the voltages appearing at the two anodes is shown to be proportional to the difference between the grid voltager. The signals at the anodes are then 'subtracted' by loading them respectively to the two grids of a double triode (6SC7) one anode of which is connected directly to the H.T. line. Thus a signal proportional to the rate of change of potential gradient, i.e. to the displacement current, is effectively subtracted from the air-earth current signal. The output from the double triode, after a further stage of amplification is applied to a cathode follower and measured with a galvanometer whilst 100% negative feedback is applied from the final output stage to the "earthy" end of the air-earth current input resistor.

The reader is again referred to Adamson's thesis for a detailed discussion of the difficulties encountered in effecting compensation and in particular in balancing the time constants of the two sides of the circuit (compensating and air-earth current sides) for the effects of transients. A theoretical treatment of the circuit performance, using the method of the Laplace Transformation, is given.

In practice satisfactory compensation could be achieved for steady changes in potential gradient but not for sudden changes (see chapter 5).

(b) The Field Mill. Adamson designed and used a field mill in order to provide the output proportional to the potential gradient necessary for the compensation described above. The mill differs from the conventional type, in general use in Atmospheric Electricity, in that the negative feedback is applied not to the amplifier stage only but over the whole system of mill, amplifier and rectifier, with a resultant improvement in both stability and linearity.

The collecting plate of the mill is a full circular disc over which rotates the usual earthed sectored vane in the form of the Maltese Cross. A third fixed vane is fitted above the rotor and to this third plate is applied the rectified output of the amplifier. This sets up a potential gradient betweenthe fixed vane and the collecting plate of the same sign and very nearly the same magnitude as the natural potential gradient being measured, producing a bound charge which is modulated by the rotor in the usual way. However, this field and the natural potential gradient are modulated, one out of phase with the other, so that the output from the collector yields the difference between the two. Thus it can be seen that a negative feedback process is operating.

Rectification is effected by using a commutator on the same shaft as the rotating vane whilst an amplifier of conventional design is employed.

(c) The Site. Both the current collector and field mill are housed in a pit so that their exposed surfaces are at ground level, and are situated $4\frac{1}{2}$ m. away from the laboratory building in a plot of land which unfortunately is not ideally suited to the purpose. Previous workers have noted that the site is flanked on three sides by the laboratory building, a line of trees, and a small wood respectively, but also that the fourth side is open and that it is from this quarter that the prevailing winds blow, viz: from the West. The unsuitability of the site is now further emphasised however by a large building now being erected to the West!

The rainfall recorder (see chapter 3) which was added to the present equipment was placed in a similar position with respect to the laboratory in order to record a similar rainfall to that received by the current collector, without making any claims to identity with the rainfall over level, open, ground.

2.3. Aims of Present Research.

Adamson had time to take only a few results with his apparatus in disturbed weather conditions but these served to illustrate the efficiency of the equipment and in particular, of the displacement current compensation.

In the present work it was proposed to use the "Adamson apparatus" to measure the total vertical air-earth current density together with the potential gradient at the earth's surface in nimbo-stratus conditions. Continuous recording of the actual current over periods of several hours could be made in contrast to earlier methods in which the total charge received by a collector in a given time was measured and where in many cases, measurement took place only at selected times.

By taking large numbers of results it was hoped to arrive at a statistical relationship between current density and potential gradient and thereby obtain a comparison with the results of Chalmers (1956). All types of precipitation from nimbo-stratus clouds were to be considered in order to investigate the differences and similarities between rain and snow conditions obtained by other workers. The range of potential gradient values in which measurements were to be taken was chosen so as to eliminate the possibility of point discharge from nearby objects occurring and thereby complicating the electrical conditions prevailing; showery weather, where the "steady state" assumptions (see 1·5) are not applicable was also excluded.

The design and construction of a rainfall recorder was undertaken to investigate how the current density/potential gradient relationship depended on the rate of precipitation.

Also, since the "Adamson apparatus" was being used as an improvement on earlier forms of current measurers employing as it did an exposed collector and the method of compensation described above, it was considered that interesting comparisons could be made if a "shielded collector" was also used to record current densities simultaneously. For this purpose, a shielded collector of the type used by Scrase (1938) was constructed and is described in a later chapter.

In addition it was anticipated that useful information could be gained concerning the effects of splashing at the ground by examining the results in conjunction with the space charge measurements of Smiddy (1958) taken at the same time and in the same place.

CHAPTER 3.

THE RAINFALL RECORDER

3.1. Alternative Methods.

In order to measure the rate of rainfall, a number of alternative methods were considered.

The instrument, produced and marketed by the Road Research Association relies entirely on mechanical principles. Rain from a collecting funnel is led into a vessel with a capillary tube outlet, the rate of outflow being proportional to the head of water in the vessel. This is measured by connecting a float through a system of levers to a pen recorder. The whole unit is precision engineered, and measures the rate of rainfall directly, but was considered too expensive for the present research.

Both Simpson (1949) and Sorøase (1938) used a "tilting bucket" device in which the times were recorded each time the "bucket" emptied itself, i.e. each time a fixed volume of rain had fallen into the collecting funnel. The average rates over these times were determined from the record. The instrument proved inefficient in periods of very heavy rain, and had the disadvantage of having moving parts. Also, with this method, a sharp increase in rainfall for a short period of time would not be detectable.

3.2. "The Rainfall Condenser."

It was finally decided to employ an electrical method making use of the high dielectric constant of water (Kaye and Laby (1956) give this as 80) by leading the rain from a collecting funnel, between the plates of a parallel plate or cylindrical condenser and measuring the change in capacitance so produced. If the system were fitted with a capillary tube outlet, then in theory, the capacitance of the condenser would be proportional to the head of water and hence to the rate of rainfall. However, this arrangement would be very sensitive to variation of viscosity with temperature and contamination; to the risk of partial or total blockage of the tube by dirt brought down by the rain, and possibly also to surface tension effects. It was considered simpler therefore merely to measure and record the capacitance as the condenser filled up and to determine the rate from the record obtained as described in 5.10.

Since rainwater is not a good insulator it was of course necessary to insulate the plates of the condenser from its contents and an attempt was made to construct the first condenser in the following manner.

Two parallel aluminium plates, 10 cm. square and coated with a suitable substance were fixed 0.5 cm. apart in a perspex framework, cemented and made watertight with "Araldite" adhesive resin. Considerable difficulty was experienced in finding an efficient way of thinly coating the plates and, by trial and error, all the following substances were found to fail in providing a flawless insulating coat: (i) Perspex, applied by

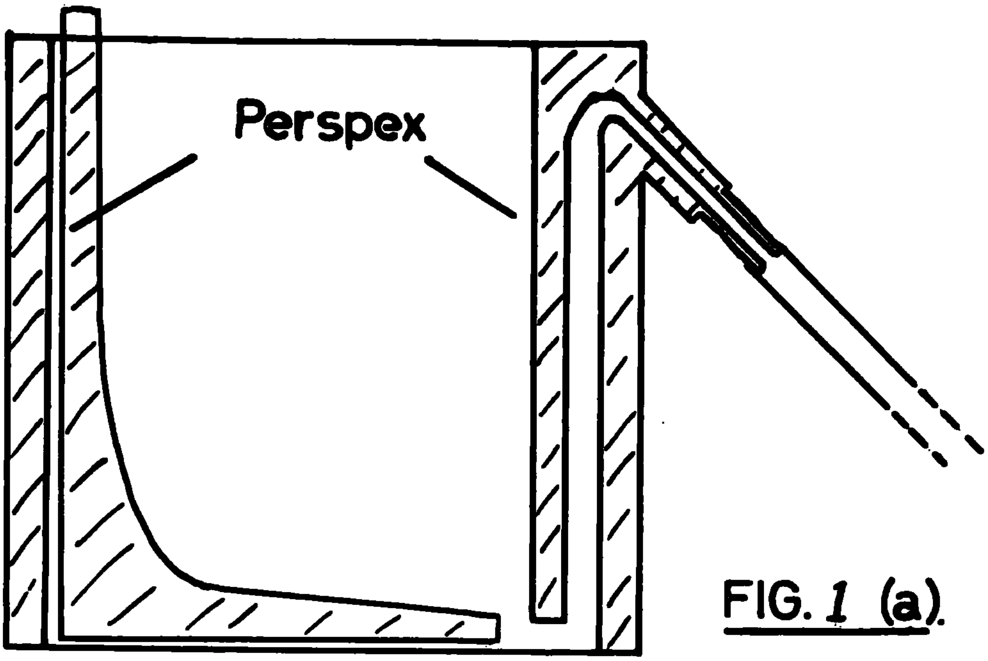


FIG. 1 (a).

The "Rainfall Condenser"

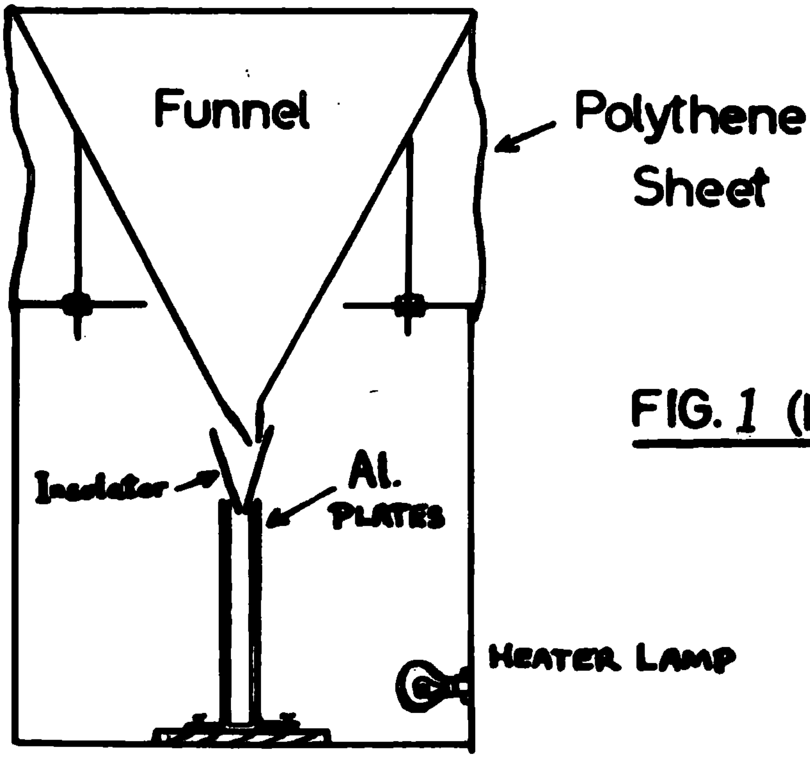


FIG. 1 (b).

painting with a solution of perspex in chloroform. (ii) Celluloid applied in a solution in acetone. (iii) "Araldite".

The idea of coating the plates was now abandoned in favour of constructing a dielectric container of dimensions 10 x 10 x 0.5 c.m. which could be inserted between the plates. For maximum sensitivity, it is required that the container walls are made as thin as possible. If the thickness of the walls is $a/2$ and the internal width of the container is b then the capacitance of the condenser when empty is

$$C_0 = \varepsilon_0 \varepsilon_a A \Big/ (a + b\varepsilon_a) \quad \cdots\cdots \; 3.2\,(a)$$

and when full of water is

$$C_{max.} = \varepsilon_0 \varepsilon_a \varepsilon_b A \Big/ (a\varepsilon_b + b\varepsilon_a) \quad \cdots\cdots \; 3.2\,(b)$$

where ε_a and ε_b are the dielectric constants of the material of the container, and of water respectively, and A is the area of the plates.

Hence $$C_{max}/C_0 = \varepsilon_b (a + b\varepsilon_a) \Big/ (a\varepsilon_b + b\varepsilon_a) \quad \cdots\cdots \; 3.2(c)$$

Since $\varepsilon_b = 80$ and $\varepsilon_a = 2.6$ (for perspex), then for this ratio to be large $b \gg a$

In practice, the walls and base of the container were made from a single sheet of cellulose acetate, thickness 0.15 mm. cemented to rigid sides of perspex with "Araldite" (Fig. 1a). The cellulose acetate sheet satisfied the thickness condition but lacks great rigidity.

3.3. The Syphon Tube.

To make the apparatus automatic, it was necessary

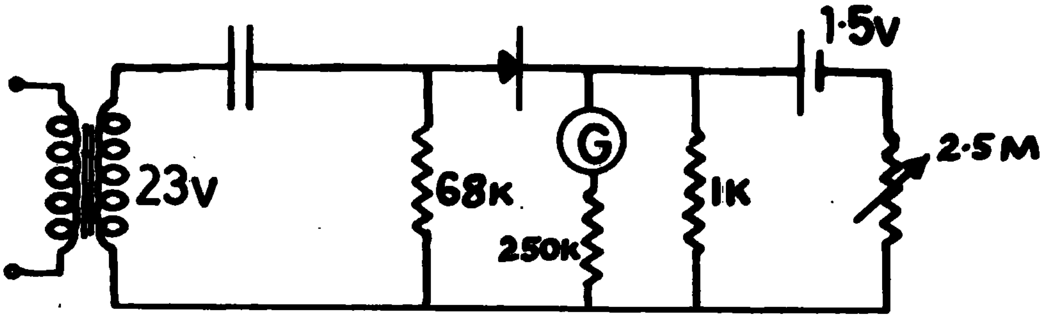
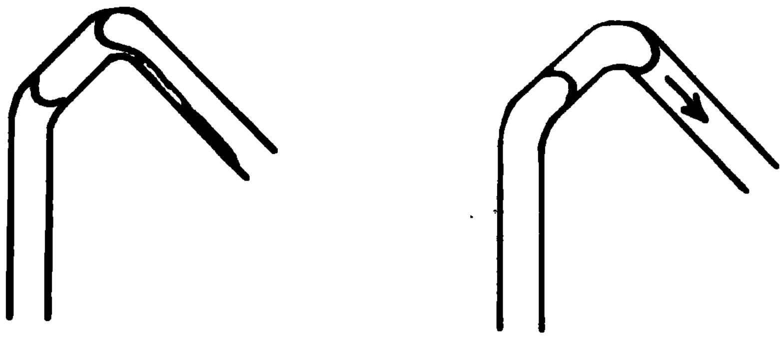


FIG. 2.



(a) FIG. 3. (b)

to have an arrangment by which the condenser would empty itself as soon as it had filled up. An extension to the dielectric container was constructed and into this was inserted a rubber syphonning tube. Fig. 1a shows a later, improved form of this, in which the rubber tube is replaced by a "built in" syphonning tube made of perspex. With the first device, it was found necessary to have a constriction in the bend at the top of the rubber tube before efficient syphonning would take place. The container was emptied by the syphon in a very short time, of the order of a few seconds, whilst it took several minutes for it to fill even in very heavy rainfall (see Fig. 6 where the rate of rainfall is as high as 0.2 mm/min. towards the end of the record.)

3.4. The Measuring Circuit.

A very simple circuit was used to measure the capacitance of the condenser (Fig. 3). A mains transformer giving 23 volts passed an alternating current, which after flowing through the condenser, was rectified by a Germanium diode (G.D.3 Brimar), and measured. The battery B, passed a current through the galvanometer in the opposite direction, cancelling out the comparatively large zero deflection due to the 9 metres of co-axial cable used to connect the condensor to the indoor apparatus. This zero output could have been avoided by having the connecting cable in the D.C. side of the circuit but this would have involved having the rectifier outside, thereby increasing the possibility of instability due to temperature variations.

3.5. Housing.

The condenser was housed in an earthed metal box under a funnel of "tin" sheet made in the form of a cone of semi-angle 30° and having a collecting area of 0.07 m^2. (Fig. 1.b.). A small celluloid funnel led the rain from the metal funnel to the container thereby preventing its contents being connected to earth as the water flowed in from the collecting funnel. A polythene sheet kept the inside of the box dry. This was stuck on to the rim of the funnel, as shown, with rubber solution which serves as a fairly efficient adhesive for the metal- polythene joint providing no great strain is involved. It was found necessary to keep the condenser warm to prevent moisture condensing and providing a low resistance path between the aluminium plates. A 12 v. 24 watt galvanometer lamp bulb served this purpose and was run at reduced voltage to give long service. The bulb was wrapped in metal foil so that it emitted heat but no light as the latter attracted large numbers of flying insects, and consequently spiders, adding considerably to the insulation and syphonning problems.

3.6. Performance.

The first "rate of rainfall recorder" was found to having the following disadvantages:

1. The capacitance of the condenser did not vary linearly with the volume of water contained, the instrument proving to be most sensitive when about half full, and least sensitive when nearly empty. This departure from the theory of an ideal parallel plate condenser could have been caused by

(a) end effects especially at the bottom of plates, and (b) lack of rigidity in the sides of the dielectric container resulting in air spaces of unknown size between the container and condenser plates.

2. The stability of the system was unsatisfactory. This was attributed to the fact that the germanium diode was operating at a very low current (of the order of $0.1 \mu A$).
3. When the condenser "syphonned out" the zero output did not return to its original value. This effect was much in excess of what would be expected from a variation in the "dead volume" left in the container on syphonning, or from drops remaining on the sides of the container. No satisfactory reason for this zero drift was found.
4. The automatic syphon device was often inefficient. The constriction in the tube mentioned above proved to be highly critical and could only be adjusted by trial and error.

The first of these four disadvantages did not prove serious as the apparatus could be calibrated at the beginning of each record or of each day's recording, by introducing water from a burette, ten or five c.c.s at a time, and assuming linearity over each increment in volume. The other difficulties however were more troublesome. Although some useful results were obtained using this apparatus in the Winter of 1957-58 it was eventually decided to redesign both the condenser and the measuring apparatus.

3.7. The Reconstructed Rainfall Recorder.

A second condenser and dielectric container were constructed as described in paragraph 3·2 but with an important modification to the syphon device, the first part of the tube being drilled out of perspex (fig. 1a) and the remaindor being made of polythene tubing. Any irregularity in the syphonning could thus be visually observed and then corrected.

It was seen that on some occasions, when the container filled up, the water merely overflowed, but did not initiate the syphonning action, due to the shape of the meniscus as shown in fig. 3 (a). If the angle of contact of the water-perspex interface had been greater than 90° this problem would not have arisen. For the syphon to work efficiently it was therefore necessary to coat the inside of the bent part of the tube with a wax or grease so that the required condition should be satisfied, i.e. that the column of water rising up to the top of the tube should have a convex meniscus, as in fig. 3 (b). The bend in the tube was first warmed in hot water (about 50°C), the inside being kept dry, and then molten "Vaseline" was introduced and almost immediately poured out again, thus giving the inside a thin coating. This treatment proved to be highly satisfactory and only rarely did the device fail to syphon in the correct manner afterwards.

3.8. The Circuit.

The capacitance was measured by passing a current from a 30 volt mains transformer through the condenser in series with a 1 MΩ resister to one grid of a double triode (6SN7)

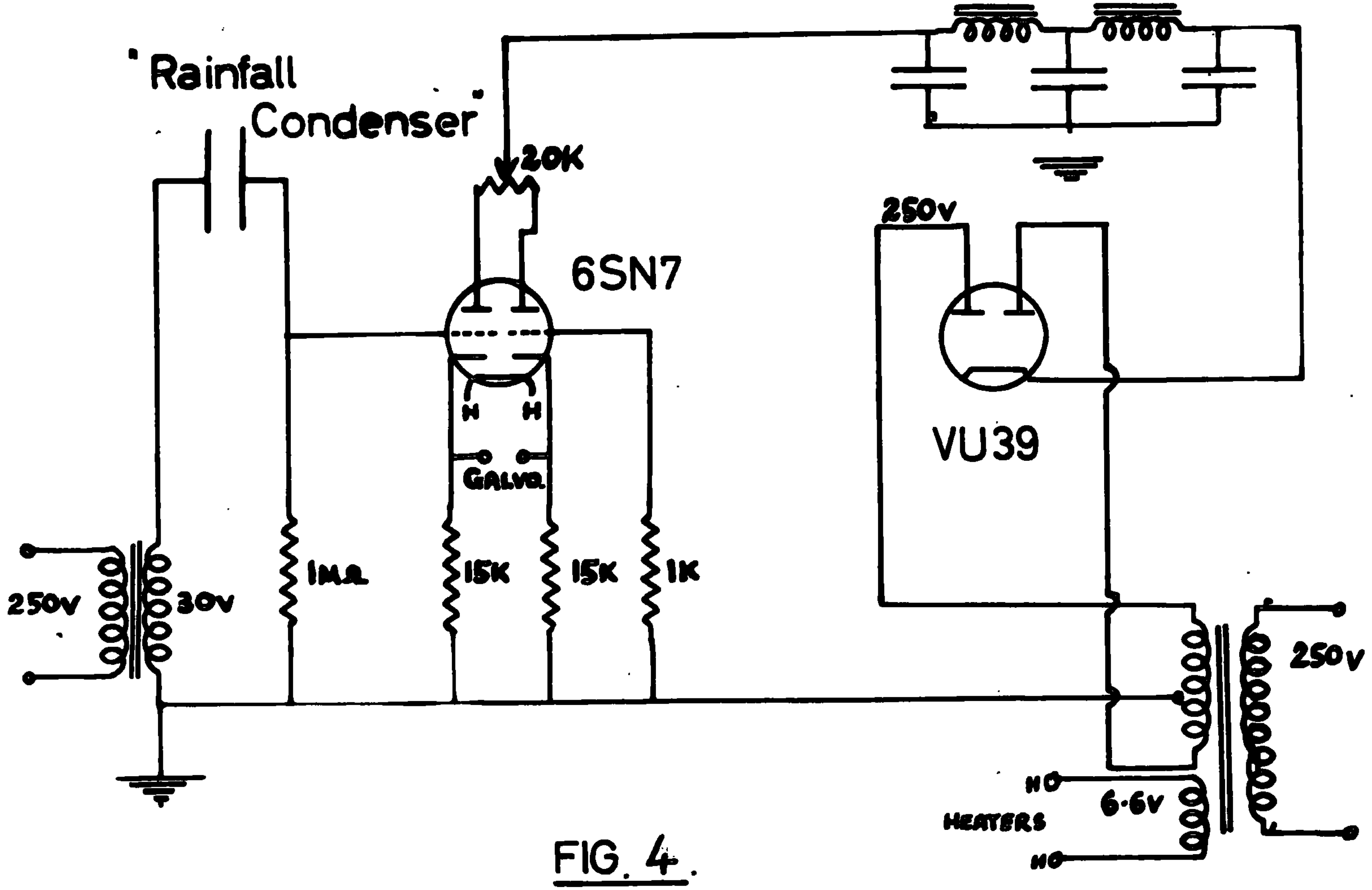

"Rainfall Condenser"
20K
6SN7
H
H
GALVO.
250V
30V
1MΩ
15K
15K
1K
250V
VU39
250V
6·6V
HEATERS
H
H

FIG. 4.

(fig. 4). This grid is biassed to cut-off in order to effect rectification whilst the second grid is earthed. The galvanometer measures the difference in potential between the cathodes; this is zero in the absence of a signal, the anode current being shared between the two halves of the valve. Use of the double triode eliminates the need for great stability in the H.T. supplies. A standard ex-Admiralty power pack was used to provide heater and H.T. voltages, and its outer casing served also to house the rest of the circuit with the exception of the condenser itself and of course the galvanometer. The unit was easily made weather-proof and was kept underneath the box containing the funnel and condenser. The lead to the latter was thus reduced to only a foot in length thereby eliminating the big zero output produced by using long lengths of co-axial cable.

3.9. Improved Performance.

The circuit was tested by replacing the "rainfall condenser by a standard condenser the capacitance of which could be varied from 0 to 350 $\mu\mu F$. Fig. 5 shows the galvanometer deflection plotted against the capacitance and it can be seen that although the variation is not linear, the departure from linearity is not great especially in the range 100 to 350 $\mu\mu F$.

Consideration of the equivalent circuit of the double triode showed that the current through the galvanometer and shunt is given by

$$I_G = -\left(\frac{15\mu V_g}{32 r_a + 350}\right), \quad mA.$$

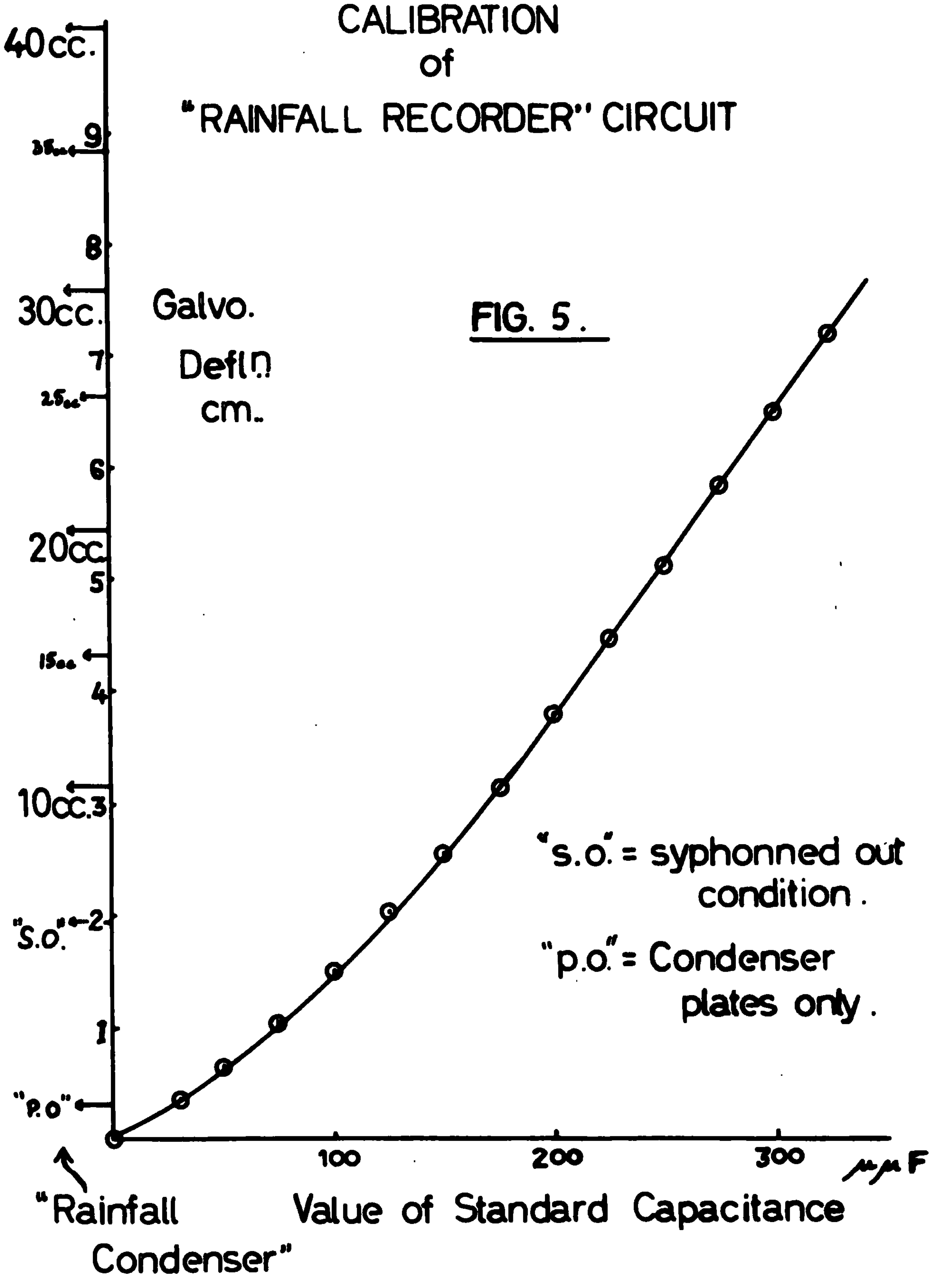


FIG. 5.

CALIBRATION
of
"RAINFALL RECORDER" CIRCUIT
Galvo.
Defln
cm.
40cc.
35cc
30cc.
25cc
20cc
15cc
10cc.
"s.o."
"p.o"
1
2
3
4
5
6
7
8
9
100
200
300
μμF
Value of Standard Capacitance
"Rainfall
Condenser"
"s.o." = syphonned out
condition.
"p.o." = Condenser
plates only.

where r_a is the a.c. resistance of the valve measured in kilohms, μ is the amplification factor, and V_g is the applied voltage at the first grid.

Thus I_a should be linear w.r.t. variation of the standard capacitance assuming μ to be constant, but this assumption is not valid due to the conditions of operation of the valve.

No attempt was made to improve the linearity of the circuit however, since there existed a much greater non-linearity inherent in the "rainfall condenser". It was found that the latter could be improved by inserting a piece of perspex of thickness approximately equal to the internal width of the dielectric container, and shaped as shown in fig. 1a To some extent this counteracted the "end effects" of the condenser but also reduced the useful volume between the plates.

The apparatus was calibrated each day recording took place, and a typical calibration is entered on the diagram (fig. 5) in which the deflection for the condenser plates only is also shown. From the graph, the capacitance of the plates alone, which now measure 10 x 12 cm, is 25 $\mu\mu F$ in close agreement with the calculated value of 22 $\mu\mu F$. Equation 3·2(c) shows that the capacitance when full should be 28 C_0 i.e. 620 $\mu\mu F$. If allowance is made for the reduction to about 40 ccs. of the useful volume of the container then it can be shown that falls to 410 $\mu\mu F$ again in accordance with the practical result.

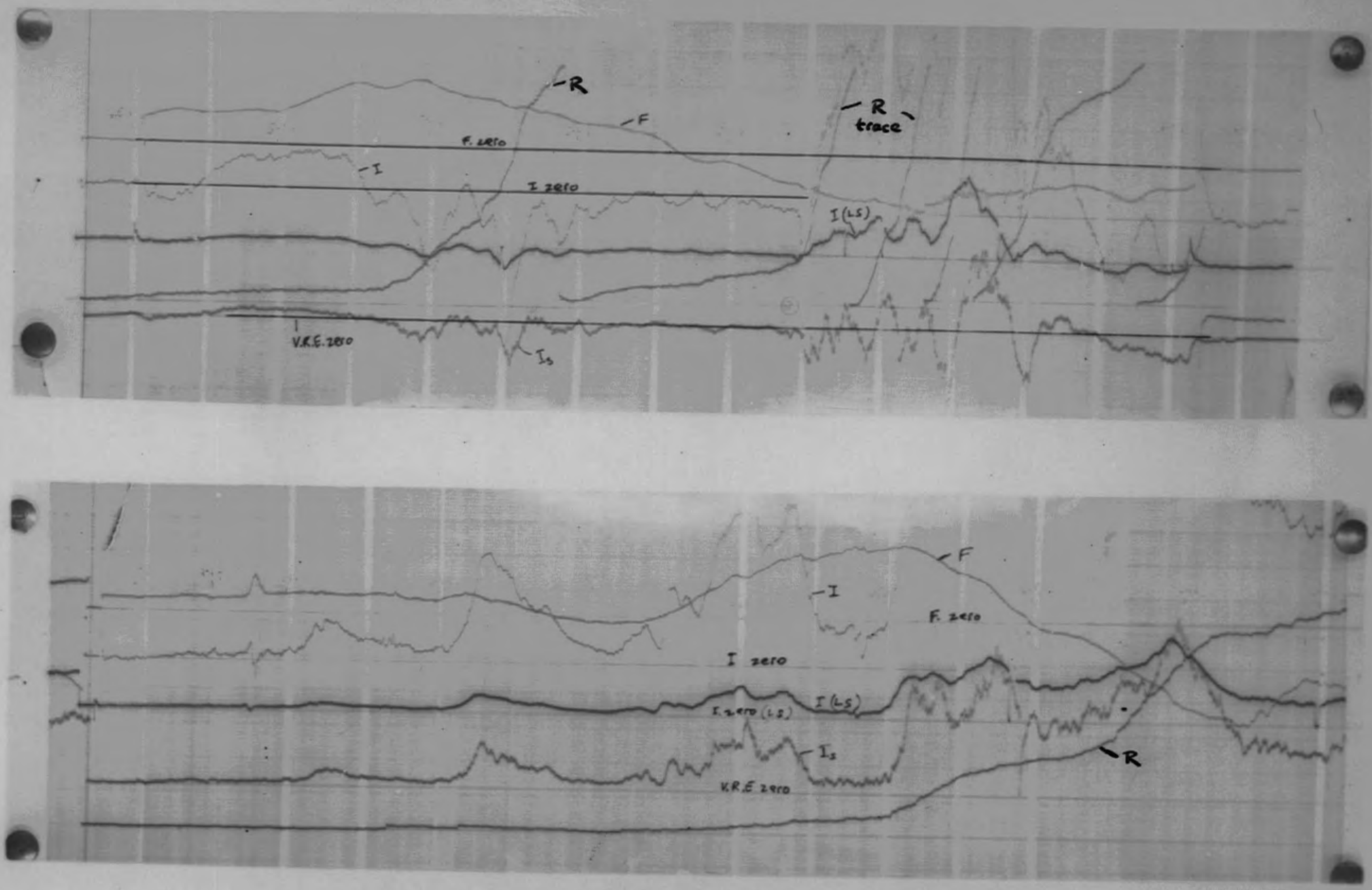

R
F
R trace
F. zero
I
I zero
I (LS)
V.R.E. zero
I_s
F
I
F. zero
I zero
I (LS)
I. zero (LS)
I_s
V.R.E zero
R

FIG. 6

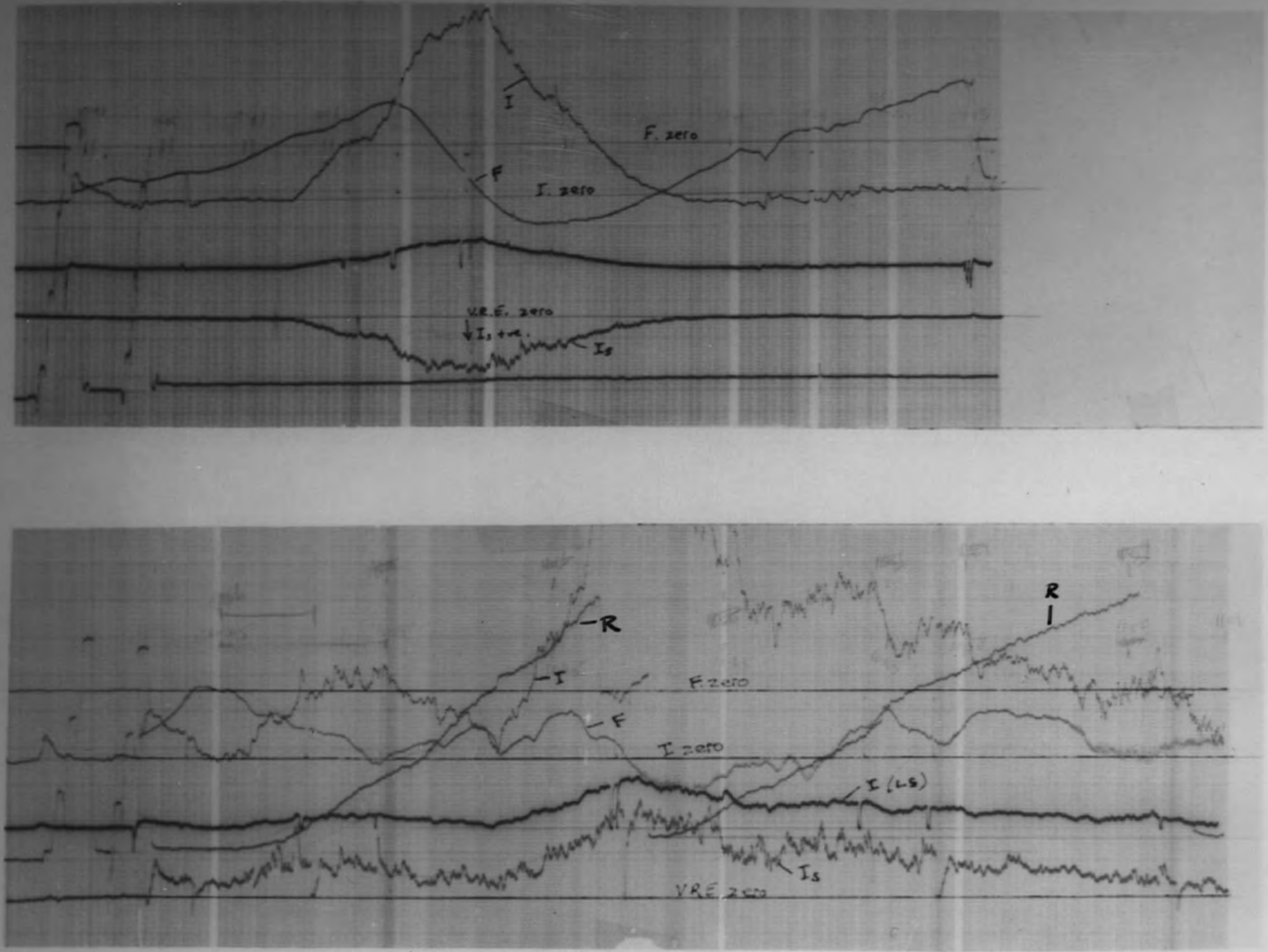

I
F. zero
F
I. zero
V.R.E. zero
↓I, +ve.
I_s
R
I
F zero
F
I zero
R
I (LS)
I_s
VRE zero

FIG. 7.

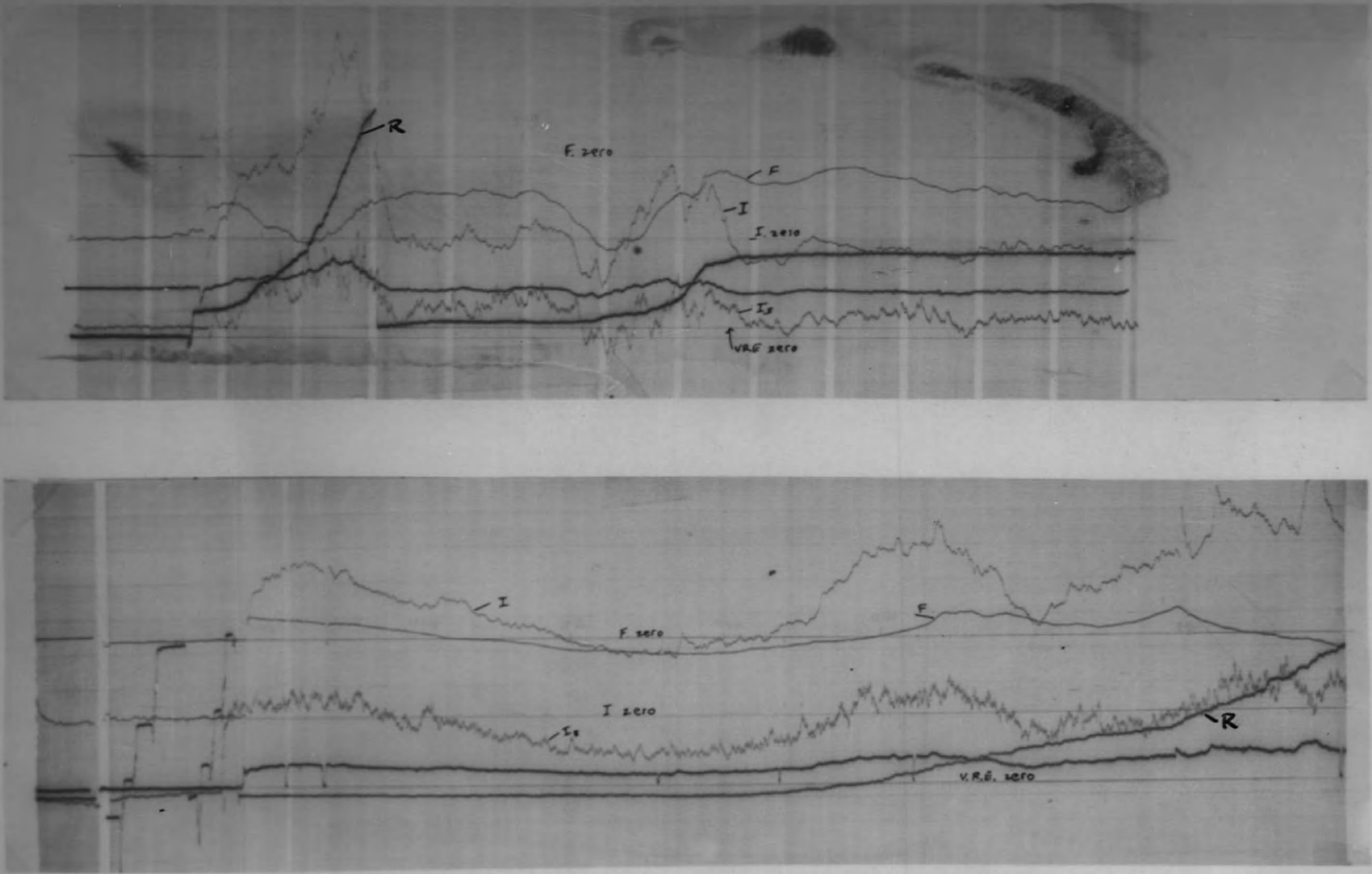


FIG. 8.

A collected volume of 7.1 ccs. is equivalent to a rainfall of 0.1 mm. so that even with the very high rate of 0.1 mm. per min., seldom encountered in nimbo-stratus conditions, the condenser took a few minutes to fill. The lowest rate of rainfall which the instrument could measure was 0.003 mm. per minute. The performance was now quite satisfactory, as illustrated in figs. 6,7,+8, taken from actual records.

CHAPTER 4.

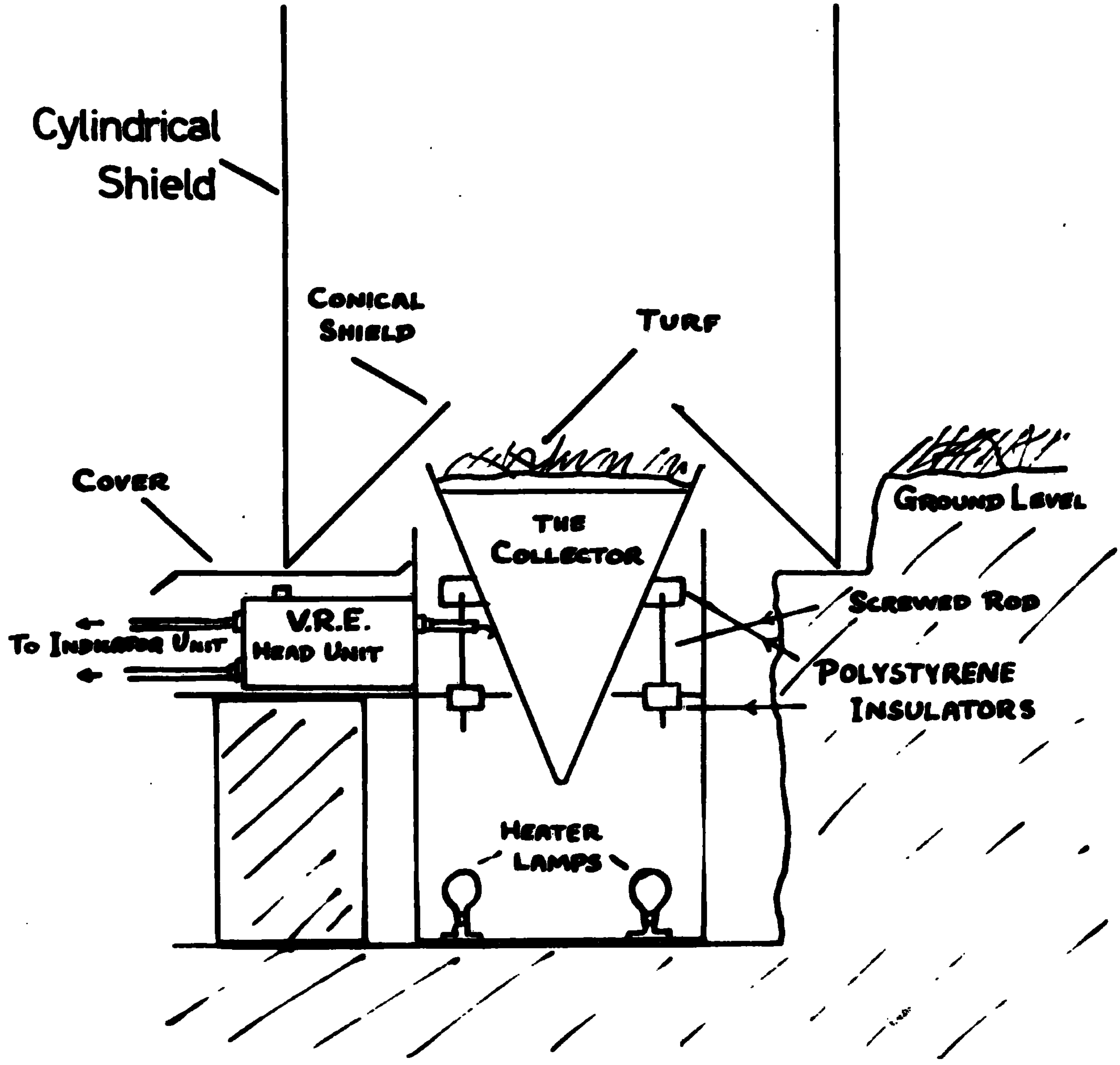
THE SHIELDED RECEIVER

4.1. General.

Most of the earlier measurements of precipitation current (Chapter 2) have been made using shielded collectors in which the effects of the potential gradient on the collecting surface are eliminated or greatly reduced by surrounding it with an earthed conducting shield. (fig. 9).

The great disadvantage of this type of receiver is the possibility of missing some of the rain especially in windy weather. Scrase (1938) found that his apparatus received only half the amount caught by a standard rain gauge. This is particularly serious if charge of different sign resides on raindrops of different size since the smaller drops will be affected most by the wind.

Simpson (1949) greatly reduced the height of the cylindrical shield so that his collector received as much rain as a standard gauge, but consequently no longer eliminated displacement currents. He found that one possible source of error was non-existant, viz. that drops could carry an appreciable charge to the collecting surface after splashing on the rim of the shield which would possess an induced charge.



The SHIELDED COLLECTOR

FIG. 9.

It was proposed to construct a shielded collector similar to that of Scrase in order to compare the results obtained by this method with those given by the exposed collector. Any significant difference in the two sets of results could then lead to interesting and possibly important conclusions.

4.2. Design and Construction. The design of the shielded receiver is shown in fig. 9 . The cylindrical shield is 60 cm high and 60 cm in diameter whilst the opening of the inner conical shield is 25 cm. in diameter giving an effective collecting area of 0.049 m^2. It was found that the potential gradient under the conical shield was approximately 2% of that over level ground. Any spurious effects due to displacement currents were therefore highly unlikely to arise in nimbo-stratus conditions where the potential gradient is fairly small and rarely undergoes violent changes.

Increasing the overall size of the apparatus compared to that of Scrase and Simpson reduces any effect of splashing on the rim which may exist (e.g. Lenard effect, independent of the potential gradient) since doubling of the size would double the perimeter but would quadruple the collecting area.

The collector itself was made in the form of a funnel with a rim diamter of 35 cm. and fitted with a false bottom containing turf in order that it should have a similar surface to that of the exposed collector. The funnel was supported on two sets of polystyrene insulators and mounted on the top of a tin box as shown in the diagram. It was found necessary to keep the insulators warm and this was achieved by having two 40 watt lamps in aluminium cans fitted inside the box. The cans served a double purpose; they provided electrical shielding and greatly reduced the emitted light but not the heat (see 3.5) Since the lamps were permanently switched on, frequent replacement was required. To overcome this necessity, they were later connected up in series, instead of in parallel, and have burned continuously at reduced voltage, for over 15 months.

The insulation of the funnel was tested by the method of leakage and found to be better than $10^{14}\ \Omega$.

The reason for the collector being funnel shaped was that it had been originally intended to measure the quantity of rain collected by leading it into a rainfall recorder. However, it was found that drops leaving the funnel carried away a quantity of charge thereby reducing the measured current. This would appear to be a serious defect of the apparatus of Simpson and Scrase where the rain from the collecting funnel fell into the "tilting-bucket" device.

The whole system of current collector and rainfall recorder could of course be connected together and insulated from e earth but this would prevent the use of a rainfall recorder employing an electrical method of measurement such as that described in Chapter 5, and would also preclude using turf as a collecting surface. It was finally decided not to attempt the measurement of the rainfall inside the shield.

4.3. The Vibrating Reed Electrometer.

The current received by the shielded collector was measured continuously using an "Ecko" Vibrating Reed Electrometer, in contrast to most earlier methods where the total charge collected over short periods of time was measured. The V.R.E. is essentially a device for measuring small unidirectional currents in the range 10^{-14} to 10^{-8} amp.

The current to be measured passes through slected input resistor (a choice of 10^{8}, 10^{10} or 10^{12} ohms.) and the voltage developed is applied to the vibrating reed or dynamic capacitor. This converts the D.C. signal into an A.C. voltage, the magnitude of which is proportional to the original current being measured, whilst the phase depends on the sign of the latter. The resultant A.C. is subsequently amplified and then undergoes phase-sensitive rectification in which use is made of a reference signal from the reed regulating supply. The final output is displayed on a meter, unfortunately not a centre-zero instrument, and there is also an arrangement for connecting a recorder; in the present work a mirror galvanometer was used. Appropriate shunts may be selected by means of the range switch on the instrument so that full scale deflection on the meter corresponds to 30, 100, 300 or 1000 mV. across the input resistor.

The V.R.E. was not designed for measuring negative inputs but it can be used for currents of both sign with only very slight modification (Haberfield 1957). The meter is no longer in circuit (but still"in situ") and is replaced by a 100 ohm resistor Also, there is a diode include in the circuit which prevented damage to the meter under conditions of high negative inputs and resulted in the output being non-linear for negative inputs as the meter (with connecting reversed) approached full scale deflection. This difficulty was overcome by biassing the diode, the cathode of which is now connected to earth through a 2.2 k resistor instead of being earthed directly. Subseqently, however, it was found that the top half of the scale was seldom used particularly when the precipitation current was negative, a condition rarely encountered in steady rain although quite frequent in snow.

The V.R.E. comprises two parts, the "head unit" and the"indicator unit" connected for the present purpose by 9 m. of cable fitted with "Plessey" plug connections. The indicator unit, containing the main amplifier, phase-sensitive rectifier, range control and meter, and all H.T. and heater supply circuits, is housed indoors in the recording room.

The head unit, which includes the vibrating reed, the input resistors and the first stage of amplification, is bolted directly on to the shield surrounding the collecting funnel thereby making the connection to the latter as short as possible (Fig. 9). Initially the head unit had been connected to the collector by 2 ft. of co-axial cable but it was found later that large fluctuations in output were produced due to slight movement of the cable. This fault had proved very elusive for some time before the cause was discovered.

Further notes on the operation and calibration of the V.R.E. are contained in Chapter 5.

4.4. Expected Results.

The purpose of using the shielded collector in conjunction with the exposed collector can be seen from the following consideration of the possible results:-

(a) Effect of conduction current. Since the exposed collector measures the total air-earth current, i.e. both precipitation and conduction currents whilst the shielded collector receives only the former, it would be expected that

$I_s > I$ if the potential gradient F and hence the conduction current i are negative,

and $I_s < I$ if F and i are positive.

Where I is the current in $\mu\mu A.m^{-2}$ measured by the exposed collector and I_s is that measured by the shielded collector. If other factors can be neglected then

$$I - I_s = i = \lambda F$$

where λ is the conductivity of the air at the earth's surface and F is the potential gradient measured at the ground. This would then give an indirect method of determining λ.

(b) Effect of Splashing. If there is a "Lenard splashing effect" by which the rain and hence the collector receives positive charge on splashing whilst the corresponding negative charge is given to the air there would appear to be two possible results, directly opposite in effect:

(i) Owing to atmospheric turbulence the small ions generated by splashing will be swept away from the exposed collector but not from the shielded receiver so that a fraction of this negative charge will diffuse back to the latter. Hence $I > I_s$ for all values of F and the magnitude of this effect will increase as the rate of rainfall increases.

(ii) Only about one sixth of the negative small ions generated at the shielded surface will return to the collector by diffusion alone (neglecting losses by recombination etc.) the remainder going to the shield or escaping upwards, but above the exposed collector possibly a larger fraction will be driven down by the ambient potential gradient, usually negative in steady rain.

Thus $I_s > I$ if F is negative,

and similarly $I_s < I$ if F is positive.

The effect will increase as $|F|$ increases and, as before, as the rate of rainfall increases.

The splashing effect investigated by Adkins (1958) in which the charge received by the rain is of the same sign as the potential gradient and depends on the latter, would affect only the exposed collector. However, this would not be expected to arise under the conditions of low potential gradient existing in nimbo-stratus weather.

(c) <u>Effect of Shielding.</u> This has already been discussed at the beginning of the chapter and results in the collector missing a higher fraction of the smaller rather than the larger drops in windy weather. According to Smith (1955) the smaller drops have charge of opposite sign to the potential gradient whilst the larger ones have the same sign. Hutchinson and Chalmers (1951) however found a preponderance of drops of all sizes with charge opposite in sign to the potential gradient. The latter would give possibly no difference in I and I_s but if the results of Smith are considered it would be expected that:

$$I_s > I \quad \text{for positive } F .$$

and $$I_s < I \quad \text{for negative } F .$$

CHAPTER 5.

Use of Equipment and Experimental and Recording Details.

5.1. Compensation for Displacement Currents.

It has already been mentioned (Chapter 2) that Adamson showed that his method for compensating for the effects of displacement currents on the air-earth current collector was effective for slow, but not for sudden, changes in the potential gradient. In practice, an optimum setting of the variable capacitance, used to differentiate the mill output, was required. By careful adjustment of this capacitance, satisfactory compensation for steady changes in potential gradient could be obtained and also the time for recovery from the effects of transients could be minimised. This proved entirely satisfactory for the potential gradient changes encountered in nimbo-stratus conditions, whilst small sudden fluctuations produced recognisable fluctuations in the air-earth current trace which could be "smoothed out" when the record was analysed.

The method used to effect compensation was that devised by Adamson whereby a sawtooth voltage was applied to a large aluminium plate 8 ft. x 4 ft. placed over both collector and mill, and mounted on insulators. The applied voltage is "tapped" from a wire-wound potentiometer connected to a H.T.battery, the "wiper" of the former being driven round by a synchronous motor. During the linear rise of applied potential gradient a steady displacement current is produced and by varying the differentiating condenser mentioned above, the d.c. amplifier output is adjusted to zero. Compensation cannot however be achieved for the suddent change in potential gradient occurring at the end of each cycle. The period of the sawtooth was 225 secs. and the height of the plate above the collector and mill was 46 cm.

5.2. Calibfation for Conduction Current.

This method can also be used to find the effective area of the collector with respect to conduction current measurement. Since this area, A_e, is the same for both displacement and conduction currents, then it may be found if the sawtooth voltage is applied to the plate and the displacement current measured without compensation, i.e. with the mill output disconnected. The displacement current from the collector $i_d = \varepsilon_o \frac{dF}{dt} A_e$. amps. where F is the applied potential gradient. From the output of the d.c. amplifier and its known sensitivity this current can be measured and hence A_e determined.

Adamson found that the effective area of the collector (a hemispherical bowl) for conduction current was one half the area of its aperture. However at thebeginning of the present work, a false bottom supporting turf to stimulate natural conditions, was fitted in the bowl and it was found that the effective area was now, to a close approximation, the same as that of the aperture itself.

It was not found necessary to carry out the compensation procedure very often, but the setting of the differentiating condenser was checked periodically.

5.3. The D.C.Amplifier.

The d.c. amplifier was calibrated by disconnecting the collector from the electrometer stage and applying known voltages across the input resistor. This was done by using a 2 v. cell with a potential divider comprising two decade resistance boxes in the form of a Rayleigh potentiometer, pre-calibrated against a standard cell. The simplicity of operation was greatly increased by adjusting the total resistance of the potentiometer so that one ohm corresponded to 1mV fall of potential and hence the applied voltage could be read off directly.

Two galvanometers of different sensitivities were used in series to record the final output of the amplifier. This obviated the necessity of using a variable shunt and allowed the apparatus to record unattended even when there were large variations in the magnitude of the input, i.e. the precipitation current.

The H.T. and heater supplies to the amplifier were normally left switched on and no major failures in either amplifier or power circuits occurred during the three years of operation and the general performance was highly satisfactory.

The accumulators supplying the electrometer valve heater current (Adamson 1956) were charged up regularly, after about six days of continuous use. When the accumulators were in

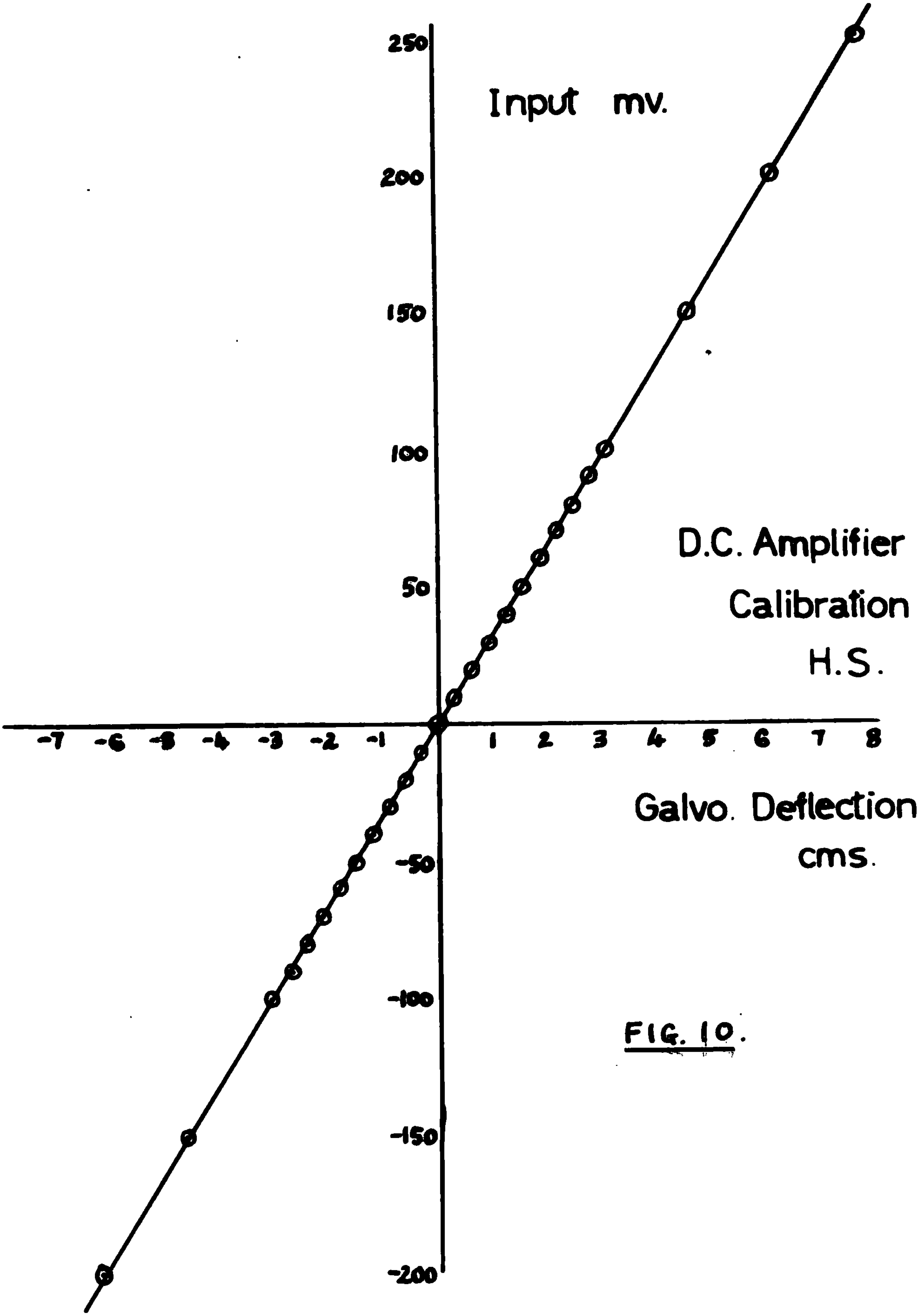

Input mv.
250
200
150
100
50
-50
-100
-150
-200
D.C. Amplifier
Calibration
H.S.
-7
-6
-5
-4
-3
-2
-1
1
2
3
4
5
6
7
8
Galvo. Deflection
cms.

FIG. 10.

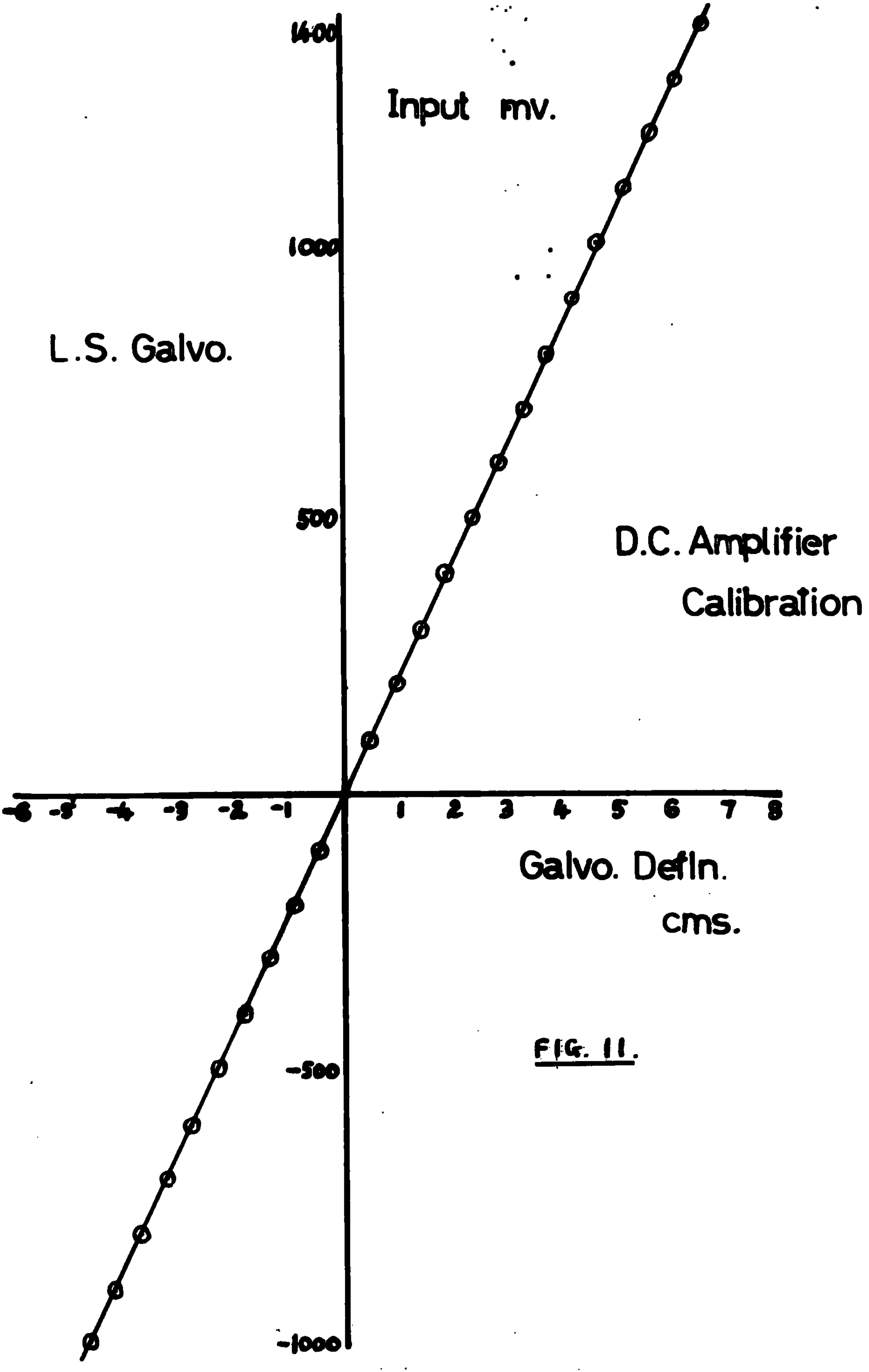

1400
Input mv.
1000
L.S. Galvo.
500
D.C. Amplifier
Calibration
-6
-5
-4
-3
-2
-1
1
2
3
4
5
6
7
8
Galvo. Defln.
cms.
-500
-1000

FIG. 11.

need of recharging and failed to give the correct current, a change in the zero output of the amplifier resulted and the accumulators were immediately changed. The amplifier zero was always adjusted before recording took place and a slight zero shift was sometimes found to have occurred, of as much as a few millimetres in galvanometer deflection, in about five hours recording. As this drift was always, without exception, in the same direction (that corresponding to a positive input signal) it was attributed to an extremely small diminution of heater current in the electrometer valve. This drift, when it occurred, was not troublesome as the zero output was recorded usually at intervals of 1½ hours during a day's recording and any error introduced by assuming a linear change of zero over these intervals must be exceedingly small.

The most recent calibration of the amplifier gave the sensitivity in terms of the galvanometer deflection and input voltage as 30.9 cm. per volt. In terms of the current received by the collecting surface this gives $3.38\,\mu\mu A.m^{-2} \equiv 1$ cm. deflection for the high sensitivity galvanometer and $22.1\,\mu\mu A.m^{-2} \equiv 1$ cm. for the low sensitivity galvanometer. The calibration is shown in figs. 10 and 11.

S.4. The Vibrating Reed Electrometer.

The V.R.E. was calibrated (figs. 12, 13) by a similar method, the voltage being applied at a socket on the indicator unit by means of a tip-and-sleeve jack plug. Despite the modification described in 4·3 there was still a very slight

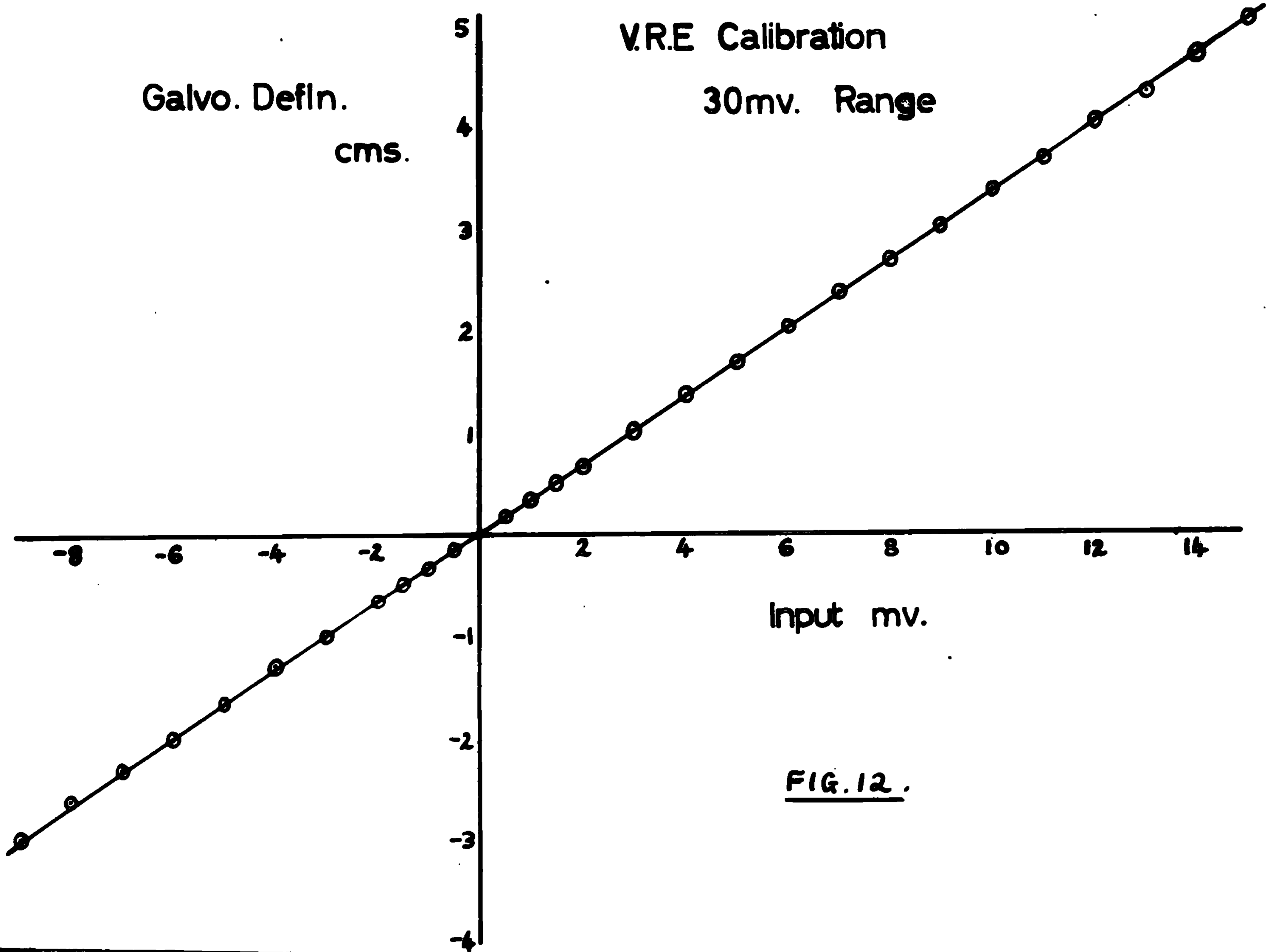

V.R.E Calibration
30mv. Range
Galvo. Defln.
cms.
Input mv.
5
4
3
2
1
-1
-2
-3
-4
-8
-6
-4
-2
2
4
6
8
10
12
14

FIG. 12.

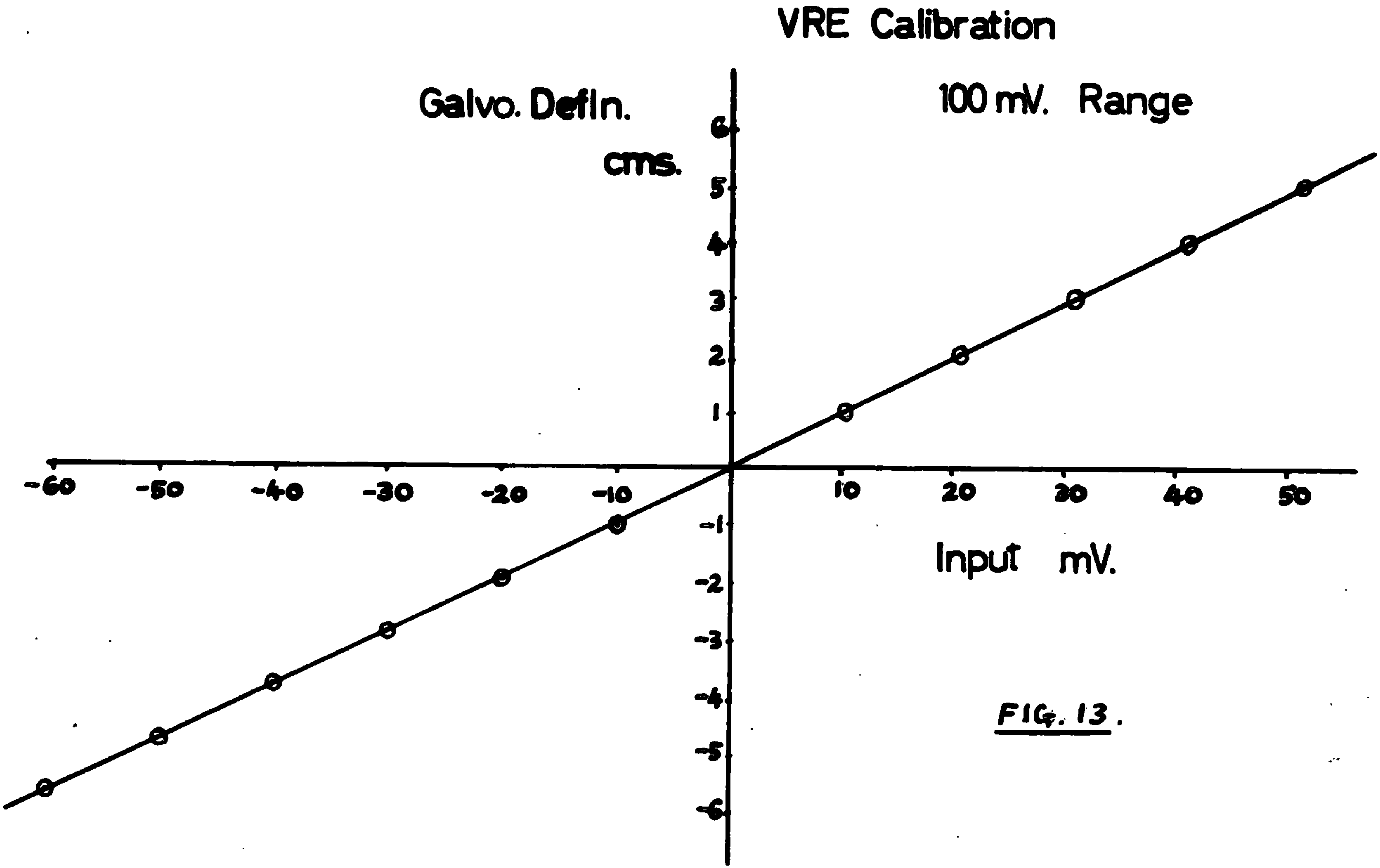

VRE Calibration
100 mV. Range
Galvo. Defln.
cms.
6
5
4
3
2
1
-1
-2
-3
-4
-5
-6
-60
-50
-40
-30
-20
-10
10
20
30
40
50
Input mV.

FIG. 13.

deviation from linearity for negative inputs corresponding to deflections near full scale on the meter. However, due to the shunts for the recording galvanometer being chosen to give a convenient sensitivity, the "top" end of the scale was never used and the non-linear part avoided. Normally the V.R.E. operated on the 30 mV range and a galvanometer deflection of 5 cm. was equivalent to 15 mV i.e. an input current to the shielded collector of 29.9 $\mu\mu A.m^{-2}$; when this deflection was exceeded, a rare event, the instrument was switched to the 100 mV range. The $10^{10}\,\Omega$ input resistor was used throughout.

Two problems arose concerning the operation of the V.R.E. and the shielded collector:

Firstly, insulation breakdown due to spider's webs connecting the collector to earth was a very real problem. The technique adopted to overcome this was simply to break these connections before the start of the day's recording by "sweeping" the surrounds of the collector manually with a short piece of cable. The exposed collector was also "cleaned" most effectively by this method but the geometrical design of the shielded receiver made the operation more difficult. Spiders, not being insects, are not discouraged by the usual insecticides, but an interesting and useful fact concerning them came to light. Once the collectors had been "cleaned" in the morning, further failure of insulation from this cause occurred only very rarely during the day from which it was concluded that web-building takes place overnight or in the early morning. This was later confirmed by the Durham Colleges Zoology Department as being a known fact about spiders!

Secondly, after switching from the "set Zero" position of the range switch of the V.R.E., when the input resister is shorted out, to any of the ranges (usually the 30mV range) the instrument could take several minutes to settle down to give a steady zero. This was partially overcome by leaving the instrument normally on the 1000 mV. range and switching carefully (to avoid piezo-electric effects at the switch) to the 30 mV. range before use. The problem was further complicated by having to switch to the "set Zero" position in order to carry out the "cleaning" of the collector described above. If the onset of rain could be anticipated however, these preliminary preparations could be carried out and the apparatus made ready for use in good time.

The performance of the instrument itself was highly satisfactory and no irregularities appeared which were not attributable to insulation breakdown at the collector. The apparatus was kept permanently switched on as recommended by the makers for maximum stability and a 1000 $\mu\mu$F capacitor of high insulation (better than $10^{14}\Omega$) was connected across the input resistor increasing the response time in order to yield a steadier output.

5.5. The Input Resistors.

After a few months of taking results during conditions of precipitation it became apparent that any differences between the current densities measured by the two receivers were small and depended critically on the degree of accuracy with which the quantities were known. Now the calibrations of both the V.R.E. and the d.c. amplifier, described above, gave no check on the values of the input resistors and it was evident therefore that a careful measurement of these was needed.

Hence the resistances of the $10^{10}\Omega$ (nominal) resistor in the V.R.E. head unit and the $5.8 \times 10^{10}\Omega$ (nominal) input resistor of the d.c. amplifier electrometer stage were determined by the method of leakage using a standard capacitance of known value in parallel with each resistor in turn. The resistors were removed from their respective circuits with great care and the minimum of handling. The condenser was charged and subsequently discharged through a ballistic galvanometer using a high insulation switch of paraffin wax with mercury contacts. The well known equation $Q = Q_0 e^{-t/RC}$ gives the value of the charge Q remaining of the condenser C after leaking for time t through the resistance R, Q_0 being the value of Q when $t = 0$, and series of readings of Q and t were made.

Graphs of t against $\log {}^{Q_0}/_{Q}$ were plotted and the gradients of the straight lines so obtained were determined by the method of least squares and a statistical estimation of the probable error of the gradients were also made. The resistance of the standard condenser itself was pre-determined by the same method and taken into account in the calculations.

The values arrived at for the V.R.E. $10^{10}\,\Omega$ input resistor R_v, and the input resistor R_A of the d.c. amplifier were:

$$R_v = 1.02 \times 10^{10}\,\Omega \quad (\pm 3\%)$$

$$\text{and} \quad R_A = 5.32 \times 10^{10}\,\Omega \quad (\pm 3\%)$$

5.6. Temporary failure of the d.c. amplifier circuit.

Following the calibration of the input resistors, a fault developed in the d.c. amplifier circuit and its location proved to be a lengthy task. An exhaustive check of the whole circuit from collector to galvanometer revealed by an odd coincidence a broken connection and a "dry joint" but did not uncover the source of the trouble which was observed as large and frequent random pulses in the output even with no current flowing into the collector. Finally the input resistor was again removed, carefully cleaned with tissue and resoldered in place with meticulous care, after which no further trouble was encountered. The value of this incident lies in emphasising the great care needed in handling very high resistances.

5.7. The Areas of the Collectors.

A check was also made on the areas of the apertures of both the shielded and exposed collectors. This revealed that the value given by Adamson for the area of the latter was in error. It was in fact 0.18 m^2. and not 0.19 m^2. as stated in Adamson's thesis. The area of the aperture of the collector itself is 0.19m^2 but it had been neglected to take into account the fact that the aluminium guard ring which surrounds, but does not of course touch the collector, slightly overlaps the rim of the latter giving this reduction in area.

5.8. The Field Mill.

Calibration of the field mill took place at frequent intervals usually at the beginning or end of each day's recording. This was carried out by applying a known potential to the large horizontal aluminium plate used in the compensation procedure. It was assumed that the exposure factor of the mill was the same under these conditions as when it was exposed to the atmospheric potential gradient.

The zero output, given by Adamson as +50^{V}/m and attributed to a contact potential difference between collecting plate and rotor, was found to have a value of +25^{V}/m which remained more or less constant. This difference from Adamson's value could be due to a change in the condition of the surfaces of the vanes by weathering, but if this were so it is not clear why no further change should have occurred in the zero output in the subsequent three years.

The mill performed satisfactorily and required no attention in the first two years apart from changing the commutator brushes after 18 months use. However, after this time, due probably to some slight lack of alignment in construction, the driving shaft and pulley became very badly worn. (The mill is driven by an external motor via a V-belt on the pulley). As a result the whole commutator system was thrown out of line subjecting the brushes, and in fact, the whole machine, to excessive vibration. Although this did not at first affect the output, much trouble was caused later through broken connections and brush springs, and since the mill had to be partly dismantled and taken indoors even for such minor repairs this became increasingly inconvenient. Finally a new pulley and a new shaft were made for the mill which was completely stripped down and re-assembled in the process.

Further trouble was encountered when spurious pulses of remarkable regularity, with a period of approximately 4 secs. occurred in the final output. This was traced to a fault in the neon Mullard O.C.3. used for stabilising the amplifier H.T. Otherwise the amplifier circuit was entirely trouble-free.

After periods of moderately heavy or prolonged rain, the mill output became irregular due to the insulation breaking down between the feedback vane and the earthed framework supporting it. The polystyrene stand-off insulators of this vane were fitted with small aluminium covers which protected them from direct rain but could sometimes make contact with the pools of water collecting on the vane in heavy rain. The most efficient method of counterating this was the somewhat crude one of the observer kneeling over the mill and blowing the accummulated water off the vane. As it was not necessary to stop the mill, this inelegant technique was the least wasteful of recording time and was usually successful. When the precipitation was in the form of snow the difficulty was increased and in many cases the mill had to be stopped before the vanes could be effectively "cleaned".

5.9. Recording Procedure.

All recording was carried out photographically. Mirror galvanometers were used in conjunction with a clockwork drum camera carrying a strip of photographic recording paper. In all, five galvanometers were in use: (i) mill galvanometer recording the potential gradient; (ii) and (iii) high and low sensitivity galvanometers recording the air-earth current measured by the exposed collector and d.c. amplifier; (iv) measuring precipitation current from the shielded collector and V.R.E.; (v) rainfall recorder galvanometer.

A timing circuit triggered by half-minute pulses from the Lab.clock via a uniselector, switched off a fogging lamp for 30 seconds every 5 minutes thus providing each record with a time-scale. After some experimenting, the camera was geared to run at a rate of one revolution (i.e. 16" of recording paper) in 1½ hours, this being found the most convenient time. The use of an alternative camera having a take-up spool and able to run for several hours without changing the record was considered but finally rejected. When the "1½ hour record" camera was used, any fault arising in any of the apparatus, usually through insulation failure, would make itself apparent in less than 90 minutes since each record was developed, as a rule, almost immediately after it was taken. Frequently such a fault could be rectified without much loss of time. If, however, a whole days recording were taken and then developed, a fault could have occurred quite early and remained undetected thereby rendering many hours of recording useless. In practice the paper in the camera could be changed in under two minutes so that very little recording time was lost.

Recording took place whenever meteorological conditions were favourable; sometimes the onset of rain could be anticipated but in many cases precipitation had already commenced when the apparatus was switched on.

Firstly the heating current of the electrometer valve of the d.c. amplifier was connected up and the valve allowed to "warm up" whilst the collectors were "cleaned" as described in 5.4. The electrometer valve H.T., field-mill motor and mill amplifier H.T. were now switched on, the compensating circuit connected, and the V.R.E. switched to the 30 mV range. Finally the galvanometer of the rainfall recorder was switched into circuit. The camera was now set up in position, the time noted, and recording commenced. Whilst the current zeros were being recorded with the earthed plate over the mill and exposed collector, and an earthed cover over the shielded collector, the rainfall recorder was calibrated (see 3.6.) The funnel was first thoroughly wetted by sprinkling with water from a burette; it was found that the volume required to do this before the sides became saturated was remarkably constant at about 8 ccs. The covers were then removed and the equipment could then be left unattended. The covers were replaced usually at the beginning or end of each record, and always at the end of a day's recording, providing a check on any zero drift which may have occurred and facilitating the analysis of the records.

5.10. Record Analysis.

In analysing the records two possible alternatives were considered (a) to take instantaneous values of potential gradient and current density every minute or half-minute from the record, or (b) to take the average values over minute or half-minute intervals. The former alternative was too dependent on transient effects particularly in the inadequacy of the compensating circuit to deal with sudden small potential gradient fluctuations, and so it was considered a truer assessment of the quantities involved to average over minute intervals.

At first, the records were analysed by ruling vertical lines on the record at "minute" intervals and measuring the traces with a transparent ruler, the average values being judged by inspection. This proved an extremely tedious and lengthy task and a more efficient method was devised. This was achieved by making a graticule out of a thin transparent sheet ofcellulose acetate (the same material used in constructing the dielectric container of the rainfall recorder - Chapter 3). Horizontal lines at millimetre intervals and vertical lines corresponding to minute time intervals on the records were ruled accurately on the sheet using a milling machine with a gramophone needle as the drawing implement. The graticule could be placed over the record to be analysed, fitted to the zero line of the quantity being measured and the minute averages of the quantity read off. The efficiency of the method could be greatly increased if an assistant was employed to write down the values as they were read out. In fact a "time study" on the operation showed that two persons working in this way took less than half the time taken by one worker alone, thereby resulting in a saving of man-hours!

In determining the rate of rainfall from the record, the instantaneous reading at the beginning of each minute was noted and hence the change in deflection over each minute interval was found, this being related to the increment in volume of rain collected. Hence by reference to the calibration carried out at the start of the record, the average rate of rainfall in millimetres per minute for each minute interval was determined.

CHAPTER 6.

RESULTS - PART I.

6.1. The Winter of 1957-58.

The first useful results comprising total air-earth current, potential gradient, and rate of rainfall measurements were taken on the 5th of November 1957, and under the heading "Winter of 1957-58" are included all results taken between this date and the end of April 1958. This period is considered separately from the later work and is distinguished by the fact that the shielded collector was not in operation at that time. Although it was set up in position during the Winter, and attempts were made to make use of it, its performance remained inefficient until the correction described in 4.3 was carried out in the April of '58.

Results were taken whenever nimbo-stratus conditions occurred and precipitation in the form of rain, snow or sleet was falling; actual recording began whenever these conditions prevailed or were imminent. All results were confined to the range of potential gradients of $\pm$ 500 $V.m^{-1}$, those outside this region being rejected so that the condition of no point discharge could be satisfied with certainty. This value was fixed rather arbitrarily but potential gradients of either sign as high as 500 $V.m^{-1}$ were rare anyway. No particular restrictions were imposed regarding the length of time precipitation had to occur before the conditions were "entitled" to be called nimbo-stratus provided the above criterion was satisfied and that the weather was not obviously showery.

Recording took place on 20 different days giving 50 different record sheets (each record normally representing about 75 mins. useful recording time) from which a total of 3,144 points were obtained, the number of "points" being the number of minute intervals over which the three quantities, current density, potential gradient, and rate of rainfall were simultaneously recorded. On seven other days recordings were taken but no useful results obtained as the weather proved showery or otherwise unacceptable; also recording time was lost through a number of miscellaneous causes, e.g. insulation breakdown, minor faults in the apparatus, etc. No satisfactory method of determining the rate of precipitation in snow or sleet was devised, so that this quantity was absent in the data for these conditions.

The frequency with which the various sorts of precipitation were recorded may be seen from the following table.

	No.of days.	No.of Records.	No.of Points.
Rain.	10	25	1677
Snow.	5	15	862
Sleet.	4	9	472
"Wet Snow"	1	2	133

6.2. Treatment of Results for Rain.

The records of each day were analysed as described in 5.10 and the values of current density I ($\mu\mu A.m^{-2}$), potential

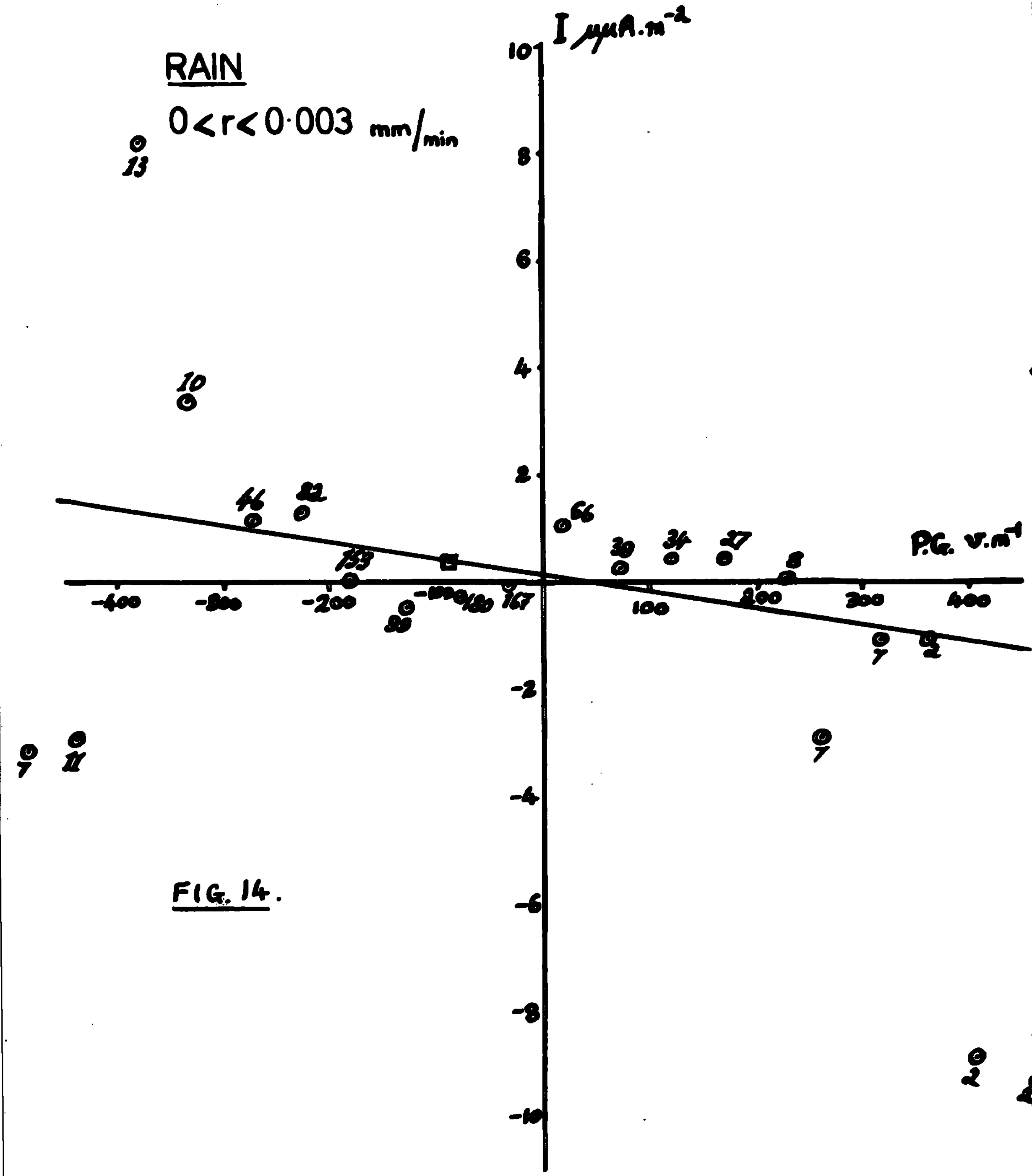

RAIN
0<r<0·003 mm/min
I μμA.m⁻²
P.G. v.m⁻¹
10
8
6
4
2
-2
-4
-6
-8
-10
-400
-300
-200
-100
100
200
300
400
13
10
46
22
66
153
39
34
27
8
99
180
167
7
2
11
7
7
2

FIG. 14.

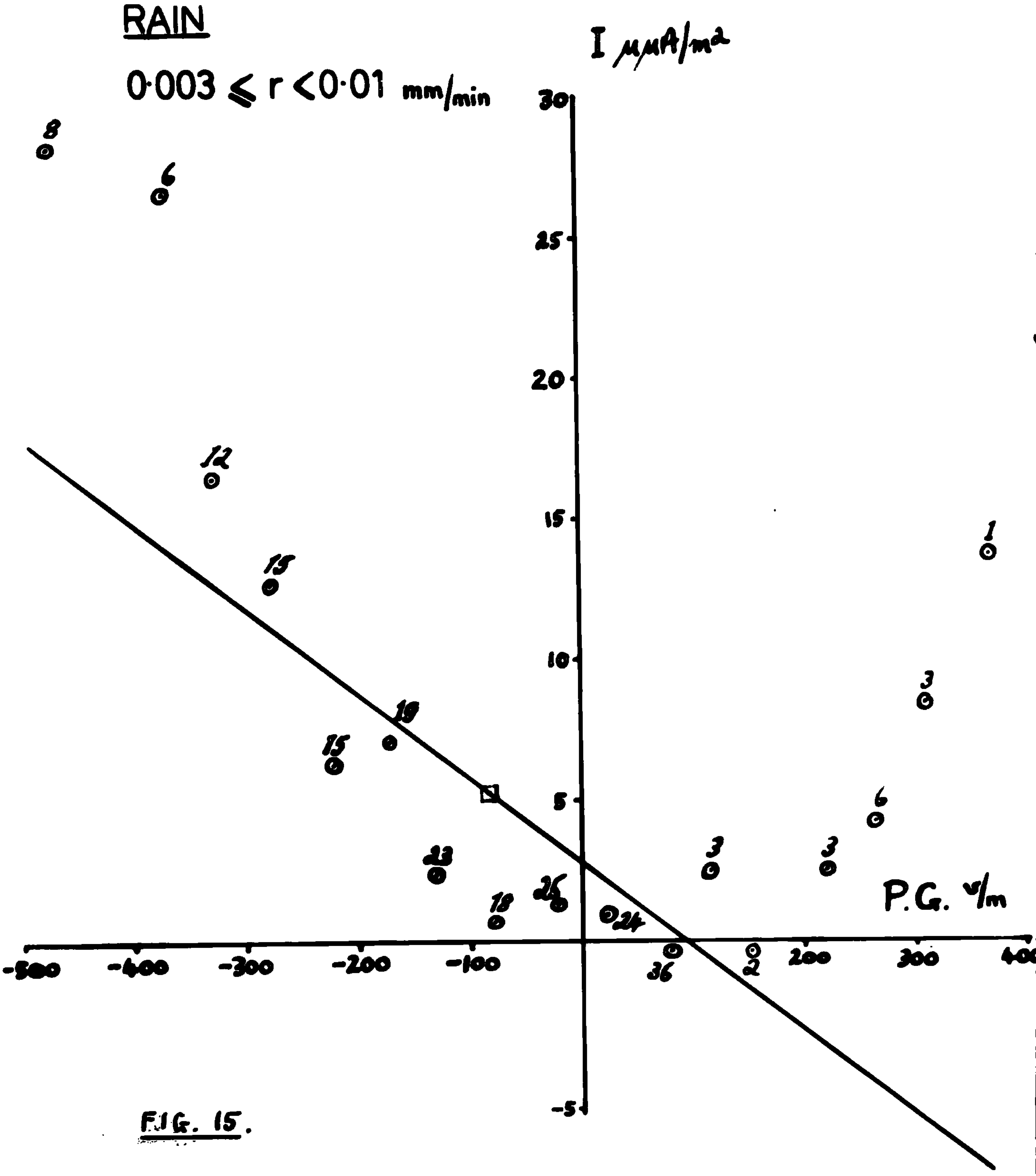
RAIN
0·003 ≤ r < 0·01 mm/min
I μμA/m²
30
25
20
15
10
5
-5
P.G. v/m
-500
-400
-300
-200
-100
200
300
400
8
6
12
15
19
15
23
18
26
24
36
2
3
3
6
3
1

FIG. 15.

RAIN

0·01 ≤ r < 0·02 mm/min

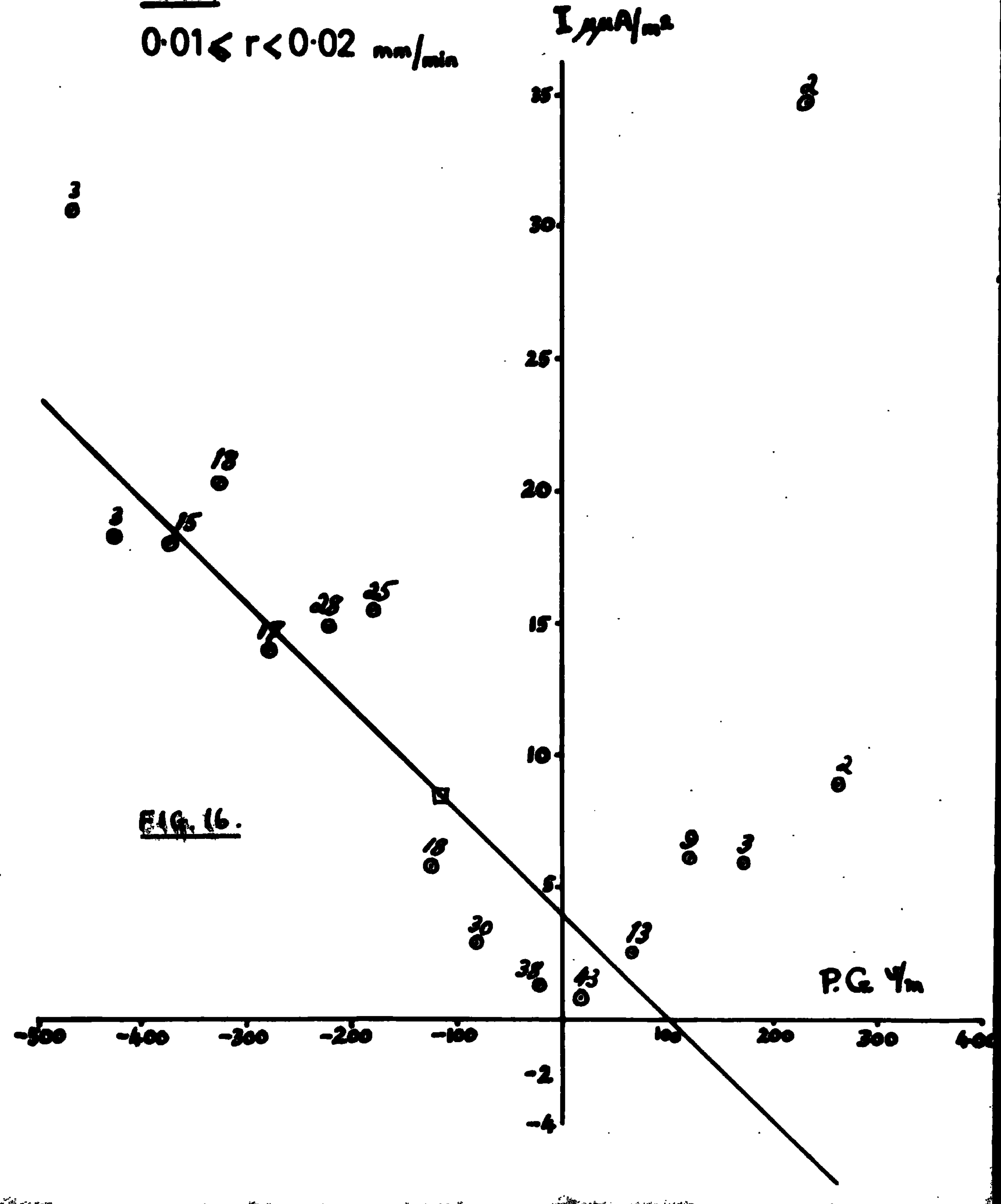
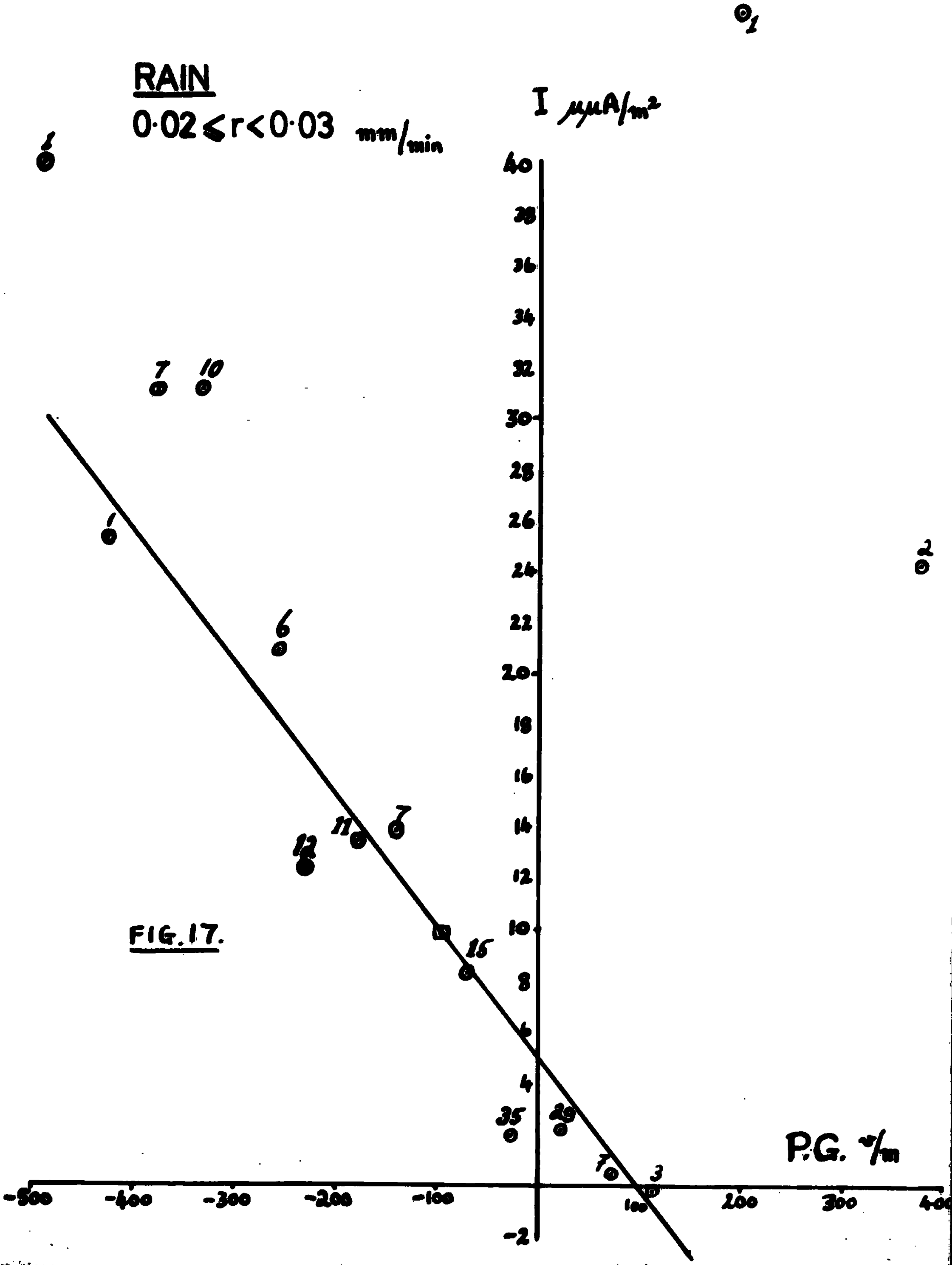


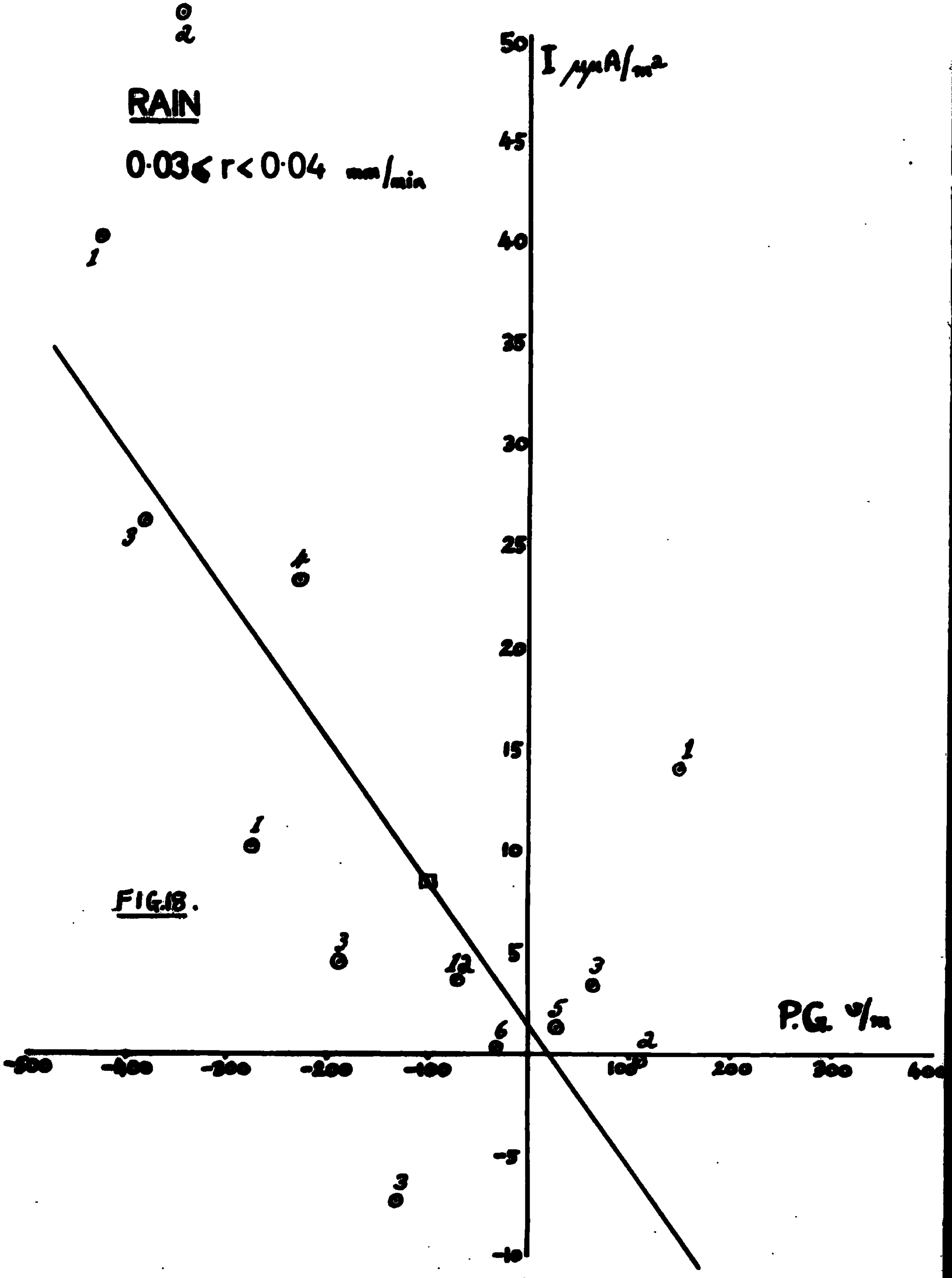
FIG. 16.



RAIN

$0{\cdot}02 \leqslant r < 0{\cdot}03$ mm/min

FIG. 17.



RAIN

0·03 ≤ r < 0·04 mm/min

FIG.18.

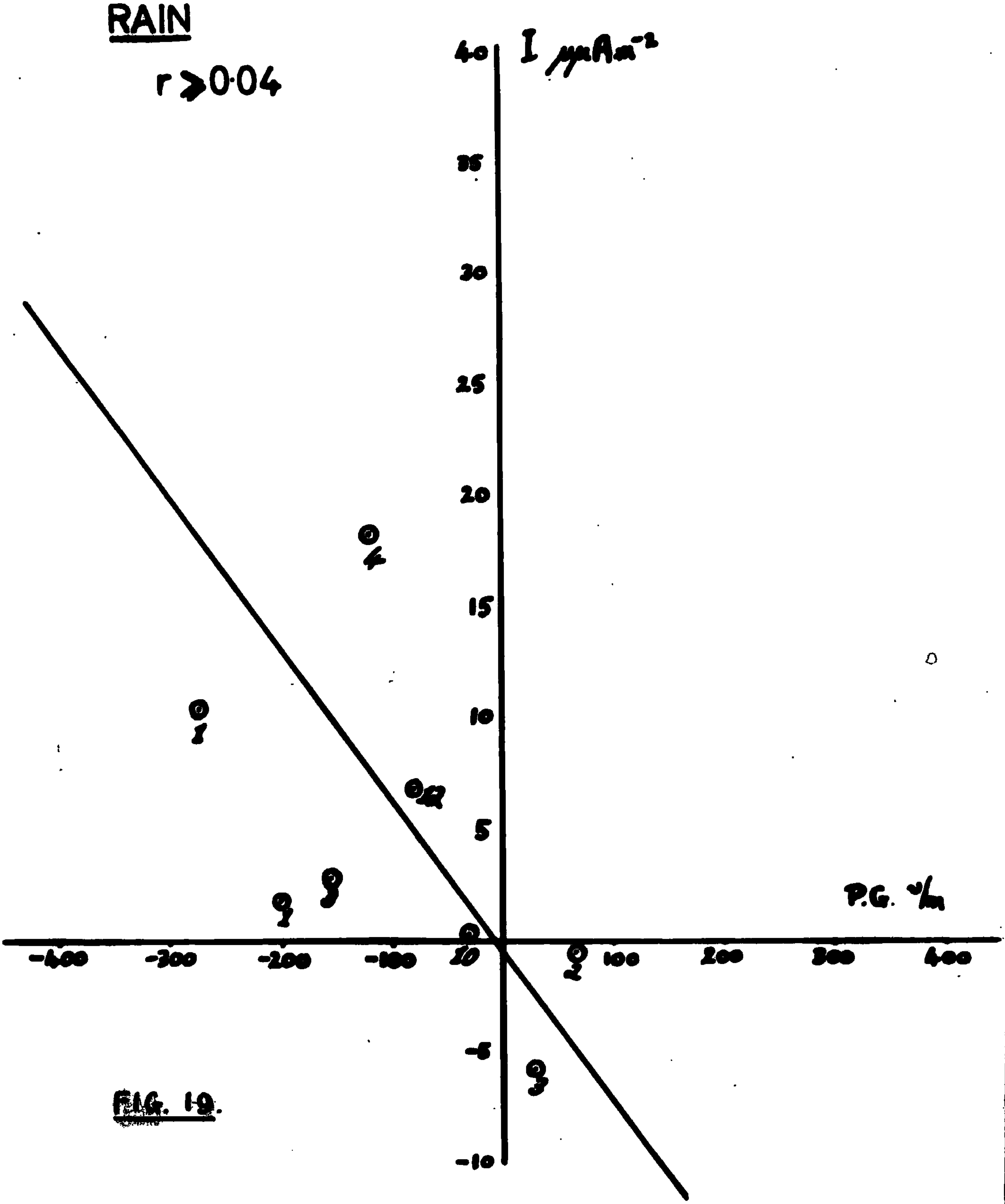

RAIN
r ≥ 0·04
I μμA m⁻²
40
35
30
25
20
15
10
5
-5
-10
P.G. v/m
-400
-300
-200
-100
100
200
300
400
4
1
12
9
8
10
2
3

FIG. 19.

gradient F ($V.m^{-1}$) and rate of rainfall r ($mm.min^{-1}$) were tabulated.

In order to investigate how the I/F relationship depended on r, all the results for rain had to be sorted into groups according to the value of the rate of rainfall. The ranges of this quantity were chosen to be: zero to 0.003, 0.003 to 0.01, 0.01 to 0.02, 0.02 to 0.03, 0.03 to 0.04, and "greater than 0.04"; these may be abbreviated to the symbols <, I, II, III, IV and >, respectively (all values in mm. per minute). A value lying on a range boundary was included in the higher range thus "0.01 $mm.min^{-1}$" was included in the 0.01 to 0.02 group.

The relative frequency of the different rates of rainfall in the Winter results is shown in the following table:

r	<	I	II	III	IV	>
n	962	219	267	147	46	37

all but 2 of the 37 points in the last group lay in the range 0.04 to 0.09.

To obtain a comparison with the results of Chalmers (1956) the results in each rate of rainfall section were now classified into potential gradient divisions of 50 $V.m^{-1}$ each, a total of 10 intervals in all between ± 500 $V.m^{-1}$.

For each "class interval" of potential gradient, the mean values of I and F were determined and plotted as a single point on a graph of I against F; these points will be referred to as the "class interval points". Graphs of I against F were made for each of the rate of rainfall ranges and are shown in figs.14

ALL RAIN WINTER 57-58

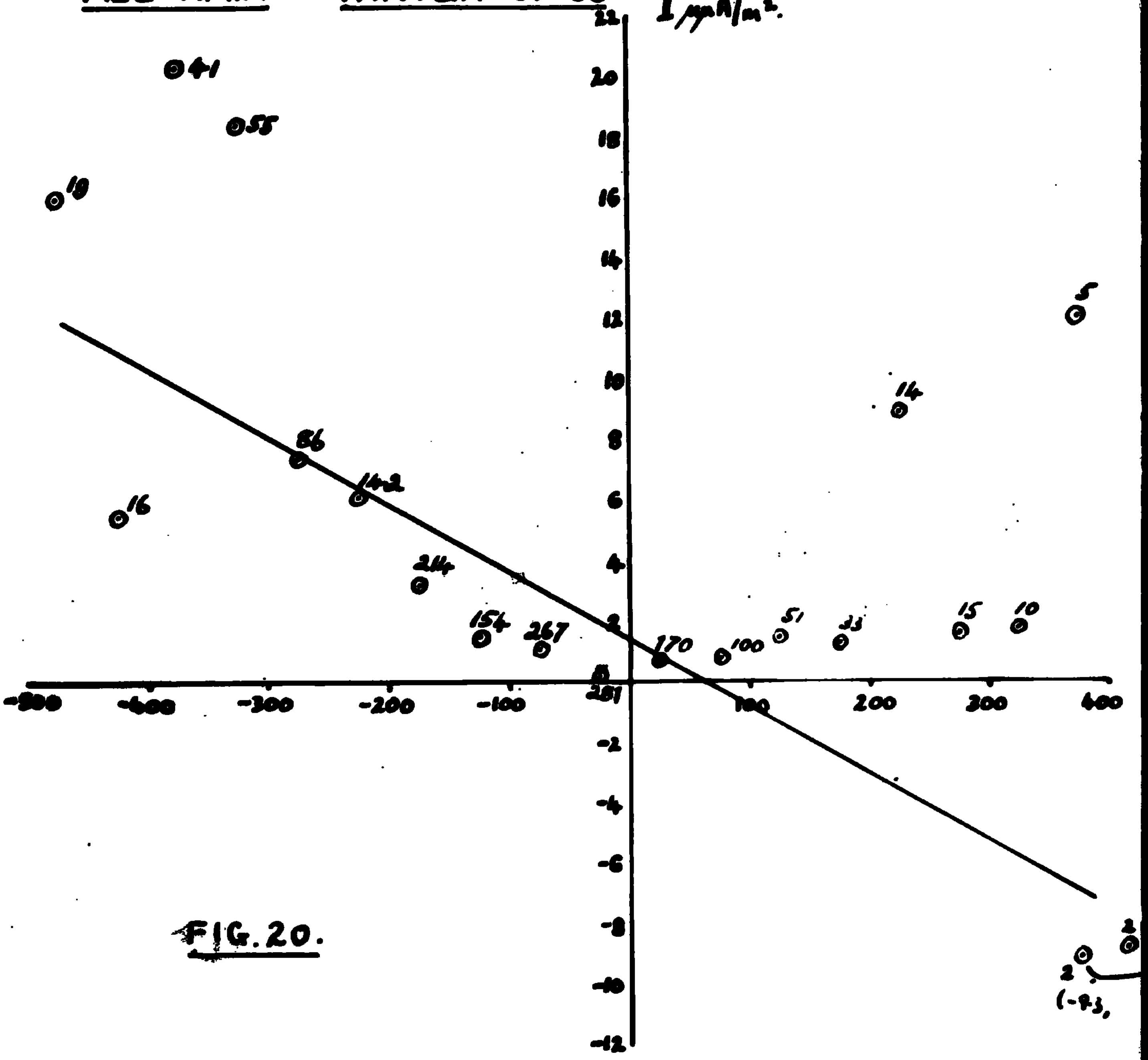


FIG. 20.

to 19 inclusive. The figure printed beside each point on the graph denotes the number of observations (minute intervals) which that point represents. In addition the results for all rates of rainfall were lumped together and a graph of I against F for "all r" was plotted, (fig.20).

It was seen that all the graphs showed a definite tendency to conform to the straight line relationship established by Chalmers (1956) who found (without rate of rainfall measurement) that his results could be represented by the equation

$$I = a\,(F + C)$$

where $a = -1.18 \times 10^{-2}\ \mu\mu A.m^{-2}/V.m^{-1}$ and $C = -140\ V.m^{-1}$ for rain.

5.3. Statistical Methods.

Using the method of "least squares" the best statistical straight line was fitted to the points in each of the seven graphs obtained from the "Winter" results.

In computing the "best" gradient of each line, account was taken of every individual observation and not merely of the "class interval" points shown in the figures. The most convenient form of the "least squares" theory gives the gradient as

$$m = \frac{\Sigma FI - n\bar{F}\bar{I}}{\Sigma F^2 - n\bar{F}^2}$$

where n is the total number of points, and $\bar{F}$ and $\bar{I}$ are the overall average values of F and I respectively. From a knowledge of the gradient and the mean point ($\bar{F}$, $\bar{I}$) the intercept on the F axis could be found, yielding the value C in Chalmers' equation.

SNOW 1957-58 WINTER

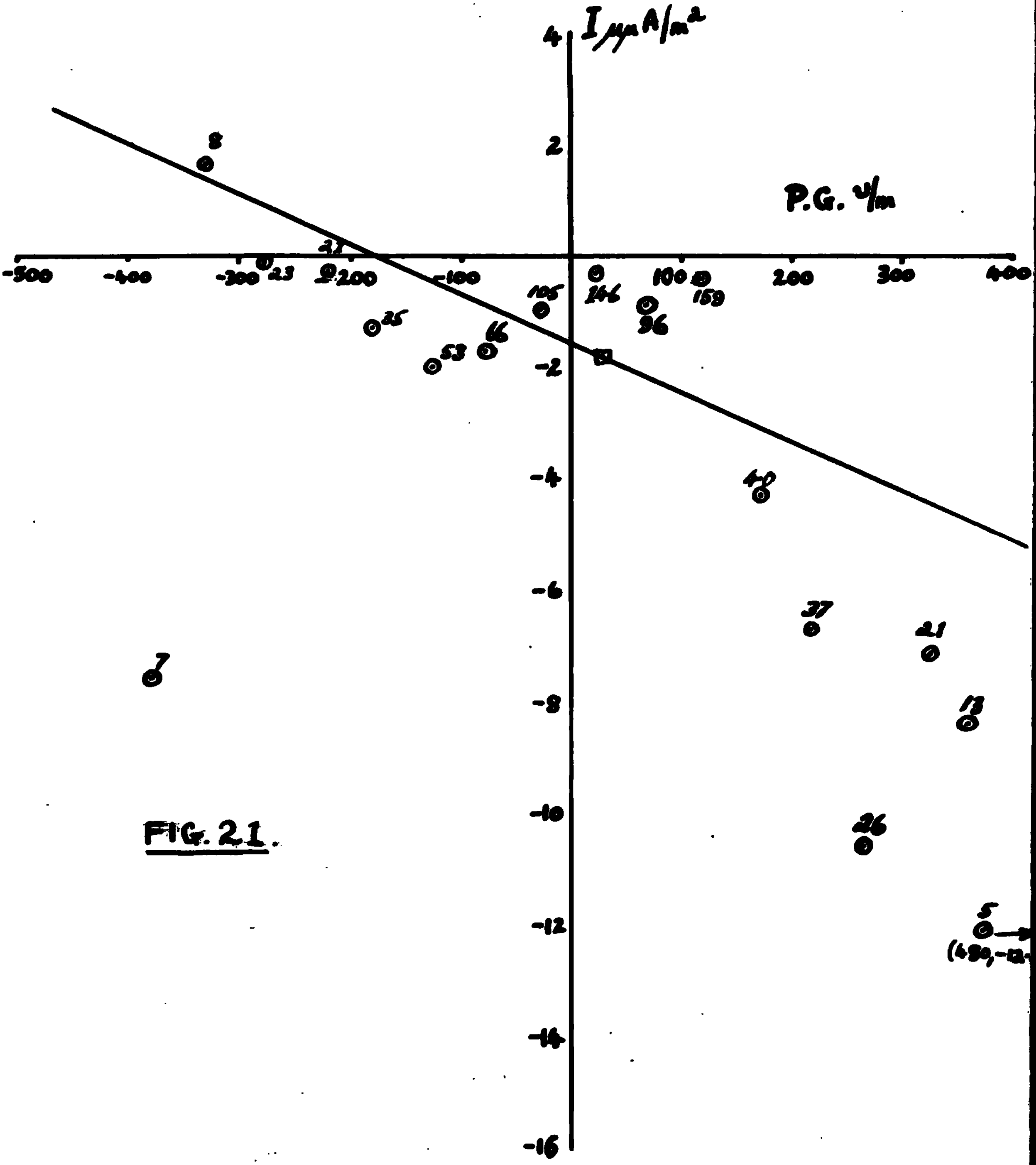
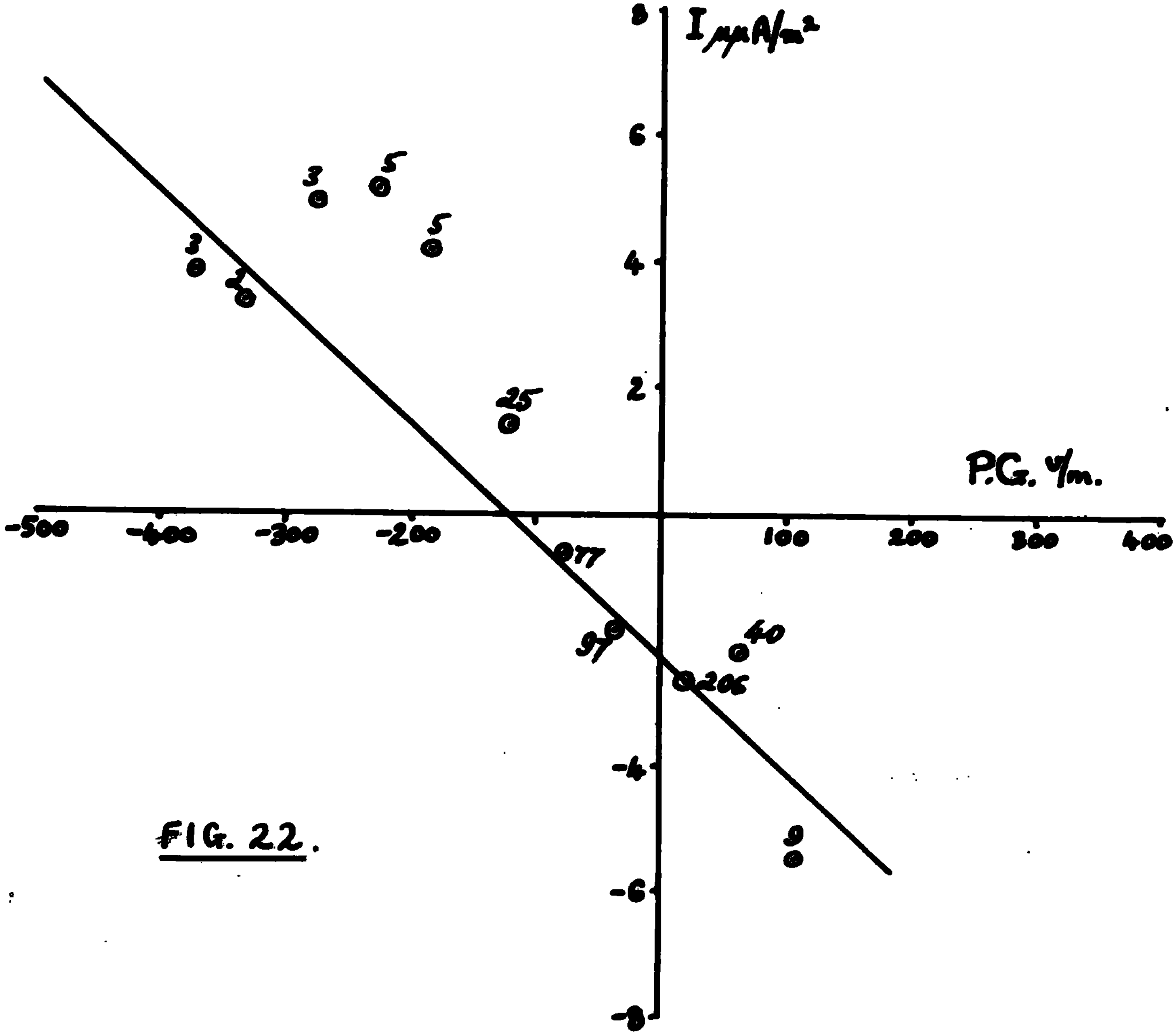


FIG. 2.1.

SLEET



8
I μμA/m²
6
4
2
-4
-6
-8
P.G. V/m.
-500
-400
-300
-200
100
200
300
400
3
5
3
5
2
25
77
97
40
206
9

FIG. 22.

"WET SNOW"

on 10:12:57

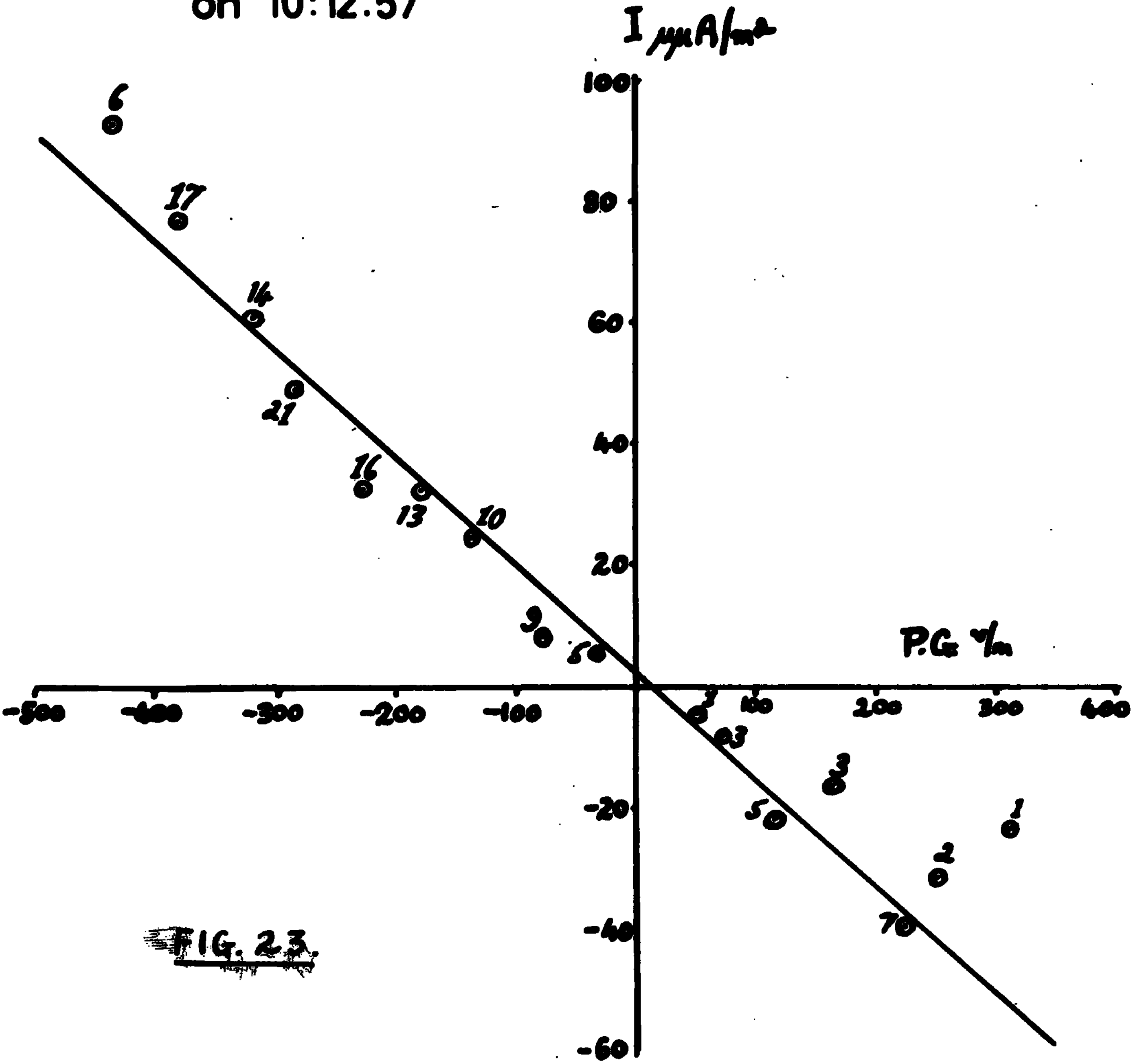


FIG. 23.

Despite the use of a desk-calculating machine, for which the form of m given above is best suited, the evaluation of the gradients proved an exceedingly lengthy and arduous task. Consequently an interesting investigation was carried out with a view to greatly reducing the volume of work required. The gradients were determined using, not all the individual observations as before, but the "weighted" class interval points, each of these being treated as p identical points, where p is the number of observations the point represented. This method involves only twenty multiplications each to find Σ FI and ΣF^2 whereas the former method requires a total of 2n multiplications where n is the number of individual observations. Except for the results for $0 < r \leq 0.003$ mm.min^{-1} the gradients found using the weighted class interval points differed in all cases by less than 2% from the previously determined values.

The formidable task of calculating the "standard deviations" of the gradients was considered unjustifiable from the point of view of time spent compared to the value of the result.

6.4. Results for Snow.

The results for snow and sleet were treated in a similar fashion to those for rain although precipitation rates were not available in these cases. Graphs of I against F were plotted for the snow and sleet, and also for the interesting case of "wet snow". This latter was the first snow of the season observed in Durham on the 10th December 1957, and as the name implies contained much liquid although it fell as snow rather than

SUMMARY of RESULTS of WINTER 1957-58

Values of the constants a & C in the equation: $I = a(F + C)$, are tabulated with rainfall values 'r'.

Type of Ppt^n.	r $\left(\frac{mm}{min}\right)$	$-a \times 10^{-2} \left(\frac{\mu\mu A\, m^{-2}}{V m^{-1}}\right)$	−C (V/m)	No. of Points
Rain	< ·003	0·32	31·1	962
Rain	·003–·01	3·00	94·7	219
Rain	·01–·02	3·93	99·8	267
Rain	·02–·03	5·18	95·7	147
Rain	·03–·04	7·09	16·3	46
Rain	> ·04	6·53	−6·3	37
Average for all Rain	——	2·19	64·8	1677
Chalmer's 1956 Results – RAIN	——	1·18	140	1418
Sleet	——	1·91	−124	472
"Wet Snow" *	——	17·8	12	133
Snow	——	0·94	−176	862
Chalmer's 1956 Results – Snow	——	0·92	−440	990

* Single Day's Recording 10:12:57.

FIG. 24.

sleet but soon melted completely on reaching the ground. It was characterised by extremely large current densities (which would have completely "swamped" the results for sleet had they been included therein) and also by a display of the mirror image effect (Chapter 8).

The gradients and intercepts of the I/F graphs for the three types of solid or semi-solid precipitation were found, as in the case of rain, and shown in figures 21, 22 and 23.

6.5. General Summary of Results.

The results of the Winter 1957-58 are summarised in the table in fig. 24, in which those of Chalmers (1956) are also included for comparison.

It is seen that the magnitude of the gradient a in the equation $I = a (F + G)$ increases with rate of rainfall and from a plot of a against r (fig. 25) it is seen that the variation can be represented empirically by $a^2 = r \times 10^{-1}$ to a rough approximation if the paucity of points in the higher rainfall ranges is taken to account for the discrepancy for large r. No great claims however can be made regarding the significance of this result without further verification and indeed the 2nd, 3rd and 4th points on the graph lie nearly in a straight line!

The intercept on the F axis, believed by Simpson (1949) to represent the fair weather potential gradient, is seen to show a remarkable constancy, at approximately 100V.m^{-1}, for the intermediate rates of rainfall which although less than Chalmers value of 140 V.m^{-1} (for all rain) is a reasonable value for the

Graph of -a against r

Winter 1957-'58

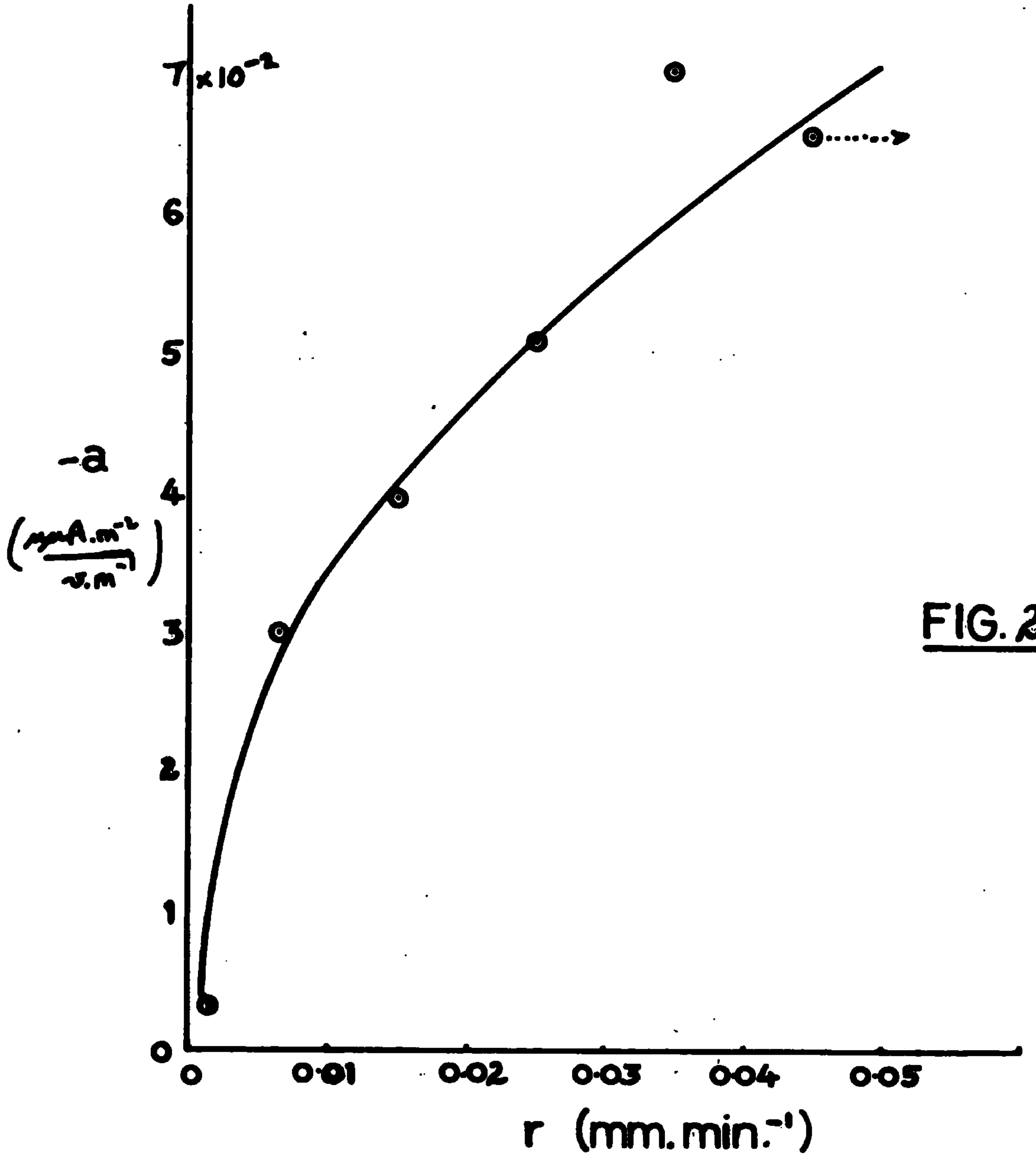


FIG. 25.

fair weather potential gradient at Durham. However, smaller values of C are given for very low and very high rates.

In the case of snow, the value of a is very nearly identical to Chalmers result but but the value of C shows a large difference, as seen in Table 24.

6.6. Additional Observations.

Four most interesting observations arose out of the results of the Winter (1957-58).

(a) The mirror image effect (see Chalmers 1957 p.105) was a frequent occurrence. The most striking phenomena associated with this were very noticeable time delays between current and potential gradient maxima. Since both I and F often varied with time in a wave-like fashion it became common to refer to these delays as pseudo-phase lags and their occurrence was of great interest. A fuller discussion of these observations is given in a later chaper.(8).

(b) A wave-like variation in current without any corresponding potential gradient changes sometimes occurred especially in low rates of rainfall, and this is also discussed in Chapter 8.

(c) On the 6th January 1958 recording was taking place in sleet when quite suddenly the precipitation was observed to change from sleet to snow. This was accompanied by a simultaneous change from conditions of positive I and negative F, to those of negative I and positive F. The meteorological and electrical changes were actually noticed by the observer within a very short time of one another probably shorter than $\frac{1}{4}$

minute so that the word "simultaneous" is justifiable in describing the change.

(d) On examining the I/F graphs for rain a "parabolic" effect can be seen. The word "parabolic" is not intended to be taken seriously in the mathematical sense but serves to illustrate the tendency for the points to lie above the line for all positive, and for high negative potential gradients and below for low negative values. This is particularly marked in figs. 15 and 16, and appears more striking because the "class interval" points only are plotted. Nevertheless, there is a strong tendency especially in the positive F and positive I quadrant to deviate from the linear law. It is to be noted that for snow this deviation also occurs in the positive F, negative I quadrant and that it may be seen also in Chalmers (1956) results for both snow and rain.

RESULTS - PART II

6.7. The 1958 Summer.

Although this was something of a misnomer from the point of view of the 1958 weather, this heading is conveniently used to cover all results taken from the 5th May 1958 to the 3rd October 1958. An exceptionally dry autumn and early winter then followed during which considerable indoor work on the apparatus was done and would have prevented recording; no suitable days occurred however.

The shielded collector was now working and particular interest became focussed on the comparison between the precipitation

RAIN

$0{\cdot}003 > r > 0$ mm/min.

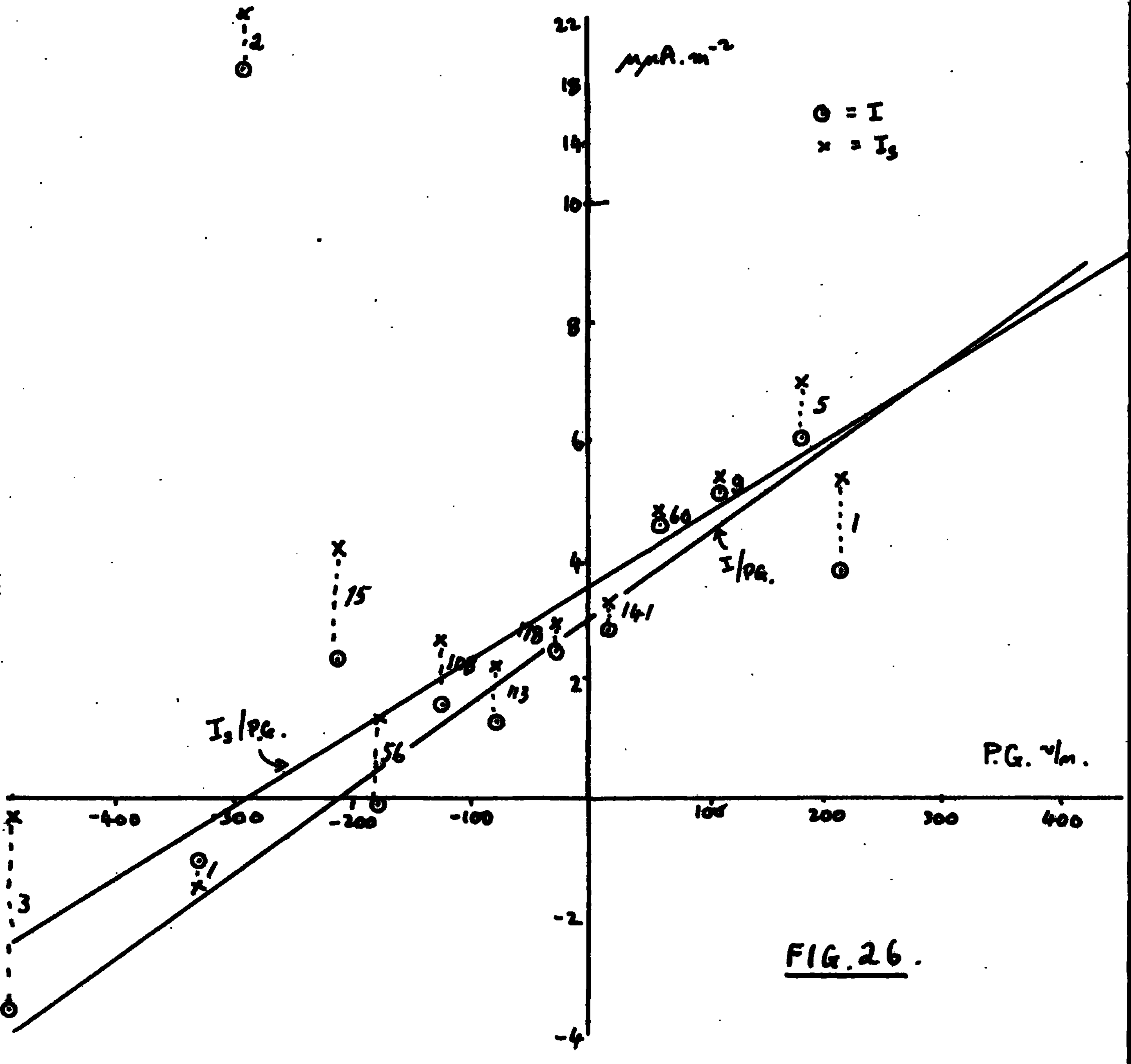


FIG. 26.

RAIN

$0{\cdot}01 > r > 0{\cdot}003$ mm/min.

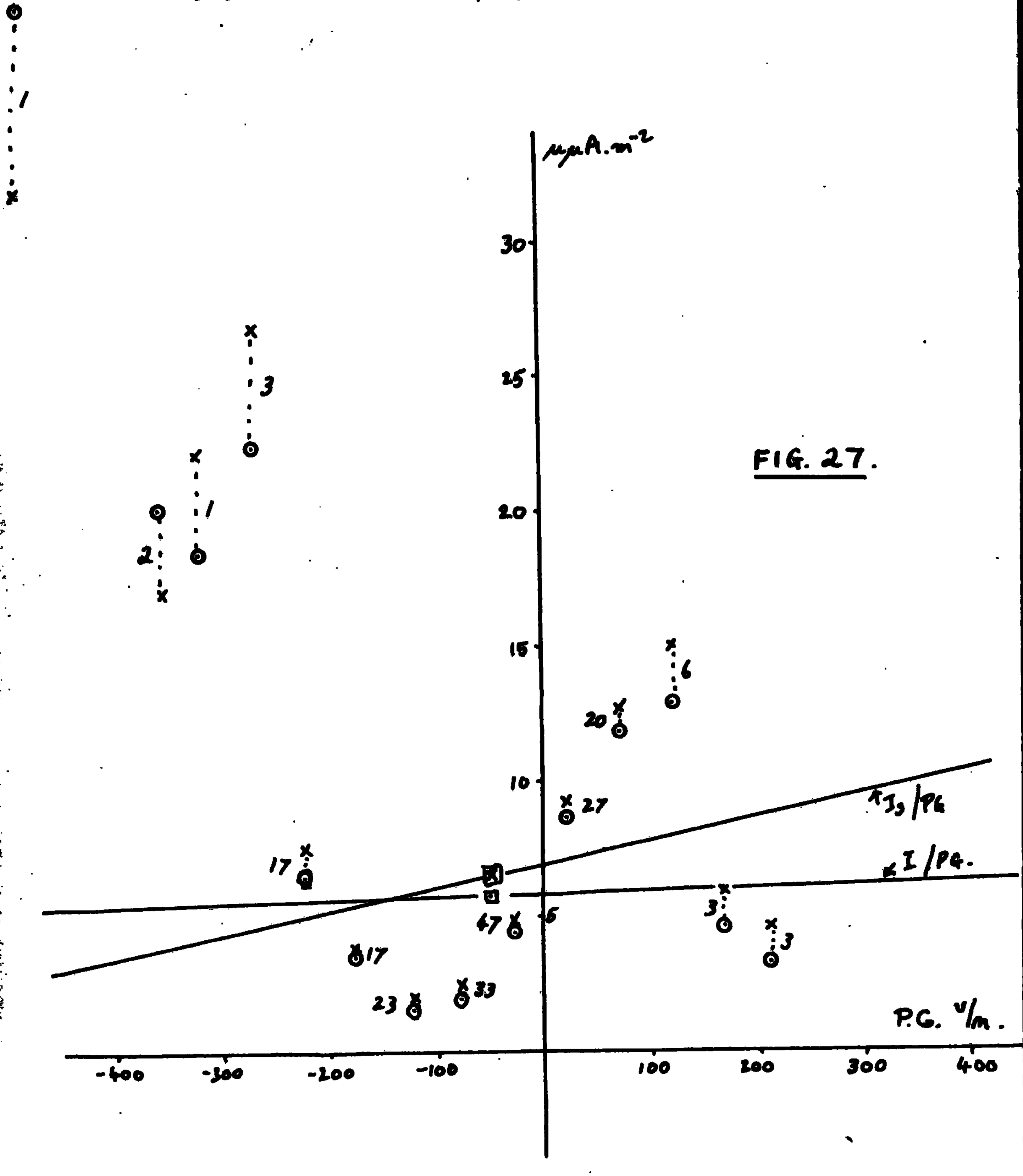


FIG. 27.

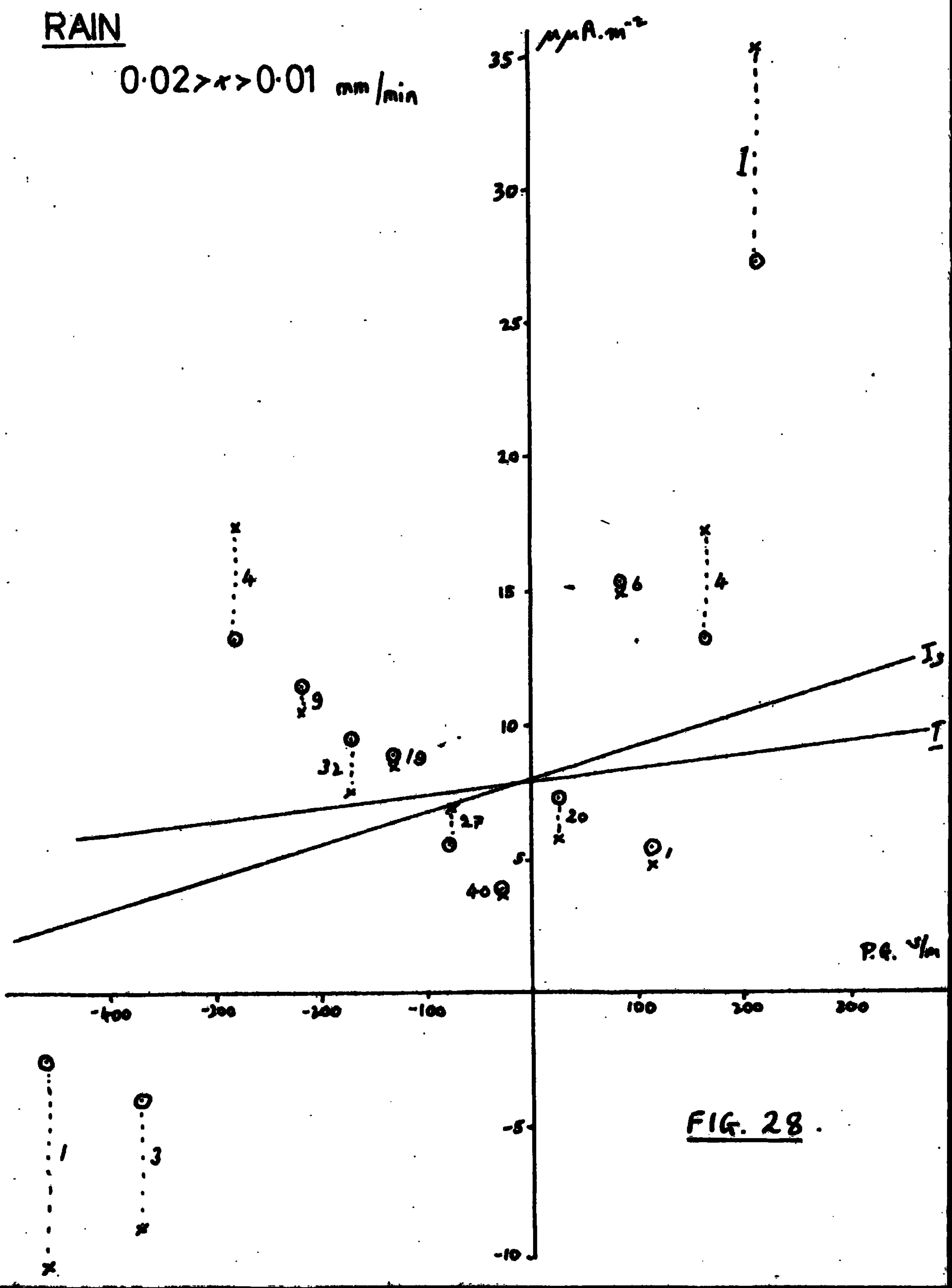
RAIN
0·02 > r > 0·01 mm/min
μμA.m⁻²
35
30
25
20
15
10
5
-5
-10
P.G. V/m
-400
-300
-200
-100
100
200
300
I
4
4
6
9
32
10
27
20
1
40
1
3
I₃
I

FIG. 28.

RAIN

$0{\cdot}03 > r > 0{\cdot}02$ mm/min

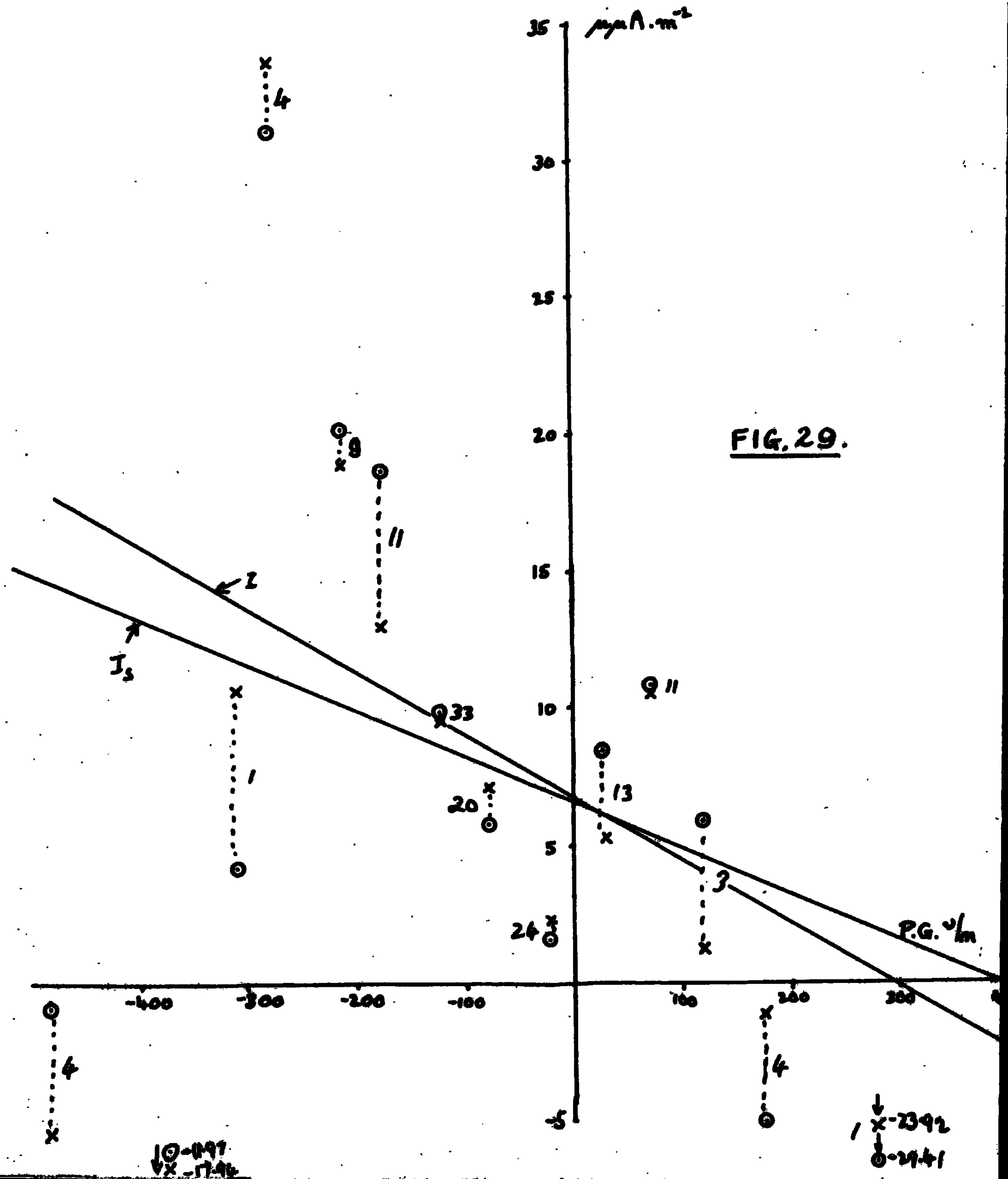


FIG. 29.

RAIN

$0{\cdot}04 > r > 0{\cdot}03$ mm/min

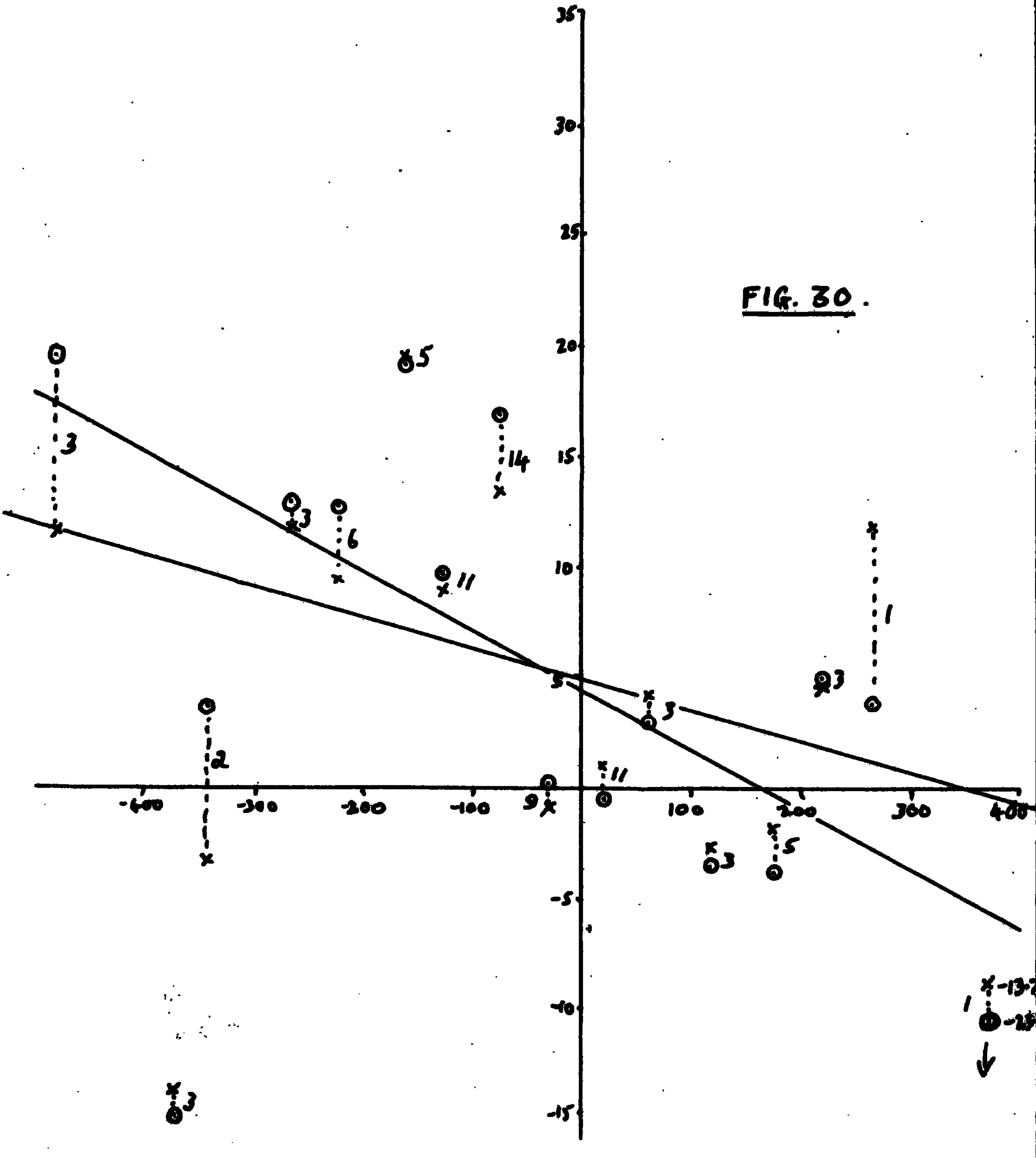


FIG. 30.

RAIN

r > 0·04 mm/min

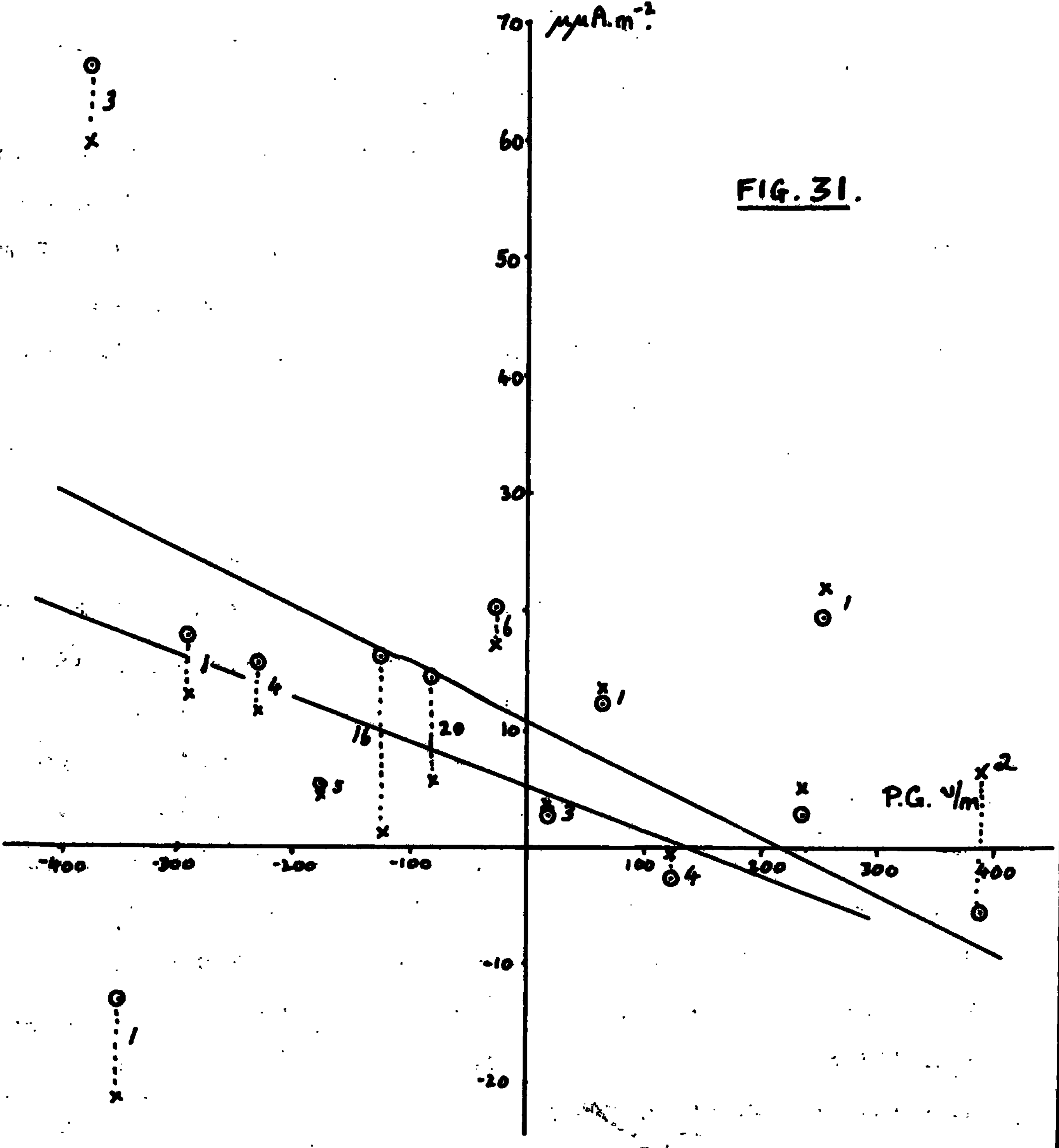


FIG. 31.

current density I_s ($\mu\mu A.m^{-2}$) recorded by this and the total air-earth current measured by the "Adamson apparatus". Simultaneous recording of potential gradient and rate of rainfall were of course still made.

All results which did not for any reason include all four values I, I_s, F and r were disregarded.

Successful recording took place on 11 different days giving 31 records and a total of 1345 points. (i.e. minute interval results) On 5 other days recording was unsuccessful due to failure of apparatus or unsuitable weather changes. No precipitation other than rain was noted (although snow had fallen on the 6th May the previous year!) and the relative frequency of the rates of rainfall is shown in the table below:-

r	=	<	I	II	III	IV	>
n	=	693	193	167	140	84	69

The records were analysed and the results classified as described in 6.2 and graphs of both I and I_s plotted against F for the different ranges of r (figs. 26 to 31). It became immediately obvious that in most cases, deviation from linearity was greater than in the Winter's results and that if the "best" straight lines were drawn they might have positive gradients for the lower rates of rainfall. The gradients were determined using the "class interval" points as described in 6.3 yielding the following results, where $m \times 10^{-2}$ equals the value of the constant a in the equation $I = a\ (F + C)$ and $m_s \times 10^{-2}$ gives the value of a in a similar expression for I_s :

r =	<	I	II	III	IV	>
m =	1.42	0.04	0.46	-2.29	-2.62	-4.94
m_s =	1.24	0.26	0.12	-1.67	-1.31	-3.72

Despite the occurrence of the positive gradients it can be seen that both m and m_s decrease as r increases. This is not contrary to the results for the Winter as it will be remembered that it was the magnitude of a negative gradient which increased with increasing r. An examination of the gradients showed that there would be no virtue in determining the intercepts on the F axes.

Whilst it was both difficult and necessary to guard against seeking a linear correlation between F and I where possibly none existed, it was believed that the chief factor "upsetting" the Summer results was the occurrence of what has been described as the "parabolic" effect (6.6 (d)). This is particularly true in the case of fig.28 where one or two points with high values greatly influence the slope of the I/F line.

6.8. Comparison of "Winter" and "Summer" results.

Considering results for all rain irrespective of the rate of rainfall, the average current $\bar{I}$ was found to be higher and the mean potential gradient $\bar{F}$ lower (in magnitude) in the Summer results. There appears to be no variation in the mean potential gradient with r except for rates below 0.01 mm.min^{-1} where F tends to be low. This is shown in the table below where mean I and F for each range of r is set out and is also supported by the 1959 results (see 6.11.)

	WINTER '57-58			SUMMER '58.			
r	n	$\bar{F}$	$\bar{I}$	n	$\bar{F}$	$\bar{I}$	I_s
<	962	-89	0.34	692	-49	2.3	2.9
I	219	-83	5.33	193	-49	5.9	6.5
II	267	-116	8.48	167	-83	7.5	7.1
III	147	-95	9.88	140	-79	8.7	8.0
IV	46	-103	8.49	84	-73	6.5	6.0
>	36	-78	4.71	69	-78	14.3	7.9
All r	1677	-93	3.46	1345	-59	5.03	4.97
	Chalmers '56:-			1418	-176	3.8	—

6.9. Comparison of I and I_s.

The main focus of interest in the 1958 Summer became the difference between the current densities recorded by the shielded and unshielded collectors, i.e. between I_s and I respectively. Any single day's recording revealed that both collectors were measuring at least approximately the same quantity; the traces on the record followed each other closely and whilst on analysis, values over minute intervals showed small differences often of the order of $1\,\mu A.m^{-2}$ little consistency was found and no correlation with potential gradient or rate of rainfall could be found. The former was expected to give a conduction current (included in I but not I_s) whilst the latter could involve a splashing term (see Chapter 4). It was necessary therefore to consider in some way the averages over large numbers of results. Accordingly the mean values of I and I_s were taken for each "class interval" point on the graphs of figs 26 to 31.

The following table shows the results of this analysis; the figures denote the number of "class interval" points in which $I > I_s$ or vice versa for positive and negative F and for all r values. It should be noted that no trend at all in the sign of $(I - I_s)$ occurred with changing magnitude of F.

r:	<	I	II	III	IV	>	
$I > I_s$	0	0	3	3	1	0	F ± ve
$I_s > I$	5	5	2	3	6	6	
$I > I_s$	1	2	6	5	7	2	F − ve
$I_s > I$	7	7	3	4	2	0	

The conclusions which will be discussed in chapter 9 are:-

For positive F and all r .... $I_s > I$
For negative F and low r .... $I_s > I$
For negative F and high r .... $I > I_s$

6.10. Mirror Image Effect.

The "mirror image effect" was observed on numerous occasions and, as can be seen from figs. 36, 37, 38, which are reproductions of actual records, both I and I_s showed this phenomena. Thus the mirror image effect does not appear to depend for its existence on the degree of shielding of the collector as has been suggested (Chalmers 1957 p.196). Also the effect described in 6.6 (b) above has been found several times in both I and I_s traces (see figs. 44 - 47.)

6.11. The 1959 Results.

(a) General. The first 9 months of 1959 were remarkable for the extremely dry weather which prevailed particularly in the Summer season, some of the months being the driest on record in Durham. Hence insufficient results were obtained to make any satisfactory comparison with the two periods already described. This was unfortunate in that the differences between the 57-58 Winter and the '58 Summer could possibly be seasonal and 1959 might have provided evidence for this.

Nevertheless recording did take place on 8 days, 7 in January-April period and one in June. The statistics are given as before:-

Ppt^n.	No. of days.	No. of records.	No. of points.
Rain	6	15	598
Snow	1	1	65
Sleet	1	2	96

(b) Rain. At first sight, the frequency of rain appears comparable to the earlier periods considered. However, of the 598 points, 471 lay in the rainfall range $0 < r < 0.01$ and 2/3 of all the points occurred when the potential gradient was between $\pm 100 V.m^{-1}$. Thus in the higher F and higher r ranges where results for comparison purposes would have been most useful, very little was obtained. It was not considered worth plotting I/F graphs because of this; examination of the results showed that occasional "rogue" points would have had a similar and more pronounced effect on any trend in the graphs than those of the 1958 Summer.

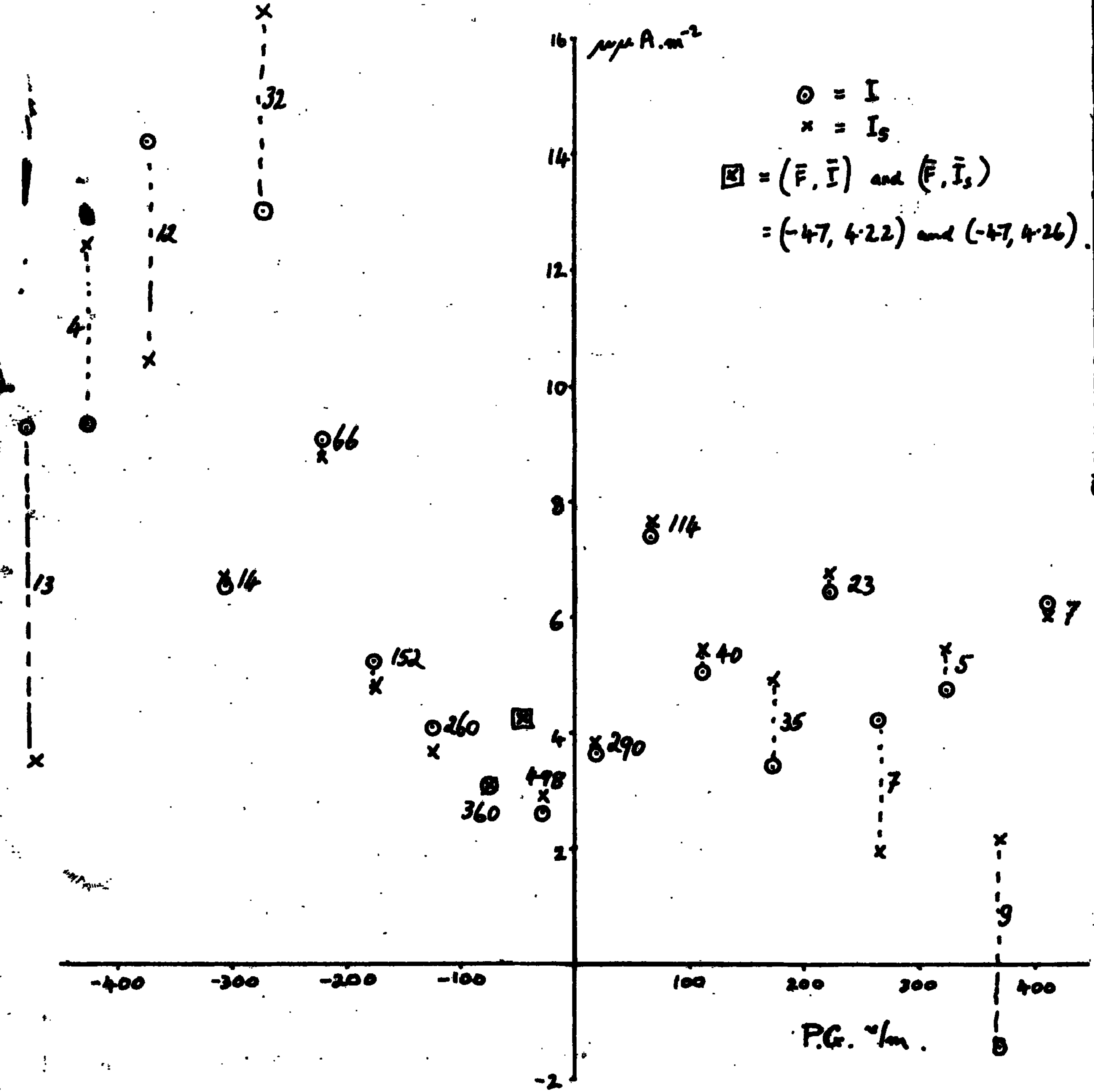
A table is drawn up below showing the mean values of F, I and I_s for different rate of rainfall (c.f. 6.8).

r	n	$\bar{F}$	$\bar{I}$	$\bar{I}_s$
<	370	-26	1.72	2.12
I	101	-26	4.27	4.42
II	66	-31	4.60	5.70
III	28	-75	2.93	3.21
IV	16	-78	-2.45	-2.75
>	17	-111	-0.5	-5.1
All r	598	-33	2.41	2.68

ALL RAIN

5:5:58 – 29:6:59

FIG. 32.



Had time permitted these 1959 results could have been added to the 1958 Summer graphs (figs 26 to 31) to collect together all results where I, I_s, F, and r were all measured. However, a graph was plotted of I and I_s against F for the two periods combined irrespective of r (i.e. for "all r") and is given in fig. 32.

(c) <u>Drizzle</u>. For about half an hour on the 29th June extremely fine drizzle fell, during which time the current density was negative (about $3 \mu\mu A.m^{-2}$) and the potential gradient was also low and negative (between -20 and -30 $V.m^{-1}$).

On a second occasion (in August) not included in the general rain results, very fine drizzle and misty conditions prevailed all day giving again a small negative F and very small negative currents to both collectors.

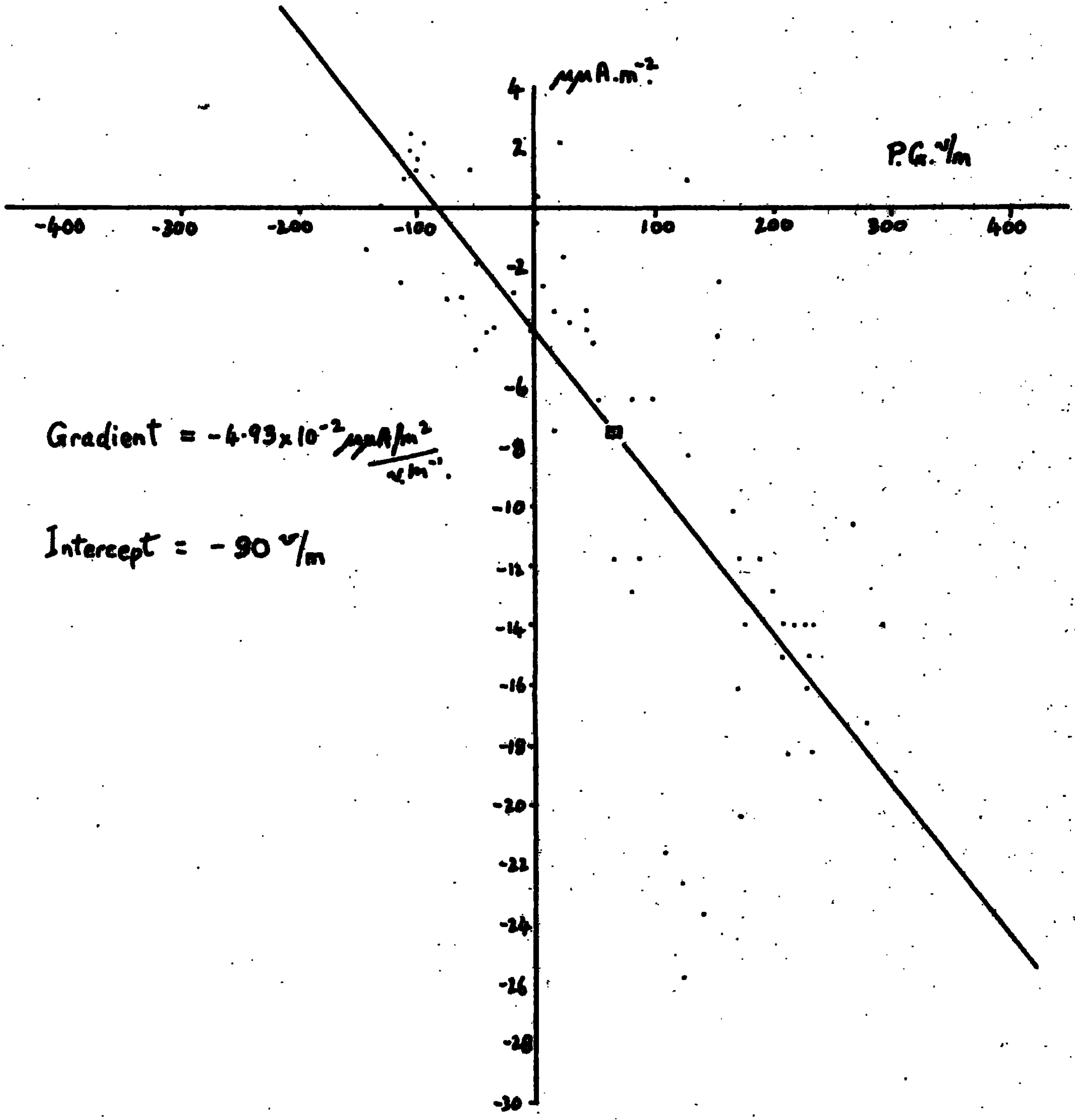
(d) <u>Snow</u>. Only one day of nimbo-stratus snow was recorded in 1959. The 65 points obtained are all plotted in fig. 33 which is a good example of the kind of scatter obtained in a single day's recording, and is indeed a more "well-behaved" example than most. The slope of the "least squares" straight line is nearer what would be expected for rain (c.f.fig.24) but the characteristic positive F and negative I of steadily falling snow are clearly seen.

(e) <u>Sleet</u>. Results for sleet are shown in fig.34 which shows a very fair agreement with the sleet results of the previous year. The constancy in the difference between I and I_s is to be noted and fact that sleet generally shows a close adherence to the linear

SNOW

7:1:59

FIG. 33.



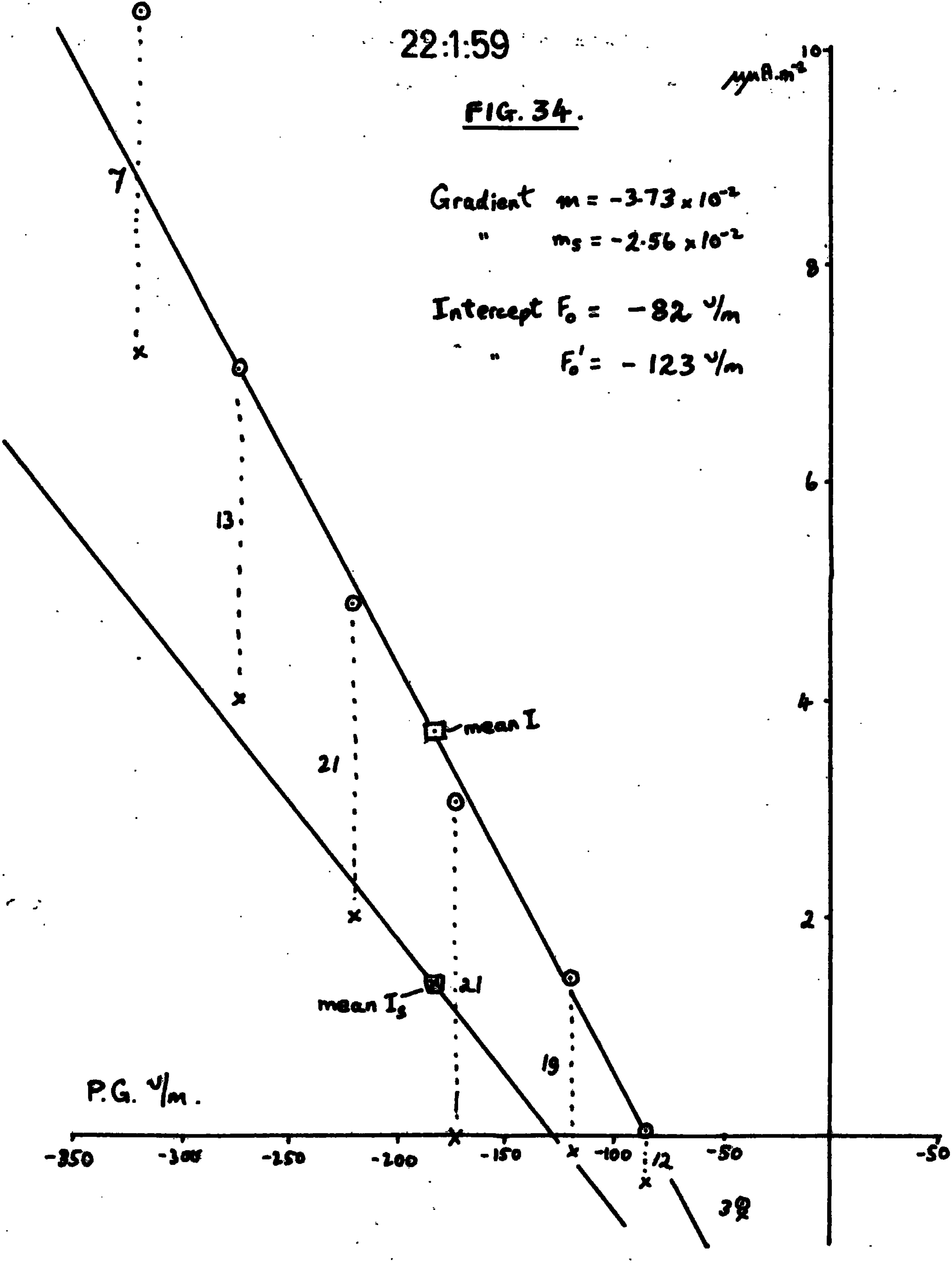
Gradient = $-4{\cdot}93 \times 10^{-2}\ \frac{\mu\mu A/m^2}{v\,m^{-1}}$.

Intercept = -90 v/m

SLEET

22:1:59

FIG. 34.



Gradient $m = -3.73 \times 10^{-2}$

" $m_s = -2.56 \times 10^{-2}$

Intercept $F_o = -82$ V/m

" $F_o' = -123$ V/m

I/F relation than either snow or rain may well be significant with respect to the origin of rain charge.

CHAPTER 7.

ADDITIONAL EXPERIMENTS AND OBSERVATIONS.

7.1. Conduction Current Measurements.

The ionic conduction current density given by $i_c = \lambda F$ where λ is the local conductivity, contributes to the total air-earth current I measured by the exposed collector. However, no evidence of the presence of conduction current can be found by comparing the values of I with those of I_s (precipitation current only) as seen in 6.9. Hence either i_c is much smaller than expected from a knowledge of the accepted values (Chalmers 1957 p.286) or else it is masked by a greater factor governing the $I - I_s$ difference.

Measurements of i_c in fine weather were made and an average value of $0.8 \mu\mu A.m^{-2}$ per 100 $V.m^{-1}$ was found. This is less than the expected value and could be due to a low local conductivity but it is also less than the measurements of Chalmers taken at the same place.

By applying fixed potentials to the large test plate (mentioned in 5.1) "artificial" conduction currents were measured and found to give a value of $0.6 \mu\mu A.m^{-2}$ per 100 $V.m^{-1}$, this further reduction being attributed to the "unnatural" conditions where ion replenishment between test plate and collector might be inadequate.

The possibility arose that the "Adamson apparatus" was in some subtle way not measuring the full conduction current and so this was carefully investigated.

(a) The most obvious possibility that the collector had an exposure factor less than unity was dismissed from the determination of the effective area for displacement and conduction currents (5.2).

(b) The condenser C_c which is used to differentiate the field mill output in Adamson's compensating circuit, feeds a signal to the second grid of the electrometer valve proportional to the rate of change of potential gradient (see 2.2.) If this condenser had a sufficiently low leakage resistance (about 5×10^{13} ohms) it is possible that a steady output from the mill could flow through C_c and the input resistor giving a signal to the second grid proportional to the potential gradient itself and hence to the conduction current. Thus, total or partial compensation could occur for i_c and the output from the d.c. amplifier would lack a conduction current component.

By disconnecting the mill output and applying a fixed potential to the mill side of C_c (equivalent to a 400 $V.m^{-1}$ mill output) no change whatever could be detected in the d.c. amplifier output indicating that the leakage current was negligible and that the theory that the apparatus was eliminating i_c by compensation was incorrect.

(c) A further possibility was investigated; this was that the leakage current between the collecting bowl (2.2) and the earthed guard might be appreciable due to the finite conductivity of the air and the fact that the bowl is above earth potential when receiving a current. This problem was analysed as follows. If I^1 amps. is the total current flowing into the collector and down the input resistor R, the collector potential because of the effect of negative feedback is $I^1R/1+G$ where G is the gain of the amplifier. Hence a field is set up between the hemispherical bowl and earth giving rise to a leakage current across the gap. Without attempting the difficult problem of the form of the electrostatic field the current was calculated by making reasonable approximations and found to be 10^{-5} of the input current I^1. Thus, despite the approximations it can be safely considered to be negligible.

The conclusions finally drawn were: (i) the conduction current was in fact smaller than the values usually given, and (ii) it was not of prime importance in determining the difference between I and I_s.

7.2. Drop Size Determination.

To test the possibility that the shielded collector was missing the smaller rain drops in windy weather (Chapter 4) it was decided late in the final year to attempt the measurement of the size of drops reaching both an exposed surface and a surface below a shield identical to that described in 4.2.

The method adopted was that used by Hutchinson (1951) in which the drops were received on filter paper specially prepared by depositing rhodamine dye in the form of a fine powder on the surface; the drop then makes on the paper a bright red stain, the diamter of which is related to the size of drop.

Drop Size Calibration

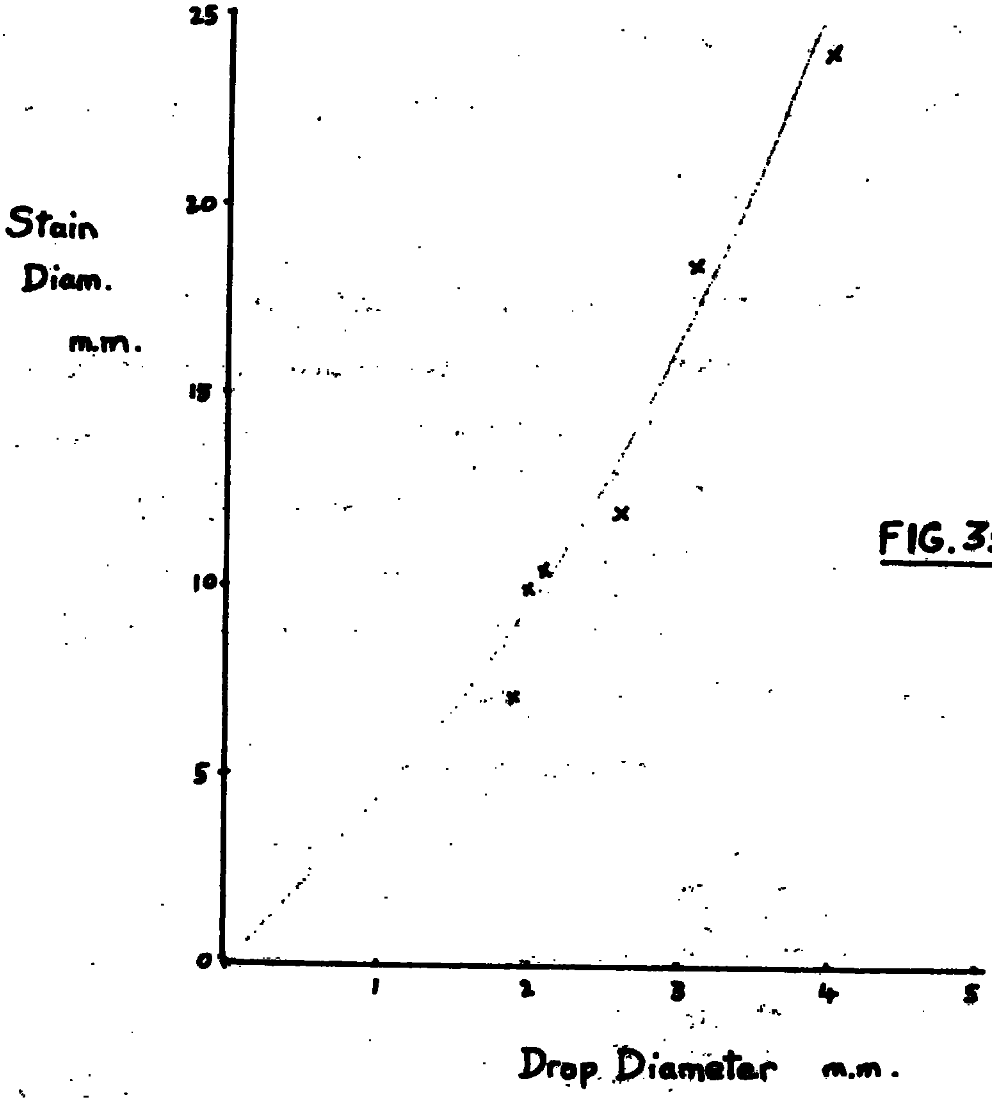


FIG.35.

A calibration curve of drop diameter against stain diameter is shown in fig. 35.

Two samples of the prepared paper were simultaneously exposed to the rain for a period of the order of 20 secs., one sheet on level ground and the other inside the shield. A count and classification of the stains were made using a thin sheet of perspex with holes of graded size drilled in it to measure the stain size.

Unfortunately, due to the exceptionally dry weather and the time spent in perfecting the technique of carrying out the exposures of the papers without splashing or otherwise ruining them, only three useful results were obtained. The stain diameters were measured to the nearest millimetre except that all those less than 1.5 mm. diameter (corresponding to 0.05 mm. drop diameter) appear under the "zero" heading

Stain diameter (mm)

16.4.59.(a)	0	1.5	2	3	4	5	6	7	8	9	10	Total
Exposed	199	35	34	34	12	7	6	5	1	2		136
Shielded	216	39	37	19	15	12	7	6	1	3		139
16.4.59.(b)												
Exposed	200	29	57	28	19	9	11	3	2	2	2	363
Shielded	223	45	28	20	14	8	3	2	0	1	1	355
27.4.59.												
Exposed	396	141	115	74	42	8	9	0				785
Shielded	177	132	73	45	21	10	7	1				466

The first day showed a remarkable identity in the size/frequency spectrum for the exposed and shielded samples, considering the considerable "experimental error" involved in counting the very smallest drops.

The second day which was more windy showed that the shield did reduce the number of drops received and in particular the proportion of the very smallest drops to the total collected was greatly reduced by the shield.

At the times when the drop size measurements were carried out, the currents I and I_s were, on the first day, very small and virtually equal, and on the second, varying rapidly at the time in question.

No satisfactory conclusions can be drawn as many more results would be required. Simultaneous measurement of I and I_s are of course necessary and would have to be carefully synchronised with the time of the drop size sampling to show any significant results.

7.3. Splashing.

The possibility of splashing effects on the receiving surfaces of the two collectors have been discussed in Chapter 4.4. As far as is known, the charging of drops by splashing can occur in one of two ways. (i) Lenard (1892) found that on impact, a positive charge was given to the drop and a negative charge to the air. (ii) Adkins found a field-dependent effect already described in Chapter 4.

Smiddy (1958) made measurements of space charge density in the first six metres of the atmosphere and made frequent references to the measurement of precipitation current and rate of rainfall described in this volume, both research projects being carried out concurrently during 1957 and 1958 onthe same site.

It was found that a big increase in space charge density consistent with the generation of negative charge by a Lenard type splashing did occur but only for very high rates of rainfall, greater than about 0.07 to 0.10 mm. min^{-1}. For rates below this no such effect could be detected. Thus it can be concluded that no charging by splashing took place in any of the results described in the last chapter except possibly in the very highest rates of rainfall recorded (note the rates > 0.04 in the tables for 1958 and 1959 - (6.8) and(6.11) respectively)

Adkins (1958) found his splashing effect to be present only when the potential gradients were high and gave 700 V.m^{-1} as a lower limit for the effect to occur. All results in the present work were limited to potential gradients of between ± 500 V.m^{-1} so that an "Adkins splashing current" could be dismissed as a possible contributor to the currents measured.

Finally, attempts were made to detect charging by splashing by dropping uncharged drops from the earthed nozzle of a "water dropper" on to (i) the turf surface of the shielded collector and (ii) a sheet of aluminium placed on top of this. The drops were allowed to fall through heights varying from 35 cm. to 122 cm. this latter height giving a terminal fall velocity similar to that of falling rain (about 4 m.sec.$^{-1}$). The drops were much bigger than normal raindrops and would therefore be expected to give greater splashing effects.

In no case did the V.R.E. give any deviation from its zero output. That the instrument was working at the time was was verified by running in charged drops at a known rate and observing the deflection so produced.

Thus the work of both Smiddy and the present author at Durham indicate that in nimbo-stratus conditions, splashing effects may be rejected as a possible source of rain-charge.

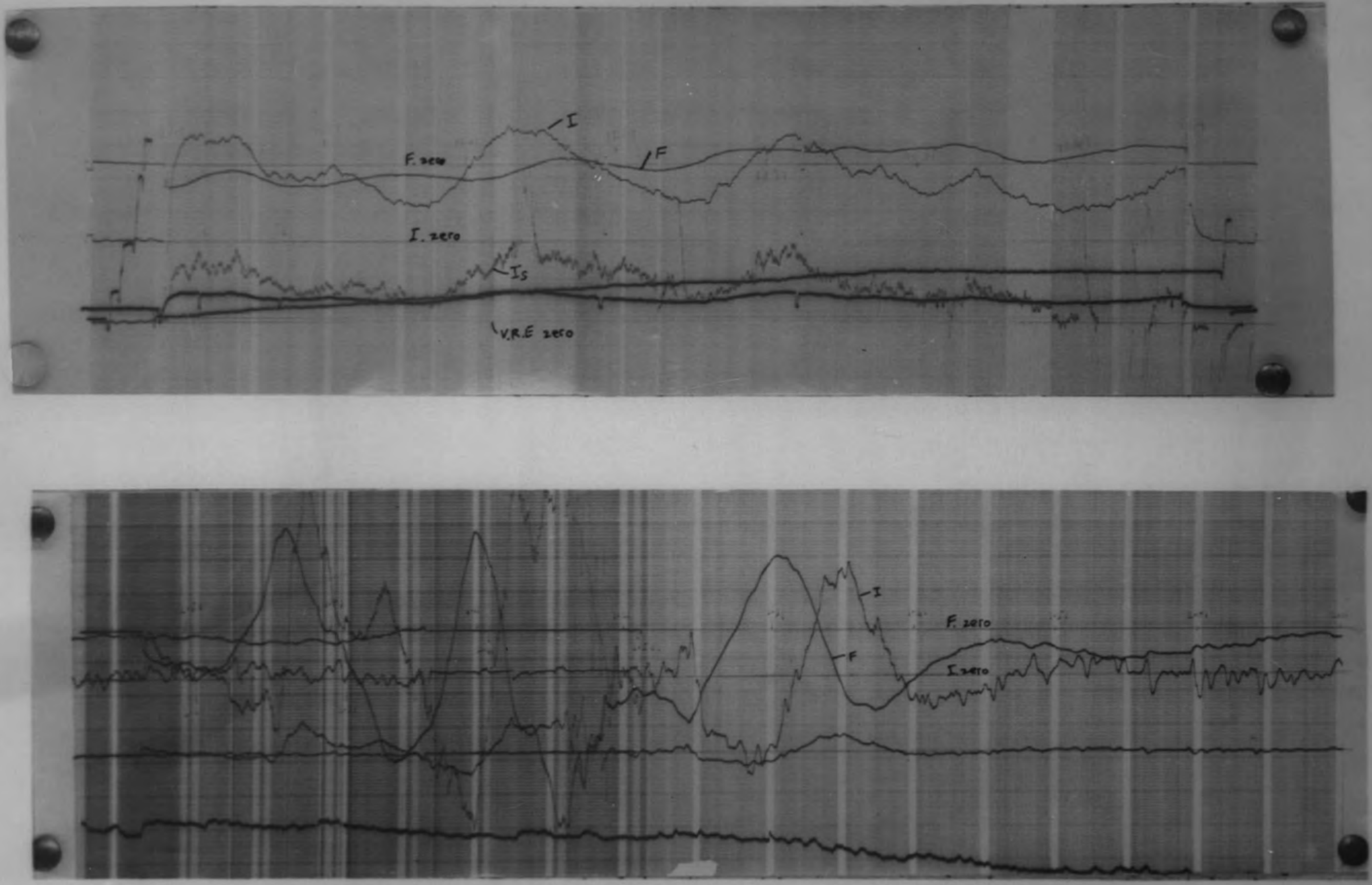


FIG. 36.

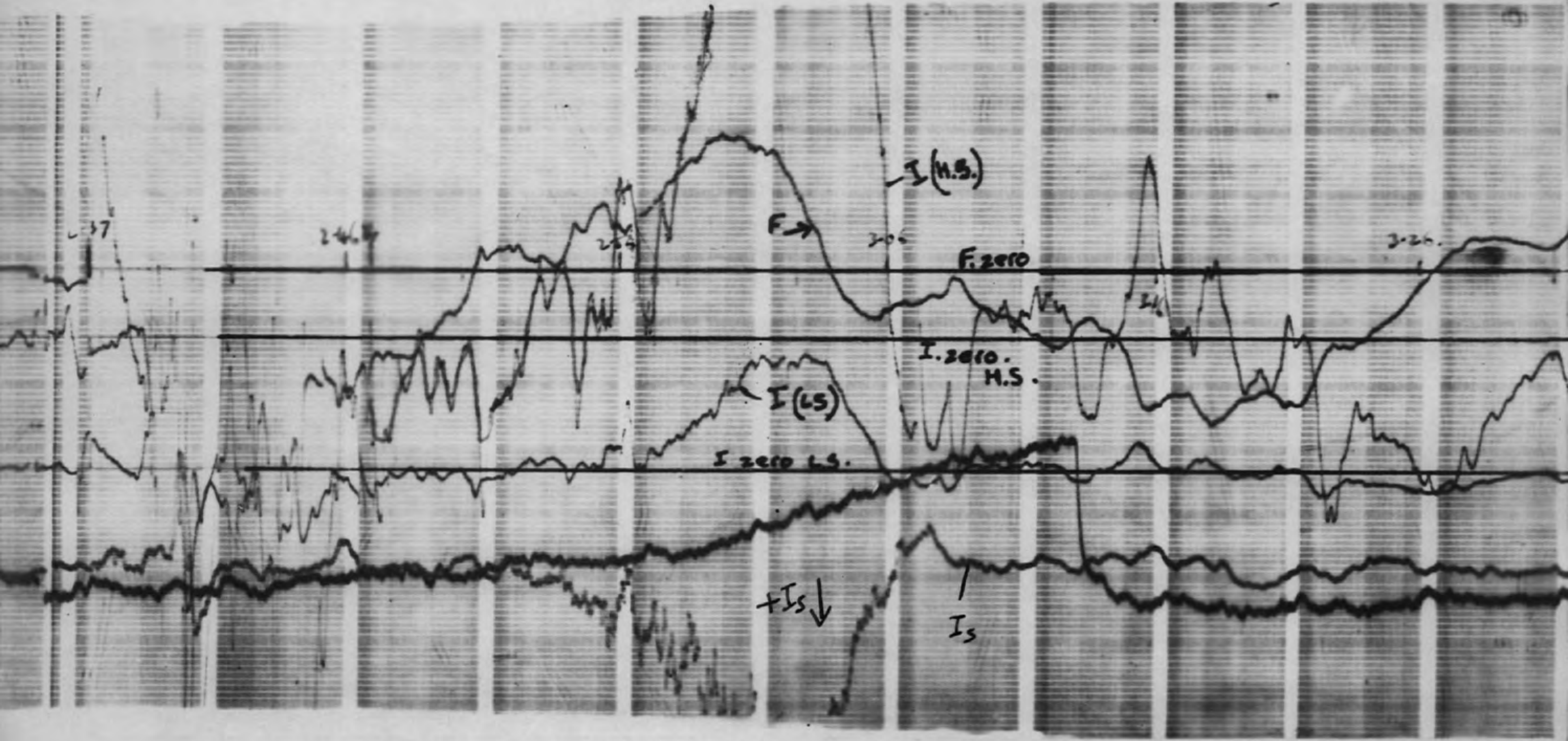
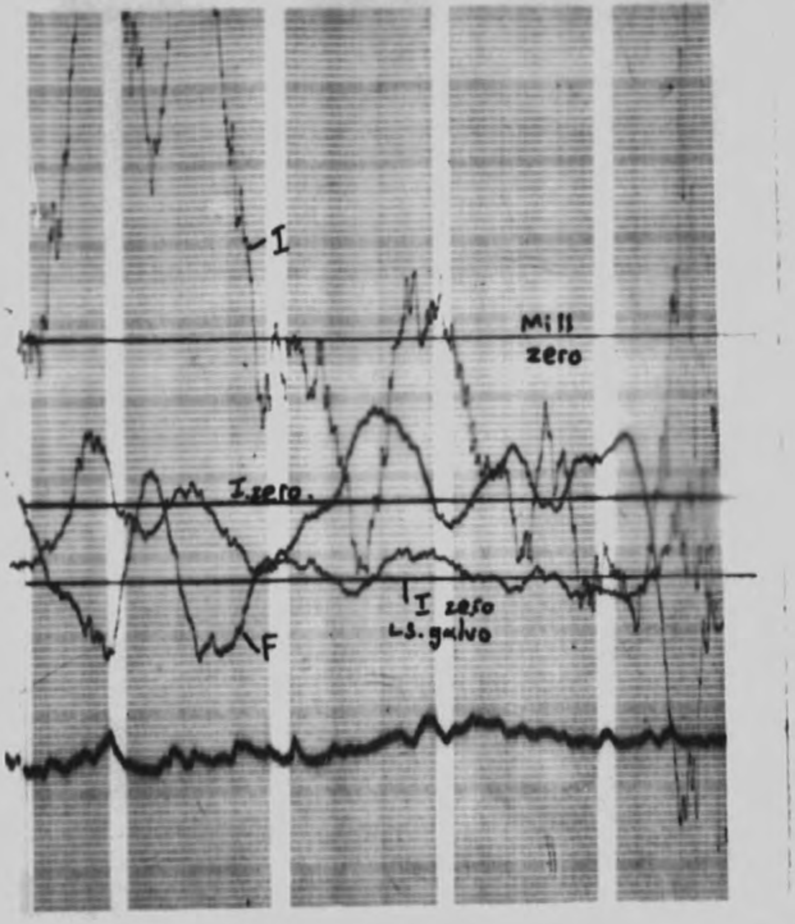
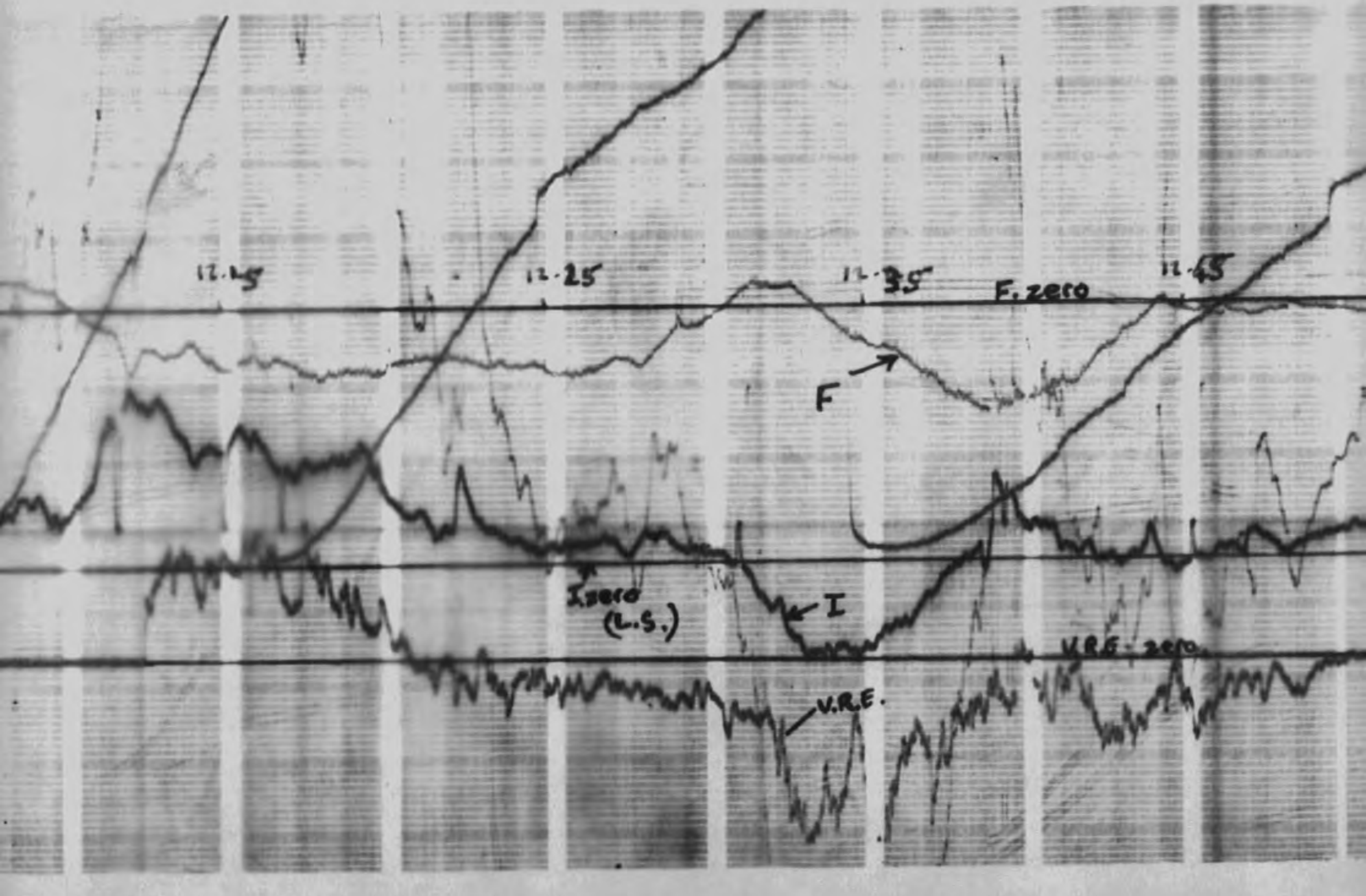


FIG. 37.

FIG 38



I
Mill zero
I zero.
I zero L.S. galvo
F
V



12.15
12.25
12.35
12.45
F. zero
F
I zero (L.S.)
I
V.R.E. zero
V.R.E.

CHAPTER 8.

THE MIRROR IMAGE EFFECT.

8.1. The Phenomena.

The mirror image effect, conveniently abbreviated to "M.I.effect" has already been mentioned several times in this volume and it is the purpose of this chapter to give a fuller account of the effect. When it is observed, the precipitation current/time, and the potential gradient/time traces are inverse curves, one appearing as the "mirror image" of the other. Wave-like patterns (Simpson 1949, and Whitlock 1956) are often found and the two traces resemble sine waves out of phase by π . This will be refered to as the "normal" M.I. effect when the maxima of I.and F occur simultaneously, (a maximum of F being so called when F has its highest negative value; in nimbo-stratus conditions I is usually positive and F, negative.

In the course of the present research, however, it was found that whilst the M.I. effect was sometimes "normal" e.g. fig. 6 (lower half) and fig. 38, on many occasions a time delay existed between the occurrence of the current and potential gradient peaks. The "classic" example of this "phase shift" is seen in the record of the 11th February 1958 a copy of which is shown inthe lower half of fig. 36; the "shift" is also seen but is less well-defined in the figs. 7 (top half), 8 and 37.

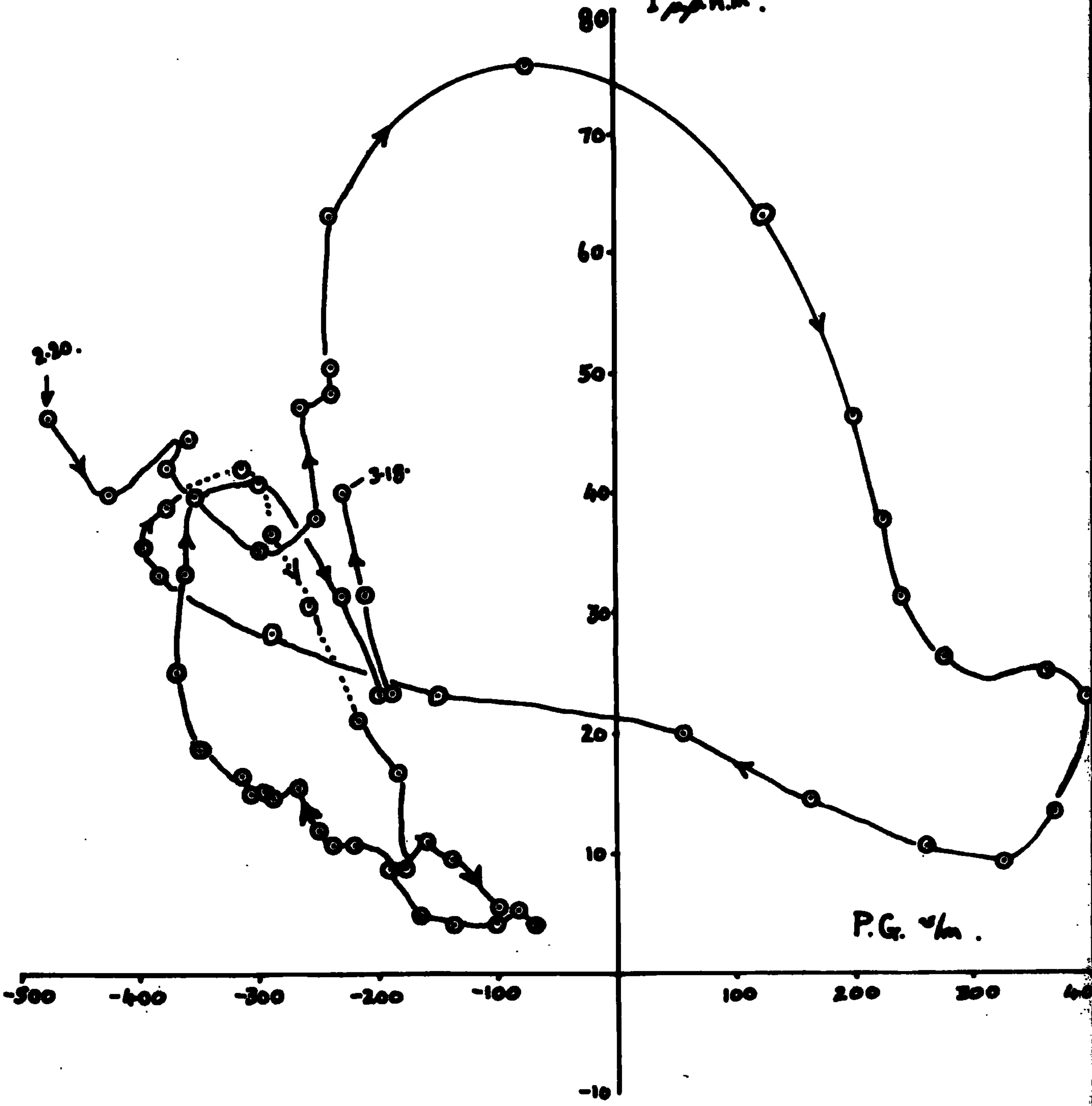
8.2. The So-called "Ellipse Effect".

11:12:57.

2·20–3·18

FIG. 39.

RAIN



20:1:58.

3·55 – 4·33 p.m. SNOW

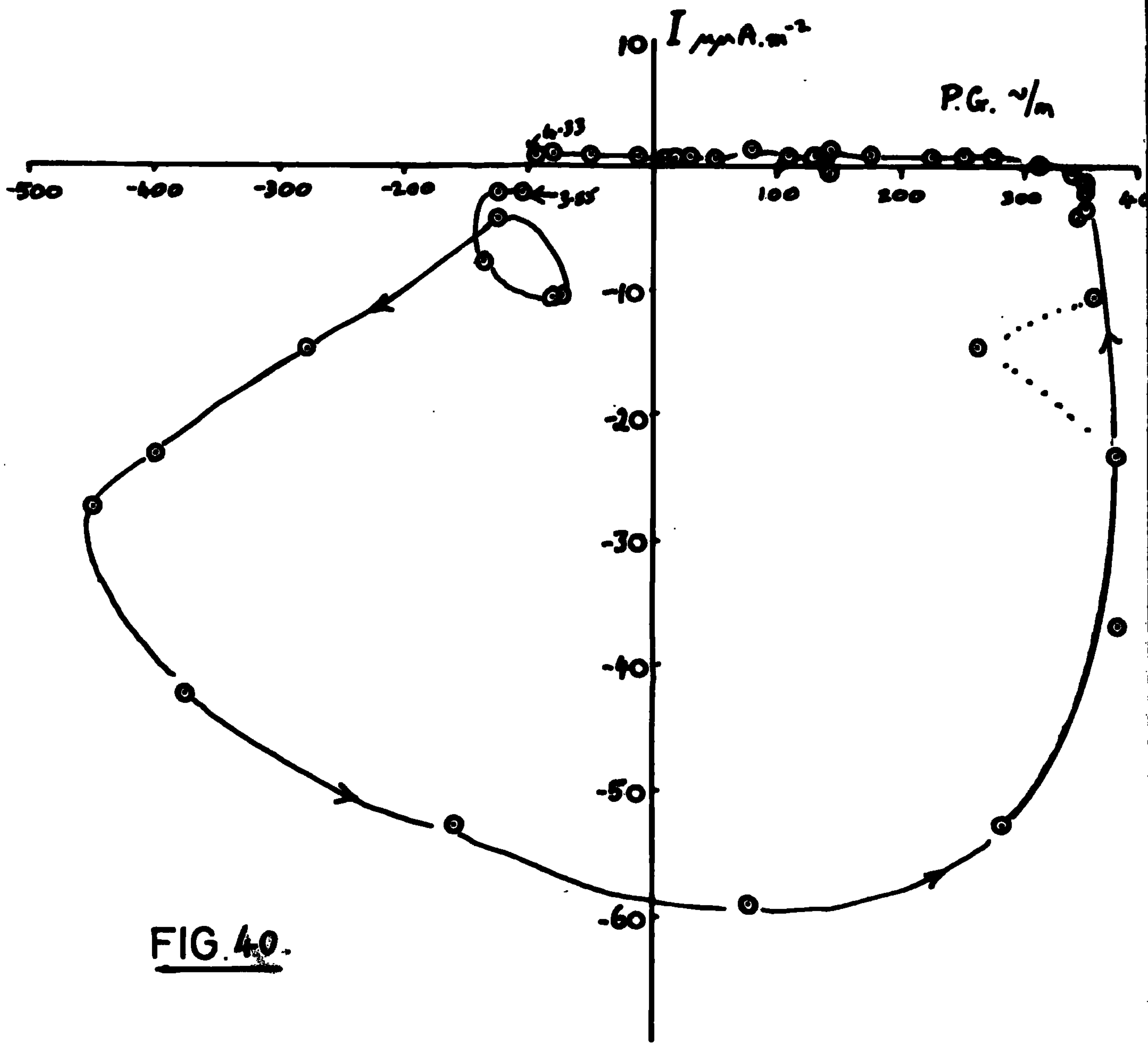


FIG. 40.

11:2:58

12·51–1·51 p.m.

RAIN

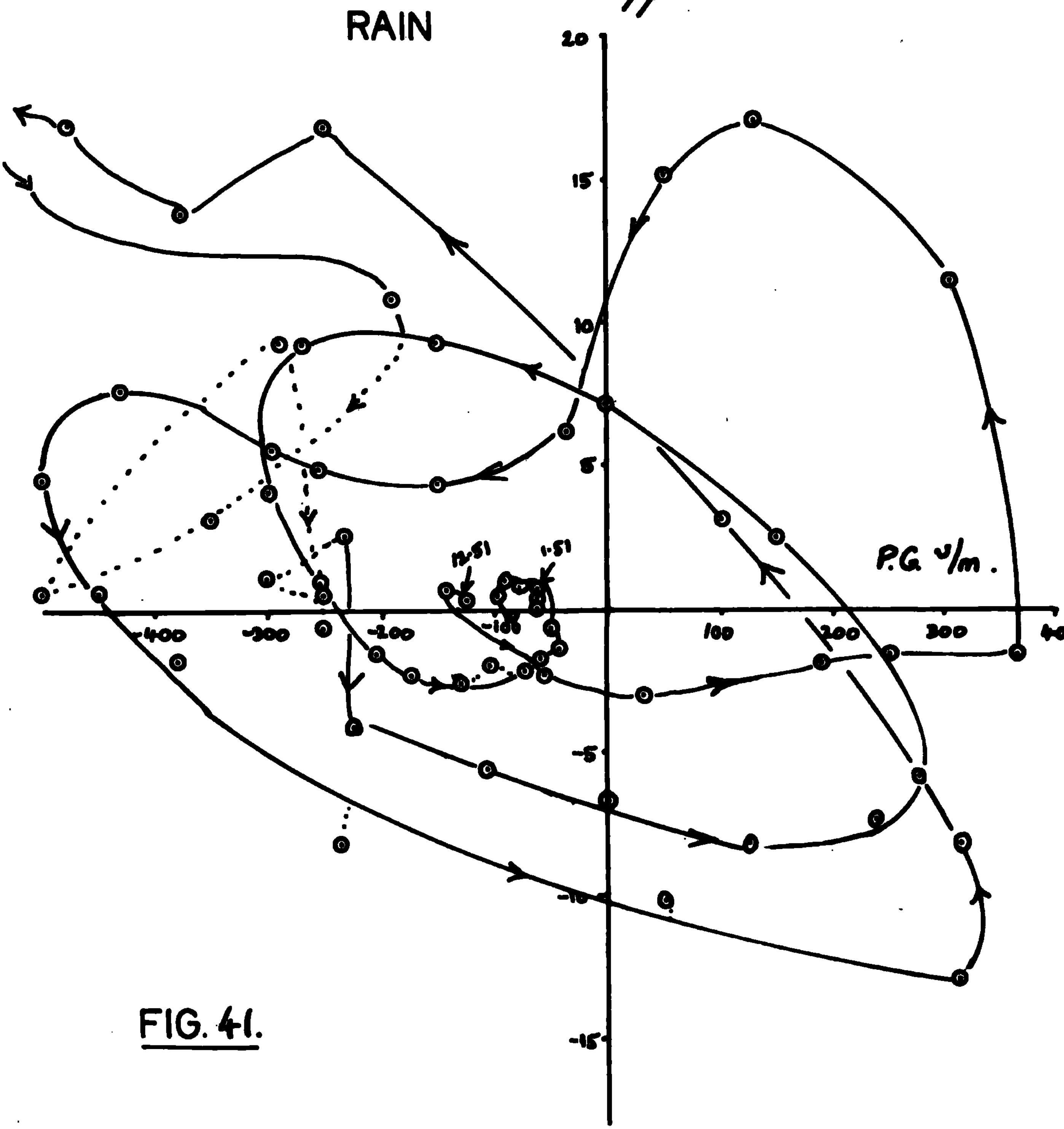
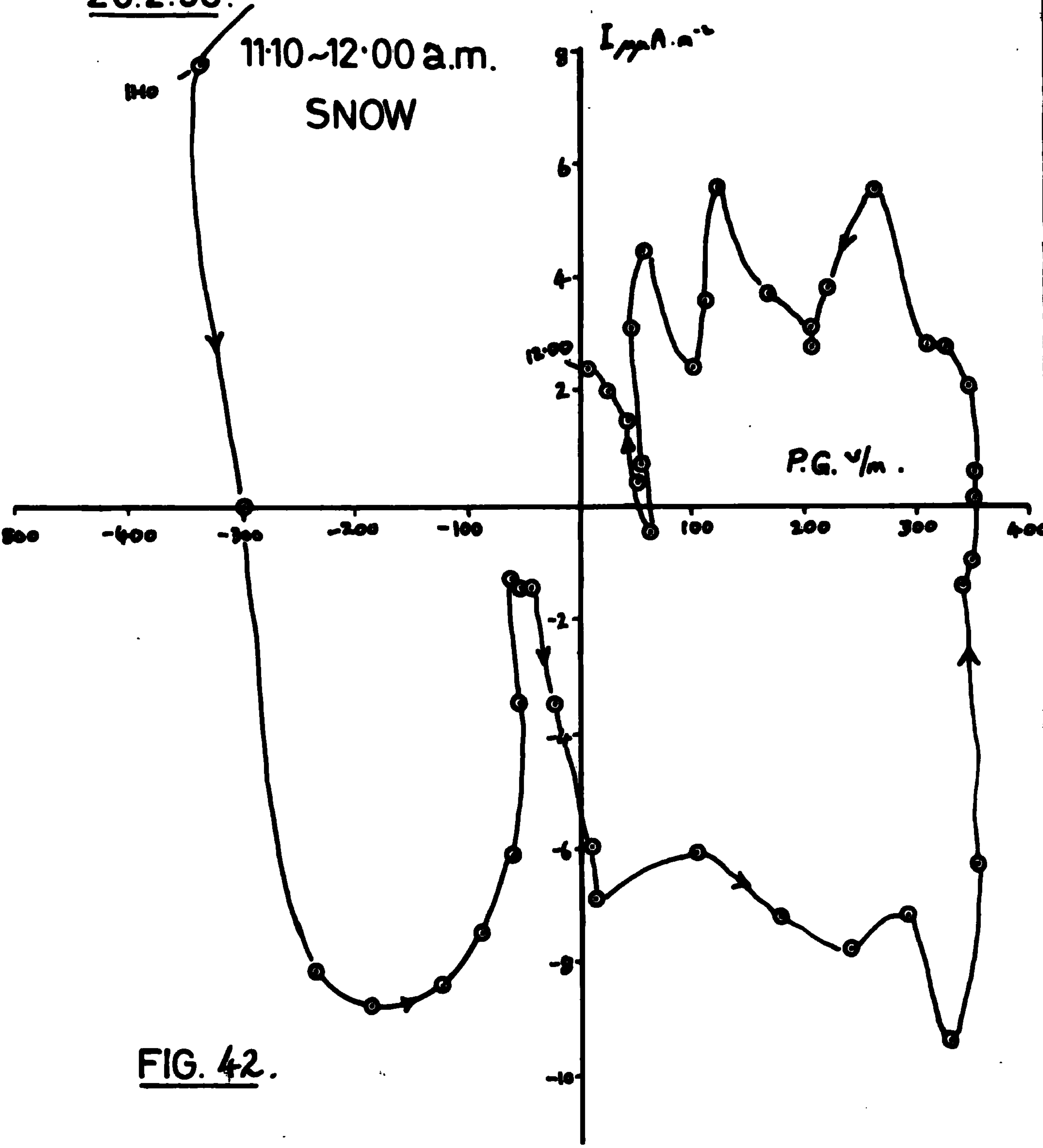


FIG. 41.

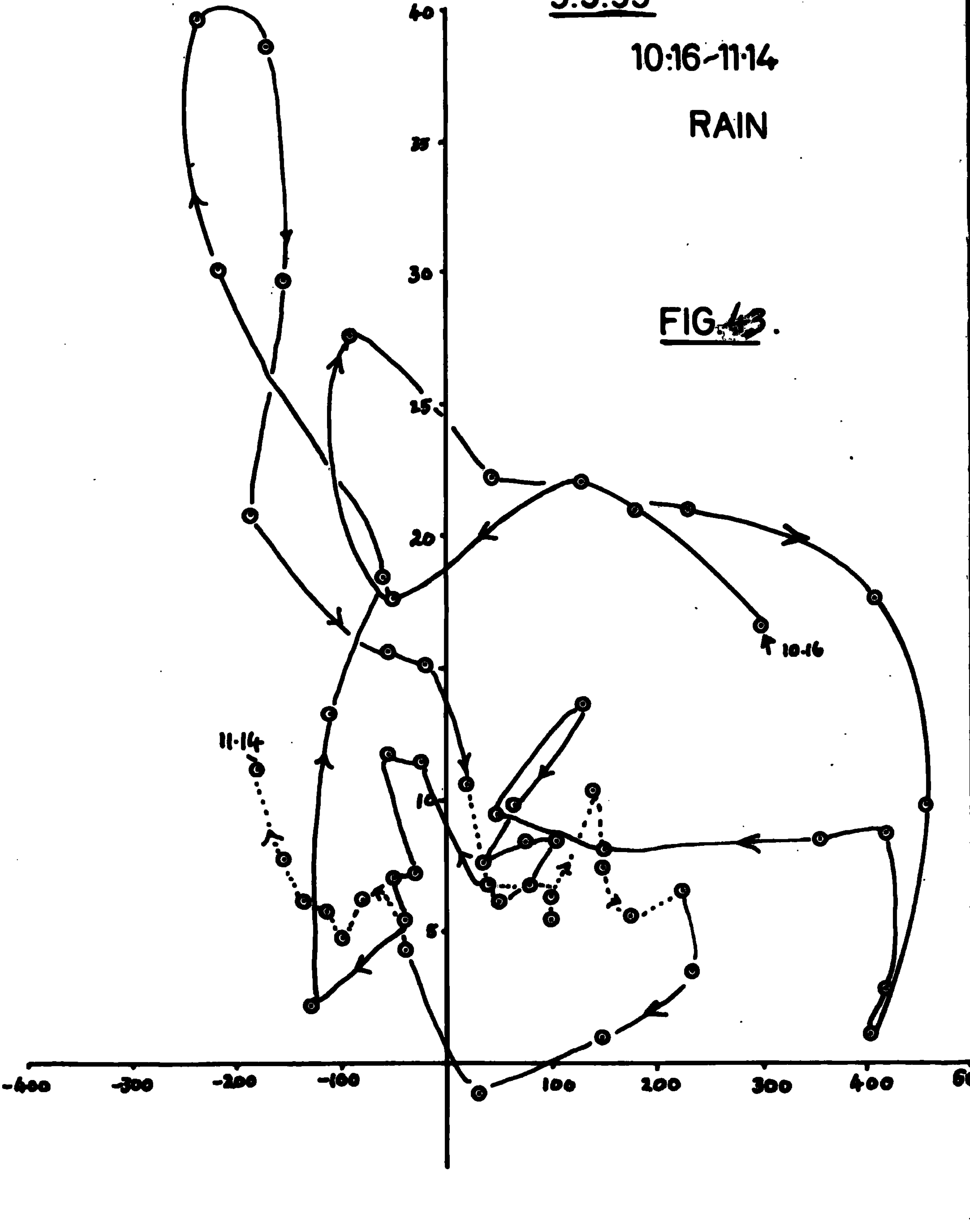


26:2:58.

11·10~12·00 a.m.

SNOW

FIG. 42.



3:3:59

10:16-11·14

RAIN

FIG. 43.

The nature of this variation in two earlier records immediately suggested that if I and F were plotted against each other with due regard to time, a kind of "Lissajous figure" would result. When this was done for the 11.2.58 data the fig. 41 was obtained. Without joining up consecutive points (minute interval values) no trend could be seen in the I/F graph but on doing this a remarkable series of ellipses was produced as a direct consequence of the "phase lag" in the M.I. effect.

The first two graphs plotted in this way were figs. 39 and 40 and showed ellipses having opposite senses for rain and snow, an apparently significant result, not unfortunately, borne out by later results.

Whenthe ellipse is anti-clockwise it illustrates the occurrence of a maximum in I before the (negative) maximum in F whilst a"clockwise ellipse"shows that the current "wave" is lagging behind the potential gradient. Graphs of I/F were drawn for 5 days on which the effect was well-defined and are shown in figs 39 to 43 inclusive. Fig. 43 shows the rather chaotic result of plotting a rapidly varying M.I. effect with phase lags of both senses and illustrates how little correlation can exist between F and I in a single hour's recording.

The mirror image effect was observed on a total of 21 days (out of 40 on which useful recording took place in nimbo-stratus conditions) although it was not always so well defined or so prolonged as the 11.2.58 example. The following table shows, for all types of precipitation; the number of days on which (a) no phase-shift occurred (b) I maxima preceded F maxima, and (c) F max. preceded I max.,

	Rain	Snow	Sleet	"Wet Snow"	Total.
(a)	6	1	1	1	9
(b)	3	3	1	0	7
(c)	5	0	0	0	5
Total	14	4	2	1	21

8.3. The M.I. Effect and the General Inverse Relationship.

The M.I. effect and the general inverse relationship between I and F are not to be confused since the former is a short-period variation compared to the relaxation time of the atmosphere whilst the latter is a statistical correlation of the two quantities over many results. However, the two are not unrelated; if the "normal" M.I. effect is operating and the I/t, F/t variations were in fact sine waves, then a plot of I against F gives a straight line with a negative gradient passing through the origin. Now I is seldom negative in steady rain conditions so that this line is shifted upwards, consistent with the Chalmers formula $I = -a (F-G)$.

When a phase lag occurs, if F lags behind I, an anticlockwise ellipse is given with its major axis on this line. But when I lags behind F, then an ellipse occurs with its major axis having a positive gradient, the extreme case being when the two waves are exactly in phase (mathematically) and a straight line with a positive gradient is given. Thus the result of frequent occurrences of a lag of I behind F could give, on averaging, an I/F straight line with a positive gradient. This could have some bearing on the result of the 1958 Summer (figs.26 to 29) and will be referred to again in Chapter 9.

8.4. Causes of the Phase Lag.

The reason for the observed time delays in the M.I. effect became a point of great interest. The "normal" M.I. effect may be explained in a very broad elementary way as the result of the precipitation becoming charged by some process in the cloud base or below with the charge of opposite sign remaining behind and giving rise to the potential gradient observed at the ground. (The I/F relationship is explained but not the wave-like variation.) This over-simplification takes no account of (i) the horizontal motion overhead of the cloud, or (ii) the space-charge present on the precipitation.

The former has no effect if, in nimbo-stratus conditions, horizontal planes may be considered as equi-potential surfaces; but it is important if there is considerable horizontal variation in charge density in the cloud giving rise to wave patterns in the potential gradient (Whitlock 1956). The normal M.I. effect will then be observed if the arrival of the precipitation coincides with the arrival overhead of that part of the cloud from which it came (i.e. no variation of wind speed with height). If, however, the wind speed does vary with height then a time delay would occur in the M.I. effect. Most frequently it would be expected that wind speed would increase with height though the reverse is sometimes true, so that F maxima should be found preceding I maxima more often than vice versa (see table in para. 8.2.) This was found to be so for rain but it is notable that it was not so in the case of snow and it is probable that in the latter at least, the effect of the space charge residing on the precipitation is more important.

If the potential gradient at the ground is considered to be equal to the sum of F_1, due to the charge of opposite sign to the precipitation residing in the region of separation, and F_2, due to the space charge of the falling rain or snow, then F_1 and I (the precipitation current) will be related by the "normal" M.I. effect as described above (without wind speed variation). If now the wave-like variations in F_1 and I are assumed to occur, and the effect of F_2 is superimposed on F_1, the resultant observed potential gradient $F = F_1 + F_2$ may be shown to lag behind I (i.e. I maxima occur before (negative) F maxima).

F_2 at time t is proportional to $\int_t^{t+\tau} I \, dt$ where τ is the time taken for the precipitation to fall from cloud level to the collector. Thus F_2 at time t is a result of the space charge present at that time between earth and cloud. If I varies with height as well as with time then the conditions become more complicated but this simple treatment shows that a "phase lag" of this kind can occur as a consequence of precipitation space charge. That the magnitude of the latter is sufficiently great may be seen from the calculations given in Chalmers 1957 p.187 and since τ is of the order of 3 minutes, perhaps a quarter of the "period" of a typical M.I. wave, then it is quite feasible that the sort of phase differences observed could arise from this cause.

The observed result that this occurs more often in snow than in rain is in agreement with this discussion since τ will be greater for snow than for rain.

8.5. Further Notes.

Before leaving the discussion of the M.I. effect the following points should be noted.

(i) No fundamental cause is known for the sinusoidal nature of the I and F curves but it may be significant that the period of the waves is comparable to the relaxation time of the atmosphere (Chalmers 1957 p.24). It may be that the M.I. effect represents a variation or oscillation about the quasistatic or steady state. This is at present only a tentative suggestion and may merit further investigation. It can be shown that the two conditions of a quasistatic state and no variation of precipitation current with height are mutually exclusive on account of the space charge on the precipitation (Chalmers 1959) and it may be possible to consider this in connection with the M.I. effect.

(ii) If one of the "waves" lags behind the other by a sufficiently large phase angle then it may appear to be preceding the other, a difficult thing to recognise on examining the records.

(iii) The conduction current i_c may not be "in phase" with the potential gradient for changes in time comparable to the relaxation time (Chalmers 1957 p.25). This has been neglected however because the M.I. effect was observed using the shielded collector (see figs.36-28) which did not of course measure i_c.

FIG. 44.

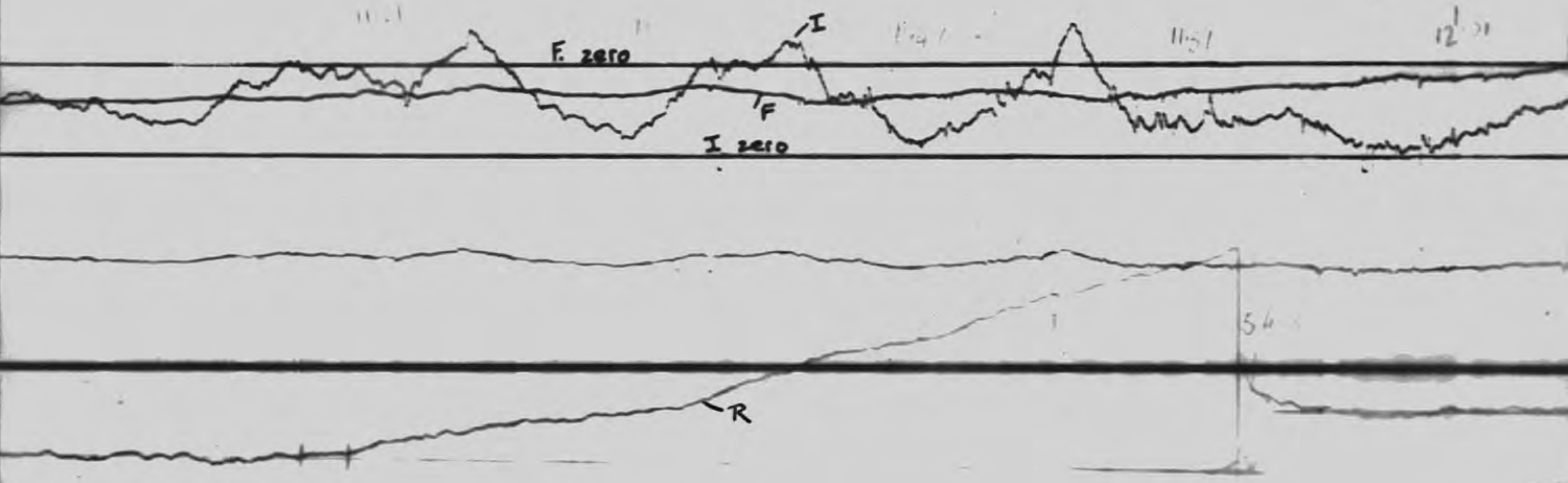


FIG. 45.

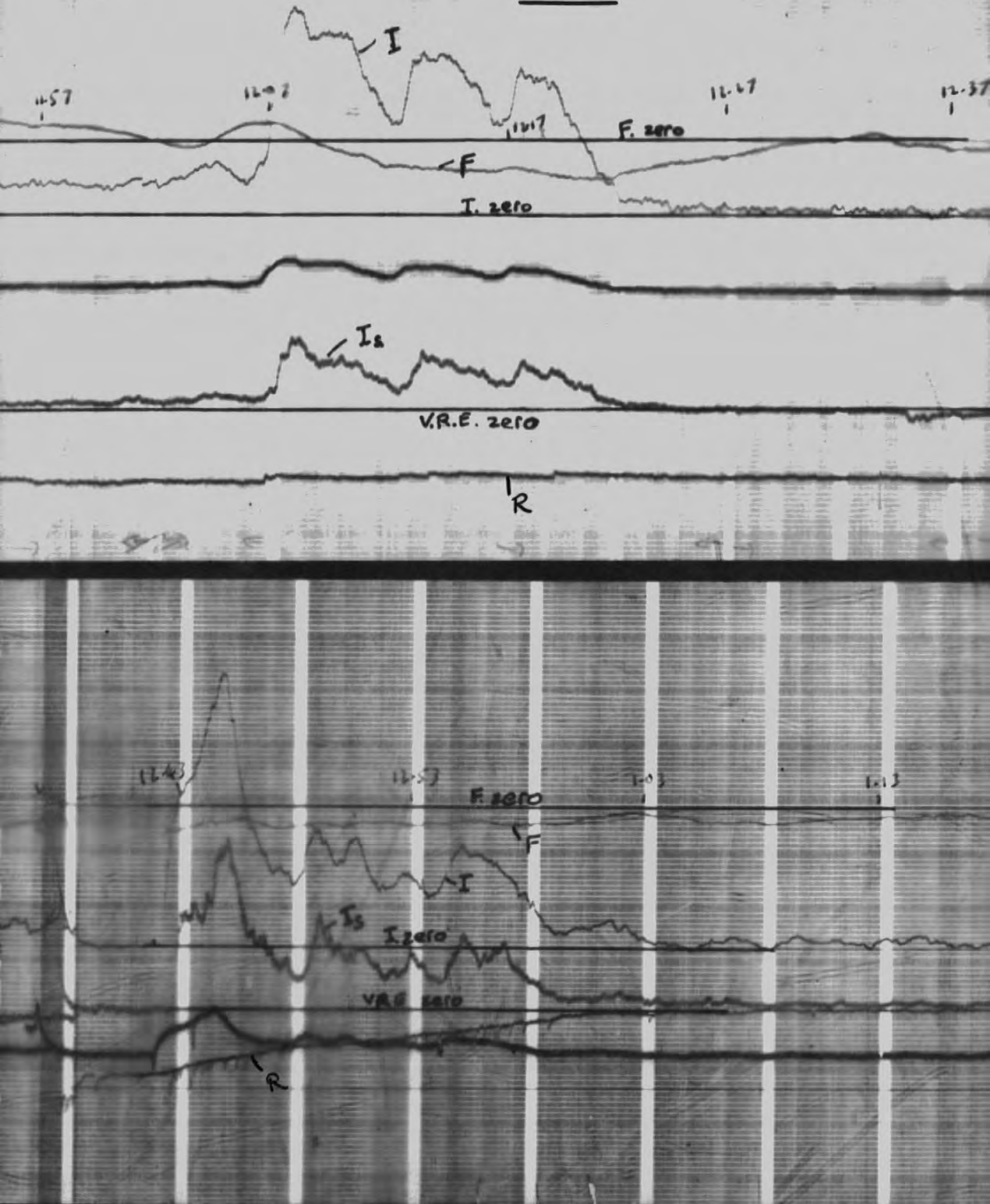
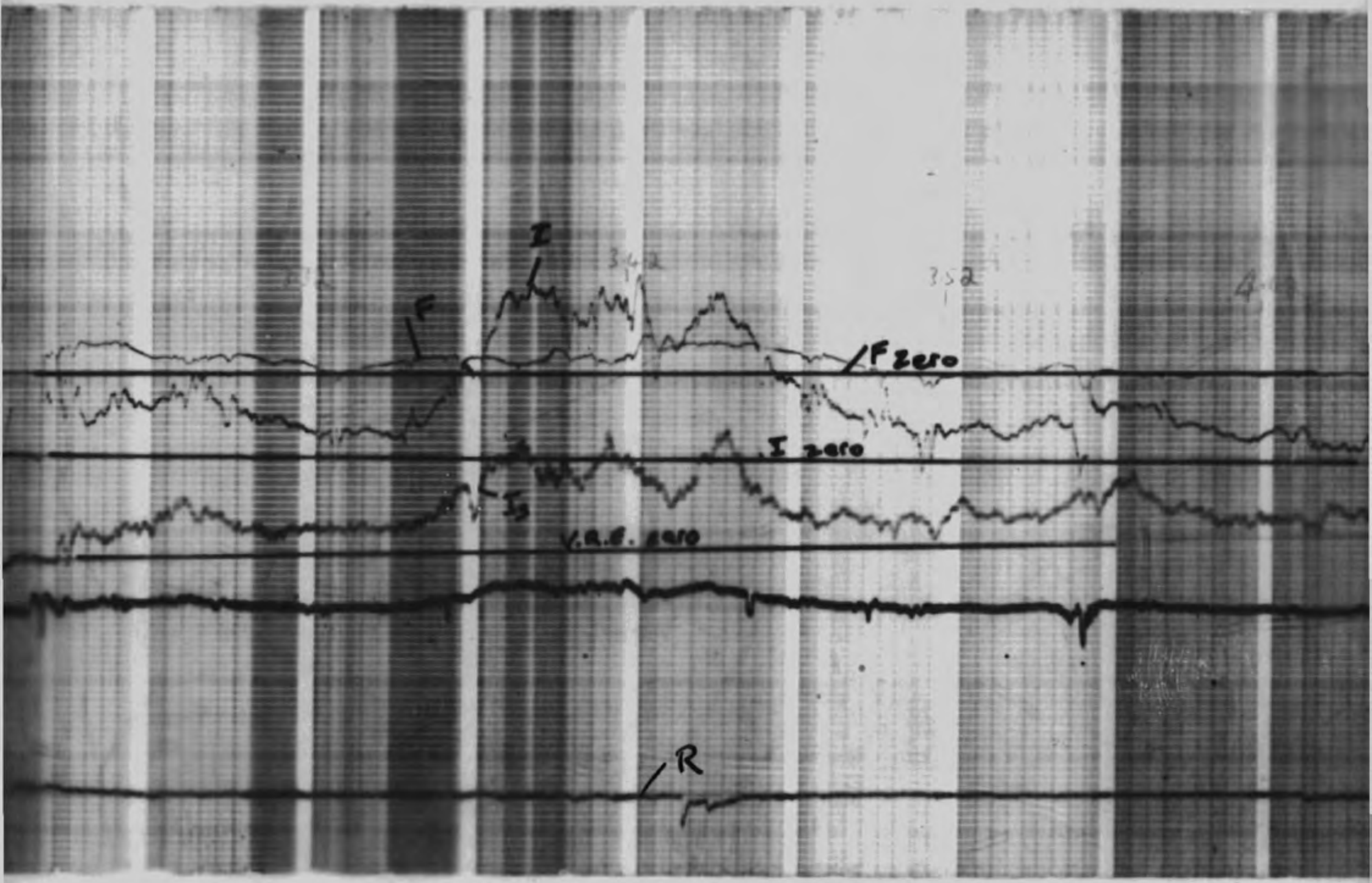

I
11.57
12.07
12.17
12.27
12.37
F. zero
F
I. zero
Is
V.R.E. zero
R
12.43
12.53
1.03
1.13
F. zero
F
I
Is
I. zero
V.R.E. zero
R

FIG. 46.



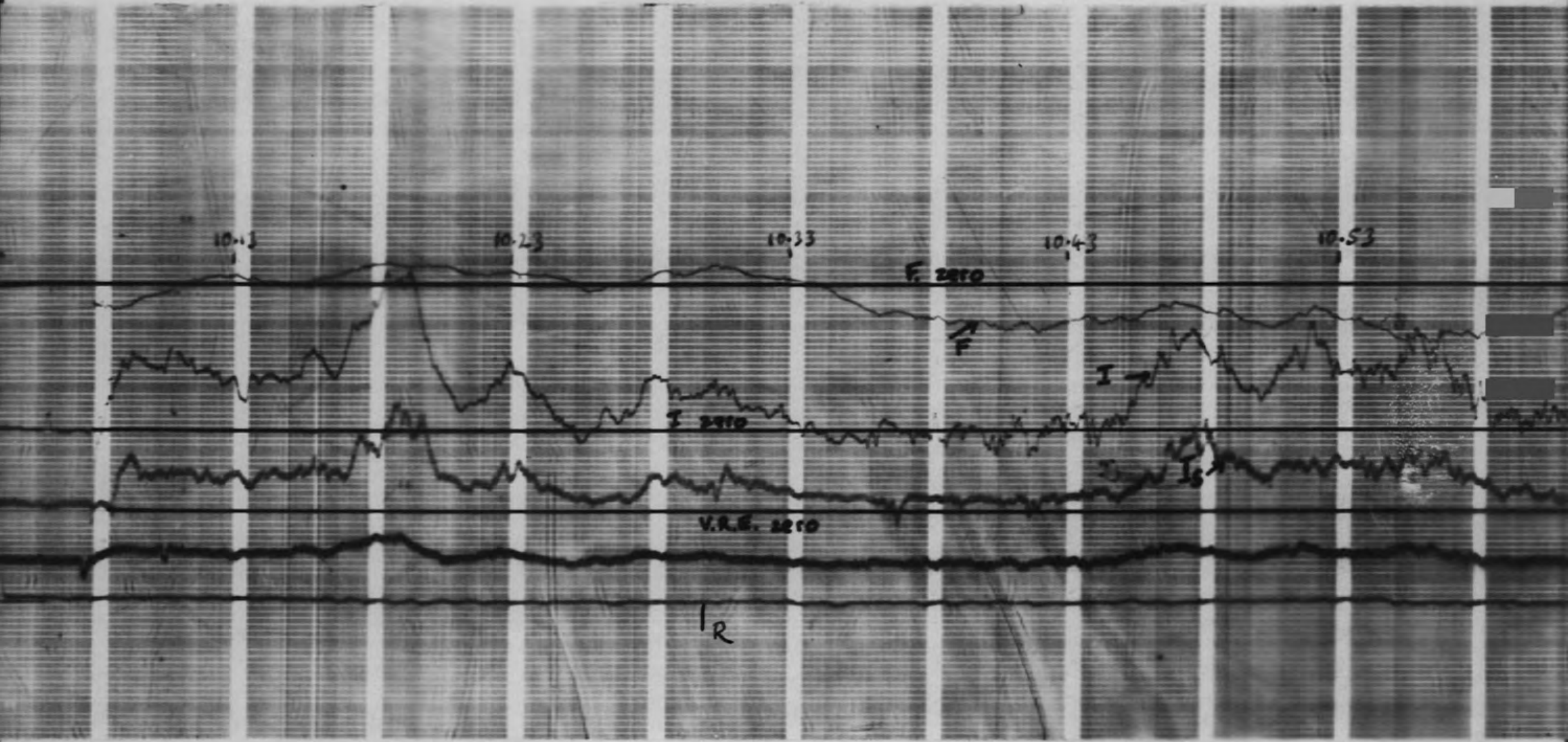


FIG. 47.

8.5. Current Peaks.

On several occasions variations in current density (in rain) occurred without any corresponding variations in potential gradient (figs. 44-47). These variations often appeared as a series of "peaks" in groups of 3 or 4, each group being of 10 to 30 mins. duration. No change in the rate of rainfall could be detected and it was found that the "peaks" usually occurred in conditions where this quantity was very low. No explanation was found for this phenomenon particularly as the converse, viz. similar potential gradient variations without precipitation current changes, was never observed.

CHAPTER 9.

GENERAL DISCUSSION OF RESULTS.

9.1. Topics for Discussion.

The results may be divided into three main topics for discussion:

(i) The Winter 1957-58 results where the chief interest lay in the comparison with those of Chalmers 1956.

(ii) Later data (1958 and '59) including records using the shielded collector, where attention was drawn to (a) the deviations from earlier results and (b) the differences between the current density recorded by the two collectors (i.e. I and Is)

(iii) The mirror image effect.

The third topic has already been fully considered in Chapter 8 so that it remains to discuss what conclusions can be drawn from the results averaged over long periods as described in Chapter 6.

9.2. The Chalmers Formula.

$I = -a\,(F - C)$, where a and C are positive constants.

The general agreement of the Winter results with those of Chalmers (1956) has been described in 6.5. together with the increase of the gradient "a" with the rate of rainfall (figs. 24 and 25). The latter implies an increase of precipitation current with increase of rate of rainfall r, at constant potential gradient.

That an increase of r should give an increase of I seems reasonable but it is not at all clear why no corresponding increase should occur in F (see table paragraph 6.8.) i.e. why the values of I and F do not both increase and still comply with the Chalmers formula - the (I, F) point simply "moving up" the straight line.

The value of "a" did not increase linearly with r as in Simpson's equation (1.5) the variation approximating to a square law (see 6.5) but no significant conclusion could be drawn from this.

The values of the intercepts on the F axis for intermediate ranges of r give strong support to the theory that "C" represents the fair weather potential gradient (see 6.5). Less reliance can be attached to the results for very high and very low rates since in the former, due to comparitive scarcity of results, occasional points representing very high I, F values can greatly effect the general trend, and in the latter, effects such as those described in 8.6 can produce a disturbing influence.

The tendency for what has been called the "parabolic" effect to occur (6.6) may possibly be due to the operation of the mirror image effect on several occasions with an appropriate phase lag tending to give some points lying on an I/F line with a positive, rather than a negative, gradient (8.3.) Without more detailed observation of this it is difficult to derive any convincing conclusions about this phenomenon.

Results for snow also show good agreement with Chalmers results (fig.24) so that in general, support is given to the conclusions drawn by Chalmers (1956) from his results and further developed by Chalmers (1959). Briefly these are that in the nimbo-stratus cloud, precipitation starting as snow receives a negative charge with the corresponding positive charge being left behind, as a result of separation in the cloud. If the snow subsequently melts to give rain, a second process gives charge separation in the opposite direction and of greater magnitude giving the familiar positive I and negative F for rain.

9.3. Charging by Melting.

It is hardly surprising that sleet being a mixture of solid and liquid precipitation should give results intermediate between snow and rain (as seen in figs. 22 and 34) and particularly good correlation between I and F is found even for the "1959 sleet" (fig. 34) where the results were not very numerous.

There is considerable evidence supporting the belief that charging by melting is the dominant process by which rain receives its electric charge. It is reasonable to suppose that if charge separation occurs close to the ground a much closer correlation will exist between precipitation current and potential gradient than when the process takes place higher up. In the latter case, factors such as turbulant diffusion, convection currents and variations of horizontal wind speed with height may destroy much of the correlation between I and F.

Thus if charging takes place at the melting level then where melting occurs close to the ground as in the case of sleet or of the "wet snow" of fig. 23, much greater conformity to linearity would be expected and is indeed found, than for days when rain or snow was falling. The sudden change from sleet to snow on the 6th January 1958 see 6.6. is to be noted in this respect. The results of Adkins (1959) taken in, and just below, clouds of the nimbo-stratus type, also support the "charging by melting" theory.

Also, as mentioned in 6.7 the results of the Summer 1958 show greater deviationsfrom the Chalmers equation than the Winter 57-58 data and this can be attributed to the differense in the height of the freezing (or melting) level. This too may be the cause of the greater incidence of points in the "positive I", positive F" quadrant due to there being a much greater total positive space charge above the apparatus because of the greater height of this level (where the positive chafge is given to the rain). Further evidence could be obtained for this by obtaining data for the height of the freezing level and comparing with the results obtained.

It is felt that a very close agreement cannot be expected between results of either different workers or of different periods, due to the varying conditions prevailing. Unless all precipitation without exception was observed over a particular period the dangers of "sampling" and assuming the samples to be typical, may be considerable. The larger the number of results, of course, the better the sampling will be.

9.4. Concerning the Shielded Collector.

The expected differences in the current density recorded by the shielded collector and that measured by the exposed collector have been described in Chapter 4 and details of the actual observed differences were given in 6.9. It is now proposed to discuss how the practical results can be accounted for particularly in the light of the "Additional Experiments and Observations" of Chapter 7.

Firstly the ionic conduction current i_c included in I but not I_s (using the same notation as before) cannot account for the difference between the two since the value of $I - I_s$ shows no correlation with the magnitude of the potential gradient. Thus any effect of i_c is small compared to other factors influencing the two quantities. This is well illustrated in fig. 34 (sleet '59) where i_c would be negative all the time and could not possibly account for I being consistently greater than I_s.

With regard to the results of Smiddy (1958) and the author on the charging of drops by splashing as described in 7.3. it can be concluded that this mechanism does not operate except possibly for the very highest rates of rainfall recorded and can therefore be disregarded as a cause of the $I - I_s$ difference.

The most likely source of this difference lies in the shielding effect of the shield itself, resulting in smaller drops not contributing to I_s. The drop size determinations (7.2) though extremely inadequate in number do indicate that the very smallest drops (less than 0.05 mm diameter), can be missed in conditions of only slight wind and this can be discussed in terms of the results of Smith (1955) (see 4.4.) which give $I_s > I$ for positive F and $I_s < I$ for negative F.

This is in agreement with the results of 6.9 for positive F and all r, and for negative F and high rates of rainfall, but not for negative F and low r.

Alternately if it is supposed that negative charge always predominate on very small drops as suggested by the drizzle results of 1959 (6.11 c) then I_s will be greater than I for all F and all r. This is in agreement with the observations except for the very high rates with negative F. It is significant that in both Winter and Summer results the current increases, i.e. is more positive, as r increases and it is known that there is a greater preponderance of larger drops as the rate of rainfall increases, (Best 1950).

Thus no explanation has been put forward which completely covers all the observations and whilst some possibilities have been rejected, the problem is still not finally solved.

9.5. Suggestions for Further Research.

(a) Confirmation is required of the seasonal differences found in the Winter and Summer results, together with an attempted correlation with the height of the freezing level.

(b) In order to adapt the apparatus for continuous recording over longer periods than has been customary the problem of insulation breakdown due to spider's webs must be overcome. Since no way has been found of discouraging these creatures a web-breaking device could be constructed. For instance, the earthed guard-ring surrounding the collector could be slowly and continuously rotated by a suitable mechanism. It would be necessary to start recording automatically when the rain commenced or else much recording paper would be wasted, and if very large numbers of results were accummulated a more efficient method of analysing and computing the data would be highly desirable.

(c)- Close correlation with meteorological phenomena is required; for instance the examination of precipitation current with the passage of the warm front of a depression could be carried out, and wind speed measurements could be of use.

(d) A refinement and continuation of drop size determination may yield conclusive data regarding the I, I_s difference. Also it may be worth while to develop a highly efficient "water dropper" to act as a calibrating instrument to apply a known current to each collector in turn.

(e) The Rainfall Recorder (Chapter 3) is regarded as satisfactory in both design and operation but considerable improvement could be made in materials and more accurate construction.

(f) In Atmospheric Electricity the lack of control over conditions, the possibility of several unknown factors contributing simultaneously to the quantity being measured and the consequent difficulty in interpreting results, always exist, and it is possible that not a great deal of further information concerning the nimbo-stratus conditions will be obtained from more precipitation current measurements at ground level.

Measurements by aircraft both in the cloud itself and at various heights above and below it would be highly desirable and would probably make a greater contribution towards solving the problems of precipitation electricity.

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