The development of the apparatus to measure electric field in the presence of ionisation

Wildman, Peter J. L.

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by

Peter J. L. Wildman. B.Sc. (Dunelm).

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P J L Wildman

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P R E F A C E

The rationalised M.K.S. system of units is employed as widely as possible, but exceptions are made in the case of quantities such as current density, which is given in the literature in amps/cm^2. Some dimensions are given in either cms or inches and this is due to the fact that the working drawings from which the items in question were constructed had to be given in convenient values of these units.

The abbreviation pF denotes a capacitance of 10^{-12} Farads, and resistors measured in thousands and millions of ohms are labelled 'k' and 'Meg' respectively.

The term 'Potential Gradient' is employed when measurements of potential are considered rather than the variation of potential with distance when the term 'Field' is used. In both cases the polarity usually employed in (lower) Atmospheric Electricity is used, namely that a charge of a given polarity produces a potential gradient ('field') of that sign in its vicinity, distances measured towards the charge being positive.

The abbreviation A.F.C.R.L. signifies, Air Force Cambridge Research Laboratories, Bedford, Massachusetts.

At the present time (June 1962) the apparatus described in this thesis is scheduled to flight in September 1962, and it is hoped to give details of the performance of the 'mill' elsewhere.

ABSTRACT

An introductory survey of investigations in the Earth's Atmosphere and beyond, gives evidence from phenomena such as Aurora, Dynamo Theory, and Ionospheric irregularities, for the desirability of detecting and measuring electrostatic fields in these regions.

The electrical phenomena associated with isolated conductors in ionised regions are discussed, and the differences and similarities between electrical measurements in laboratory plasmas and extraterrestrial plasmas are pointed out. Estimates for the electric fields and currents interacting with an exposed conductor isolated from the main body of a rocket or satellite in the extra-terrestrial plasma are obtained.

Considering these estimates, a theory for a device to detect such fields and currents is obtained. This device is in effect, two field mills each having the layout first put forward by Malan and Schonland (1950), rotating about the same axis but working at two different frequencies. This allows two equations to be set up which may be solved for applied field or for applied current. The means for testing and calibrating such an instrument in the laboratory are discussed and the test chamber constructed for the preliminary model is described, and an idea of the results obtained is given.

The construction of a mill for flight in an Aerobee-Hi rocket, and of apparatus for its accurate calibration is described, and results given for the field, and current sensitivities of both 'halves' of the mill.

The field sensitivities (9.0×10^{-6} and 6×10^{-6}. volts/v/m. approx) are as much as 85% of the outputs predicted by theory, but the current sensitivities are best expressed by powers, less than unity, of the applied current, giving for total currents greater than 10^{-9} amps;

$$(V - a) \approx (10^{10} I)^{b}$$

where V is the mill output, I is the total applied current, a. is the mill output when $I \leqslant 10^{-10}$ amps, the lowest sensitivity of the current measuring element in the calibration circuit (a. is negligibly different from zero output) and b is the slope of V against I plotted on log. log. axes.

The interpretation of the 'field and current' total mill output signals is discussed, and suggestions made to explain departures from theoretical predictions.

CONTENTS.

Chapter I

Introduction

1.1. Historical survey.

The objects and phenomena in the sky have attracted the attention of man for at least as long as we have historical evidence. The Sun and Moon, Shooting stars and Aurorae, could all be observed with the naked eye, and on a more immediate plane, man was often affected by rain, thunder and lightning.

Because of their usefulness for navigation, the motions of the stars and planets received the most attention, but those who wondered about the nature of these moving lights above them became the first Astronomers and Geophysicists. It was not until the late 15th Century, that the development of the telescope by Galileo Galilei of Pisa, made it possible to examine them in more detail. For almost two hundred years this and the study of the Geomagnetic field with the compass needle, remained as almost the only observational physical sciences, but in the 17th Century the barometer and thermometer were developed, and investigations into the lowest portions of the atmosphere, hitherto limited to wind vanes, began and have continued ever since.

The studies and direct measurements of the past two decades, made at ever increasing distances from the earth are continuations of these 17th Century studies, though with the exception of the region between the Earth and the Sun, they have not yet reached those regions studied by the Astronomer and Astrophysicist. Let us examine briefly how these first studies of the lower atmosphere led to the present state of knowledge of the Earth's physical environment.

At first, limited to the range of heights afforded by mountains, and with only temperature and pressure measurements available, Pascal's correct assumption that pressure was a measure of the mass of air above the point of observation led to an erroneous image of the atmosphere. From these early measurements it seemed that density decreased exponentially with height so that it would become negligible at about 50 kms. It was not until the late 19th Century that direct temperature measurements to a height of about 10 kms using kites, by de Bort, revealed a rise in temperature commencing at about 10 kms, this point is now called the Tropopause.

Interest in the electrical nature of the lower atmosphere began in the 18th Century, prompted no doubt by the similarity between lightning discharges and the sparking observed with the newly invented sources of large quantities of electricity such as the Leyden jar and Wimshurst machine. This work continued, and a great deal of observational and quantitative data were obtained in the 18th and 19th Centuries (Franklin 1752, Lemonnier 1752. D'Albibard 1752).

1.2. The first interest in the Upper Atmosphere.

It was not until the late 19th Century that the work on the transmission of electromagnetic waves, culminating in Marconi's successful transmission across the Atlantic, created an interest in the electrical conditions at distances of tens and hundreds of kilometers above the earth. Some years previously in 1860 Kelvin had drawn attention to the similarity in electrical properties which should exist between the highest portions of the atmosphere and the then newly developed electrical discharge, vacuum tubes (Chalmers 1962). Balfour Stewart (1882) suggested that large electrical currents of the order of thousands of amps, were flowing in the regions above the earth and giving rise to the observed daily variations in the geomagnetic field, as the regions in which they were flowing moved under the tidal and heating effects of the sun's transit.

In view of these earlier suggestions and to explain Marconi's observations Heaviside (1902), and Kennelly (1902), working independantly, postulated the existence of an ionised region at some distance above the earth, which would reflect and refract electromagnetic waves. There was then a further halt in progress until the development of a means of searching for this ionised layer. This was introduced by Breit and Tuvé (1926) and consisted of sending short pulses of radio waves vertically upwards and observing the time taken for the reflected component to return to the transmitter/receiver aerial. By finding the frequency at which the waves penetrated this layer an estimate of electron content could be obtained.

This device known as an 'Ionosonde' is still used to-day over a world-wide network of stations to monitor the condition of the 'Ionosphere' as this ionised region was named. Until about 1946 it was the only means of investigating this region but it suffers from two grave limitations. Firstly, at the radio frequencies necessary to obtain reflection, the effects observed are due to the influence of the R.F. signal upon the electrons present. The positive ions are so massive relative to the electrons that they are almost unaffected by the R.F. waves. Thus no information regarding ions may be obtained using an Ionosonde. Secondly, and perhaps the greater limitation, is that any given electron density distribution may only be studied up to the point of maximum density. Even if appreciable quantities of electrons are present above this maximum they cannot be detected since the frequencies low enough to be reflected by them have already been reflected below or at, the maximum.

1.3. The rise of direct measurements.

With the advent of high altitude sounding rockets, and of artificial satellites it has been possible to transmit radio waves to and from vehicles in and beyond the ionosphere. (Seddon 1954). Even though this method has the disadvantage that the signals concerned must traverse the total electron content between the receiving station and the vehicle, starting in 1946 with captured German V-2 rockets, it has been possible to obtain estimates of electron content in regions above local and overall maxima.

The main advance so far from this work is that what were formerly regarded as discrete layers of ionisation (D, E, F_1 and F_2 layers), now appear to be places where the electron density gradient with height, increases abruptly. In fact the troughs between these former layers are very shallow and electron density does not fall off steadily until above the F_2 'region' (as the 'layers' are now named) maximum at around 300 to 500 kms. (Ratcliffe. 1959).

These same vehicles have also made it possible to measure directly temperature, pressure, Solar UV and X rays at heights above those attained by balloons, that is about 35 kms. This height provides a convenient dividing line between the 'Upper' and 'Lower' Atmosphere. It is also the region of maximum absolute, and relative, O_3 concentration and the only ionisation present is due to Cosmic Rays occasionally enhanced by meteor trails. The lowest 'permanent' ionisation being the D region starting at about 60 kms.

At the present time the region between 35 kms and 50 kms cannot be explored satisfactorily since the motors of most rockets do not 'burn out' until between 30 kms and 40 kms; electronic apparatus must not be switched on until after this time due to the vibration which would damage the heated filaments in vacuum tubes, which are still necessary in devices requiring high impedence. This process takes a few seconds to occur and in addition any mechanical protrusions beyond the smooth skin of the vehicle cannot be erected until an altitude of about 50 kms is reached, since at the velocities involved (approx. 10^4 cms/sec) they would be burnt up or distorted, at lower altitudes.

Until 1946 there was thus a gap in observational measurements between 35 kms and about 70 kms. The latter figure was determined by the low density of electrons at these heights (approx. 10^3 per C.C.) which required the use of an Ionosonde capable of working at low frequencies (300 kc/s) to obtain reflection, and at such frequencies there is also a great deal of loss through absorption and scattering. Some work has been done on the electrical conductivity between the lower atmosphere and the Ionosphere (Bourdeau et al. 1959). This region is still little explored, however, and the main incentives for further work come from Auroral studies and (lower) Atmospheric Electricity.

It has been found (Freier 1960, Sheppard 1937) that the electric field at the earth's surface is affected both by Auroral and Sunspot activity. These changes are small, however, and are difficult to observe except over long periods, due to the disturbing effects of local, low level, space charges, and the electric charges present in clouds. It would therefore be of great interest to make 'in situ' measurements of electric fields both just above the altitudes subject to meteorological disturbances, say at high flying aircraft altitudes, and also in the Auroral regions between 80 kms. and 120 kms. In this region electric fields could be the cause of the drifts observed of Auroral radar echoes and also may be one of the primary causes of the Aurorae themselves (Ratcliffe 1960a). This latter point is put forward by Alfven (Störmer 1955) who forecasts electric fields of the order of hundreds of volts per meter in the charged particle clouds emitted by the Sun which possibly cause the Aurorae. This is only one of several theories of the Aurorae however, but evidence of such strong electric fields at any altitude in Auroral latitudes would lend it strong support.

Imyanitov (1957) has pointed out that it would be difficult to detect any electrostatic phenomena from the Earth's surface that had their origin within or beyond the ionosphere due to its conducting, and therefore its electrostatic screening properties. Measurements made in such situations might help us to answer some of the outstanding problems from Atmospheric Electricity, the chief of which is the maintenance of the Earth's negative charge relative to the ionosphere. Is there a net charge on the Earth/Ionosphere system which maintains this potential despite the current flow to the earth of about 1,800 amps. (Gish 1951) by attracting charged particles from outside this system? In addition it is not known if any electric fields exist beyond the ionosphere, due to this screening action so that at the moment any measurements here would be of interest.

The movements of any such particles would also be subject to the influence of the geomagnetic field and would thus be connected both with the Aurorae and with the recently discovered Van Allen belts of trapped protons and electrons. These belts are believed to be supplied with their particles by the Sun, in whose outermost atmosphere the Earth is now considered to be situated (Chapman 1958).

1.4. Physics of the Ionosphere.

In addition to these phenomena, an intensive theoretical study has been made in the past thirty years of the physical properties of the Ionosphere itself. These are based on many years ionosonde measurements of electron density, and although electrical neutrality has been assumed, it is only very recently that any direct evidence of this has been obtained. (Bourdeau 1960).

Leaving aside the processes of photoionisation and recombination which maintain the local overall charged particle densities at any level in the Ionosphere, the most widely applied process affecting the whole ionosphere is that known as the 'Dynamo Theory.' This is concerned with the coupling of movements with electric currents, within and between the several regions of the Ionosphere. These are greatly complicated by the geomagnetic field and the theory was in fact first postulated by Balfour Stewart in 1882 to account for the daily variations in this field noted at the Earth's surface. It was later shown mathematically, by Schuster (1889. 1908) and by Chapman (1919) that the main steady geomagnetic field had it's origins inside the Earth, and that the 'quiet day' disturbances to it came from above the Earth's surface.

In the Dynamo Theory the initial disturbance to the system is provided by gravitational and convective tides in the Upper Atmosphere caused by the varying juxtapositions of the Sun and Moon. The neutral particles which predominate, are moved by these tides, sweeping along the ion electron plasma which maintains it's neutrality by the electrostatic attraction between the two components, as in Ambipolar diffusion. (Allis 1956). Although the neutrality is maintained, the movement of these charges constitutes a current and since the region in which it flows is within the geomagnetic field, mechanical forces act on the ion electron plasma to oppose the tidal motions. These forces act in different direction for positive and negative charges and the resulting charge separation sets up electrostatic fields. These fields, which are believed to be located in the E region (100 kms. to 160 kms.) cause charge movements (currents) in the F region

(160 kms. to 400 kms.) which again being placed in the geomagnetic field cause a 'motor' effect and are acted on by mechanical forces. (Ratcliffe 1960b).

So far these fields have not been measured directly, due both to their estimated low value of about 10^{-2} v/m (Matsushita 1959), and to the difficult conditions under which a measuring instrument would have to operate (see Chapter 2). Such measurements would be particularly useful in the region 80 kms. to 120 kms. since there the Dynamo theory fields would be at the same heights as the Aurorae and the estimated values are of the same magnitude as those supposed to cause Auroral drifts (Ratcliffe 1960c).

The above account has been much simplified and no mention has so far been made of the effect of a steady magnetic field upon the electrical properties of a plasma. This was first treated theoretically for an ideal plasma by Cowling (1932) (Chapman and Cowling 1952) and applied to the Ionosphere subsequently by a number of workers (Hirono and Kitamura 1957, Martyn and Baker, 1953, Martyn 1953).

The principle qualitative effect is that if a plasma is subjected to non-parallel electric and magnetic fields then electric current tends to flow both transverse to the magnetic field and along a perpendicular to both fields, as well as along the direction of the applied electric field. The transverse and normal (along applied electric field) currents flow without difficulty in the Ionosphere, being parallel to the earth's surface, but the other current, which is named the 'Hall' current due to it's similarity with the effect of that name observed in solids, flows with a vertical component so that it encounters changes in conductivity (ionisation), and thus charge builds up at these boundaries giving rise to electric fields to oppose further Hall currents. These 'polarisation fields' combine with the Dynamo, or with the Motor fields and give a total field vector.

Since it is possible to estimate the current systems in the ionosphere from magnetic measurements at the Earth's surface (Chapman and Bartels 1940), electric field and/or conductivity measurements in these regions would give self-consistent evidence of the accuracy of these estimates. For example Hines (1959) has estimated total electric field larger than other worker's estimates by a factor of 10^3. This would necessitate compensatory reductions in conductivity about which the estimates published do not vary by such factors (Chapman 1956).

In addition to the world-wide and relatively slowly changing properties of ionospheric regions, radio methods have given evidence of two classes of small scale irregularities.

The first is very small, with dimensions of tens of meters and are associated with irregularities of charge balance within Aurorae (Ratcliffe 1960c). The second class is rather larger and are from tens to hundreds of kilometers in extent. They are also an irregularity in the local charge balancing processes and due to their occurrence at altitudes of around 100 kms. (slightly above the Auroral irregularities) are known as the 'Sporadic E' region. (Jackson and Seddon 1958), (Thomas and Smith 1959).

The presence of such charge inequalities should be detectable with an electric field sensitive device, due to the modification caused to the overall ionospheric field.

The existence of fields within these irregularities would also be direct evidence that they were formed by charge inequalities and not by local variations of ion and electron densities of the same magnitude, as have been seen to cause the main changes in the Ionosphere with height.

As a final indication of the desirability of measuring electric fields in the upper atmosphere, there is the investigation of the interactions between the vehicle and its immediate surroundings to be considered. This is the subject of Chapter 2, since these interactions cause great complications in the measurement of electric field with any electro-mechanical device, and indeed, with any research instrumentation of an electromagnetic nature. Thus it is desirable to know as completely as possible, the electrical conditions at the vehicle's surface, and in it's immediate environment.

1.5. The experimental environment.

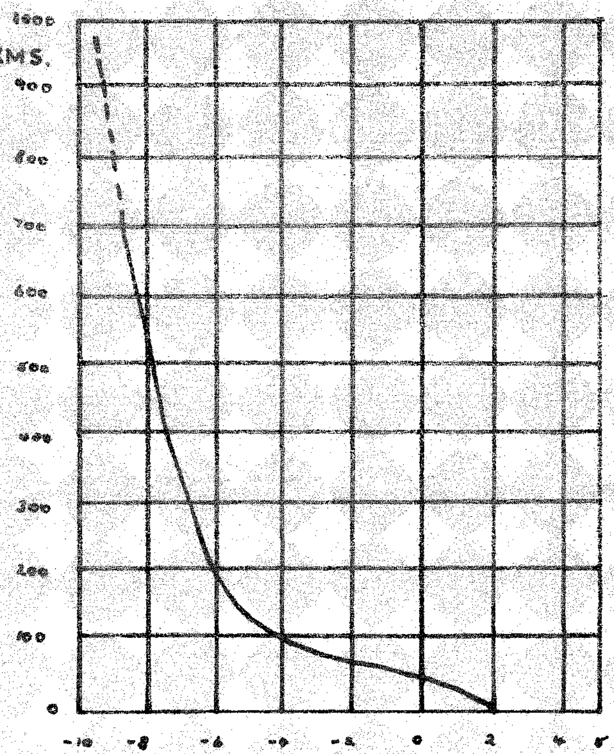
Having indicated the value of a knowledge of extraterrestrial and ionospheric electric fields it should now be pointed out that at the present time (Spring 1962) no successful attempts have been reported to measure ambient electric fields in these regions. Some success has been reported in measuring fields in the immediate neighbourhood of the vehicle (A.D. Little Inc. 1959) and the value of such results are described in Chapter 2. This lack of success has been due partly to the extremely difficult environment in which the field sensitive device is expected to operate and partly due to the interaction between the plasma in which it is situated, and the instrument and vehicle in, or on which it is mounted.

A number of relatively simple, efficient ways are available for measuring electric field in the laboratory or in the lowest portions of the atmosphere. (Chalmers 1957). As soon as the ionosphere is reached however any conductor, including the sensitive portions of a field measuring device, collects a current of charged particles from the surroundings. This current tends to mask any output due to electric field, which will be shown in Chapter 2 to be at least one and usually two, orders of magnitude smaller. In addition to this, at altitudes above 80 kms. solar UV radiation causes photoemission of electrons from all surfaces exposed to it. The photocurrents so caused are often of equal magnitude to the charged particle currents and are equivalent to an added flux of positive ions. It will therefore be imperative to provide some means of testing andcalibrating any instrument which may be devised to measure electric field under such conditions, which are dealt with quantitatively in Chapter 2.

Up to an altitude of about 100 kms. there is sufficient turbulence to maintain the various constituents of the lower atmosphere in their sea level proportions against the separating effects of diffusion. The one exception to this is the O_3 layer which is a maximum between 30 kms and 35 kms (Johnson et al. 1952). Above 100 kms however the solar UV has sufficient energy to cause dissociation as well as ionisation, and by about 130 kms. one third of all the oxygen ions present are O^+ and higher still when Nitrogen is also dissociated, the most common ion appears to be NO^+ (Ratcliffe 1960d).

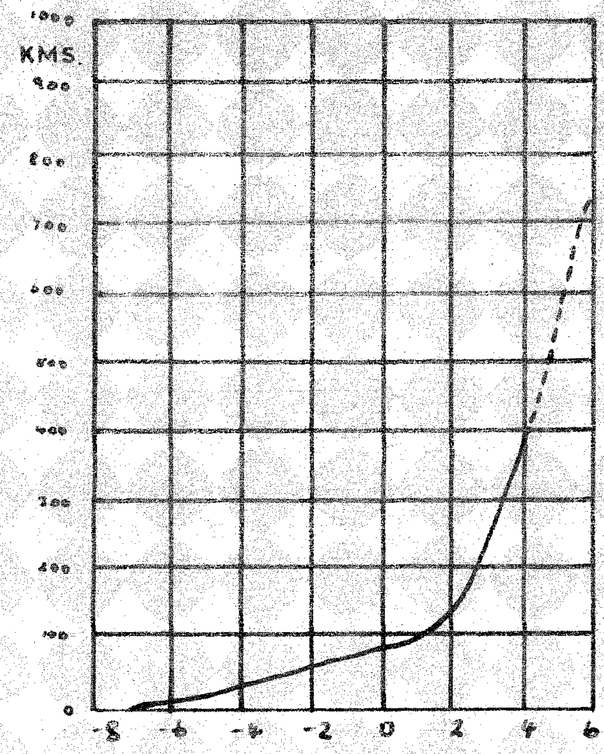
Figures 1.1, 1.2. and 1.3. show the variations to a height of 1000 kms. of pressure, mean free path and neutral particle temperature, and are taken from the U.S.A.F model atmosphere (Minsner, Champion and Pond 1959). The figures are based on experimental results up till about 1958 and with the exception of the temperatures since observed, of ions and electrons, no other inaccuracies have so far been exposed.

From the point of view of designing experiments the most important quantity of these three is mean free path. It will be seen that for a vehicle of moderate size, say a few meters maximum dimension, above about 110 kms. the mean



LOG_{10} PRESSURE

FIG. 1.1.



LOG_{10} M.F.P.

FIG. 1.2.

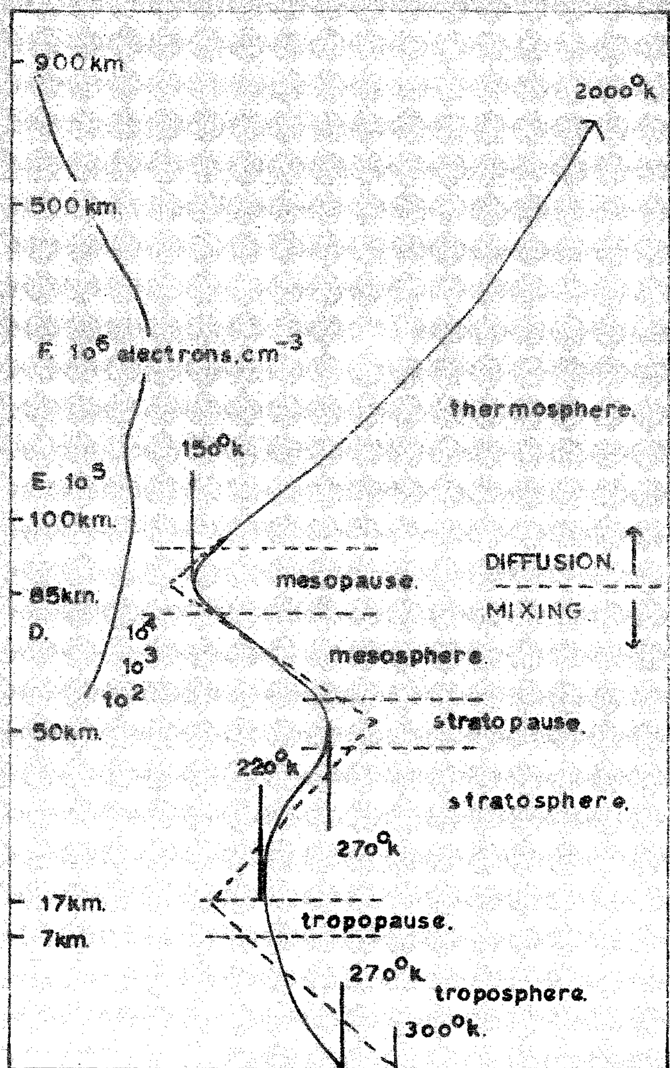

900 km
500 km.
2000°K
F. 10^6 electrons.cm^-3
thermosphere.
150°K
E. 10^5
100km.
DIFFUSION.
mesopause.
85km.
MIXING.
D.
10^4
10^3
mesosphere.
10^2
stratopause.
50km.
220°K
stratosphere.
270°K
17km.
tropopause.
7km.
270°K
troposphere.
300°K.

FIG. 1.4.

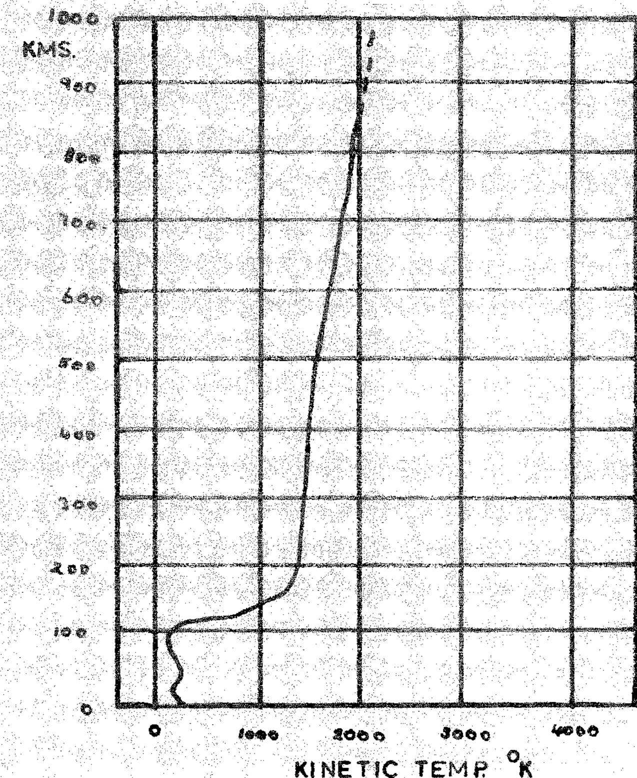

1000
KMS.
900
800
700
600
500
400
300
200
100
0
0
1000
2000
3000
4000
KINETIC TEMP. °K

FIG 1.3.

free path will be larger than the whole vehicle, and much larger than any single instrument or 'sensor', and thus all charged particles in the vicinity may be taken to interact only with the vehicle and instruments, and the influence they have upon one another and upon neutral particles may be ignored.

Such pressures and m.f.p. may be conveniently obtained in the laboratory but it will be shown in Chapter 4 that the reproduction of ion, neutral particle and electron temperatures and relative densities is much more difficult.

The neutral particle temperature at about 150 kms. is $1000^{\circ}K$, having risen continuously from the mesopause at 85 kms. (see fig. 1.4. for temperature distribution, electron densities and nomenclature of the first 200 kms). It continues to rise as far as all measurements made so far have extended, that is about 1000 kms. (Spencer et al. 1962). At such heights the atmosphere is very heavily ionised and there are a great number of H^+ ions (protons) observed, lending weight to Chapman's theory (Sec. 1.3.). Below this height in fact, a temperature has been reached at which a considerable number of the high energy end of the energy distribution of all particles present, have sufficient velocity to escape from the earth's gravitational field. The region of the earth's atmosphere above this level, believed to be at about 600 kms. is called the Exosphere. (Singer 1960).

All neutral particle temperatures quoted are assumed to be the same as positive ion temperatures. The difference in their masses is extremely small, and very little energy is imparted to them when they are formed by photionisation due to the much lighter electrons being available to absorb any excess energy, and this is so even when dissociation takes place at the same time.

The electron temperature reached in the quasi-equilibrium conditions of ionisation, dissociation, and recombination, appears to be about twice the ion temperature, at least up to an altitude of 500 kms. (Spencer et al. 1962). In this paper it is suggested that the U.S.A.F. 1959 model atmosphere (Minsner et al. 1959) is low in its estimated values of ion and neutral particle temperatures. The lack of thermal equilibrium that the differences in electron and ion temperatures indicates was ascribed both to the inhibited energy transfer between the two classes due to their large mass difference and also to the low value of collision frequency compared with the lower reaches of the ionosphere.

The problem as far as testing and calibration are concerned is therefore to reproduce the conditions shown in the Figures 1.1. to 1.4.. A relatively large volume, say not much less than a meter^3, of stable 'weak' plasma, must be produced. A 'weak' plasma (Delcroix 1960) is one where $\alpha < 10^{-4}$ when

$$\alpha = (N_i/(N_i + N_o), \qquad \ldots\ldots \qquad \text{eq'n 1.1.}$$

$N_i = N_e$, and N_i, N_e and N_o are ion, electron and neutral particles densities. The atmosphere is a weak plasma up to an altitude of about 200 kms. and gradually become stronger above this.

The creation and maintenance of such conditions to enable useful work to be carried out within them will be discussed in Chapter 4.

Chapter 2

The electrical state of conducting bodies in an ionised region.

2.1. Introduction

It will be shown in this chapter that the presence of charged particles of both signs complicates the procedure which must be used to obtain a true picture of the studied regions. This is true in the case of all devices using electrical and magnetic sensors, which interact with the ambient particles and fields to obtain their information. For the measurement of electric field an induced charge, due solely to the unknown field must be obtained. This necessitates the exposure to this field of the sensitive parts (sensors) of the measuring system, and in ionised and conducting regions this is merely part of a total charge accumulating on the sensors, due to the impacts of the charged particles present.

These charged particles are electrons, and the positive ions of the environmental constituents (Ratcliffe 1960f). In the higher regions, say above the F_2 (400 - 500 kms.) there are also particles from extraterrestrial sources, principally high energy solar protons which predominate above 600 kms. (Oglivie et al. 1962). In fact, where the atmosphere of one body ends and another begins is a point which has only recently been raised (Chapman 1958).

Until the higher parts of the ionosphere are reached the neutral particles greatly outnumber the charged ones forming the previously defined 'weak' plasma (Delcroix 1960), as long as charge neutrality is maintained over all the volume. The positive and negative constituents are not necessarily at the same temperature in such a plasma, and due to their much lighter mass than the ions or neutral particles, the electrons acquire the greater portion of the available energy in any collision, ionising or dissociative process which they undergo, reaching an equilibrium with each other at a higher temperature than the more massive particles. This temperature difference has its most important effect in accentuating the velocity difference between the electrons and all other particles and this has to be borne in mind when dealing with the introduction of conducting bodies into such a region.

Any rocket or satellite ('vehicle') in such a region is an isolated conductor and the plasma reacts so as to minimise and localise the disturbance caused by its introduction. For the moment a true plasma only ($N_i = N_e$ see eq'n 1.1.) will be considered, since if only charged particles of one polarity are present, as occurs with the solar proton flux, matters are simpler but of less general application.

These 'localising' reactions of the plasma have a grave effect upon the validity of electromagnetic measurements such as the mass spectrometry (Johnson and Meadows 1955) and rendered the earliest 'in situ' measurements by these instruments and by electric field sensitive devices of little value (see Chapter 3).

2.2. The relevance of laboratory work on plasmas.

Until the last decade the greatest interest in the plasma state came from workers concerned with the electrical properties of gases. They dealt with gases at pressures of a few microns to a few mm's Hg, and with ion and electron densities a thousand or more times greater that those found in the ionospheric and extra terrestrial regions (Sanborn Brown and Allis 1958).

Nevertheless a great deal of work has been done under controlled conditions, and by remembering the basic differences between these conditions and the Upper Atmosphere (Boyd 1954) it is possible to propose means of investigation for the Upper Atmosphere.

One of the most difficult things which enter into the theory of any proposed system is the fact that with rockets especially, the velocity is not constant and for a considerable portion of the rockets' ~~it's~~ useful life is of a value intermediate ~~to~~ between those of the positive ions and the electrons, in its surroundings. When dealing with satellites things are slightly simpler; it is unusual for satellites to range below about 150 kms., which means that the m.f.p. of the neutral particles will be greater than the dimensions of the satellite and since many orbits do not involve great changes in velocity, conditions remain fairly constant throughout the flight.

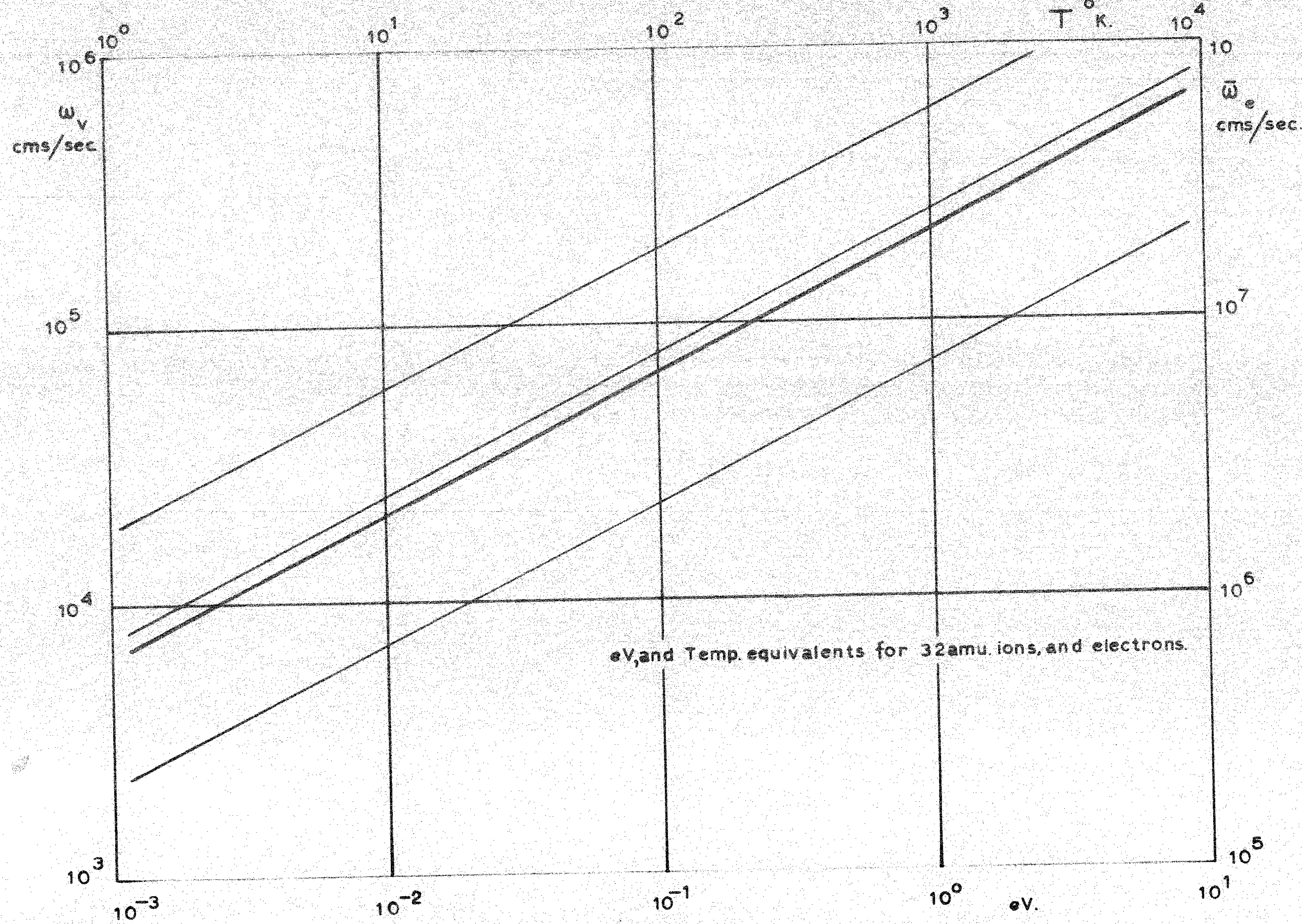

T °K.
ω v cms/sec.
ω̄ e cms/sec.
eV,and Temp. equivalents for 32amu. ions, and electrons.
eV.

FIG. 21.

A rocket on the other hand has a maximum velocity of say 10^5cm/sec., an order of magnitude less than that of a satellite and little more than the positive ion velocities corresponding to the ion temperatures noted experimentally (Spencer et al. 1962). Figure 2.1. plots energies in electron volts, and Temperatures in ^oK for both ions of 32 a.m.u. and for electrons for a wide range of velocities. The ion mass of 32 a.m.u. (O_2^+) was chosen since these are the heaviest ions found in noticeable quantities in the vicinity of the earth (Ratcliffe 1960f). For a given velocity of an ion, the values given in figure 2.1. will therefore be a maximum.

In the case of the electrons these are average velocities as defined by kinetic theory (Delcroix 1960b) and are relative to a set of axes in which the vehicle also moves, in this case with a velocity w_v. The ion temperatures, however, are merely obtained by placing

$$\tfrac{1}{2}m_i w_i^2 = kT_{ri} \qquad \ldots \quad 2.1.$$

where m_i is the ion mass, k is Boltzmann's constant and T_{ri} is the 'relative kinetic temperature' of an ion with velocity relative to the observer of w_i, in ^oK.

It may be seen that the values of ion temperature obtained experimentally (Spencer et al. 1962) correspond to velocities less than all satellite and most rocket velocities, and in fact the energy or temperature that these ions (and neutral particles) have for purposes of determining the environment close to the vehicle, are almost completely determined by the vehicle's velocity relative to the arbitrary frame of reference referred to above. If an absolutely accurate value is required, however, the relative velocity between the ions and the vehicle must be used in eq'n 2.1.

To summarize, taking all velocities relative to the arbitrary reference then if, w_i is ion velocity, w_v is vehicle velocity, $\bar{w}_e$ is average electron velocity, λ is the m.f.p. and L is a characteristic dimension of the vehicle or instrument under consideration.

Table I

Satellite	Rocket	
w_v approx. constant	w_v max.	w_v mid flight
$w_e \gg w_v \gg w_i$ $\lambda > L$	$w_e \gg w_v > w_i$ $L \gg \lambda$ *	$w_e \gg w_i \gg w_v$ $L < \lambda$ *

*These results occur since the maximum values of w_v are attained below about 60 kms ($\lambda = 2.10^{-2}$cms.).

Further complications arise due to the action of the geomagnetic field which causes potential differences to be set up upon the conducting surface of the satellite and the effect of this is given in section 2.7.

2.3. The Laboratory plasma probe.

The value of a small, conducting body ('probe') placed within a plasma was first extensively investigated by Langmuir and co-workers in the 1920's. (Langmuir and Mott Smith 1924, Langmuir and Compton 1930, 1931). These workers were primarily concerned with Hg discharges at pressures of a few mm. Hg. thus making the m.f.p. less than the probe size.

In a laboratory system, as opposed to the ionosphere it is simple to vary the probe potential relative to the plasma (discharge) and by observing the current taken by the probe connected through high impedance to the potential source, the energy distribution and density of the electrons may be obtained. It has since been shown (Boyd 1950) that both electron and positive ion collection are determined by the electron temperature once more due to their much higher velocity and collision frequency, but Langmuir's early work is still the starting point for extending these techniques to the ionosphere.

To obtain a simplified picture of what happens in the absence of a magnetic field it will be assumed that the ions and electrons are each in thermal equilibrium within their own species. This will allow a Maxwellian energy distribution to be assumed for each, whilst not ignoring the experimental results obtained in the ionosphere and mentioned earlier. This also means that for either species of charged particle the ratio of their densities in the region separated by an energy drop of V volts will be the Boltzmann function;

$$\frac{N'}{N} = \exp. \frac{eV}{kT} \qquad \ldots. \ 2.2.$$

if the region of N' is positive with respect to that of N; k is the Boltzmann constant, and $T^{o}K$ is the temperature corresponding to the Maxwellian distribution curve holding for the particles in question.

This will give a means of determining the concentration around a vehicle if Maxwellian equilibrium exists.

In the laboratory, and elsewhere, in the absence of interfering phenomena such as thermionic-emission and photoemission, a high-impedance or isolated probe will acquire a negative potential with respect to the mean potential of the plasma. This is due to the higher velocities of the electrons, since kinetic theory holds that the number of particles of Maxwellian temperature $T^{o}K$, striking a unit area in one second is;

$$N\overline{w}/4 \qquad \ldots. \ 2.3.$$

where N is the density of the particles and w is the average velocity given by:

$$m\overline{w}^{2}/2 = (3kT/2)^{\frac{1}{2}} \qquad \ldots. \ 2.4.$$

where m is the mass of the particle k is Boltzmann's constant and T is Maxwellian temperature in ^{o}K.

Since the electrons have a higher temperature and lower mass, the value of $\overline{w}_e$ is much higher than $\overline{w}_i$ and therefore a much greater electron flux than positive ion flux reaches the conducting probe.

As a consequence the probe takes up a negative potential which repels the lower energy end of the electron energy spectrum and attracts positive ions. A quasi equilibrium is reached when equal positive and negative fluxes reach the probe. If the equilibrium potential is Vp then only those electrons with energies greater than eVp on the Maxwellian distribution can reach the probe. This process is aided by the increasing ability of the probe to attract positive ions over a wider radius and higher energies, with increasing negative potential. (Boyd, Allen and Reynolds 1957).

The plasma region is conducting however, and the negative charge sets up an electrostatic field which causes the plasma to try to localise this field. This is done by the formation of a region near the probe where $N_i \gg N_e$ and which acts as an electrostatic screen, preventing most but not all of this field from extending into the plasma. The net flux of ions reaching the outer edge of this sheath and leaving it to the probe is zero and it is also penetrated by the high energy electrons with energies greater than eVp.

Because of their relatively slow speeds however the positive ions cannot replace those ions in the vicinity of the probe which are taken up both by the formation of the sheath and by the steady ion current Ip^+ flowing to the probe. The equilibrium, which is maintained by the electrons, again due to their higher velocity and collision frequency, is lost for the positive ions and for the case of a stationary probe at least ($w_v < w_i$) Maxwellian energy distribution cannot be assumed (Schulz and Brown 1955). There is, in fact, a shortage of positive ions in the region of the region surrounding the probe and sheath and this permits the electric field of the negatively charged probe to penetrate into the plasma.

2.4. The limitations imposed by the Ionosphere

The phenomena described above may also be obtained in the laboratory with all polarities reversed; that is an electron sheath will form about a conductor which is maintained at a positive potential with respect to the plasma. With no external source to return the 'drained off' electrons to the plasma, such a positive potential can only be applied for short times to a vehicle in the Ionosphere or Upper Atmosphere (Beard and Johnson 1962). However, although overall changes of potential are not possible in a research vehicle, small areas may have a varying voltage with respect to the rest of the vehicle, applied to them, thus reproducing the laboratory, Langmuir probe situation. Fig. 2.2. reproduces this plot, the straight line section representing the space charge limited current of eq'n 2.25 below. When the current is zero, equal positive and negative currents are reaching the probe, at the lower end where the curve sets in electrons are beginning to be repelled so that the probe is then at plasma potential, and at the top of the curve all available electrons are being collected and saturation takes place if there are no ions of sufficient energy to overcome eVps if Vps is saturation voltage.

Once the quasi equilibrium condition of a 'floating' probe has been attained, the sheath region, although still traversed by the high energy electrons, becomes a region of positive ion space charge controlled current, and Child's law may be applied. (Langmuir 1923). It will be seen later that this equation requires two boundaries at different potentials if any calculations of currents less than saturation currents are to be dealt with. In the case of a probe (vehicle) immersed in a positive ion sheath the usual concept of the anode and cathode are reversed, since it is the negative electrode which receives the space charge limited current in this case (Guthrie and Wakerling 1949.a). It is the position of the positive boundary in the present arrangement that is in doubt and which causes the uncertainty as to the disturbance caused to the plasma at large.

Since the positive ion sheath does not fully screen the negative potential of the probe, ions will be accelerated towards it, instead of diffusing to the outer surface of the sheath. Since the space between any ion and the probe is occupied by similarly charged ions, there will be electrostatic repulsion between these ions which is expressed as a screening of the field due to the probe. This is expressed in terms of a screening length, such that over distance D_L known as the

Debye length, the potential due to the charge on the probe falls to 1/e of its initial value, that is;

$$V_x = V_o \exp. - x/D_L \qquad .... 2.5.$$

where x is the distance from the point at which potential is V_o.

$$D_L \text{ is given as } (kT/4\pi ne^2)^{\frac{1}{2}} \qquad .... 2.6.$$

where T and n are the temperature, density of the charged particles, and e is the electronic charge. (Delcroix 1960c).

It has been shown (Jastrow and Pearse 1957a) that the conditions for assuming this simple shielding scheme do not hold in the ionosphere and Upper Atmosphere, even if more recent values of the necessary parameters are used (Vp, deduced from probes see Chapter 4, and T_e). Thus a more qualitative approach was used by Jastrow and Pearse in the same paper, in which the total positive and negative charges within a certain radius of the centre of the probe was estimated for a spherical configuration. This was possible knowing the Debye length for the undisturbed positive ions, and by solving Poisson's equation for spherical coordinates. The increase in effective positive ion cross section mentioned before, is seen here. This method gives a possible value for a distance between the two electrodes as is required later in section 2.7.

2.5. Estimated values of probe and vehicle conditions.

If the assumption of $\bar{w}_e \gg w_{ri}$ is retained, then the ion current I_p^+ flowing to a collector of a cm^2 moving at a velocity of w_v cm/sec, through a plasma of density $n_i(=n_e)$, will be;

$$I_p^+ = n_i \, a \, w_v \text{ amps} \qquad \ldots. \ 2.7.$$

Since the ions do not have time to rearrange themselves to meet the oncoming collector they appear to this collector to be an almost unidirectional monoenergetic stream of charges, impacting upon the collecting area. They have a temperature due to the velocity of the vehicle (Section 2.2.) corresponding to;

$$T_{ri} = m_i w_v^2/2k \qquad \ldots. \ 2.8.$$

where k is Boltzmann's constant

m_i is the mass of the ions

w_v is vehicle velocity

The suffix r_i denotes that this is a temperature different from the ambient Maxwellian temperature $T_i (< T_{ri})$ of the undisturbed plasma ions. In this case the velocity obtained $\overline{w}_i$ would be due to

$$T_i = (m_i \overline{w}_i^2/3k)^{\frac{1}{2}} \qquad \ldots. \ 2.9.$$

as is always the case when dealing with electrons (eq'n 2.4.).

It may be seen now how much more difficult it is to analyse the situation of a rocket experiment, performed at varying velocity in varying surroundings. T_{ri} and T_i must be used at different times (Table I), for when $w_v < w_i$, T_i is applicable and kinetic theory applies both to the electrons and ions.

Substitute in eq'n 2.~~10~~8, and continuing to consider 32 a.m.u. ions, to obtain T_{ri} and the electron volt equivalent, the following quantities must be defined (U.S. Inst. Phys. 1957).

If mass of 32 a.m.u. ions $\approx$ 32 m_p where m_p is proton mass, ignoring mass defect and masses of electrons.

Now $m_p = 1.68 \times 10^{-24}$ gms.

$k = 1.38 \times 10^{-16}$ ergs/°K.

$1 \text{ eV} = 1.6 \times 10^{-12}$ ergs

Thus $$T_{ri} = \frac{32 \times 1.68 \times 10^{-24}}{2 \times 1.38 \times 10^{-16}} w_v^2 = (1.95 \times 10^{-7} w_v^2)\,°K \quad .... \; 2.10.$$

and $$eV_{ri} = \frac{32 \times 1.68 \times 10^{-24}}{2 \times 1.6 \times 10^{-12}} w_v^2 = (1.68 \times 10^{-11} w_v^2)\,\text{eV}. \quad .... \; 2.11.$$

In the case of the eletrons, and also the positive ions when $w_v << \bar{w}_i$, remembering that these quantities are average values from kinetic theory so that there will be a spread of higher and lower values corresponding to the Maxwellian energy distribution, then, substitute in eq'n 2.4. and rearrange knowing that,

$m_e = 9.1 \times 10^{-28}$ gms.(U.S. Inst. Phys.1957) then;

$$T_e = \frac{9.1 \times 10^{-28}}{3 \times 1.38 \times 10^{-16}} \bar{w}_e^2 = (2.2 \times 10^{-12} \bar{w}_e^2)\;°K. \quad .... \; 2.12.$$

and $eV_e = \dfrac{9.1 \times 10^{-28}}{2 \times 1.6 \times 10^{-12}} \bar{w}_e^2 = (2.84 \times 10^{-12} \bar{w}_e^2).$ eV.

.... 2.13.

It may be seen that by substituting m_i and $\bar{w}_i$ in 2.12, and 2.13. that;

$T_i = 2T_{ri}/3.$ .... 2.14.

and $eV_{ri} = eV_i$ .... 2.15.

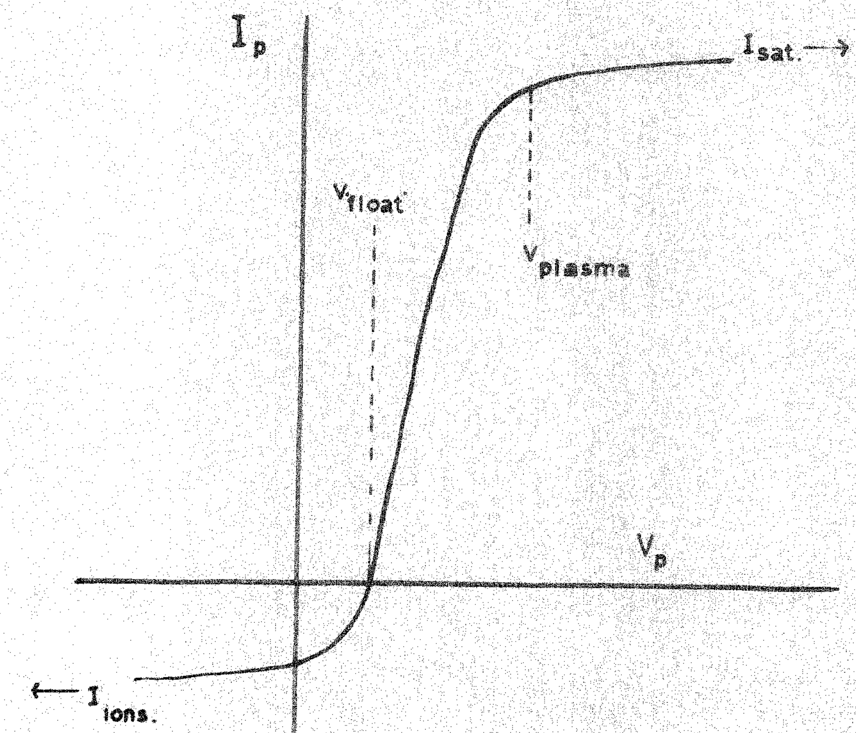
The expressions 2.10. to 2.13. are plotted in figure 2.1. for values of $\bar{w}_e$ and w_v likely to be of interest in Ionospheric and Upper Atmospheric investigations.

Upon investigation the values shown in figure 2.1. it may be seen that within the first 800 kms. or so of the earth where $T_i \leqslant 1000^oK$ and $T_e \leqslant 2000^oK$ (Spencer et al. 1962), then vehicle velocities are within one order of magnitude of ion velocities, electron velocities, or both. The first condition does not arise often however but there will be intermediate stages where the positive ion flux will be very difficult to estimate since $w_v \approx \bar{w}_i$.

On the other hand if a satellite orbits close to the earth (radius 7×10^8 cms.) in 100 minutes, then if the orbit is approximately circular its velocity will be

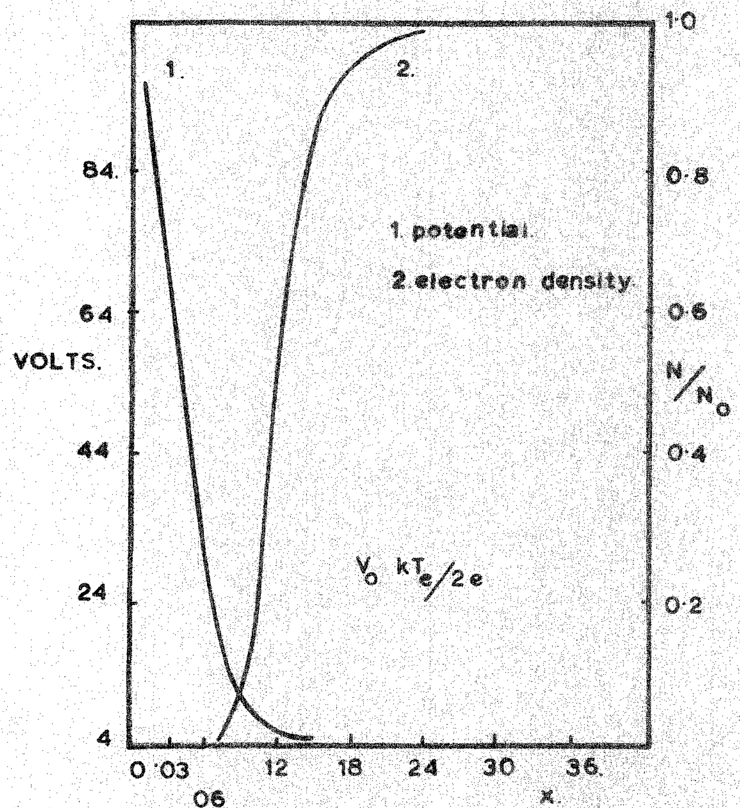
$w_v = 2\pi r/t = 7.4 \times 10^6$ cms/sec. .... 2.16.

From figure 2.2. and eq'n 2.14. this may be seen to be much greater than the average velocity of 1000^oK ions ($\bar{w}_i = 8 \times 10^4$ cms/sec) and less than the average velocity of 2000^oK electrons ($\bar{w}_e = 3 \times 10^7$ cms/sec).



I_p
$I_{sat.}$
V_{float}
V_{plasma}
V_p
$I_{ions.}$

FIG.2.2.



1.
2.
84.
64
44
24
4
VOLTS.
1.0
0.8
0.6
0.4
0.2
N/N$_o$
1. potential.
2. electron density.
V_o $kT_e/2e$
0 ·03
06
12
18
24
30
36.
x.

FIG 2.3.

On the other hand if a rocket attains its maximum velocity at about 50 kms. and reaches a maximum altitude of 200 kms, then its maximum velocity will be $w_{v\ max.} \approx 5 \times 10^5$ cms/sec, and thus although this will always be much less than the electron average velocity, it is of the same order as the positive ion velocity though less than it in the upper portion of its flight.

2.6. The stability of the vehicle sheath and potential.

When the probe is stationary, that is there is no net ion or electron drift relative to it, then Bohm (Guthrie and Wakerling 1949b) by considering the region over which the Debye length permitted electrostatic attraction of ions (eq'n 2.5.) which he called the 'transition region', was able to show that a stable sheath could not be set up unless the positive ions reached the sheath edge with at least one half the energy of the electrons. It is the 'transition region', in which ions are accelerated to these energies, and figure 2.3. taken from Bohm's work shows again how difficult it is to define a 'sheath edge', though the greater the value of (eV_i/kT_e) the more sudden the rise in n_i and the falling off of n_e becomes. The curves in figure 2.3. are plots of the 'plasma sheath' equation first obtained by Langmuir and Blodgett (1923). This is a means of determining the distribution of potential with position in a space charge limited current of either polarity where the particles enter the system with kinetic and potential energy. For a given value of V_o the plasma potential, T_i, T_e and T_e where these terms have their previous meanings then for a plane electrode the curves of fig. 2.3. are obtained, and has the form. (Guthrie and Wakerling 1949b).

$$\frac{1}{2}\left(\frac{dV}{dx}\right)^2 = 4\pi n_o e\left[2\sqrt{V_o V} + \frac{kT_e}{e} \exp \frac{-e(V-V_o)}{kT_e}\right] + C. \qquad \text{.... 2.17.}$$

where V is the potential at a point x from the collector.

Now it has been stated (Sec. 2.3.) that the Maxwellian energy distribution is 'cut off' at V_p the probe potential and thus the number of electrons with energies in excess of this, which strike the probe will be (Jeans 1940a)

$$2\pi n_e (hm_e/\pi)^{3/2} \int_{w'_e}^{\infty} \exp(-hm_e w'^2_e)\; w'^3_e .\; dw'_e \qquad \text{.... 2.18.}$$

where $h = (2RT_e)^{-1}$ and R is Universal gas constant, T_e is electron temperature such that average velocity is $\overline{w}_e$, w'_e is cut off electron velocity such that

$$eV_p = mw'^2_e/2. \qquad \text{.... 2.19.}$$

The only unknown term in this expression is w'_e, and by equating 2.18 to the positive ion flux it may be found ($w_v \gg \overline{w}_i$).

This problem was first evaluated by Jastrow and Pearse (1957), and resulted in estimates of vehicle (probe) potential for values of T_e then believed to apply in the

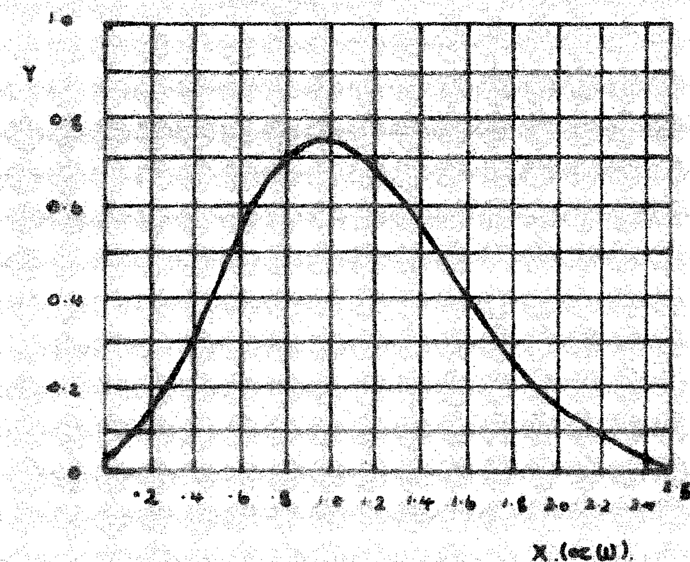


FIG. 2.4.

Upper Atmosphere, with values of V_p of the order of tens of volts negative.

An approximate solution may be obtained graphically however, by plotting Maxwell's distribution function in the form

$$y = x^2 \exp -x^2 \qquad \text{.... 2.20}$$

where x is the velocity term. (Jeans 1940b).

This function is plotted in figure 2.4. and the maximum value (w_{max}) of y is at the most probable velocity which is $(2/3)^{\frac{1}{2}}\ \overline{w}$ as used in previous calculations.

With this curve it is possible to determine the relative numbers of like particles of a given velocity (energy) provided that they are in thermal equilibrium with one another.

If the ion and electron currents are equal, taking 'typical' values;

$\overline{w}_e \approx 8 \times 10^7$ cms. ($T_e \approx 2 \times 10^3\ {}^oK$)

$w_v \approx 10^5 (T_{ri} \approx 3 \times 10^3\ {}^oK)$

$n_i = n_e = 10^5/cm^2$.

e(electronic charge) $= 1.6 \times 10^{-19}$ coulombs.

In the absence of an electron repelling potential the electron current density j_e on a plane conducting surface will be

$$j_e = e\, n_e \overline{w}_e/4 = 1.6 \times 10^{-19} \times 10^5 \times 8 \times 10^7$$

$$= 3.2 \times 10^{-7}\ \text{amps/cm}^2. \qquad \text{.... 2.21}$$

and the positive ion current density j_i will be

$$j_i = e\, n_i w_v = 1.6 \times 10^{-19} \times 10^5 \times 10^5$$
$$= 1.6 \times 10^{-9} \text{ amps/cm}^2. \qquad \ldots .\ 2.22$$

Thus the potential of the probe V_p has to be sufficiently negative so that only $(1.6 \times 10^{-9})/(3.2 \times 10^{-7})$ = 0.002 of the electrons have sufficient energy to overcome the repulsion, reach the probe and equalise the ion current.

From figure 2.4. this is the case when only those electrons with a velocity greater than $2.4 w_{max}$:
Since $\overline{w}_e = (3/2)^{\frac{1}{2}} w_{max.} = 1.22\, w_{max.}$ then the cut off velocity will be;

$$\frac{2.4\ \overline{w}_e}{1.22} = \frac{2.4 \times 8 \times 10^7}{1.22} = 1.56 \times 10^8 \text{ cms/sec.} \qquad \ldots .\ 2.23$$

From figure 2.2. this corresponds to an electron energy, and hence a probe or vehicle potential of $V_p = -6$ volts.

Such potentials have been inferred from the data from rocket and satellite flights (Chopra 1961, Johnson and Meadows 1955) and at first sight it would seem that when these potentials have been reached the net current to any collector should be zero. However if a passive collecting area is isolated from the remainder of the vehicle surface through a high impedance measuring device, then a positive current is obtained. Figure 2.5. shows the variation of this current with altitude for a collector of 18 cm^2 mounted flush with the skin of a USAF Aerobee hi-rocket, for a

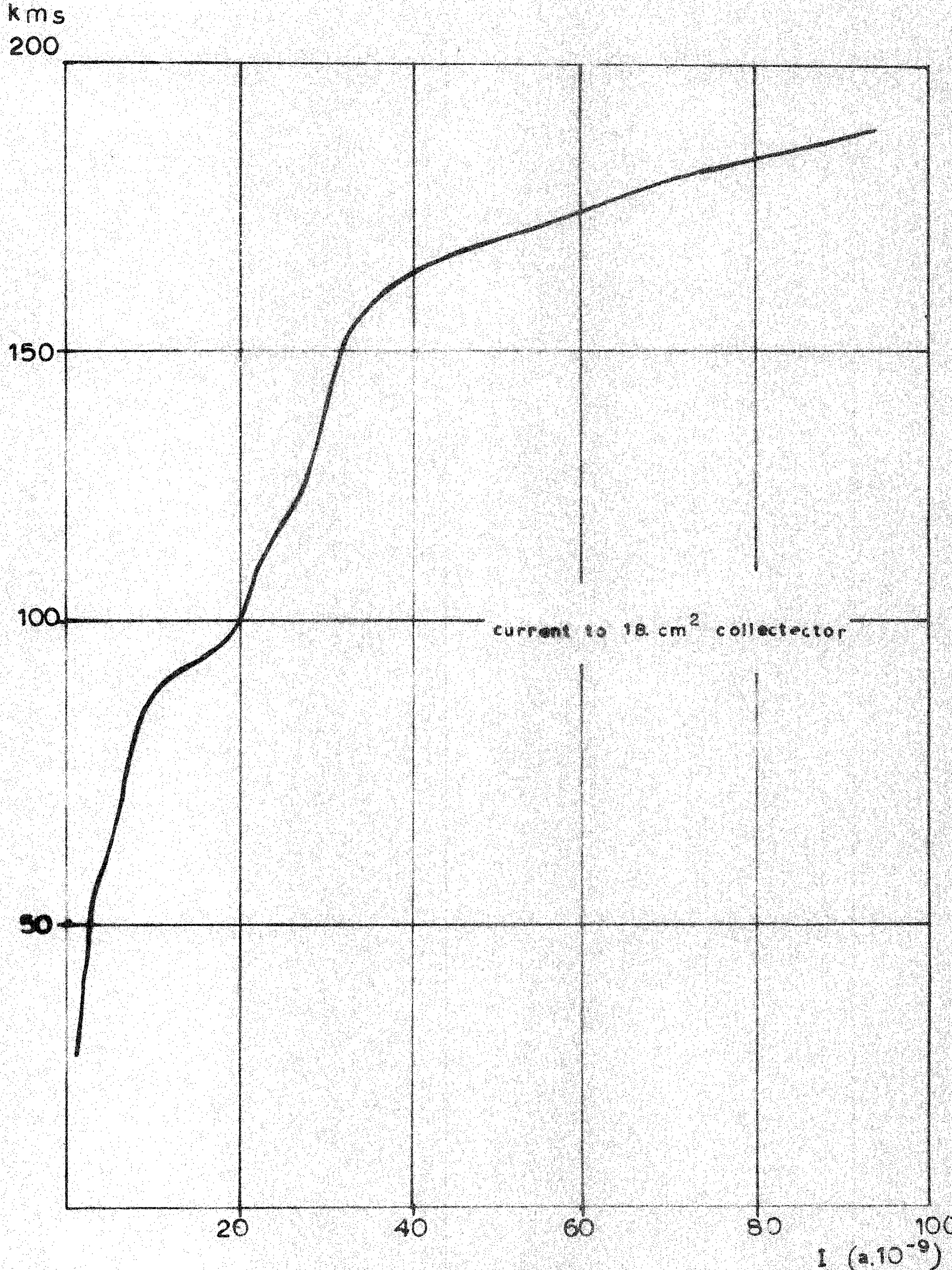

kms
200
150
100
50
current to 18 cm^2 collector
20
40
60
80
100
I (a.10^{-9})

FIG.2.5.

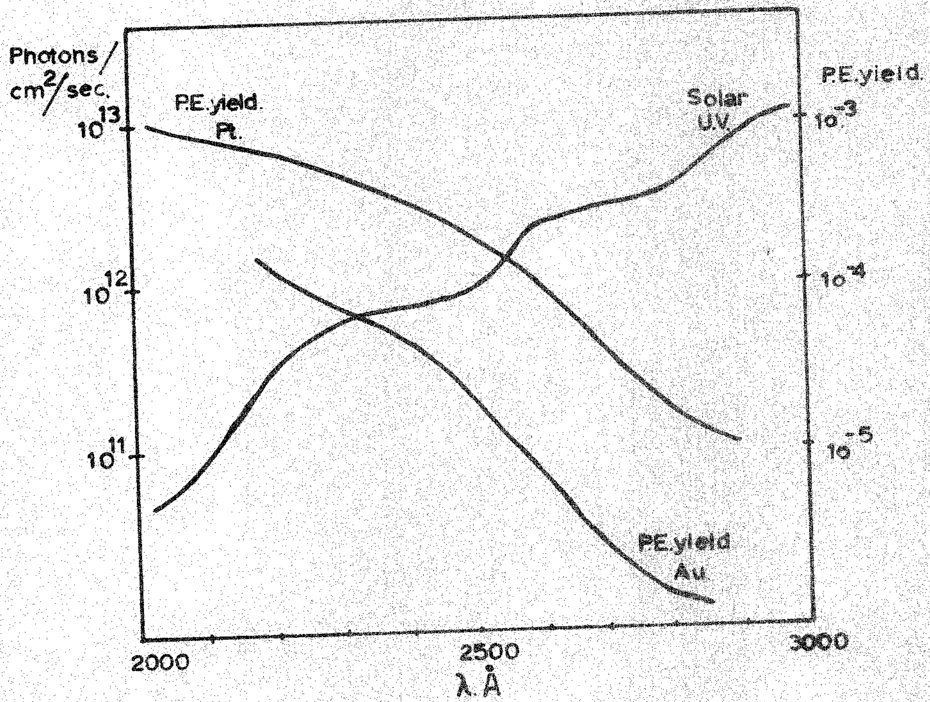


FIG. 2.6.

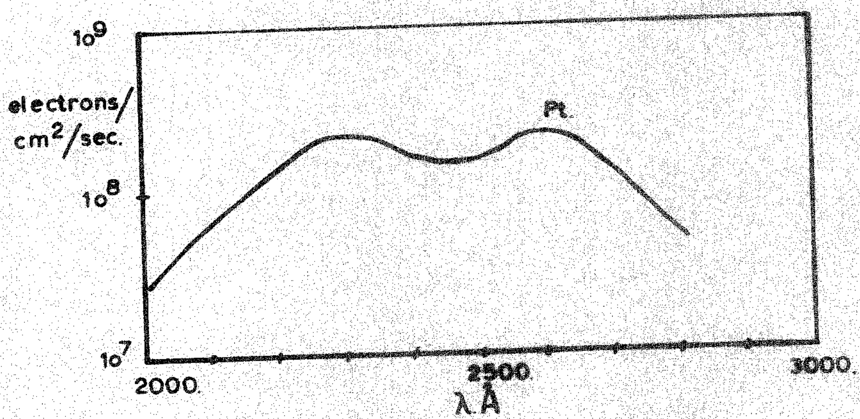


Photo current, derived from above

FIG. 2.7.

daylight flight (M. Smiddy AFCRL 1960). The measuring devices used for such instruments are logarithmic, current amplifiers which are sensitive to currents of one polarity only, and overload immediately a current of the opposite polarity is applied (Praglin and Nichols 1960). Thus the current shown in figure 2.5. is a net current and not merely the positive component of a zero net current.

What can be the source of this current and its variation with altitude? So far no mention has been made of the photoemission which takes place at all parts of the vehicle skin, and instrumentation when exposed to solar UV rays. Smiddy (personal communication) has stated that the telemetry records used to obtain figure 2.5. and similar records, show sharp drops in the current collected which last a very short time and may be identified from their frequency as occuring when the vehicle or instrumentation come between the collector and the sun. Figure 2.6. and table II give the solar UV spectrum at about 100 kms. and figure 2.7. shows the expected photoelectric yields for surfaces of Pt (Ichimaya et al. 1960).

In the first few hundred kilometers of the atmosphere where appreciable absorption of solar UV takes place and where ion and electron densities are known, the photocurrents indicated, whilst measurable do not interfere with the vehicle potential as determined by equations 2.21 and 2.22.

Where little absorption takes place and where ion and electron densities are falling (Hanson and McKibbin 1961) it may be that the photocurrents have a large determining effect upon the vehicle potential, as long as it is in sunlight (Hinteregger and Damon 1959).

2.7. Interpretation of Electric fields measured

It is now of value to consider what quantities may be deduced with the aid of a device which is able to measure electric field when placed in the Ionosphere, Upper Atmosphere or beyond. It must be remembered that whether the device is mounted flush with the vehicle skin or is separated from the vehicle by a long cable as has been done in some mass spectrometry work, there will always be a flux of charged particles of one or both polarities so long as these are present in the undisturbed region and the device will have to eliminate the disturbing effect of these fluxes on its output due to field.

If this region is a plasma then the conditions described in this chapter hold, if charged particles of one sign only occur together with neutral particles then the photocurrents will have to equalise an electron flux or if a positive ion flux occurs there will have to be some mechanism for limiting the charge and potential build up on the vehicle.

Two possibilities to overcome this last problem exist. Firstly as the potential of the vehicle builds up the electric field existing between itself and its surroundings will vary from point to point on the vehicle due to its shape, and corona discharge currents will occur when they reach a sufficiently high value. (Clark 1957) (Smythe 1939). If the surroundings are sufficiently conducting then the charge will be enabled to leak back to the surroundings without discharge needing to occur. Leakage will also occur by a different process when the vehicle is moving through a plasma with a velocity w_v such that

$$\bar{w}_e > w_v > w_i \qquad \text{.... 2.24}$$

This means that the slow moving ions will not fill in the vacuum left by the passage of the vehicle, as quickly as will be electrons and thus a cone of negative space charge will build up behind the vehicle, into which positive charge will leak from the vehicle or which will neutralise the charge building up on the vehicle. (Gringauz and Zelikman 1957). (Bourdeau, Serbu et al 1961).

In the next chapter the theory of a device to eliminate the interfering effects of the charged particle fluxes will be given, but for the moment it will be assumed that the true electric field may be measured, together with the value of net current density to any vehicle in a plasma.

Now using Childs law, when;

a	is the area of the collector in meter^2
ε_o	is the permittivity of free space
S	is the distance between the electrodes in meters
V	is the potential difference between them
m_i	is the mass of the ions in kgms
e	is the electronic charge in Coulombs
I_i	is the current to area a in amps.

$$I_i = \frac{4\sqrt{2}}{9} \varepsilon_o \left(\frac{e}{m_i}\right)^{\frac{1}{2}} \frac{aV^{3/2}}{S^2} \qquad \ldots . \; 2.25$$

Noting that in the present case S is open to several interpretations (section 2.4.) and also that the terms anode and cathode should be replaced by collector and emitter then if S' is the distance from the undecided 'sheaf edge' and ϕ is the potential at S'.

$$\phi = \left(\frac{3}{2}\right)^{4/3} \left[\frac{1}{\varepsilon_o} \left(\frac{m_i}{2e}\right)^{\frac{1}{2}} \frac{I_p}{a}\right]^{2/3} S^{4/3} \qquad \ldots . \; 2.26$$

Thus $$\frac{\phi}{V_p} = \left(\frac{S'}{S}\right)^{4/3} \qquad \ldots . \; 2.27$$

since when $S' = S$, $\phi = V_p$ the potential difference between the probe (vehicle) and the plasma

$$E = \frac{d\phi}{dS} = \frac{4}{3} \frac{V}{S'} \left(\frac{S'}{S}\right)^{1/3} \qquad \ldots . \; 2.28$$

and $$\frac{E_{S'}}{E_p} = \left(\frac{S'}{S}\right)^{1/3} \qquad \ldots . \; 2.29$$

where $E_{S'}$ is electric field at S' and E_p is electric field at the probe (vehicle) surface (Booker 1959).

Thus from eq'n 2.28

$$E_p = \frac{4}{3} \frac{V_p}{S} \qquad \text{.... 2.30}$$

Shvartz (1960) has shown that together with a knowledge of I_p, the above theory may be used to obtain V_p without a knowledge of S being necessary.

From eq'n 2.30 letting a = 2, b = 1.5.

$$E_p = \frac{V}{S} \frac{a}{b} \qquad \text{.... 2.31}$$

and eq'n 2.25 becomes

$$I_p = K. \frac{V_p^b}{S^a} \qquad \text{.... 2.32}$$

where K is a numerical constant.

S may be eliminated from 2.31, and 2.32 to give

$$V_p = K^{1/(a-b)} \left(\frac{b}{a}\right)^{a/(a-b)} E_p^{a/(a-b)} \quad I_p^{1/(b-a)} \qquad \text{.... 2.33}$$

substituting; $V_p = K^2 \left(\frac{3}{4}\right)^4 E_p^4 \ I_p^4$ 2.34

To determine any ambient electric field from this, one major assumption will be necessary. Since the disturbed region around the vehicle has a higher conductivity than the undisturbed region, for a vehicle with an equipotential surface it will be assumed that whatever ion and electron distribution is caused by the vehicle it will be radially symmetrical. This would mean that equations 2.25 to 2.34 could be applied to varying values of V_p, E_p and I_p, treating S as a constant. This would also depend upon the successive values being taken within a short period so that no variation in external conditions need be considered (Imyanitov 1957).

However as has been indicated, the surface of the vehicle when in the vicinity of the earth, will not be an equipotential due to the influence of the geomagnetic field upon any conducting body moving through it. Since the vehicle is isolated eddy currents are set up in the conducting outer skin, which result in a potential difference being set up between the two opposite sides of the vehicle on a line perpendicular to its motion and the geomagnetic field (Zonov 1961).

If H is the magnetic field strength in Gauss, and w_v the vehicle velocity relative to this field, then V_H, the potential difference due to this will be (Beard and Johnson 1960).

$$V_H = 10^{-6} \ H.w_v \ \text{volts/cm cross section} \qquad \ldots. \ 2.35$$

and since the maintenance of a steady positive voltage upsets the equilibrium in the surrounding region (Beard and Johnson 1961) one side of vehicle may be considered to be more negative with respect to the external plasma than the other, whose potential will be determined by the previously developed methods.

Further the total potential difference will be $L.V_H$, where L is the relevant dimension of the vehicle in cms. and Beard and Johnson show in their first paper (1960) that this dimension should be taken as the total effective cross section for positive ion collection as developed by Jastrow and Pearse (1957), being

$$L = \left(\frac{2_e V_p}{kT_e}\right)^{\frac{1}{2}} L_D. \qquad \ldots . \quad 2.36$$

where V_p is vehicle potential

L_D is Debye length

T_e is electron temperature

k is Boltzmann's constant

This can be of the order of tens of cms thus giving magnetically induced potential differences between the sides of the disturbed region of the order of tenths of a volt ($H \approx 3 \times 10^{-1}$ Gauss.Zonov 1961)

If this value is known and radial symmetry retained then if r_v is the radius of the vehicle skin, the two values of V_p obtained from equations 2.37a,b. will be

$$V_{p1} = \left[V'_p + (r + L)\ (E_a + \tfrac{1}{2}V_H) \right] \qquad \ldots . \quad 2.37a$$

$$V_{p2} = \left[V'_p + (r + L)\ (E_a - \tfrac{1}{2}V_H) \right] \qquad \ldots . \quad 2.37b$$

where V'_p is the potential of the satellite in the absence of E_a and H.

Thus $(V_{p1} - V_{p2}) / (r + L) = (E_a + V_H)$. 2.38

and a series of values of V_{p1} and V_{p2} in varying attitudes of the vehicle would allow L and V_H to be eliminated.

The above sections have all ignored the complicating factors arising when the vehicle does not cross the geomagnetic field perpendicularly or when the exposed areas of the field sensitive device is not normal to the direction of motion. This first factor will multiply the rhs of eq'n 2.36 by $\sin \alpha'$ where α' is the instantaneous value of angle between the geomagnetic field and the direction of vehicle motion. In the case of the electron and ion fluxes and of the field induced signals dealt with in the next Chapter, the sensitive area must be multiplied by $\cos \beta'$ the instantaneous value of the angle between the direction of vehicle motion and the normal to this area.

Thus the altitude and velocity of the vehicle must be known at all times if E_a is to be extracted from a knowledge of E_p, I_p, and L_D. If H is also known then this result may be checked by insertion of V_S in equation 2.38.

Chapter 3.

Techniques of electric field measurement.

3.1. The Lower Atmosphere.

In regions of the atmosphere where little ionisation exists, and where meteorological and cloud physics phenomena are investigated, there are two principal classes of device for the measurement of electric field. The first is the Radioactive collector, which utilizes the increased local conductivity of its surroundings caused by the ionising radiations it emits, to allow the R.A. source and its conducting mounting to attain a potential proportional to that of its position, (Chalmers 1957). This method is unsuited to use in the Ionosphere due to the pre-existing high conductivity, the slow time constant due to the high resistance of the R.A. source, and to the impossibility of obtaining a steady reference potential.

The second class of device is electromechanical in operation and relies upon the fact that when an area A.meter^2 is placed in an electric field of E. v/m, a charge of $Q = -\varepsilon_0 EA$. is induced upon it, where ε_0 is the permittivity of free space (8.86×10^{-12} Farads/meter). The negative sign indicates that a positive field is that which induces negative charge upon a conductor placed within it. The devices in this class have the conductor screened from the field periodically, allowing the 'bound' charge to leak away to earth through a resistive impedance. This generates a voltage which may be fed to an amplifying system, and which is proportional to the applied field (Gunn 1954). Such devices give an A.C. output, are known as 'Field Mills' and are the most widely used means of electric field measurement on or near the earth's surface.

As an indication of performance it may be said that a 'Mill' with a collecting area of 10^{-3} meter^2 will generate approximately 10^{-4} volts/v/m, across 100 Megohms, operating at a few hundred c.p.s. The impedance across the output is capacitative as well as resistive due to the construction of the mill itself as well as the leads connected to it, and it will be shown in section 3.4. that this capacitance should be kept to a minimum at all times to obtain maximum output. These are relatively bulky instruments however and it is difficult to reduce the effective capacitance of the mill and amplifier first stage to much below 100 pF, without employing feedback (Adamson 1960) which is not always convenient.

Nevertheless these values allow a time constant of about 10^{-3} seconds which allows operation at two or three hundred cycles per second; low enough for all Lower Atmosphere problems unless the very rapid changes in electric field due to lightning discharges are being studied. Field Mills working at a few kilocycles per second have been developed for this purpose (Smith 1953), one of which forms the basis for the device developed in the present work (Malan and Schonland 1950).

3.2. Previous work in the Upper Atmosphere.

The relatively rapid response time of all types of Field Mills and the considerable amount of experience in their use, caused it to be one of the first instruments to be sent into the Ionosphere and Upper Atmosphere when captured German V-2's were available between 1946 and 1949.

It now seems clear that the mills used were unsuitable due to their lack of compensation for the effects mentioned in the previous Chapter. Thus Clark (1949), describes what appears to be a conventional five bladed, sector type field mill mounted flush with the skin of a modified V-2. It is stated that vehicle potential and any ambient electric field were measured but no results are given nor is any method of analysis of results given.

Similarly Bourdeau (1959), in describing work carried out in 1950 mentions the use of a 'Field Meter' (Field Mill) to estimate any potential difference between the vehicle and its surroundings. Using the 'Field Augmentation Factors' derived by Clark (1957) the minimum detectable signal of the Field Mill ($\mp$50 v/m), is equated to a vehicle potential of $\mp$55 volts and Bourdeau merely records that this value was not exceeded.

The first quantitative treatment of Field Mill performance under Upper Atmospheric conditions was given by Imyanitov (1957), who, with a number of co-workers seems to have been the most persistent advocate for the use of Field Mills, at a time when direct measurement of electrical quantities was very little developed. This first work of Imyanitov was not translated until 1958, by which time it seems that more of the difficulties had been appreciated, since in 1959, he published a proposal for a modified field mill to overcome the 'interfering effects' of charged particle flow (Imyanitov and Shvartz 1959). In this modified mill the charged particle flux was reduced by making both the stator (collecting system), and the rotor (screening system), from a wire mesh with very high optical transparency. The flux of charges was reduced by the mesh stator system which permitted a high proportion of the charged particles to pass straight through to the earthed baseplate, and the modulation of the flux was similarly reduced by the mesh rotor. The mesh was taken to be fine enough for no reduction in 'bound charge' collection to occur, so that for electrostatic purposes the stator may be considered as solid. It is likely that field mills of this type were mounted on Sputnik III, but this was the only apparatus that has not been described in detail, nor have any results been given.

By 1960 experiments were described in which a field mill was used to measure surface charge density (Bourdeau et al. 1960), and this suggests that space charge theory was used to determine vehicle potential (Shvartz 1960. Booker 1959).

Most United States field mills so far described have been of the conventional, solid sector type, but two variants have been tried which should be mentioned. In the first, two long arms were fitted to the rocket with an isolated probe at the end of each. The rotation of the rocket in the ambient electric field turned the arm/probe assembly into a large field mill, since the probes were continually gaining or losing charge through a high impedance detector, as they attempted to adjust to the potential of the changing surroundings (A.D. Little Inc. 1959).

No results were published, but a signal of the same frequency as the rotation of the rocket (1 c.p.s) was reported, indicating that the method might give a means of detecting ambient fields.

In the second variant, a sector type mill was constructed having a mesh stator, but a conventional, solid rotor. (Smiddy A.F.C.R.L. personal communication). This would obviously reduce the photocurrents from the collector, but whether the flux of charged particles would be reduced by a similar factor is open to doubt. The distortion of the electric field in the region of the mesh might cause a high proportion of the charged particles to be deflected onto it instead of passing through.

A stator assembly of this instrument with rotor removed, was tested by the author in the test chamber shown in figure 7.8., and the current collected by it when exposed to an electron flux was not much less than that collected by a solid stator of the same dimensions. Although by no means a rigorous test of the complete instrument as proposed by Imyanitov and Svartz, this result emphasises that the main problem, caused by the total signal being composed of two parts, may be reduced but very probably not eliminated.

Two signals must be dealt with, one due to bound charge induced by the applied electrostatic field, and the other caused by the charge flux, and these two signals will be shown to be 90° out of phase. In effect the signal from the mill at any time is the instantaneous value of an expression with two independent variables. The Imyanitov and Shvartz mill aims at reducing the charge particle to a negligible value but the above observations cast doubt on the possibility of this. In some cases (Smiddy A.F.C.R.L. personal communications), the value of the charged particle current density has been obtained independently as in figure 2.5. It is then assumed that the same current density applies to the exposed surfaces of a nearby field mill and an estimate of the effect of this total current upon the mill output derived from

$$V = j\ A\ R \qquad \ldots.\ 3.1.$$

where V is the peak to peak signal produced across input resistence R ohms, when a current density j amps/ m^2 acts upon an area of A.meter^2.

Since these mills are not directly calibrated against known applied currents, the results of Chapter 8, would suggest that such estimates are extremely unreliable.

A solution to this problem would be some means of mounting two field mills in close proximity. This would permit the assumption to be made that both mills were subjected to the same electric fields and charged particle fluxes at any instant. Two simultaneous equations could then be obtained if each 'mill' were calibrated for output against applied electric field, and applied charged particle flux. The two components would also have to be applied simultaneously to deduce the rules governing the combination of the two signals produced by each channel (mill). This is dealt with further in section 4.2.

3.3. The principle of the two frequency field mill.

In order to obtain these two simultaneous equations in E and I, where these are the applied field, and applied current, it is first necessary to decide upon the most suitable configuration.

At first sight it would seem that since it is desired to eliminate the charged particle component then a configuration of two close mills should be obtained which have the same current sensitivity but different field sensitivities. Although this is not in fact a straightforward matter of subtracting the two total outputs (Section 4.2.) it happens that a very compact assembly may be obtained assuming that equation 3.1. holds and making the two mills with equal areas.

The usual sector shape is not suitable since the only way that this could be arranged to give differing field signals would be some means of electrically linking different numbers of isolated vanes; a system which would result in different collecting areas, and in intermittent signals being delivered to the two amplifying systems.

In the high frequency mill developed by Malan and Schonland (1950) however, a series of identical studs are mounted in a circle on an insulating base and connected electrically beneath this base. An earthed rotor with a similarly arranged set of holes rotates above these studs, exposing and screening them Np times per second, where N is the number of studs and p the rotational frequency of the rotor. If two such sets of studs and holes were arranged concentrically on one baseplate with two corresponding sets of holes in a single rotor, there would be in effect two separate field mills in close proximity.

The configuration would have to be such that there was no 'leakage' or electrostatic coupling, between one mill and the other, and ideally the 50/50 open/solid ratio of the sector type mills should be maintained in order to deliver a continuous AC signal. This may be difficult due to the small dimensions of the individual studs when compared to the larger vanes of conventional field mills. This means that since the clearance of rotor above the stator cannot be substantially reduced, relatively more distortion of the electric field may take place resulting in a loss of induced ('bound') charge for a given field. This will be dealt with in Chapter 6.

3.4. Theory of operation

The most complete theories of mill output are those given in a paper by Mapleson and Whitlock (1955). Two treatments are given, one in which the area of collector exposed varies sinusoidally, resulting in a sinusoidal waveform, and the other for a sector type configuration, which results in a triangular waveform output. The first case is given below with some modification to suit a Malan Schonland type mill, and the required outputs.

The mill described in part II of this thesis and that constructed by Mapleson (1954) both gave outputs which appeared sinusoidal when displayed on a CRO before or after amplification. With the mill constructed in Durham the waveform is best described as 'rounded off' triangular, but on comparing the estimated outputs from the two treatments with the observed outputs there is relatively little difference between the two outputs when compared with observed value.

In both cases it may be shown that an electric field signal which is sensitive to frequency of operation may be obtained, together with a current output inversely proportional to frequency.

If a conducting collector area A_o meter^2 is subjected to a sinusoidal screening cycle of f.cps, in an electric field of E volts/meter, then the instantaneous value of the bound charge Q' is;

$$Q' = \varepsilon_o E A_o \sin.wt. \qquad \ldots. \; 3.2.$$

where $w = 2\pi f.$ and $\varepsilon_o = 8.86 \times 10^{-12}$ Farads/meter

Then the current leaving the conductor at any instant is;

$$I' = \frac{dQ'}{dt} = \varepsilon_o w E A_o \cos.wt. \qquad \ldots. \; 3.3.$$

This may be written as;

$$I' = \varepsilon_o w E A_o/2 + \varepsilon_o w E A_o \cos wt./2. \qquad \ldots. \; 3.4.$$

The conductor has an inherent capacitance C.farads, which is connected to earth through a resistor of R ohms. These are in parallel (since the rotor is earthed), and if their impedance is Z, then the instantaneous A.C. voltage generated across R is;

$$V'_E = I'\ Z/2. \qquad \ldots.\ 3.5.$$

Now $$Z = R/(w^2C^2R^2 + 1)^{\frac{1}{2}} \qquad \ldots.\ 3.6.$$

Thus $$V'_E = \varepsilon_o wEA_o\ R \cos wt/2(w^2C^2R^2 + 1)^{\frac{1}{2}} \qquad \ldots.\ 3.7.a.$$

or $$V'_E = \varepsilon_o\ EA_o \cos wt/2(C^2 + 1/w^2R^2\ )^{\frac{1}{2}} \qquad \ldots.\ 3.7.b.$$

This is a sinusoidal signal 90^o out of phase with the screening cycle.

Now the voltage V'_c generated across R by a charged particle current density j amps/meter^2, will be an alternating component superimposed upon a steady D.C. signal.

The instantaneous current I'_c will be;

$$I'_c = j\ A_o \sin wt. \qquad \ldots.\ 3.8.$$

giving rise to a voltage V'_c;

$$V'_c = I_c Z \sin wt = \frac{jA_oR}{2} + \frac{jA_oR. \sin wt}{2(w^2C^2R^2+1)^{\frac{1}{2}}} \qquad \ldots.\ 3.9.$$

The AC component is thus in phase with the screening cycle, and 90^o out of phase with the field induced voltage.

From equations 3.7. it may be seen that when $w^2C^2R^2 \gg 1$, R and w may be eliminated and;

$$V'_E = \varepsilon_o EA_o \cos wt./2.C. \qquad \ldots.\ 3.10.$$

Under these same conditions equation 3.9. becomes;

$$V'_c = jA_o \sin wt/2.w.C. \qquad \ldots.\ 3.11.$$

Here is one possible arrangement for producing two mills with differing sensitivities at different frequencies.

Using frequencies $f_1 > f_2$, and collecting areas $a_1 > a_2$

so that;

$$a_1 : a_2 = f_1 : f_2 \quad \text{.... 3.12.}$$

the current signals would be equal and the field signals would be in a ratio $(f_1/f_2)^2$, with the higher frequency giving the greater output.

However, this would involve constructing a mill satisfying the conditions in section 3.5. whilst having the outer studs of much larger total area than the inner, all studs would be the same size in fact. This would mean that nowhere near the 50/50 solid/open ratio could be maintained for both sets of studs, and it was therefore decided to construct a mill with, $w^2C^2R^2 < 1$, and also

$$a_1 : a_2 = 1. \quad \text{.... 3.13a.}$$

$$f_1 > f_2 \quad \text{.... 3.13b.}$$

In this case from equations 3.7, when $(w^2C^2R^2 \ll 1)$ the field signals become proportional both to w and to R, and from equation 3.9. the current signals become proportional to the function; $R/(w^2C^2R^2 + 1)^{\frac{1}{2}}$.

Let $x = (wCR)$ and let:

$$\phi(x) = 1/(1+x^2)^{\frac{1}{2}} \quad \text{.... 3.14.}$$

The field signals will be in a ratio for constant R of;

$$\frac{V_{E1}}{V_{E2}} = \frac{w_1}{w_2} \cdot \frac{\phi(x_i)}{\phi(x_2)} \quad \text{.... 3.15a.}$$

and the current signals will be in a ratio for constant R, of;

$$\frac{V_{c1}}{V_{c2}} = \frac{\phi(x_1)}{\phi(x_2)} \quad \text{.... 3.15b.}$$

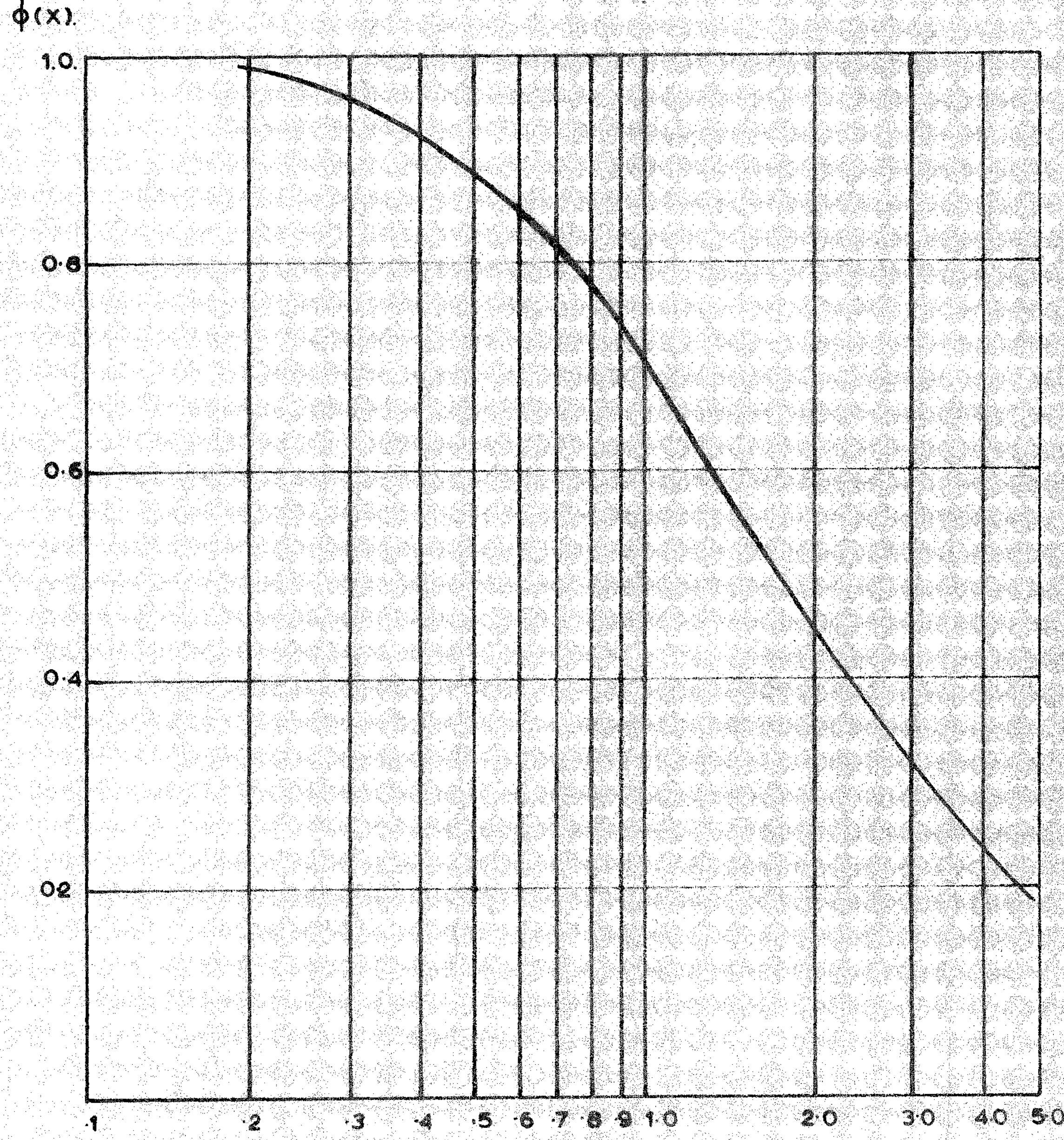


FIG. 3.1.

From equation 3.7a.

$$V_E = \text{Constant. R.w. } \phi(x) \qquad \text{.... 3.16}$$

and in figure 3.1. $\phi(x)$ is plotted for a range of values of x.

Examining the nature of equation 3.16, and remembering that w appears in x, it may be seen that V is proportional to w for constant R and x. In practice it is difficult to vary C with any accuracy so that R and w are the quantities which must be manipulated to give optimum signal differentiation, and examining $\phi(x)$;

$$(1 + x^2)^{-\frac{1}{2}} \rightarrow 1 \quad \text{as} \quad x \longrightarrow 0 \qquad \text{.... 3.17a.}$$

$$(1 + x^2)^{-\frac{1}{2}} \longrightarrow 0 \quad \text{as} \quad x \rightarrow \infty \qquad \text{.... 3.17b.}$$

so that compromise values of x_1 and x_2 for the two sets of studs must be chosen to give wide field signal separation and relatively low current separation. From figure 3.1. it would seem that suitable values are

$$x_1 = w_1C_1R_1 = 0.75 \qquad \text{.... 3.18a.}$$

$$x_2 = w_2C_2R_2 = 0.25 \qquad \text{.... 3.18b.}$$

where $w_1 = 3w_2$, $C_1 = C_2$ and $R_1 = R_2$.

Thus the field signals will be in a ratio

$$\frac{V_{E1}}{V_{E2}} = \frac{w_1}{w_2} \cdot \times \frac{\phi(x_1)}{\phi(x_2)} \qquad \text{.... 3.19a.}$$

and the current signals will be in a ratio

$$\frac{V_{c1}}{V_{c2}} = \frac{\phi(x_1)}{\phi(x_2)} \qquad \text{.... 3.19b.}$$

Chapter 4.

The Durham mill.

4.1. Construction

A mill based on the principles given in Chapter 3 was constructed, and preliminary tests of its performance were carried out in the laboratory in Durham. The best configuration to be contained within a reasonable size (less than 50 cms diameter), was found to be one in which the outer set of collectors ('studs') had three times the number of studs of the inner set, this being found by drawing suggested configurations accurately and full sized. The conflicting factors were; the overall limitations on size; the desire to retain a 50/50 open solid relationship or as close to it as possible; and the need to have a reasonable separation between the two sets of studs to minimise electrostatic coupling. It will be seen later, that ideally the outer (high frequency) set of studs should have a total area three times that of the inner set but this would make the whole device far too large if the inner studs were to be large enough to be reasonably efficient, a factor which is supported by the work with the electrolytic tank described in Chapter 6.

In the Durham mill the sets were of 6 studs and 18 studs, mounted on a 0.33 cms thick Perspex plate, 28 cms in diameter. The inner ones were made from Brass O.B.A bolts, with the heads machined flat, and edges turned giving a clean edge to the sensitive area to reduce local increases in field due to distortion at projections. They were 1.30 cms in diameter, and the outer set, made from similarly worked 4.B.A. bolts, were 0.63 cms in diameter. This gave total areas, in terms of meters^2, of $5 \times 10^{-4} m^2$ and $5.5 \times 10^{-4} m^2$, for the inner and outer sets respectively. Better agreement between the areas could only have been obtained by further machining of the 4.B.A. bolts which would probably have exposed the shaft of the bolts. As it was this shaft may have been the cause of the impaired efficiency of the smaller studs seen in the electrolytic tank work.

The rotor was of hardened Aluminium, 23 cms in diameter and 0.16 cms thick. The exposing holes were 2.22 cms and 1.44 cms in diameter for the inner and outer sets, larger than their complementary studs but chosen to give the same (hole/stud) area ratio as in both the original Malan and Schonland mill, and in a similar mill constructed in Durham by Mapleson (1954). Ultimately after studying various ratios with the electrolytic tank this ratio was found to be too high but since this was to be an experimental model it was decided to retain as much as possible from previous successful mills.

An earthed, outer 'screening ring' of width 2 cms was fitted in the same plane as the rotor with a clearance of

0.33 cms. all round. This was an attempt to ensure that an electric field as normal to the sensitive surfaces as possible was obtained. The rotor, baseplate, and guard ring assemblies are shown in figure 6.3a. and all exposed surfaces were Chromium plated to reduce contact potentials (zero outputs). Subsequently it was found necessary to cover the Perspex base with a conducting sheet, isolated from all the studs, in an effort to eliminate a very large spurious output. (see section 6.4.).

The radii for mounting the two sets of studs and holes should be chosen so that the 50/50 solid/open ratio is attained as closely possible whilst at the same time keeping the closest approach of any two holes in adjacent sets of studs equal to the sum of their diameters. The inner radius was fixed at 5.7 cms and the outer at 9.5 cms.

The rotor was turned by an A.C. induction motor nominally of 3000 rpm. Ball races were added, and the rotor fixed directly onto the motor shaft. Spring loaded, graphite earthing brushes were held against this shaft and the load thus caused reduced the rotation speed in vacuum (no air loading) to about 2000 r.p.m.

4.2. The estimated Durham mill output.

The motor in vacuum under load turns at 2000 r.p.m.

Thus $w_1 = 1200\pi$, $w_2 = 400\pi$.

The capacitance of the mill excluding coaxial cable leads each of approximately 2 feet (22. pF. per foot) was measured using a Marconi Universal bridge at 1000 c.p.s. Very little variation in C_1 or C_2 was noticed between the screened and unscreened positions and, indeed, removal of the rotor itself caused measured value to drop by less than 10pF. The values obtained with the rotor in position were;

C_1 (high frequency) $= 57 \mp 1.$ pF. .... 4.1a.

C_2 (low frequency) $= 74 \mp 1.$ pF. .... 4.1b.

That is, there is 2pF difference between the screened and unscreened positions, and the bulk of the instrument's capacitance seems to have been associated with the bulky Perspex baseplate and its Al. covering. Lengths of coaxial cable may be employed so that the total capacitance will be 100 pF for either 'mill'. In the case of any mill mounted in a rocket or satellite the leads would be shorter than the one or two feet required in this case, and this would give an easy means of trimming the outputs without making C too large.

Knowing these values, and noting expressions 3.18, the value of R may be calculated. The use of equal values of R for both sets of studs ensures that they will attain the same D.C. potential when subjected to the same charged particle flux. This minimises differences in field distortion, and in the repulsion of charged particles (i.e., the current carriers), which have energies (figure 2.1.) of the same order as the D.C. voltage generated in equation 3.9.

If $w_1C_1R_1 = 0.75$, if $w_1 = 1200\pi$ and $C_1 = C_2 = 100pF$,

then $R = \dfrac{7.5 \times 10^{-1}}{1200\pi \times 10^{-10}} = 2\times10^{6}$ ohms .... 4.2.

Substituting this in equation 3.7a. including $\phi(x_1)$;

$$V'_{1E} = \varepsilon_o E A_o \ w.R. \ \phi(x_1) \cos wt/2 \qquad \ldots. \ 4.3a$$

Dropping the cosine term to obtain a peak to peak value, from figure 3.1. $\phi(0.75) = 0.81$, so that if $A_o = 5 \times 10^{-4}$ m^2 and $\varepsilon_o = 8.86 \times 10^{-12}$ Farads/meter

V_{E1}, the peak to peak voltage will be;

$$V_{E1} = 8.86 \times 10^{-12} \times 5 \times 10^{-4} \times 8.1 \times 10^{-1} \times 1200\pi.2 \times 10^{6}/2$$

$$= 1.4 \times 10^{-5} \text{volts/v/m.} \qquad \ldots. \ 4.3b$$

Similarly for $w_2 = 400\pi$ and $\phi(0.25) = 0.97$

$$V_{E2} = 8.86 \times 10^{-12} \times 5 \times 10^{-4} \times 9.7 \times 10^{-1} \times 400\pi \times 2 \times 10^{6}/2$$

$$= 5.4 \times 10^{-6} \text{ volts/v/m.} \qquad \ldots. \ 4.4.$$

The deviation from linear frequency dependence caused by $\phi(x)$ means that $\dfrac{V_{E1}}{V_{E2}} \approx 2.54$

Consider now a charged particle current density of 10^{-5} amps/meter^2 with the same values of w, C, R, and $\phi(x)$. From equation 3.9.

$$V_c = j \ A_o \frac{R.\sin}{2} wt. \ \phi(x) \qquad \ldots. \ 4.5a.$$

Therefore, $V_{c1} = 10^{-5} x\ 5 \times 10^{-4} x\ 2 \times 10^{6} x\ 8.1 \times 10^{-1}/2.$

$= 4.05 \times 10^{-3}$ volts ptp. 4.5b

$V_{c2} = 10^{-5} x\ 5 \times 10^{-4} x\ 2 \times 10^{6} x\ 9.7 \times 10^{-1}/2$

$= 4.85 \times 10^{-3}$ volts.ptp. 4.5c

giving $\frac{V_{c1}}{V_{c2}} = 0.84$

In both cases (4.5b and 4.5c) the studs will be raised to DC potential of,

$j\ A_o R/2 = 10^{-3} \times 5 \times 10^{-4} \times 2 \times 10^{6}/2$

$= 5 \times 10^{-3}$ volts d.c. .... 4.6.

4.3. Analysis of final mill outputs

At first sight it would seem that in the analysis of results obtained from such a mill operating in an ionised region, the application of a correction factor, $\phi(x_2)$: $\phi(x_1)$ to the values given by expressions 4.3b and 4.5b would suffice to equalise the current components, and followed by subtraction of the total outputs from both sets of studs ($V_{T1} - V_{T2}$), would give a quantity proportional to the applied field.

However both of the components making up each total signal are sinusoidal, θ^o out of phase, and from AC theory (Joos 1951), (for both sets of studs);

$V_T' = V_E \cos wt. + V_c \cos (wt + \theta)$ .... 4.7.

$$V_T' = V_E \cos wt + V_c \cos wt \cos\theta - V_c \sin wt \sin\theta \quad \text{.... 4.8.}$$

$$= V_T \cos (wt + \beta) \quad \text{.... 4.9.}$$

where

$$\cos\beta = V_E + V_c \cos\theta \left[(V + V_c \cos\theta)^2 + V_c^2 \sin^2\theta\right]^{-\frac{1}{2}} \quad \text{.... 4.10a}$$

$$\sin\beta = V_c \sin\theta \left[(V + V_c \cos\theta)^2 + V_c^2 \sin^2\theta\right]^{-\frac{1}{2}} \quad \text{.... 4.10b}$$

$$V_T = (V_E^2 + V_c^2 + 2V_E V_c \cos\theta)^{\frac{1}{2}}. \quad \text{.... 4.10c}$$

In the present case $\theta = 90^o$, $\cos\theta = 0$, $\sin\theta = 1.$ and since V_c will usually be at least one order of magnitude greater than V_E, β is approx 60^o.

Thus the resultant of the two components for each set of studs is a third sinusoidal signal of the same frequency and β^o out of phase with the field component, and amplitude given by equation 4.10c.

The phase of the signal is of little interest and since $(V_E V_c)^{\frac{1}{2}} < (V_E^2 + V_c^2)^{\frac{1}{2}}$, it will have little effect upon amplitude.

If the mill has been calibrated separately for both field sensitivity and current sensitivity, then if K_1 and K_2 are these sensitivities for one set of studs; then from equation 4.10c;

$$V_T^2 = K_1^2 E^2 + K_2^2 I^2 + 2K_1 K_2 EI. \cos\theta \quad \text{.... 4.11.}$$

But when $\theta = 90^o$

$$V_{1T}^2 = K_1^2 E^2 + K_2^2 I^2. \quad \text{.... 4.12a}$$

$$V_{2T}^2 = C_1^2E^2 + C_2^2\ I^2 \qquad \ldots.\ 4.12b$$

Where E and I are the field and current applied to both sets of studs, and C_1, C_2 are the relevant sensitivities of the second set of studs.

In practice a smoothed D.C. voltage would be obtained from the telemetry system of the vehicle, and it should be noted that all the output voltages referred to in this Chapter are peak to peak A.C. voltages derived from a knowledge of the gain of the amplifying system. The amplifying system would have to be calibrated in terms of smoothed D.C. output against A.C. peak to peak input, as is in fact done in Chapter 8 when laboratory testing the flight model of the mill.

If the constants connecting these two quantities are p and q, being linear over the required range of inputs, then

$$V_{R1}^2 = p^2\ V_{T1}^2 \qquad \ldots.\ 4.13a$$

$$V_{R2}^2 = q^2\ V_{T2}^2 \qquad \ldots.\ 4.13b$$

Therefore,

$$p^2\ V_{T1}^2 = K_1^2E^2 + K_2^2I^2 \qquad \ldots.\ 4.14a$$

$$q^2\ V_{T2}^2 = C_1^2E^2 + C_2^2I^2 \qquad \ldots.\ 4.14b$$

If the amplifier outputs are not linear however, reference to the amplifier calibration curve would have to be made for each value of V_{T1} and V_{T2}.

It will be shown in Chapter 8 that the field outputs, both for the built in Durham and that constructed at A.F.C.R.L. were linear as forecast, but that the current sensitivities, which were only determined accurately at A.F.C.R.L., were best expressed in the form;

$$(V_c - a) = I^b \qquad \text{.... 4.15.}$$

where a and b are constants, differing for the two sets of studs.

Chapter 5.

The simulation of Upper Atmospheric conditions.

5.1. The problem.

Before any experimental use may be made of any device proposed to overcome the problems set in Chapter 2, some means of verifying its theory of operation under conditions of use must be devised, and it must also be calibrated. This problem is encountered by all workers in upper atmosphere and satellite instrumentation, but is particularly acute when the electrical structure and conditions of the region are concerned.

It is possible to simulate conditions with regard to density, UV, x rays, and temperature, and large test chambers have been constructed for this in the U.S. It is also possible to reproduce the mechanical conditions of the powered part of the flight when all instrumentation is subject to acceleration in the region 10g - 50g, and vibrations up to several hundred cps over an amplitude of as much as a few cms. (M. Smiddy personal communication).

When the electrical structure and properties are under consideration however, the ideal at which to aim is the production of a large volume (meters^3 in the present case) of stable, low temperature, weak plasma. This use of the term 'weak' plasma is the same as used in laboratory work on Plasmas (Delcroix 1960.b).

Assuming as in Chapter 1 that charge neutrality is maintained, then from figures 1.1. and 1.4, a charge density ($n_i = n_e$), of 10^5 c.c. at a pressure of 10^{-5} mm.Hg, will approximate to the conditions 100 kms above the earth. Figure 2.5. gives an idea of the currents that it is desirable to apply to the instrument under test.

The main problem in producing such a plasma for testing purposes is not so much its production but 'containing' it within the desired volume. The temperature of the electrons in a glow discharge, a common form of plasma, is high enough to allow them to escape to the walls of the container, leaving behind positive space charge which must be reduced by the constant external supply of electrons, and by the electrostatic fields set up by the separation of charge. This diffusion to the walls may also be opposed by applying a magnetic field around the axis of the discharge (plasma), as is done in machines for investigating controlled thermonuclear reactions. These deal with 'strong' plasmas however, where $\alpha \approx 1$, $n_i = n_e \approx 10^{13}$.c.c. and $T_i \sim T_e \approx 10^5$ °K.

Up to the present (1962) no stable volume of true plasma suitable for enviromental testing of upper atmosphere instrumentation has been described. Such attempts as have been made (Boyd 1960, Mechel and Harkins 1960, Chopra 1961) have utilised a stream of charged particles to simulate the motion of the vehicle through the ionosphere, and upper atmosphere.

All of these devices produce Hg^+ ions which contaminate surfaces placed within the beam region and this same criticism applies to a suggestion (Whitlock 1960) of using Cs^+ ions with which it is relatively straightforward to obtain a plasma due to its high vapour pressure at moderate temperatures, it being contained by R.F. fields within a waveguide.

Boyd's apparatus uses an Hg discharge at a pressure of about 10^{-3} mm Hg. with cathode that is partially optically transparent, allowing some of the positive ions to pass through and form a charged particle beam a few cms in diameter. This is large enough to test small instruments such as Langmuir probes for a short time before the surfaces become contaminated.

A more elaborate device described by Mechel and Harkins produces a small, electrically neutral volume with ion/electron concentrations up to 10^8 cc. In this case a beam of Hg^+ ions produced as in Boyd's apparatus, causes ionisation in a separate limb of the same vessel where there are also thermionic emitters of electrons to overcome the loss to the walls by diffusion of the electrons produced in the ionising processes. If a chemically and electrically correct reproduction of the intended regions of operation for the instrument cannot be produced, the various ways of producing a robust and flexible stream of charged particles should be considered.

Any apparatus devised should be robust and simple enough not to use up an undue amount of time in setting up for each time of operation, and should allow convenient access to the instrumentation being tested. Since frequent adjustments and replacements of this instrumentation are likely, the means of producing the particles should not be contaminated by the atmosphere to any extent which cannot be compensated. It should also be possible to apply an electric field to the device at the same time as a charged particle flux.

Since the chemical composition of the atmosphere does not alter appreciably up to about 100 kms, (Ratcliffe 1960g), no special gases need be introduced into the testing chamber. Bearing this in mind, and also the fact that a relatively large volume is required, we will consider the various means available for the production of ionisation or of charged particles of either sign in the laboratory.

5.2. Sources of ionisation and of charged particles.

If ionisation may be produced within a suitable volume, charged particles of either sign may be drawn off by the application of suitable voltages to accelerating grids, and made to impinge upon the instrument under test. This also applies to a stream of charged particles which may be drawn off from a thermionic emitter.

A photocurrent produced by a UV source shining on the instrument under test would be the equivalent of a flux of positive charges landing on it.

A review of methods for producing positive ions is given by Duckworth (1958), although of those given only surface ionisation is mentioned below; the others being discarded on grounds of erratic performance (gas discharge), complexity (electron impact source), or the production of unsuitable ions (gas discharge).

Three means of producing ionisation or charged particles will be considered in more detail, they are

a. Photoemission

b. Radioactive sources

c. Thermionic emission

a. Photoemission.

If the use of X rays is discounted on grounds of safety, and the quantity of auxiliary equipment needed, then the photocurrents that could be obtained using UV lamps may be calculated.

Before an electron can be ejected the condition, $h\nu > \phi$ must hold, where h is Planck's constant, ν the frequency of the (UV) light, and ϕ is the work function of the surface involved. In the present case this surface is the working surface of the instrument under test, which is most likely to be Au (ϕ = 4.54 volts, Hermann and Wagener 1951). This is the material which has been found to give the lowest and most stable contact potential errors when used in upper atmosphere instruments (Smiddy. personal communication).

Thus to give rise to emission the wavelength λ of the UV light must be not greater than;

$$\lambda' = \frac{ch}{\phi} \qquad \text{.... 5.1a.}$$

where c is the velocity of light, and ϕ is expressed in ergs.

Thus. $$\lambda' = \frac{3 \times 10^{10} \times 6.625 \times 10^{-27}}{4.54 \times 10^{-12} \times 1.6.}$$

$$= 2.74 \times 10^{-5} \text{cms.} (2740 \text{Å}). \qquad \text{.... 5.1b.}$$

If suitable UV sources were available with a similar power output to the Mazda MBW/U. series, which give 0.25 watts/steradian at 3640.Å (Mazda data sheet I/DIS/MB/3), then there is still the question of photoelectric yield ('efficiency') to be considered. Not every photon incident upon the working surfaces releases a photoelectron, and although Au has a higher yield than most (Walker et al 1955), this is only about 4% at a wavelength of 1000Å and decreases with longer wavelengths.

Assume that a 'yield' of 1% were possible, and that similar power outputs to above were available then a working surface of 1cm^2 at 25 cms from a lamp emitting 0.25 watts/steradian (2740Å) would give a photocurrent of;

$$\frac{\text{power output x steradians x e}}{\text{photon energy (ergs).}} = \frac{4 \times 10^{-4} \times 10^{-2} \times 10^{7} \times 1.6 \times 10^{-19}}{1.6 \times 10^{-12} \times 4.54}$$

$$= 8.8 \times 10^{-7} \text{amps/cm}^2. \quad \ldots\ldots 5.2.$$

This is a current as great or greater than is likely to the needed in testing instrumentation designed for use in the first few hundred kms above the earth (figure 2.5), but the only way that it's intensity could be varied would be by various filters, which would be very inconvenient to adjust within a vacuum chamber. On the other hand if a constant high intensity were required (simulation of solar UV) then this would be quite suitable (Bridge et al 1959).

b. Radioactive sources.

There are two processes which need to be considered, by which charged particles are found in the vicinity of the R.A. source.

Firstly some of the emitted particles will themselves impinge on the working surfaces, and secondly all the emitted particles including those in the first category will undergo ionising collisions along their paths. The number of ion/electron pairs produced depends upon the type of particle, its energy, and the type and density of the gas through which it is travelling. Only α and β emitters will be considered due to the screening and careful handling required by γ rays.

Upon examining the pressures at which it is desired to operate, it becomes apparent that the second process above, is of little value due to the low number of collisions per unit track length.

The number of ion/electron pairs produced per cm track length is, for α particles (Fermi 1950);

$$\frac{dN}{dx} = \rho \cdot \frac{dE}{dG} \; \frac{1.}{30 \times 1.6 \times 10^{-12}} \qquad \text{.... 5.3a.}$$

where ρ is the density of the gas through which they pass in gms/cc.

$\frac{dE}{dG}$ is the energy loss in ergs/gm . cm^2.

1 eV = 1.6×10^{-12} ergs.

30 eV are required to produce one ion/electron pair.

At an altitude of 125 kms above the earth (10^{-5}mm Hg) the value of ρ is 10^{-11}gms/cc.

(ARDC) and dE/dG is 1200 ergs/gm cm^2 for 4. MeV α's (Fermi 1950), thus;

$$\frac{dN}{dx} = \frac{10^{-11} \times 1200}{30 \times 1.6 \times 10^{-12}} = 250 \text{ ion pairs/cm track} \qquad \text{.... 5.3b}$$

and thus the range of each 4. MeV α particle will be;

$$\frac{4 \times 10^6}{30 \times 250} = 5.33 \times 10^2 \text{cms.} \qquad \text{..... 5.4.}$$

In a chamber with a greatest dimension of half a meter a considerable amount of radioactivity would be needed. One millicurie will give 3.71×10^4 disintegrations per second and if these are spread over all directions, then for a useful track length of 50 cms, over 2 π steradians (one side of source in chamber) a total of;

$$3.71 \times 10^4 \times 250 \times \frac{2\pi}{4\pi} \times 50 = 2.32 \times 10^8 \text{ ion pairs/second.} \quad \ldots. \ 5.5.$$

Which gives a total charge/second (i.e. current) made available of $2.32 \times 10^8 \times 1.6 \times 10^{-19} = 3.72 \times 10^{-11}$ coulombs/sec.(amps).

It is very unlikely that more than a small fraction of this charge could be drawn onto the instrument by accelerating grids, and since R.A. sources of more than a few millicuries require careful handling this method does not give sufficiently large currents to simulate upper atmosphere conditions. Obviously the method of direct impacts will be even less satisfactory since only one charged particle results from each disintegration, and a much smaller proportion of them leave the source in the right direction.

c. Thermionic emission.

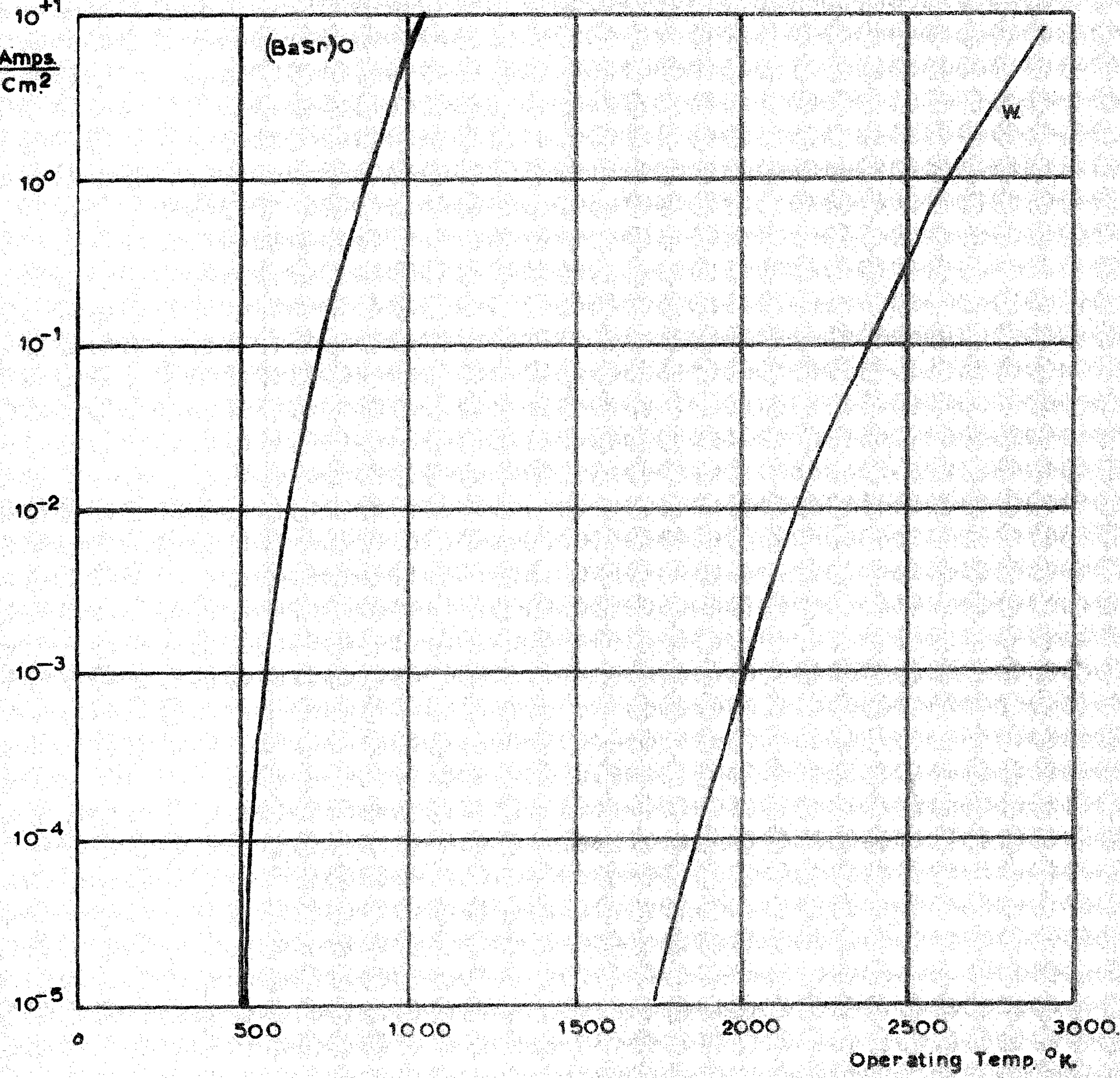
The chief attraction of this method is the ease with which the emitted current may be varied by varying the power applied to the emitting elements.

Ideally, to reproduce upper atmosphere conditions it would be desirable to produce positive ions; although this is possible (Moak et al 1959, Duckworth 1958) the coating of the oxide of the required ion, which is usually applied to the filament is contaminated by the atmosphere, thus rendering it useless for a 'demountable' apparatus which would be frequently opened to the atmosphere.

On grounds of simplicity and robustness a system using Tungsten (W) filaments gives a useful source of electrons. These electrons may be directed onto the instrument under test by applying accelerating potentials to a number of grids, which should have as high an optical transparency as possible. If the wire of the grid is of small diameter compared with the mesh spacing, and if these gaps are small compared with the distances between the grids then the electrostatic field will be perpendicular to the plane of the grids except very close to the wires themselves, and most electrons will pass perpendicularly through the grids.

Tungsten has the advantage of a high melting point (3387^{o}K), which means that if run normally at a moderate temperature (a domestic lamp bulb operates at about 2500^{o}K) a falling off in emission due to any contaminations may be compensated for by increasing the running temperature. Suitable filaments may be made from small lamps such as Galvanometer lamps, by carefully removing the glass bulb. This also gives a convenient way of mounting a number of filaments as required.

Figure 5.1. (Hermann and Wagener 1951) shows the variation of current emitted per unit area, with temperature



10+1
Amps.
Cm.2
(BaSr)O
W.
10°
10-1
10-2
10-3
10-4
10-5
0
500
1000
1500
2000
2500
3000.
Operating Temp. °K.

FIG 5.1.

and was obtained by substituting in Richardson's equation;

$$i = AT^2 . \exp(-\phi/kT). \qquad .... 5.6.$$

where A is a constant, ($A = 120$ amps/cm^2 for most metals)

ϕ is the work function of the emitter in ergs.

k is Boltzmann's constant

T is the absolute temperature of the emitter

i is the saturated current, that is the total charge emitted per second.

Now if the instrument to be tested has a total area of some hundreds of cm^2 (overall dimensions) and a current density of about 10^{-8} amps/cm^2 is required then total emitted currents must be at least of the order of microamps and probably a great deal higher to allow for the low efficiency to be expected when electrons are in a container with many conducting components besides the instrumentation itself.

On removing the glass envelope from a 12v. 24 watt galvanometer lamp the filament was found to have an overall length of 0.45 cms, an outside diameter of 0.08 cms, and to be made of Tungsten wire 0.01 cms in diameter. It is wound with very small spacing between adjacent turns and for a quick approximation it was assumed that the effective exposed area of each turn, of which there were over twenty, compensated for the spaces thus giving a total emitting surface of;

$$\pi \times 4.5 \times 10^{-1} \times 8 \times 10^{-2} = 1.4 \times 10^{-2} \text{ cm}^2. \qquad .... 5.7.$$

Six such lamp filaments in their original base caps mounted in lampholders would give a total area of $0.84 cm^2$, which from figure 5.1. would give a saturated current of 5×10^{-6} amps, at a temperature of $1650^{o}K$.

It may be shown (Hermann and Wagener 1951. vol. 2) that the mean energy of the emitted electrons is kT, where these symbols have their usual meanings. They have a Maxwellian distribution of velocities, where $\bar{v}$ the mean velocity is;

$$\bar{v} = 5.53 \times 10^{5} \quad (T)^{\frac{1}{2}} \text{ cms/sec.} \qquad \ldots.\ 5.8.$$

Expressed in terms of electron volts, at $1650^{o}K$ the mean energy will be;

$$\frac{kT}{1.6 \times 10^{-12}} = \frac{1.38 \times 10^{-16} \times 1650}{1.6 \times 10^{-12}} = 1.42 \times 10^{-1} \text{ eV} \qquad \ldots.\ 5.9.$$

and thus low voltages will be required to influence the motion of electrons in the vacuum chamber, always remembering that with a Maxwellian spread, some electrons will have much higher energies.

Due to the simplicity and flexibility of this method it was decided to construct such a device, to provide a flux of electrons onto the mill under test.

5.3. The Durham test chamber.

There was available in Durham a vacuum system capable of attaining a pressure of 10^{-5}mm Hg, when carefully set up, after two to three hours pumping. A Mercury diffusion pump, backed by a rotary oil pump, evacuated a vessel formed by a 20" length of $\frac{1}{4}$ steel piping, 14" internal diameter. It rested on a 20" diameter machined flat, stainless steel baseplate, in which there was an opening to the pumps. The top of the chamber was formed by a similar plate and both were vacuum sealed to the piping forming the walls by demountable L sectioned rubber seals. Thus the three components could be electrically isolated from one another, although the baseplate was earthed.

In both top and bottom plates, there were four vacuum sealed electrodes for power supplies and signal leads, and in the bottom plate there were three O.B.A. threaded sockets for mounting apparatus.

Figure 6.1. gives a section through the completed chamber with the mill in position and figure 6.4b shows the filament and grid assembly, together with the top plate. Two models of this 'test rig' were constructed, the present one described here, and a second one at A.F.C.R.L., based on the same idea and described in Chapter 7.

The emitting filaments are arranged so that they are the most negative part of the apparatus, the instrument under test is earthed, and is the most positive part. The power source for these filaments has its positive end connected to the top plate of the chamber, which is connected to one lead of the filaments, the negative end is connected

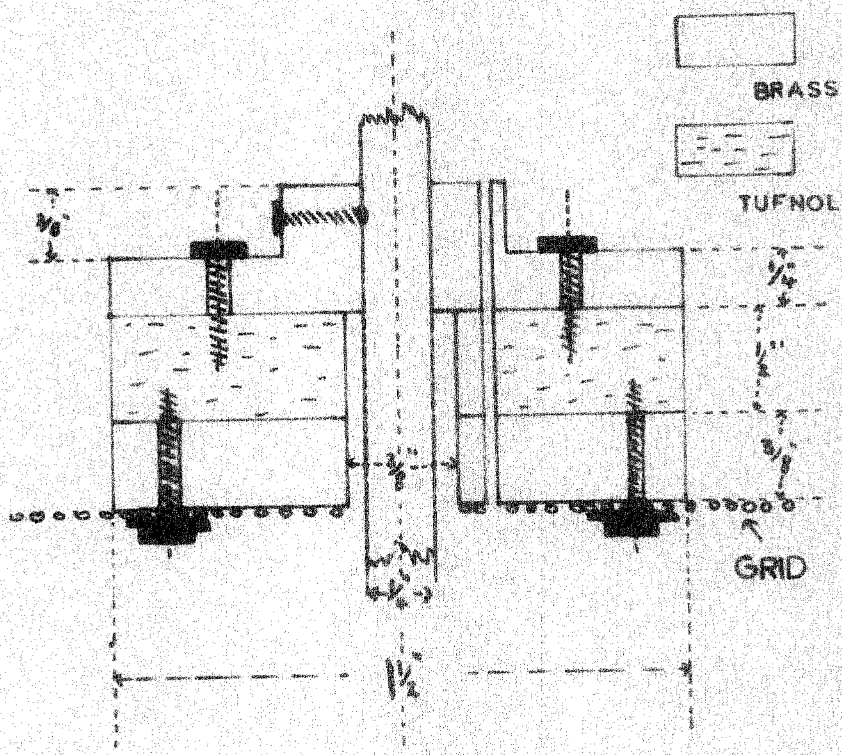


fig 5.2 GRID HOLDING BUSH

to the other lead of the filaments. In the Durham case, six 12 volts 24 watt galvanometer lamps were used in series, but in the A.F.C.R.L. model ten 28v 24 watt aircraft lamps in parallel were employed. The latter arrangement is more satisfactory since the potentials of the bulbs connected in series varies along the circuit and thus the potential distribution is not symmetrical over the plane of the filaments.

Figure 5.2. shows a section through one of the three identical bushes which supported the accelerating grids, and insulated them from the central mounting column. A small hole was drilled through each one to allow the electrical leads to the grid and the lower bushes, if any, to pass through.

As soon as the electrons are emitted they are in an electrostatic field, positive downwards, and are attracted to the uppermost grid G1 through which some of them pass. The potentials of the second and third grids are successively less negative than the first, and the third one will be at earth potential if no electric field is being applied to the mill.

Two accelerating grids in addition to this lowest screening grid were used in an attempt to prevent too great a loss of electrons to the conducting walls of the chamber. It was possible to vary the potential of the walls and this gave some measure of control over the distribution of current flow (see below).

The grids themselves were made of Cu mesh of 1/32" wire with $\frac{1}{8}$" spacing giving an optical transparency of 45%, which was as high as could be obtained in any commercially obtainable mesh. They were 13" in diameter and bound by fuse wire to a 14 gauge steel wire former around the circumference.

The power supplies for the emitting filaments came from a Post Office surplus, full wave rectifier, rated up to 110 volts, 2.5 amps. Three stages of L.C. smoothing ($L = 10.H.$ $C = 5 \times 10^{-3}F$) were added and the residual mains ripple was 0.25 volts p.t.p. at 100 volts, 1.5 amps. Three stages of smoothing were needed since with two stages when the filaments were drawing above about 1 amp, 50 cps mains ripple of several hundreds mV p.t.p was observed superimposed upon the current to a passive collector in the chamber. The power from 240 a.c. mains was supplied to this rectifier through a 'Regavolt' variable transformer, allowing control of the voltage supplied to the emitting filaments between 20 volts and 125 volts d.c.

5.4. The test chamber performance.

With the power pack and six emitting filaments as described previously, the mill was placed in the test chamber mounted on three O.B.A. screwed rods in the base of the chamber, and the two sets of collector studs connected by screened leads to the vacuum sealed electrodes in the base. These led into a screened can on the underside of the chamber base and from here by means of coaxial leads to the two amplifying systems.

At first the screening rotor was removed from the mill so that some idea of the magnitudes of currents produced could be gained, and these were initially measured simply by placing a Tinsley 4500A moving coil galvo between the studs and earth. This had a sensitivity of 1500 mm/μA(at one meter mirror-scale distance) and with the 5cm^2 total collecting area gave 1 cm. deflection for a current of 1.33 x 10^{-9}amps. This was within the range desired but to measure very small currents it was necessary to use a Vibrating Reed Electrometer (Vibron 33B) to measure the d.c. voltage generated across a known high resistor placed between the collecting studs and earth. This had a wide range and with a 10^{12}ohm resistor currents as low as 10^{-15}amps could be detected but it was not found possible to maintain steady currents less than 10^{-12}amps, sufficiently low for the present purpose however. Using an input resistor of 10^{8}ohms, and using all ranges of the electrometer (0 - 10mV. to 0 - 1000mV), it was possible to measure current densities as high as 2 x 10^{-9}amps/cm^2 and as low as about 5 x 10^{-12}amps/cm^2(both over 5 cm^2 collectors).

It was found that the emitters could not be run when the pressure in the chamber exceeded 10^{-4} mm Hg. Doing so would either drastically shorten their lives, or cause them to burn out immediately.

Each of the three grids (G1, G2, G3 downwards) and the top plate of the chamber which held the filament mounts, was connected to a separate potentiometer across a 120v battery. The usual values of the voltages applied were;

$V_f = -120v$

$V_{G1} = -100v$

$V_{G2} = - 30v$

$V_{G3} = 0$ (no applied field).

Coarse variation in the currents to the mill (x100), could be obtained by varying the power to the filaments, and V_{G1} gave fine adjustments.

At this stage a disadvantage of the apparatus became apparent which could be minimised but not eliminated. This was, that for any set of values of filament power, filament and grid voltages, the currents flowing to the inner and outer sets of collector studs were not equal. That of the outer set was always smaller and this was even more pronounced with the rotor in position. Two possible causes of this were, firstly the attraction of the electrons to the walls of the vessel, and secondly distortions of the electric field in the vicinity of the rotor and collecting studs (see next Chapter).

An attempt to minimise this first effect was made by applying various voltages to the previously earthed walls of the vessel, and the best results were obtained when these were

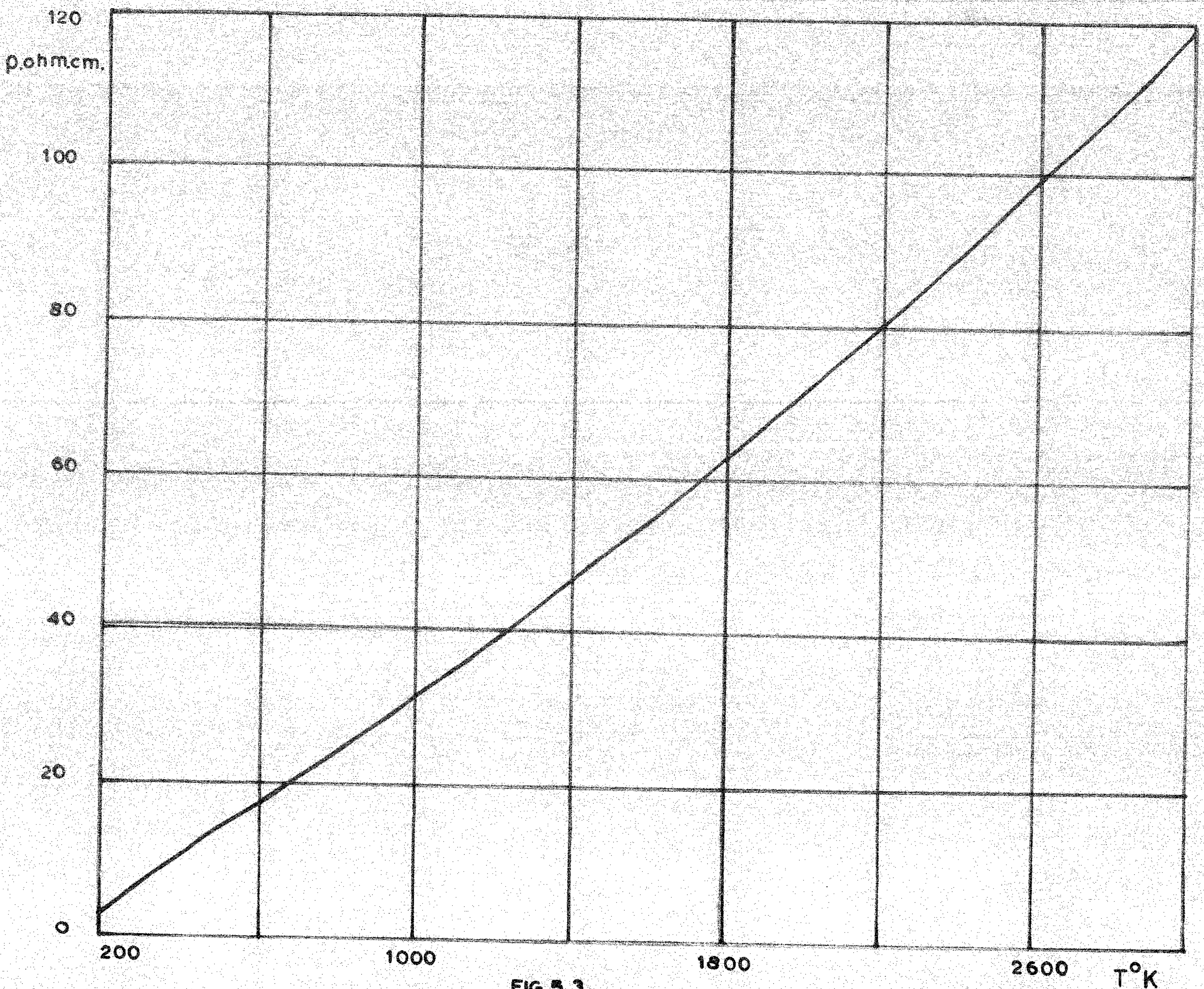


FIG. 5.3.

connected directly to the middle grid (G2). In this case the outer studs received a current approx. 0.7 times that of the inner studs. This voltage was taken to be a compromise between too great a current being drawn off if the walls are not sufficiently negative, and too little being attracted from the central regions of the chamber if they are made too negative, thus 'starving' the outer studs.

The currents flowing to the accelerating grids themselves were measured with a milliammeter placed in series with the relevant battery applying the potential to the grid in question. They were each found to be of the order of a few mA and since at the time all the measurements were made the walls of the vessel were connected to G2, this gave an indication of the total current emitted. This indicates a total emission from the filaments of about 10mA, and an overall transparency to electrons for the grids of less than 10^{-4} at the most. This is much less than the optical transparency (.09 for the three grids together) but this reduced transparency to electrons, even relative to more massive charged particles, has been noted by other workers (Bourdeau et al 1961).

Such an output agrees the expected emission (fig. 5.1.) at a temperature of approx. 2500°K derived by considering the rise in resistance of the filaments from 3 ohms. total at 300°K to operation at 74 volts, 1.8 amps. Figure 5.3.

(Langmuir and Jones 1927) gives the rise in resistivity with temperature and a rise of; $\frac{74}{1.8} \times \frac{1}{3} = 13.7$, corresponds to a temperature of 2500°K. For an emitting area of 0.014 cm^2 the current emitted is 13mA.

Chapter 6.

The experimental work in Durham.

6.1. The mill amplifiers and power supplies.

The theory of the mill suggested that amplifiers capable of detecting a signal in the region of 10^{-5} volts p.t.p. (applied field signal) to 10^{-3} volts p.t.p. (current component) would be required.

Accordingly one amplifier was constructed as shown in figure ~~5.4~~ 6.7. Negative feedback over three stages of R.C. coupled amplification was varied to give variable gain in a range 3.10^3 to 7.10^4.

A 'parallel T' filter was included in the feedback loop in an effort to reduce the signal to noise ratio of the amplifier when dealing with inputs of a few microvolts amplitude. This component has a very high impedance when $R = 1/wC$ and thus at this value of w no feedback occurs and the gain at that frequency is undiminished. In practice complications arose since there was a phase shift in the three amplifying stages not equal to a multiple of π and thus a phase shifting network had to be added (Everest 1941).

This amplifier proved to be unnecessary for the mill when constructed since the zero output could not be reduced below a mV p.t.p. thus meaning that the amplifier had to be

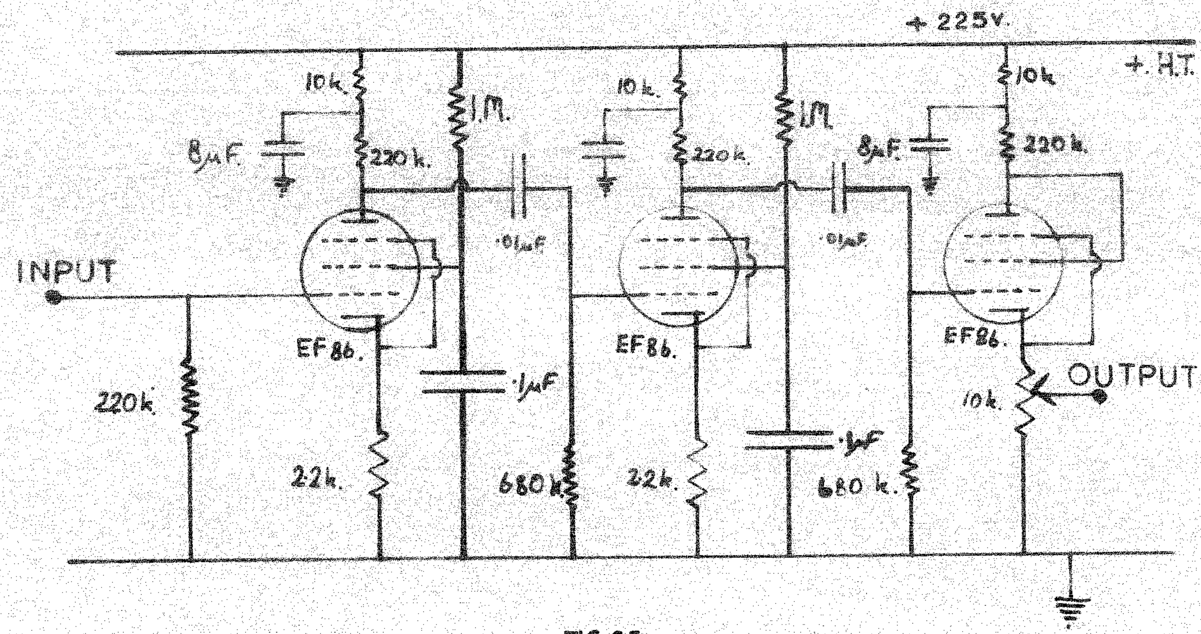
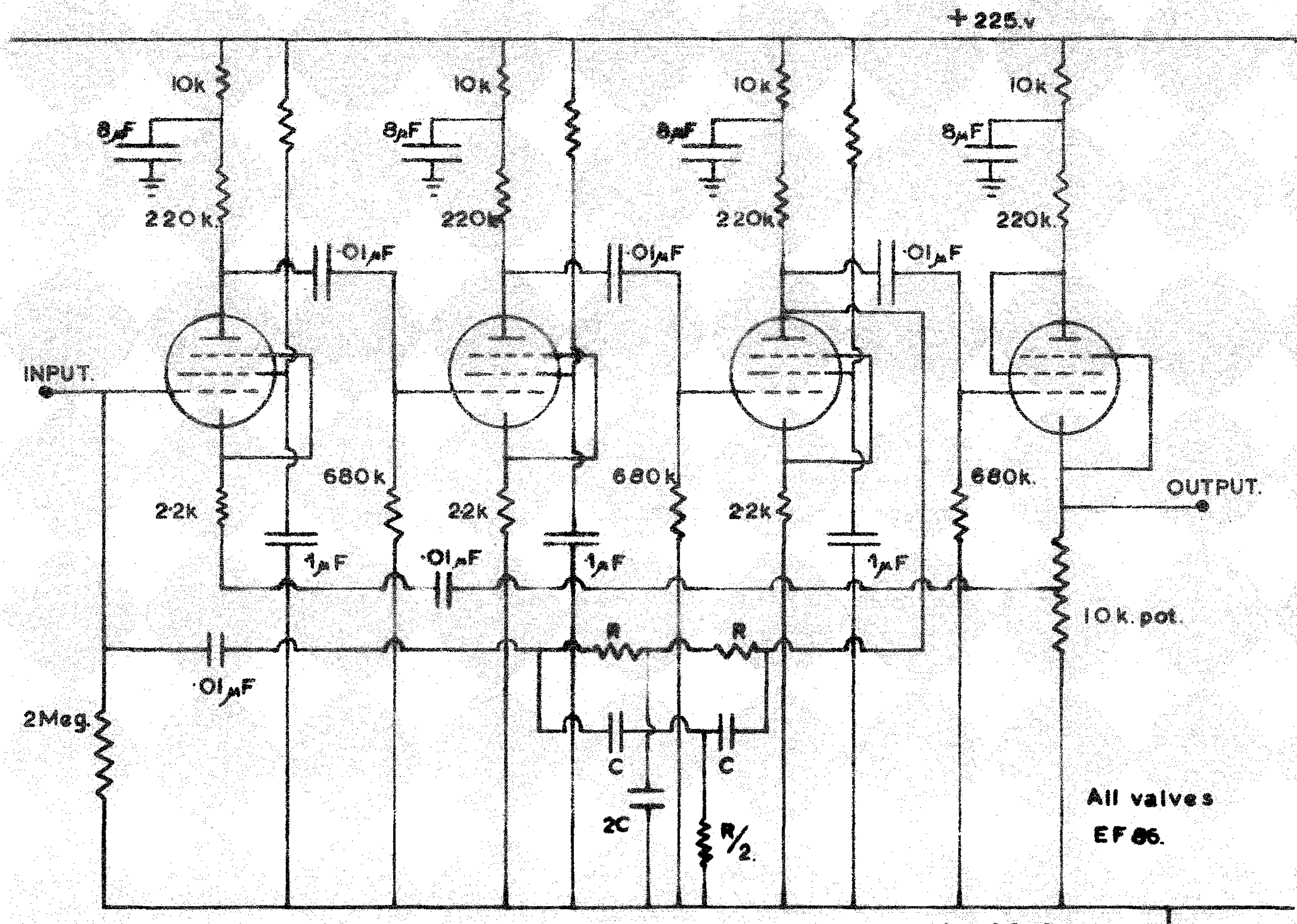
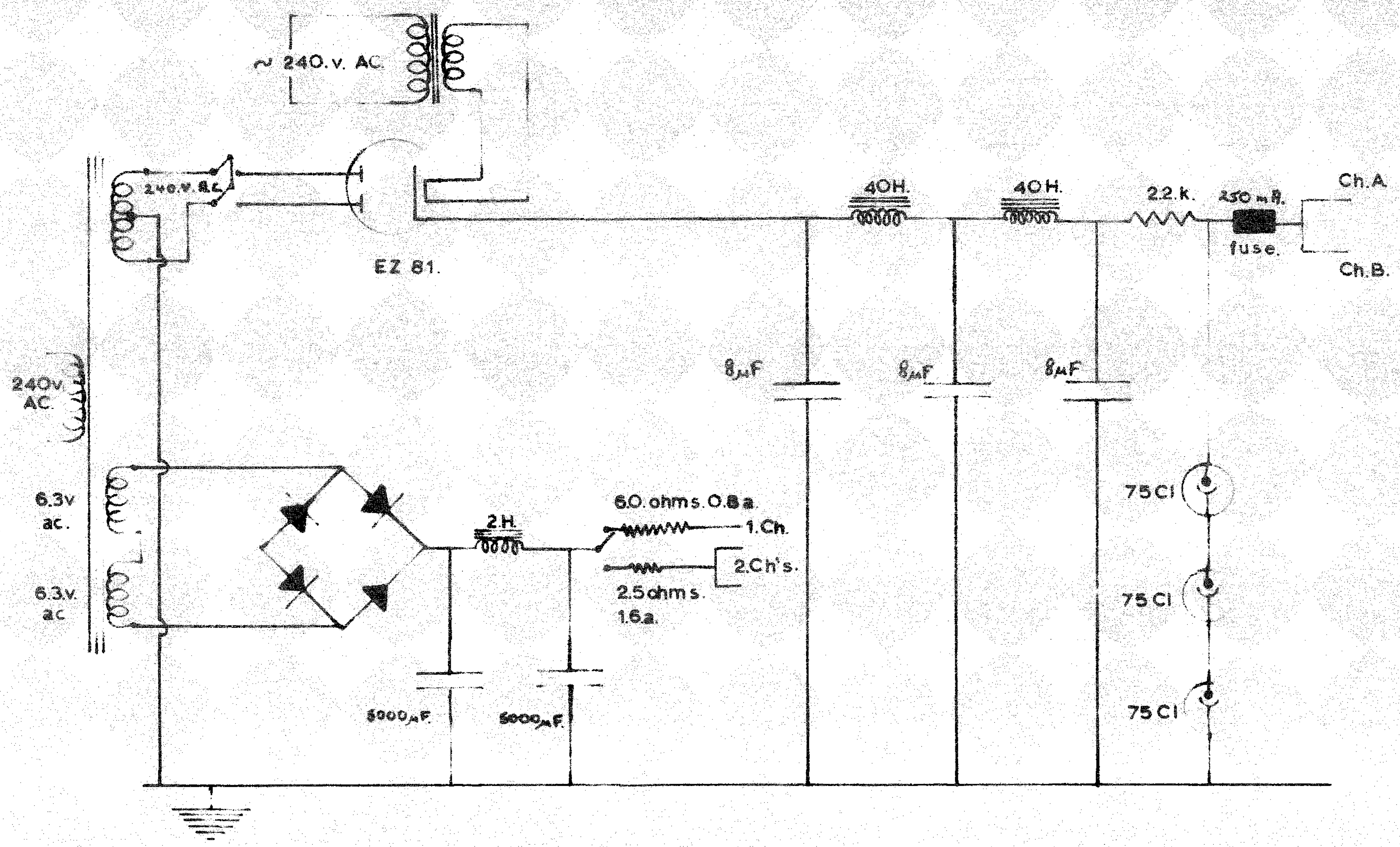

+ 225V.
+. H.T.
10k.
1M.
8μF.
220k.
·01μF
INPUT
EF86.
·1μF
220k.
22k.
680k.
10k.
1M.
220k.
·01μF
EF86.
22k.
·1μF
680 k.
10k
8μF.
220k.
EF86.
OUTPUT
10k.

FIG.65.



PROVISIONAL AMPLIFIER FOR MILL.

FIG 6.7.



'DURHAM MILL' AMPLIFIER.: POWER PACK

FIG.6.8.

run at minimum gain which could be obtained more simply, without the limit in the present case of overloading occuring at 20mV p.t.p. input.

Two amplifiers were constructed using identical EF 86 pentodes to give two stages of R.C. coupled amplification with all components the same value as in the first stage of figure 6.5, with two exceptions. The input resistor was 2 Megohms to obtain an adequate output whilst not sacrificing too much to $\phi(x)$ (Chapter 3), and the anode load of the second stage was a 1 Megohm variable to give crude control over the gain. A cathode follower as in figure 6.5. was also fitted.

The least detectable signal with this amplifier was 8 microvolts as opposed to 6 microvolts in the previous amplifer, and the variable anode load allowed a range of gains between 100 to 3000. The frequency response was effectively flat between 600 cps and 1500 cps, falling off beyond this range, and increasing below it.

The power supplies were obtained from a power pack built and shown in figure 6.8. The H.T. supplies were stablised at +225 volts with three 75C1 neon discharge stabiliser tubes. The 50 cps mains ripple remaining was 5 mVp.t.p. at 100 mA. The heaters were also supplied with D.C. power in an effort to avoid any mains ripple being fed to the amplifiers; three stages of LC smoothing gave

10mV p.t.p ripple at 6 volts, 1.6 amps. The resultant ripple at the output of the amplifier was 0.5 volts p.t.p. (superimposed on mill amplified signal of a few volts) and this could not be reduced even supplying the heater currents from accumulators.

It was necessary to insert a 'Parallel T' network tuned to eliminate 50 c.p.s. signals between the cathode follower and the C.R.O. used for observations, since no matter how much screening was employed a very large 50 c.p.s signal (many volts p.t.p.) was superimposed whenever the mill motor was running. Thus since no overloading of the valves occurred it was possible to eliminate this from the system after amplification.

6.2. The mill performance in the testing chamber.

Throughout the course of the work described in this chapter there was the continuing inconvenience that no recording equipment, such as a multichannel pen recorder, was available, making comparisons of performance, and accurate calibrations extremely difficult. The only means of observing the mill performance was by display on a double beam C.R.O., and it was found necessary to recalibrate the ranges of this instrument to know relative values of signal displayed by it, over a sufficiently wide range of values. Any amplifying systems used included cathode follower final stages for

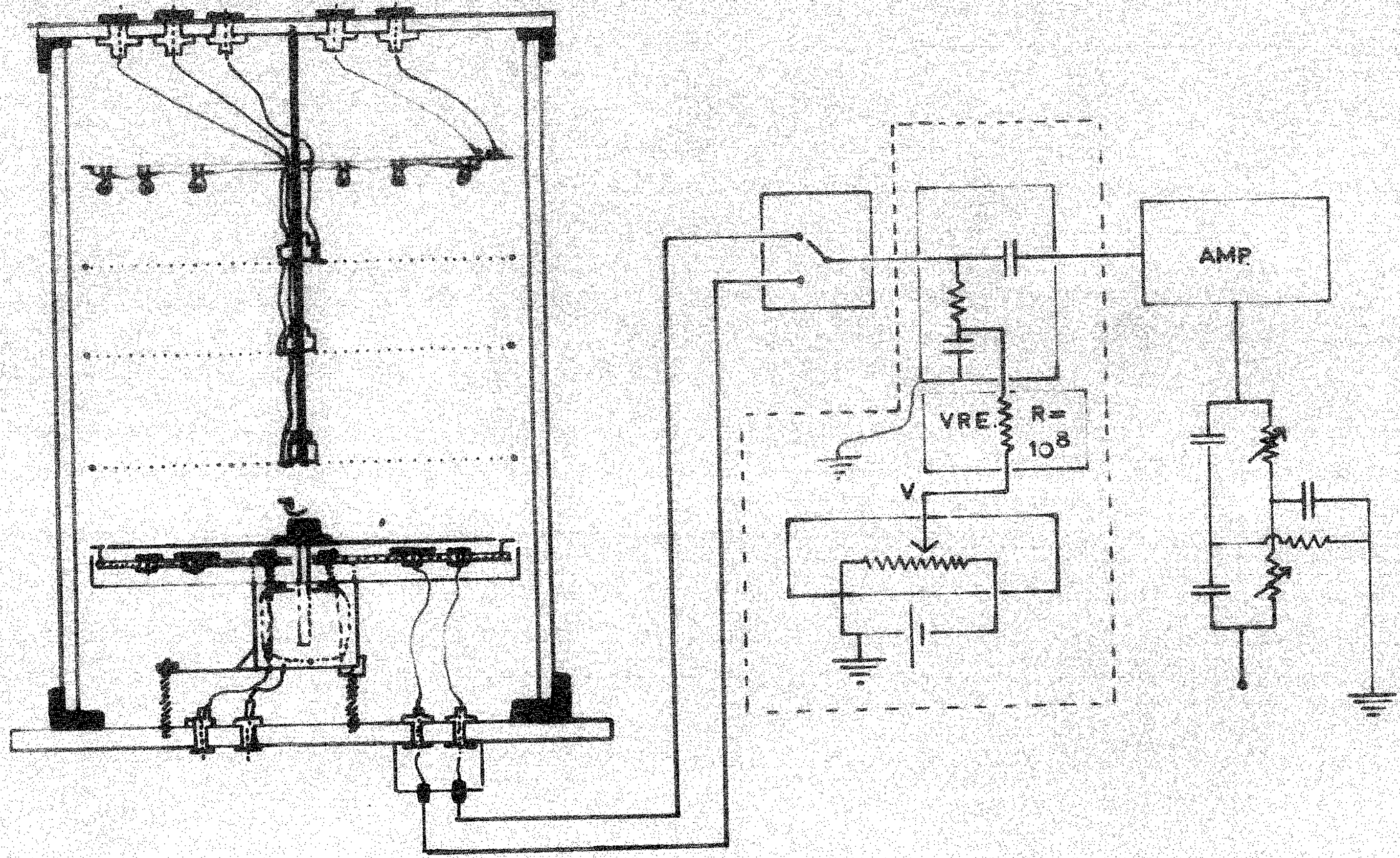


FIG.6.1

connection to dial display A.C. voltmeters or pen recorders, if required but in all the measurements quoted the C.R.O was connected across the anode load of the final amplifying stage, and peak to peak values are quoted.

Figure 6.1. shows the overall set up for examining the mill output when placed in the chamber. By shorting out that part of the circuit enclosed by the broken line the observed output became that from an 'in flight' circuit where no calibrations are possible. All leads were of screened coaxial cable, and the biassing circuit and output selector switch, were each in a separate screening can.

Initially, electric fields only were applied to the mill, both with and without biassing applied to the collector studs to minimise zero output. As the mill theory forecast a higher voltage was required to minimise the zero output from the outer set of studs, both inner and outer sets requiring voltages of between - 0.20v. and - 0.80 volts, measured by valve voltmeter at point 'V' on figure 6.1.. With the rotor/stud clearance of 0.2cms to 0.3 cms, these corresponded to zero outputs of field of a few hundreds of v/m (positive) in magnitude. The same level of minimum zero output could be obtained by disconnecting the biassing circuit and applying a positive voltage to the lowest grid. Since different voltages would have to be applied to the two sets of studs, seriously upsetting the charged particle currents flowing to the two sets, it would be better not to attempt to eliminate the zero output, but to allow for it in calibration, even taking advantage of the possibilities of sign discrimination that if offers.

With the gains of the amplifiers set at x1000 the zero outputs of the inner and outer sets were found to be 4×10^{-4} volts, and 6×10^{-4} volts, peak to peak.(p.t.p). These are two orders of magnitude larger than the field sensitivities expected from mill theory, but since they remained at steady values corresponding to negative fields of several hundreds of v/m, this was no overriding disadvantage.

If the actual curves of output against applied field were plotted, then taking into account the inaccurate methods of measuring the values of output, the slopes of these curves gave field sensitivities of between 5×10^{-6} volts/v/m. and 10^{-5} volts/v/m, with the outer set always having the greater value. This was less in magnitude than expected, but experience with conventional sector type mills has shown that the theoretical output is rarely, if ever achieved.

The fact that there was at most a 2:1. differentiation between the two signals, whether zero outputs or applied field sensitivites, was more disturbing, expecially since when the electron emitting filaments were switched on and the mill subjected to a charged particle flux then the inner (low frequency) set of studs had the greater sensitivity as forecast in Chapter 3. However, in Chapter 3, the condition for $V_i \propto 1/w$ (equation 3.11) was that $w^2C^2R^2 \ll 1$.(see Chapter 3 for symbols), but the above result in practice was found whether or not the current measuring device a VRE with input resistances of 10^8 ohms and higher, was in circuit or the value of R as determined in Chapter 3 was the resistive load of the mill.

At a constant speed of rotation, which was assumed throughout the experiments since the pressure was not permitted to rise above 10^{-4} mm.Hg, the output of either set of studs when subjected to a charged particle flux was not linear as expected. An increase of from say 10^{-10} amps/cm^2 to 10^{-7} amps/cm^2 would result only in a ten or twenty fold increase in output. If such a sensitivity could be accurately calibrated and the field sensitivity retained as indicated, then the deviation from theory could be turned to advantage. Overloading of the amplifying systems due to high currents, when they were being operated at high sensitivity to detect small fields, would not occur until much higher values of charged particle flux were incident upon the mill. The calibration would involve setting up two simultaneous equations which would differ from equations 4.14. in that the current (I) term would be of an as yet undetermined form. Further discussion on this is delayed until Chapter 8, in which the more accurate data from A.F.C.R.L are also considered. The remainder of this chapter is devoted to observations of the operating characteristics of the vacuum chamber and mill, and to an account of an attempt to investigate the 'electrostatic efficiency' of various stud configurations.

The field sensitivities were not affected by the application or otherwise of a zeroing potential to the studs or to the lowest grid. If the emitting filaments were turned on for a short while however, and then switched off, the zero output of the mill was increased to a greater positive field equivalent. Since no zeroing would be possible in a 'flight' model, accurate observations would be impossible if this shift were caused by changes in the mill itself, such as contact potentials changing due to bombardment by electrons or ions. It was noticed that the shift did not seem apparent during the time when the current was being applied to the mill, that is for a given current measured with the V.R.E. the mill output remained constant with time. Any change however may have been obscured by the relatively large signal due to this current since the zero current signal corresponds to a value of I_c in equations 3.8. and 3.9. of about 3×10^{-11} amps/cm^2, and in most cases the applied currents were two or three orders of magnitude greater.

If changes in the mill are discounted, another possible cause of this zero shift, which is supported by the slow return of the zero output to its initial output over a period of minutes, is that a large number of free electrons are left in the volume of the chamber when the emitting filaments are switched off. Workers concerned with similar large volume chambers (Oldenburg A.F.C.R.L personal discussion) have suggested that a thin film of oil from the diffusion pumps of the vacuum system covers all exposed surfaces in the chamber. Usually free electrons have been found to have a higher affinity for a 'dirty' surface than a clean metal surface but a film of oil may have the properties of a very smooth surface and it is therefore a long time before the space charge in the chmaber may leak away to earth.

On some occasions it was noticed that unless the collecting studs were cleaned with CCl_4 the zero output would never return to its initial value although the greater part of the enhanced zero disappeared within a few minutes of switching off the filaments. The mechanical cleaning of the studs involved the opening of the vacuum chamber and this could have removed the last traces of space charge but when the apparatus at A.F.C.R.L. was used in which it was possible to open and close the chamber more conveniently and gain access to the mill this same remanent output was observed with the chamber open and mill running, after allowance had been made for the reduction in mill speed due to its running at atmospheric pressure.

Thus both surface contamination of the mill, and residual space charge in the vacuum chamber seem to occur, but the latter is more important and after several hours of use without mechanical cleaning, over a period of several weeks, the surface contamination effect becomes negligible presumably as the surfaces 'weather'. It might therefore be worthwhile 'weathering' in such a current flux, any apparatus intended for use in actual experimental flights.

It was at this stage (May 1961) that confirmation was received from the Photochemistry Laboratory A.F.C.R.L, of the availability of space for any device developed in this work on two Aerobee-hi research rockets, scheduled for firing in 1962. Bearing in mind the performance of the mill as just described, it was decided to complete the development and design of the final 'flight' model, at A.F.C.R.L itself, and four months (July to November 1961) were spent there for that purpose.

The factors supporting this decision, apart from its more obvious attractions, were;

a) The availability of a large volume, rapid pumping, vacuum system suitable for testing and calibrating the instrument.

b) The availability of multi-channel recording equipment, power sources and amplifiers.

c) The fact that no alterations of any kind are possible to any research instrumentation later than about four or five months before the scheduled firing date. A strict check on all stages of construction of this instrumentation and of its testing and calibration is therefore desirable.

6.3. The electrolytic tank.

In the time remaining before this work could be arranged, it was decided to try and devise some means of comparing the relative amounts of field distortion and loss of bound charge, caused by the various rotor/stator configurations. This could have been done by constructing a number of mills of various dimensions and configurations, but this would have involved considerable time and expense. It was reasonable to suppose that one stud and its complementary screening hole, would display the same properties and relative 'electrostatic efficiency' with respect to bound charge as a complete set of studs, so a means was sought of testing a range of studs and holes under controlled conditions.

Now a means of reproducing the potential distribution in a multi electrode system is the electrolytic tank (Cosslett 1950, Bromer 1960). In this, a model, full sized or otherwise, is set up so that the various potentials may be applied to it as in practice, and it is then completely immersed in an electrolyte solution. Due to the conductivity of this solution no space charge can exist within it and Poisson's equation for the system becomes;

$$\frac{d^2V}{dx^2} + \frac{d^2V}{dy^2} + \frac{d^2V}{dz^2} = 0 \qquad \ldots.\ 6.1.$$

Where V is the potential at any point in the system. The solution thus has an ohmic resistance and the current flowing across any elementary surface within it is directly proportional to the value of dV/dx, etc. at that surface.

Usually an A.C. field is applied at about 1000 cps. to reduce polarising effects in the solution, which is often $CuSO_4$, though in many cases, including the present one, tap water was found to be satisfactory. With a reference potential, usually one of the electrodes, and a tip probe on insulated leads, it is possible to determine the potential at any point in the electrode system, by making the resistance of the solution between the tip probe and the reference electrode one arm of an A.C. bridge circuit.

In the present case however it is the potential gradient at the working surface of the collector stud which is of interest, and due to the ohmic resistance of the solution this will be indicated by the current flowing to such a stud set up in an electrolytic tank.

In the mill theory for a non conducting medium the charge Q on the collector is;

$$Q = \varepsilon_0 EA \qquad \ldots.\ 6.2.$$

then the electrostatic efficiency for bound charge collection, and hence for field sensitivity will be directly proportional to the current flowing. With a constant value of the A.C. field applied, a quick comparison of various configurations may be obtained.

The screening cycle cannot be reproduced of course, though due to the 1000 cps applied field the total current flowing through the collector will vary in a similar way to the field mill, although the geometry will not alter.

Figure 6.2a shows diagramatically the apparatus used for this work, and figure 6.2b. shows the stud configuration in more detail. A series of studs ranging from 0.4 cms to 2.5 cms in diameter, and a range of plates 10 cms by 8 cms with corresponding holes ranging from 0.65 cms to 2.6 cms diameter were constructed. The screening plates were of Al and the studs brass soldered onto 4B.A. screwed rod. The field was applied by placing the studs between the Al baseplate (45 x 30 cms), and a similar upper Al sheet which slid up and down Tufnol rods mounted in the base, by means of rubber grommets. A third Al sheet, also sliding on the Tufnol rods supported the plates containing the screening holes. This plate, and the base were earthed and A.C. field voltage was applied to the top plate. The whole was immersed in tap water in a six inch deep glass tank as shown in figure 6.3b. Figure 6.4a. shows the lower two

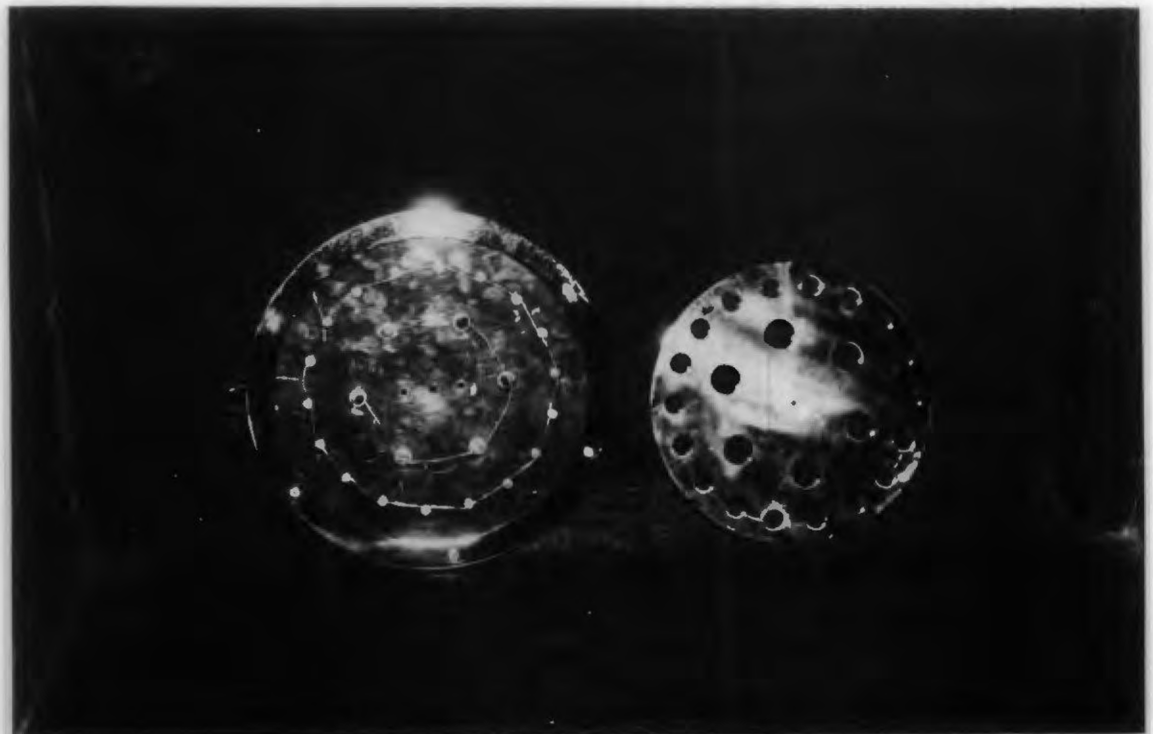


Fig. 6. 3a.

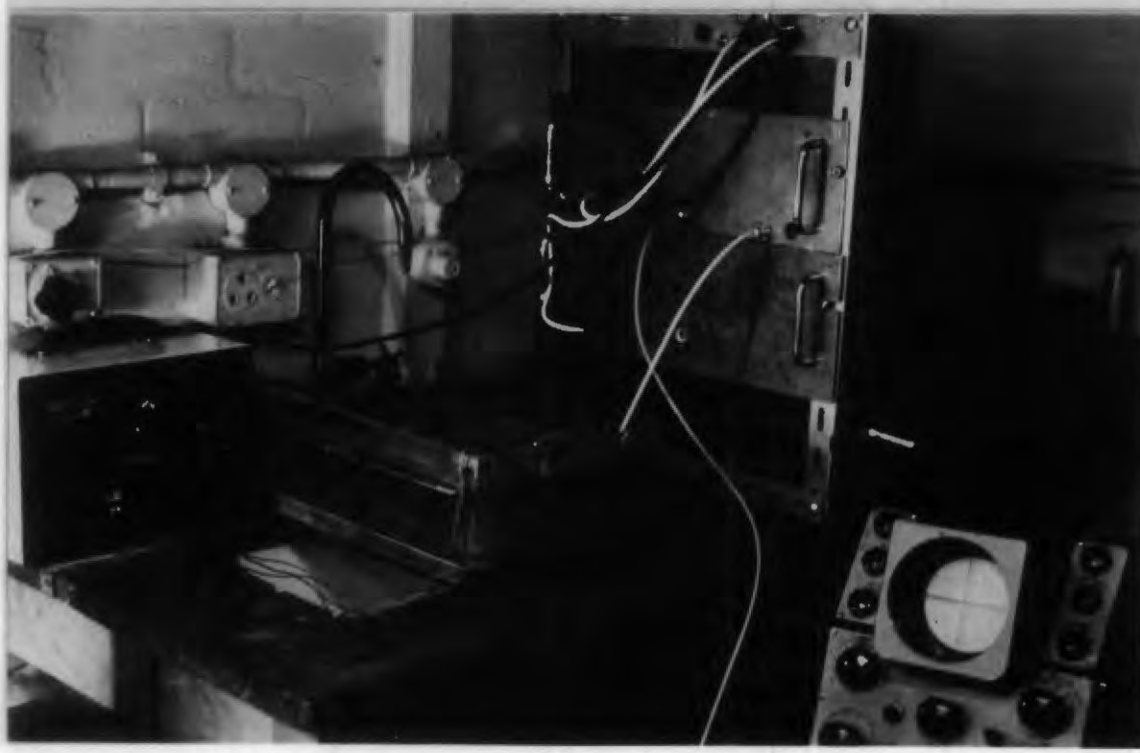


Fig. 6. 3b.

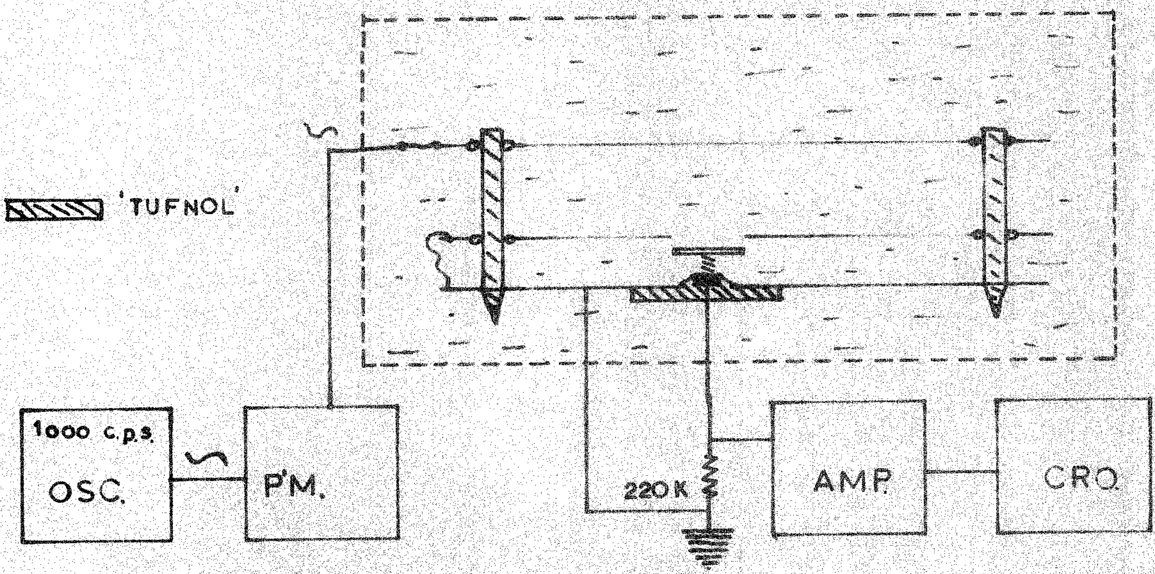


FIG.6.2a.

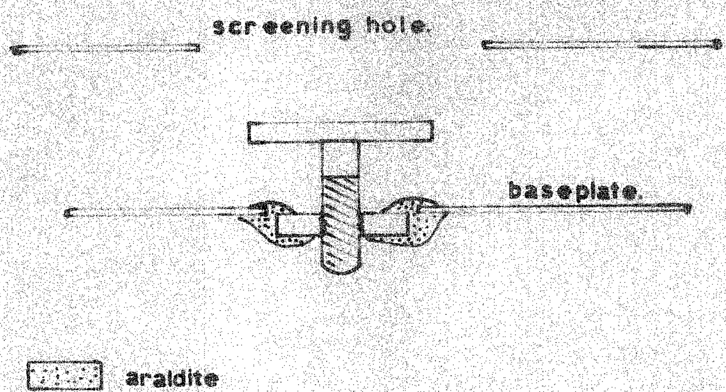


FIG.6.2b.

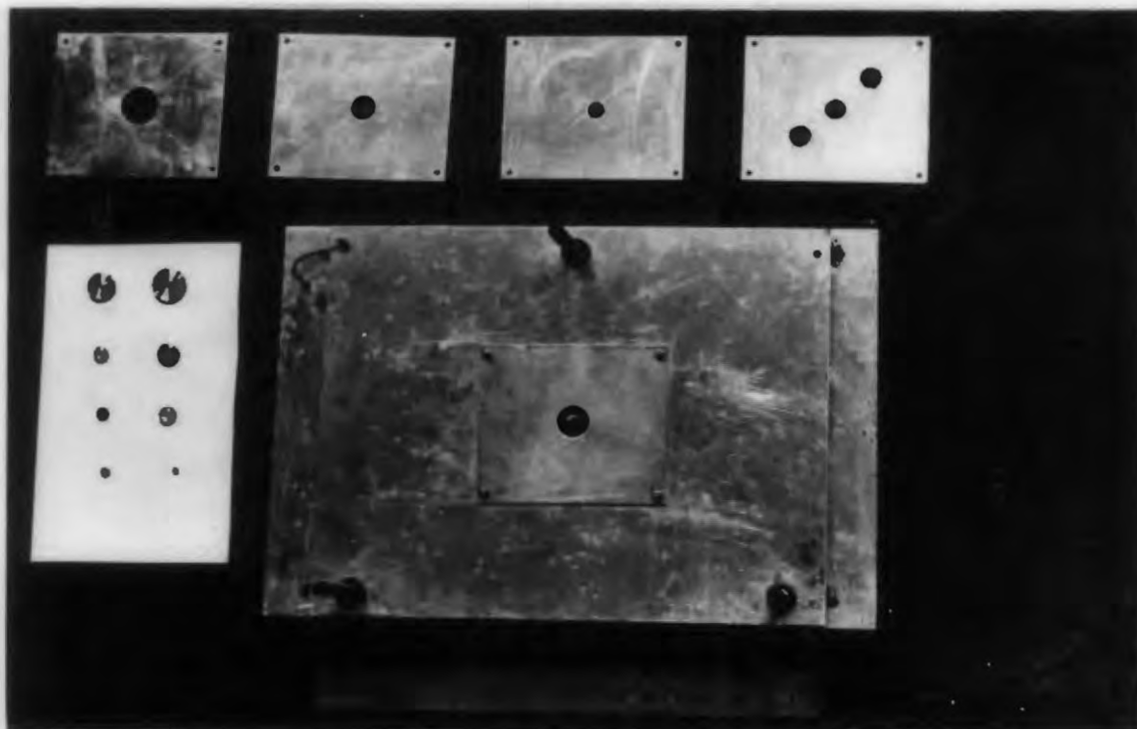


Fig. 6. 4a.

Fig. 6. 4b.

plates with a stud and screening plate in position, as well as showing the same plates, and collector stud prior to being mounted on screwed rod.

The A.C. flowing to the stud on its insulating mount was passed through a resistance R = 220k, which formed the first grid resistor of an amplifier modified from those described in Chapter 5, and shown in figure 6.5. The input resistor was reduced to reduce the loss of current flowing from the stud to the baseplate through the solution rather than through R.

6.4. Results and conclusions from electrolytic tank.

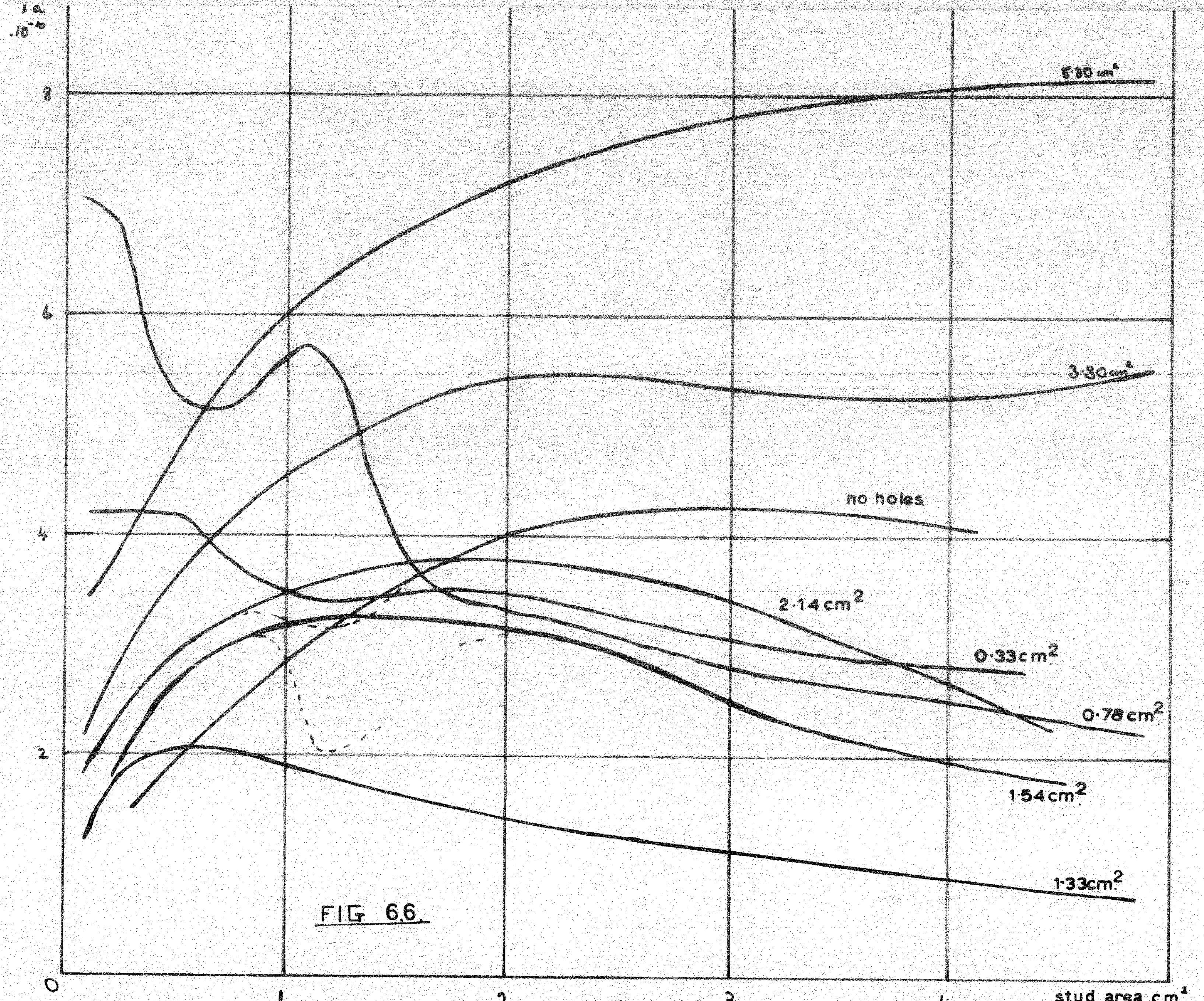
Before the main set of readings were taken, a number of subsidiary tests were carried out, which are given below in note form.

i) For a given applied field, and stud and hole size, the current collected varied by as much as a factor of three when the height of the upper surface of the middle plate was varied between 0.2 cms and 0.5 cms above the upper surface of the stud. In a mill of course, this distance would be subject to a lower limit determined by the thickness of the rotor, to allow it to clear the stators at all times. In addition the capacitance of the rotor/stator system is inversely proportional to the rotor/stator distance, thus although an increased bound charge should be collected the zero output from a mill would also increase with it.

ii) If no middle plate and screening hole are used then when exposed to the A.C. field a fortyfold increase in area resulted in a three fold increase in current for a given field. During this experiment the upper surface of all studs were 0.6 cms above the baseplate giving the curve labelled 'no holes' in figure 6.6. If for a given stud and field, this height were varied however, then the output varied by a factor of from three times to five times as in i.

iii) If the A.C. field were kept at a constant voltage but its frequency varied by using a B.F.O. as the source, then the current collected by any one stud decreased by about 15% from 100 cps to 1000 cps.

iv) To examine whether or not the close proximity of adjacent holes in the rotor would cause any further field distortion and loss of 'efficiency' a plate was constructed with a line of three holes, each 1.0 cm diameter (0.78cm^2), with 2.0 cms between centres. This corresponded to the conditions of closest approach between holes in the mill constructed in Durham. A 1.0 cm diameter stud was



.10⁻¹⁰
8
6
4
2
0
1
2
3
4
stud area. cm²
5·30 cm²
3·30 cm²
no holes
2·14 cm²
0·33 cm²
0·78 cm²
1·54 cm²
1·33 cm²

FIG 6.6.

placed under the centre hole with a clearance between the upper surfaces of the stud and middle plate of 0.3 cms. The current collected by this was no different from that collected using a single screening hole with the same clearance, so it was assumed that no interference to the low frequency signal would result from the nearby outer set of studs giving the high frequency signal, being exposed and screened three times during the course of a single low frequency cycle.

The full results of the various combinations of stud and hole size are given in figure 6.6. The range of both variables covers all values that are likely to occur in practice, the hole sizes being indicated on each curve and the various stud sizes used in the construction of the curves is also indicated. The actual dimensions to be used were employed since results, cannot be extrapolated in either direction reliably due to what appears to be the effect of the [edge length: surface area] ratio ($\propto 1/r$). In the case of the smallest studs this may be very appreciable due to field augmentation similar to that described by Clark (1957), and for the studs area 0.33 cms^2 and 0.78 cm^2 the curves have little similarity with the other curves obtained.

The field applied was 25v. peak to peak with an upper to middle plate separation of 8 cms, giving a free space applied field of $\mp$ 125 v/m. This was monitored continuously on one beam of the Cossor C.R.O, which was used to obtain the results shown.

Upon examining figure 6.6. it would seem that for any stud size there appears to be an optimum screening holes size and since small signals are to be dealt with it is worth while considering their actual magnitudes as well as the differentiation due to the working parameters of the mill.

The falling off in current collected with increasing hole size above this optimum value may be due to the concentrating effect of the rim of the hole upon the electric field. When the hole is too small for the size of stud most current flows to the middle, earthed, plate, and when it is too large the current falls off since the field is undisturbed, causing no increase in field at the stud.

As mentioned, with the two smallest studs no trend is discernible; this may be due to the edge length: surface area, ratio mentioned, and also to the fact that the diameters of the studs are not much greater than the 4.B.A. rod on which they are mounted, and may tend to spread out the potential distribution and hence currents collected rather than letting higher gradients around the edge of the studs collect higher currents. ($I \propto dV/dx$).

Ignoring the two smallest studs the ratio of hole: stud, diameters at optimum output varies from 1.05 to 1.33, with a mean at 1.14 $\mp$ .04. and this may give a possible explanation of the relatively poor performance of the Durham mill in which this ratio was 2.17 and 2.27 for the inner and outer sets. These dimensions were chosen at an earlier stage in the work to maintain the ratio set by previous constructors of such mills. Also there is the added factor that since the sheet of Al to eliminate the large zero output (equivalent to several thousands of volts per meter) had to be added after initial construction, the upper surfaces of the collecting studs were flush with the upper surface of this sheet, and was at a clearance of about 0.1 cms all round from all studs. This may have caused loss of field strength at the collecting surfaces and this is supported by the observations concerning the relative elevations of components in sections 6.4i. and 6.4ii.

Further losses will have been caused by the fact that although the 50/50 open/solid ratio is maintained for the screening rotor dimensions due to the dimensions given this is not attained in the stud system and this will give an intermittent output signal. This showed itself as an asymmetry in the waveform produced; the decay side of a positive or negative maximum having a dog-leg near its maximum (initial) value.

To sum up, the points to be considered when designing a mill for use with small signal where optimum output is desired.

i) The collector surfaces should be raised as high as possible above the baseplate.

ii) The rotor clearance of the studs should be as small as possible even though this will increase the zero output due to increased capacitance.

iii) The separation of the holes between adjacent sets, and in the same set, should be as large as is compatible with other limits, and with the overall size limit on the instrument.

iv) The ratio of the hole and stud diameters should be approximately 1.14:1, in each set.

The above recommendations apply only to the efficiency of a configuration with respect to the collection of 'bound' charge induced by applied electric field. If the charged particle sensitivities are to be investigated a knowledge of the range of energies that such particles are likely to have would be required.

Work done at A.F.C.R.L.

July - November 1961

Chapter 7.

The 'flight model' mill, and the apparatus for its calibration.

7.1. Introduction.

The apparatus described in this chapter comprises; the final 'flight model' of the mill, as designed with the previously described work in mind, the vacuum chamber, electron emitting filaments and accelerating grids placed within it for the charged particle flux production, the circuitry for controlling the voltages on these grids and filaments, and also the amplifying and calibration circuits connected to the mill.

7.2. The Mill.

Three identical mills were constructed by Comstock and Westcott Inc. to the designs given below; two of these were for flight in the Aerobee Hi's mentioned, and the third was tested and calibrated in the vacuum chamber at A.F.C.R.L. and which is described in section 7.5.

The dimensions of the mill, which is shown in section by figure 7.1, and in plan in figure 7.2, were subject to two limitations only; the overall diameter could not exceed $6\frac{1}{4}$" (15.8 cms.) and the overall depth could not exceed 5". (12.7 cms.).

The outside diameter was fixed at 6" (15.3 cms.) being

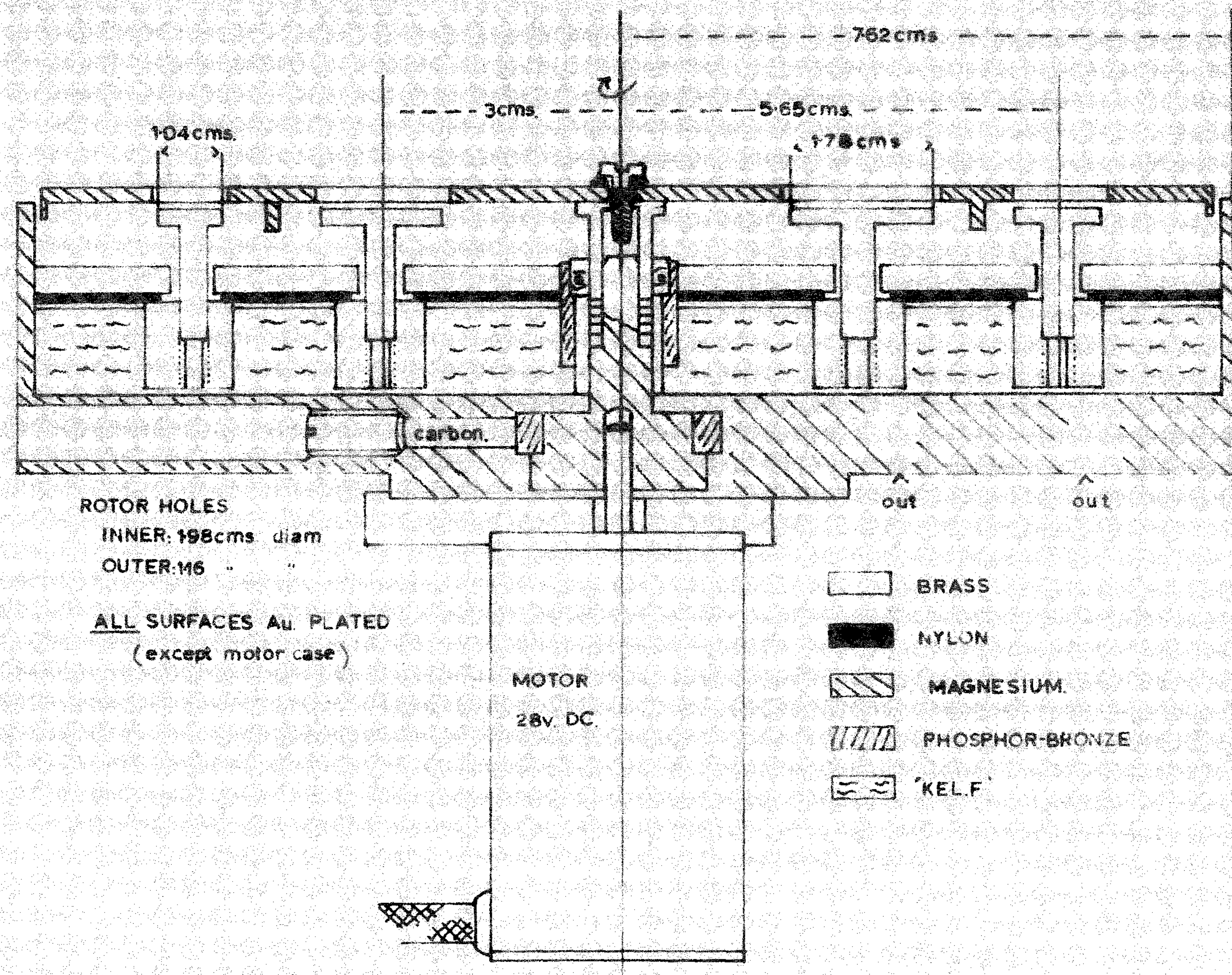


FIG.7.1. TWO FREQUENCY MILL – FLIGHT MODEL.

a convenient value and reducing the risk of damage to the mill by it striking its surrounds in the maximum permissible aperture in the rocket skin, during the vibrations in the powered portion of the flight. In order to utilise as much surface area as possible, the guard ring of the Durham model was superseded by making the screening rotor a shallow 'umbrella', with its vertical walls extending both inside and below the outer casing, to shield the stator systems from spurious 'side fields'. It would of course be possible to dispense with the casing entirely and make the walls of the umbrella deeper. This would increase the weight to be turned by the motor however, increasing the time to attain the correct running speed, an important factor in a flight lasting about fifteen minutes, and would also increase the likelihood of damage to the motor shaft and bearings due to vibration.

Bearing in mind the limiting diameter, it was decided to retain the 3:1 frequency ratio but to have only four studs in the inner set and twelve in the outer. The electrolytic tank work would suggest that the holes should be larger (1.14 :1) in area than the studs which they screen, so that 50:50, screened/exposed time division cannot be employed.

The studs were mounted in two concentric brass rings as shown in figure 7.1. and they could be screwed up and

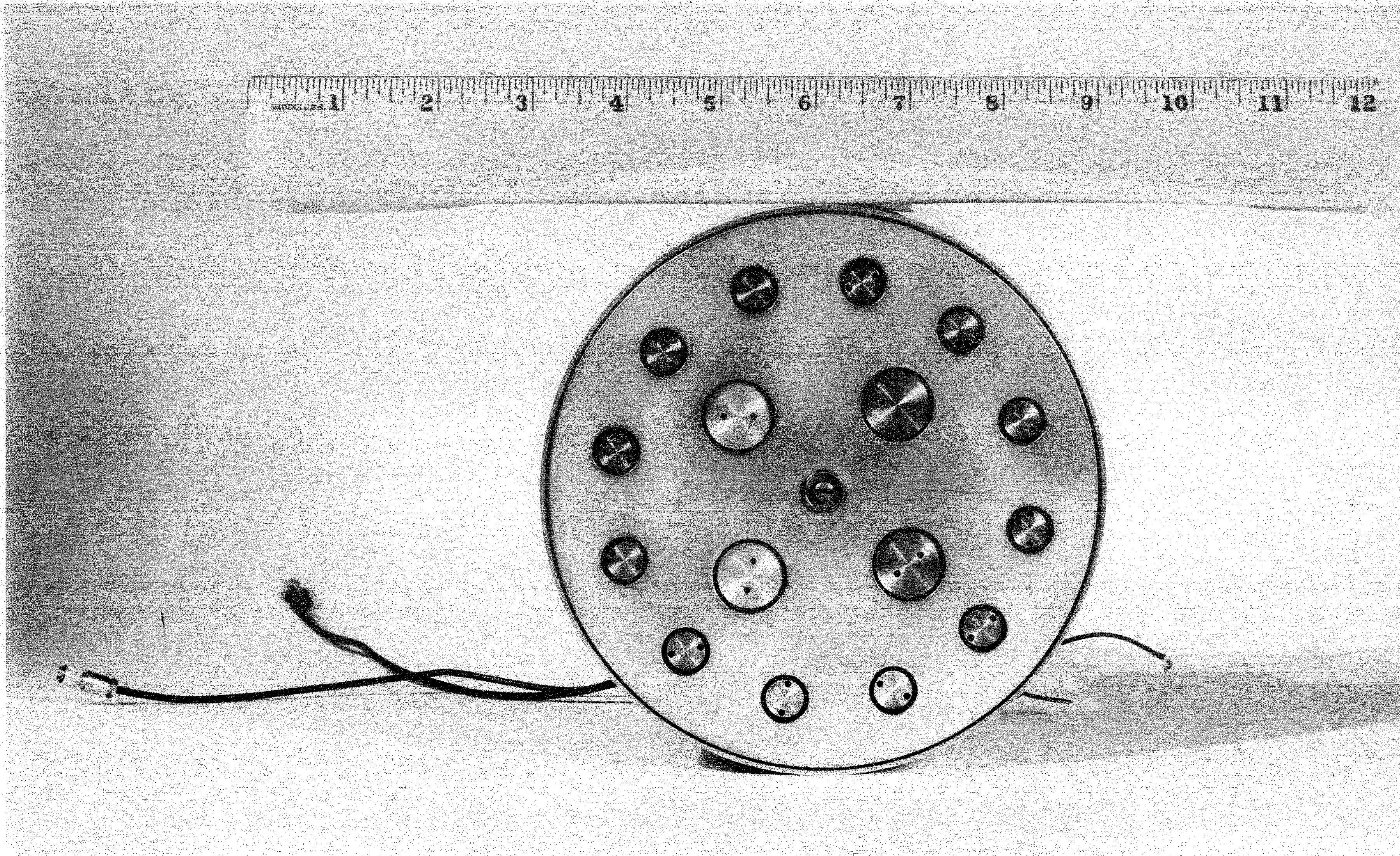


Fig. 7. 2.

down individually, being locked in position by a nylon rod which partially protruded into each threaded hole in the retaining rings. Two small holes were drilled in the upper surface of each stud into which a special tool fitted to make these vertical adjustments. The brass retaining rings were both embedded in one solid piece of insulator ('Kel F') and their upper surfaces were 0.2 cms. above that of the insulator to allow the rings to be held tightly as shown in figure 7.7. The whole assembly was then slip fitted into the outer casing and held in place by a conducting sheet through which the studs projected but did not touch. This plate sandwiched the insulator and a thin layer of Nylon which held the rings firmly in place, by four screws which went through clearing holes in the Nylon and Kel F, and screwed into the base. A brass rod was fixed in each mounting and the output leads were soldered to these below the main body of the mill, in a screening can.

All conducting parts were made of brass with the exception of the rotor and outer casing, which for the sake of lightness and ease of balancing were both turned from solid Magnesium. The rotor was screwed into a sleeve which fitted onto the motor shaft and its height could be adjusted by means of three washers each 0.15 cms. thick which fitted onto the rotor inside the sleeve. With all three washers in place the lower surface of the rotor was 1.5 cms. above the conducting cover to the Kel F and Nylon, and about 0.1 cms. above the upper surface of the studs in the highest position to which they might be raised and yet remain secure.

The dimensions chosen for the two collector systems were;

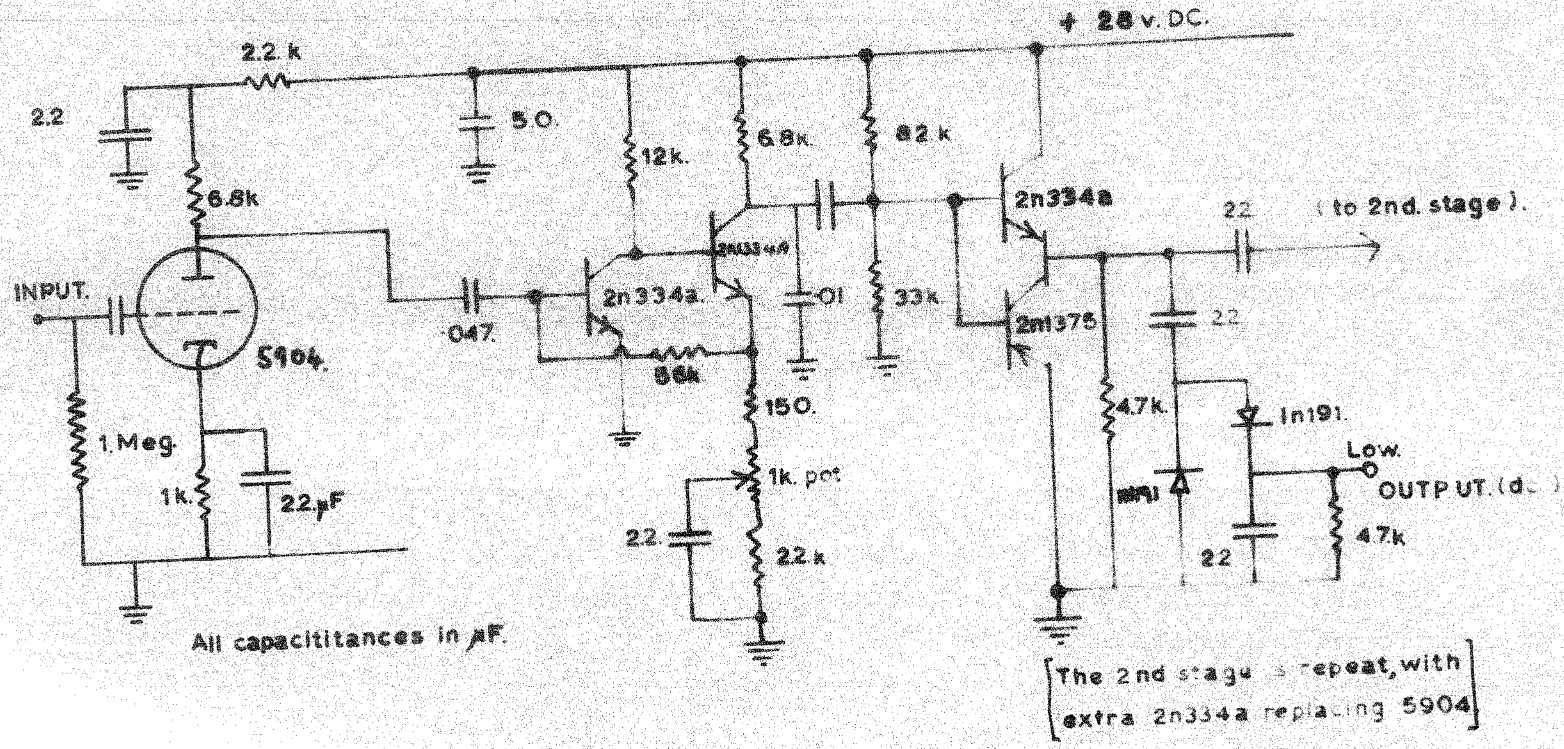
	Inner set (4)	Outer set (12).
Hole radius	0.99 cms	0.58 cms
Stud "	0.89 cms	0.52 cms
Mounting "	3.0 cms	5.65 cms.

In each case the total stud area is 10cm^2 (4 x 2.5cm^2, and 12 x 0.83 cms^2), and for the rotor the solid/open ratio on a line through the centres is in both cases 42:58.

The motor was a 24V. D.C. model, which ran free at somewhat above 10000 r.p.m, and this speed was not greatly reduced by the load of the rotor when running in vacuum. It was initially intended to maintain the rotation at 8000 r.p.m. using a centrifugal switch regulator attached to the motor shaft, but this generated so much spurious noise in the mill output that it had to be discarded. This noise could in fact be successively reduced by earthing both ends of the screening of the coaxial leads carrying the mill outputs, and by placing a miniature 100μF condenser across the terminals of the motor, but it was still too high to allow measurements to be made to the mill output proper. With the condenser and regulator connected, a C.R.O. connected across the mill terminals showed 'spikes' of as much as 0.5 volts, at a few cycles per second and these were amplified and displayed on the pen recorder employed. The regulator was therefore disconnected and then unless the motor was run in excess of 8000 r.p.m. no interference was detectable. This residual noise could probably be eliminated or further reduced by using output leads with Cu cores and screening; in fact temporary leads of this kind were tried and considerably reduced this noise, indicating that it was mainly magnetic.

However it had previously been found that even with the motor without regulation its velocity of rotation with the rotor remained constant at pressures below 10^{-1} mm. Hg and it was therefore decided to regulate the motor speed by the voltgage supplied to it.

This voltage was finally set at 13.5 volts, which in vacuum turned the rotor at 6250 r.p.m, giving signal frequencies of 416.7 c.p.s and 1250 c.p.s. This speed reduced the motor noise mentioned above, to a negligible level, and also lowered the value of (wCR) enabling a reasonable frequency differentiation to be obtained (Chapter 3). This was the only way of achieving this, since the value of C was higher than in the Durham case. This was probably due to the massive brass mounting rings



Prototype 'Flight' Amplifier.

FIG. 7.3.

for the studs, and the block of 'Kel F' insulator in which they were embedded. Measurement of the changes in capacitance caused by the total removal of the motor confirmed this, making less than 10% reduction.

7.3. The amplifiers.

An amplifier prototype for the actual flights was used for the laboratory calibrations at A.F.C.R.L.

It was constructed by Comstock and Westcott Inc. to the following requirements;

a) The telemetry system of the vehicle necessitates all information to be expressed as 0 - 5v. D.C. positive for transmission. The amplifier should therefore have two ranges giving 5v. d.c.for 15mV peak to peak (high sensitivity) and 60mV (low sensitivity).

b) A reasonably flat frequency response between 300 c.p.s. and 1500 c.p.s.

This amplifier is shown in part (low sensitivity stages), in figure 7.3. It consisted of two transistorised A.F. amplifiers, run in series to give a low sensitivity output after one stage, and high sensitivity after two. In each part the gain is varied by changing the bias resistor of the third emitter. However it was found that in order to reduce a very high zero signal from either 'stage' (approx 1 v.d.c. from low sensitivity) the first transistor had to

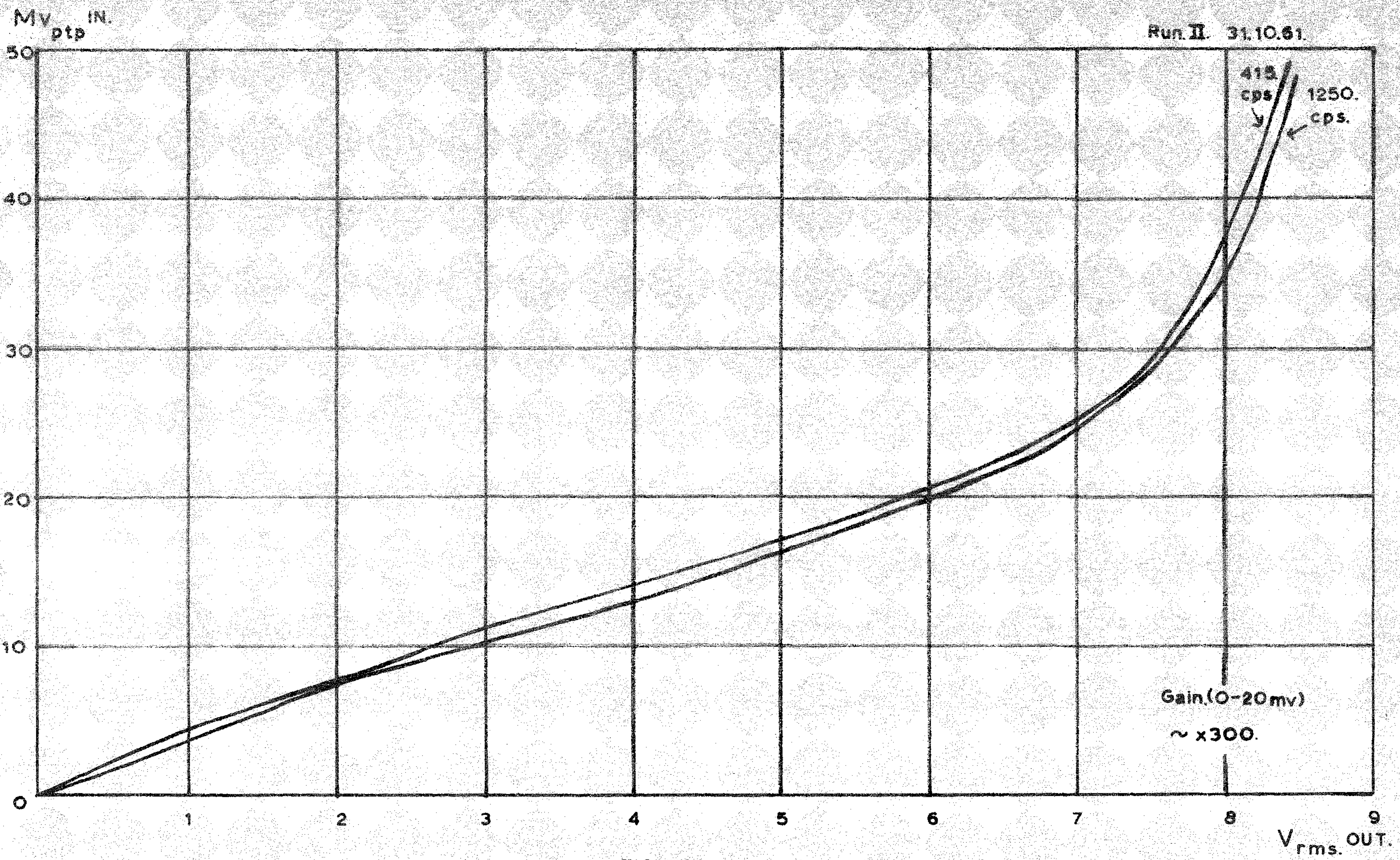

Mv ptp IN.
Run. II. 31.10.61.
50
40
30
20
10
0
1
2
3
4
5
6
7
8
9
415. cps
1250. cps.
Gain.(0-20mv)
~ x300.
V rms. OUT.

FIG. 7.4.a.

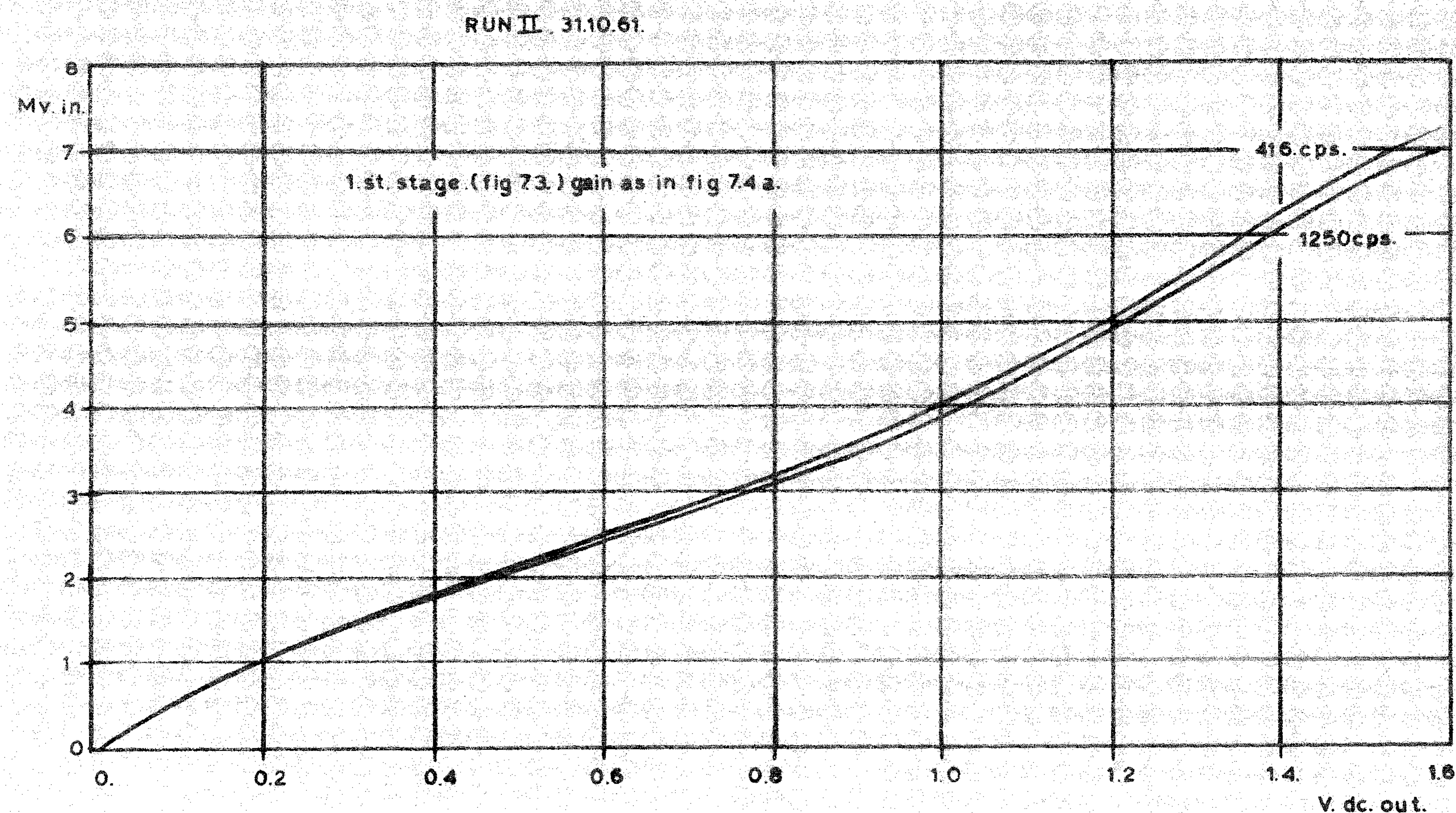

RUN II . 31.10.61.
8
Mv. in.
7
6
5
4
3
2
1
0
416.cps.
1250cps.
1.st. stage (fig 7.3.) gain as in fig 7.4 a.
0.
0.2
0.4
0.6
0.8
1.0
1.2
1.4.
1.6.
V. dc. out.

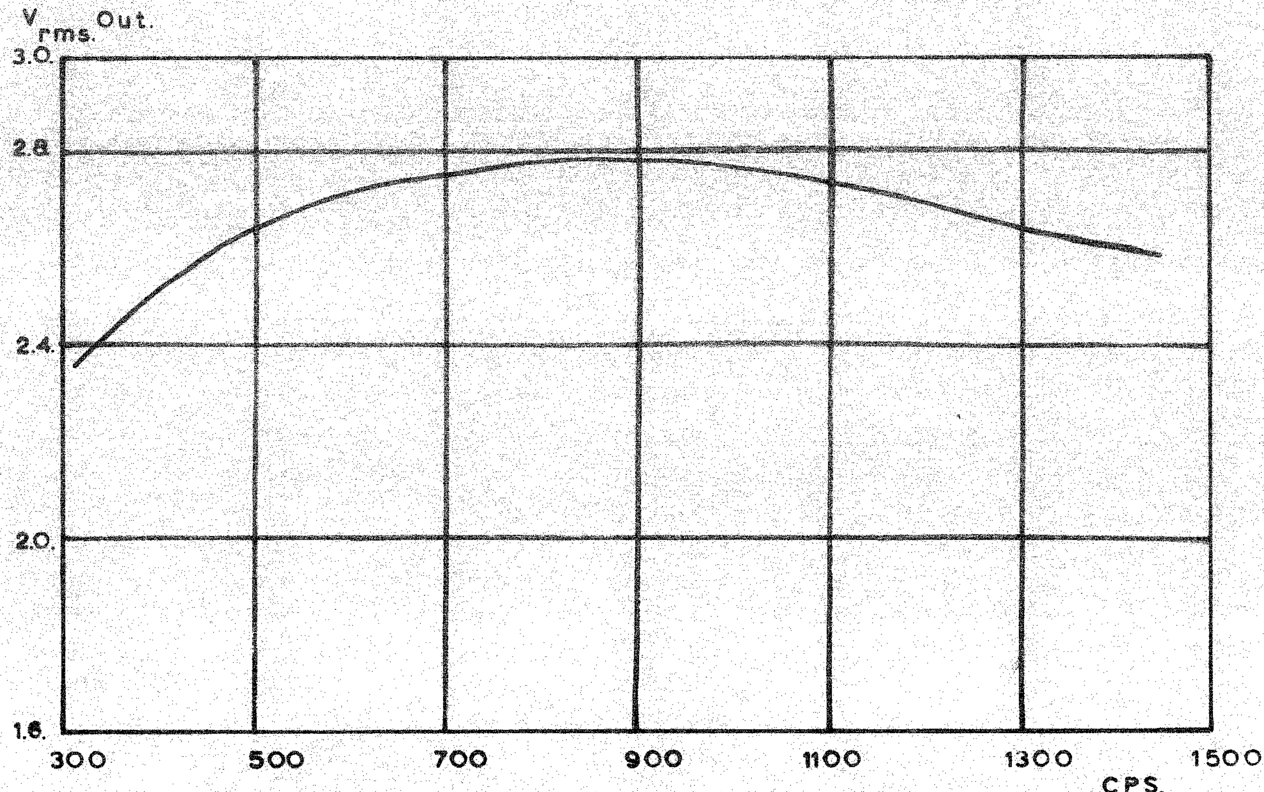
FIG.7.4b.

be replaced by a Sylvania 5904 electrometer triode since the input resistances needed to comply with $\phi(x)$ were too high for use with transistors.

The high gain stage, that is the output from the two amplifiers working in series, was originally included because the theory of the mill gives estimated field induced outputs of the order of 10^{-5} volts p.t.p. Although the Durham mill had a large minimum signal of several mV, even with biassing applied to the studs, which obscured this sensitivity, it was hoped that a properly engineered example might improve this.

The sensitivity of this prototype amplifier (first 'stage', as used) is shown in figures 7.4a. and 7.4b. In these curves, which show the sensitivities used in all calibrations used here the low sensitivity is set at almost its maximum value using an input of 10mV peak to peak at 1000 c.p.s. The frequency response at this sensitivity is shown in figure 7.5. and from figures 7.4a and 7.4b the gains at 416 c.p.s and 1250 c.p.s, may be deduced as x240 and x280 respectively.

This setting was chosen after a preliminary examination of the mill output for applied field and also having regard to the risks of overloading the amplifier when realistic values of charged particle flux (fig. 2.5.) were applied to the mill. Since the mill turned out to be less sensitive to this flux than expected, the amplifier remained on what is



Frequency Response. Input = 15 mv. ptp.

FIG. 7.5.

effectively a linear sensitivity with currents as high as 10^{-8} amps, which produced mill outputs between 5 and 10mV.

When the second portion of the amplifier was used as well, gains as high as 10^4 could be obtained but at the expense of a high zero signal, and a very limited range of inputs.

7.4. The Keithley amplifier.

For current sensitivity calibrations it was necessary to know the current flowing through the collecting studs, the input resistor, and to earth. In figure 6.1. this current is measured by the voltage that it develops across the high input resistance of a Vibron model 33 vibrating reed electrometer. This, of course, upsets the values of (wCR) so that it must be assumed that the current produced by the filament system is steady, allowing the measuring resistance to be temporarily switched out of the circuit, restoring the 'true' vâlue as decreed by (wCR).

At A.F.C.R.L. however compact D.C. amplifiers with logarithmic response of 0 to 5v. D.C. for inputs of 10^{-10} to 10^{-4} amps were available. These were constructed by Keithley Instruments Inc. to a circuit based on that given by Praglin and Nichols (1960). These have a very high percentage of feedback across the high resistance required to detect such small currents, and have thus a low external impedance. They were placed in circuit as in figure 6.1. without disturbing (wCR), allowing continous monitoring of the intermittent D.C. current flowing from the collectors. Separate amplifiers were needed for positive and negative inputs, a negative amplifier being employed in this case.

However it was quickly discovered that the resistance of this D.C. amplifier was varying considerably with applied current, and greatly disturbing the mill output as was shown by the drop in mill output when the Keithly amplifier was disconnected and (wCR) restored. It was therefore necessary to revert to the method employed in Durham with the V.R.E, and disconnect the current measuring element whilst the mill output was noted, taking care that the lead was earthed.

7.5. The test rig.

The method of producing a flux of charged particles, in this case electrons, upon the mill is discussed in Chapter 5. In the work at A.F.C.R.L, the tungsten filaments of twelve 28 volts aircraft lamps were run in parallel from a variable voltage, 0 - 28v. 0 - 3 amp. supply. Each lamp base fitted into a batten holder and twelve such holders were mounted on an Al. sheet 15½" in diameter.

The mill itself was mounted on a 1/8" Al. sheet 16" in diameter by four threaded holes in the Magnesium base, and a second Al. sheet was fitted by screwed rod, to the first so that it was flush with the upper surface of the mill

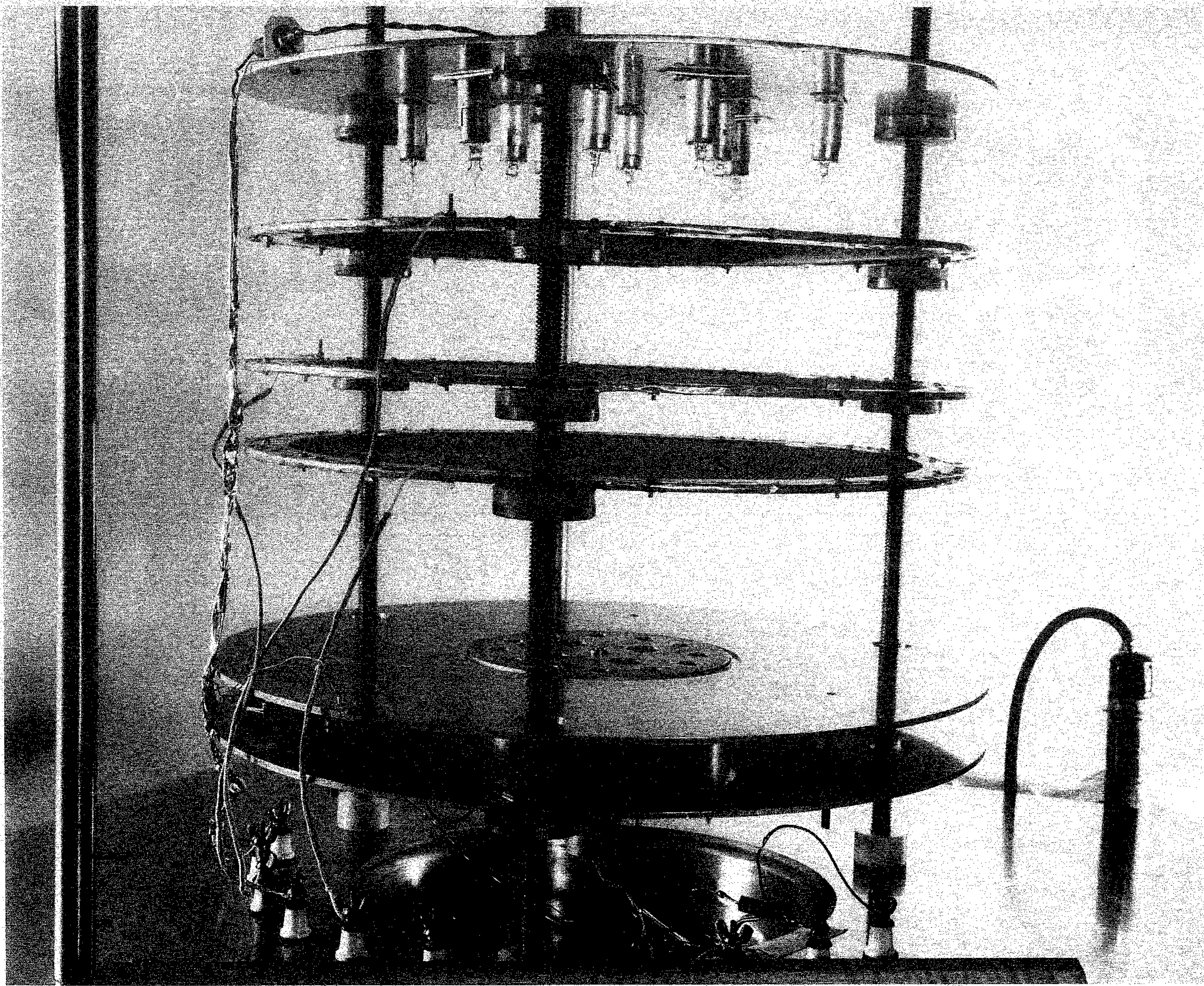


Fig. 7. 8.

rotor. This was to minimise electric field distortion due to projections, etc.

The emitter filament holder baseplate, the three accelerating grids and the mill mounting assembly were all mounted in the vacuum chamber on three $\frac{1}{2}$" screwed rods which fit threaded holes 120^{o} apart on a 7" radius in the baseplate of the vacuum chamber. Insulating mounts for these three rods were made of 'Teflon' which screwed into the holes in the base and the rods screwed into them, allowing the rods to be placed at a potential other than earth if required.

The grids and the emitter base were mounted on Nylon bushes supported by 1$\frac{1}{2}$" nuts on the screwed rods, these being shown in figure 7.6. The grids themselves were made of steel mesh of wire 0.08 cms diameter, with a spacing of 0.3 cms. giving an optical transparency of approx. 70%. Each was held taut by being clamped between two 1/16" Al. rings $\frac{7}{8}$" wide, around their edges, these rings fitting over the screwed rods and being supported as described.

The whole assembly is shown in figure 7.8, with the lowest grid raised somewhat. In this, the vacuum chamber is raised to allow access to the apparatus inside. The screwed rods were 30" high and the upper surface of the mill assembly was about 5" above the chamber baseplate.

For vacuum working the chamber (steel bell jar), was

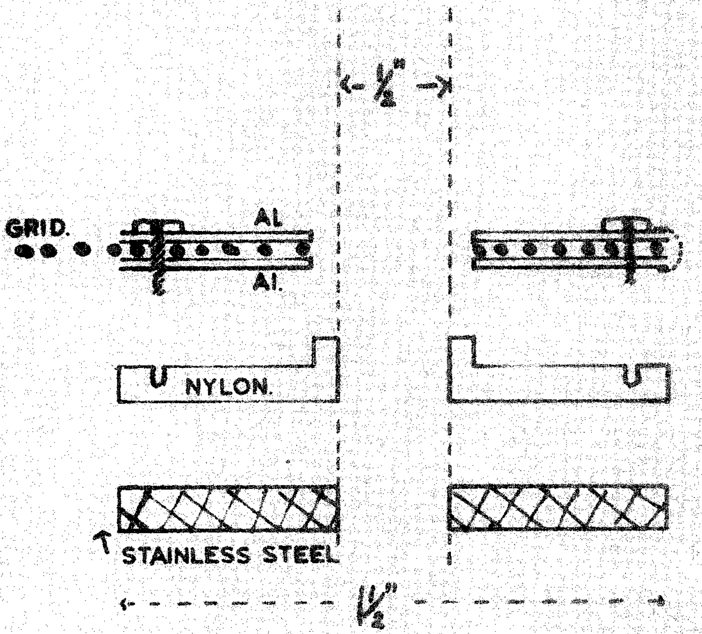


FIG 7.6. AFCRL GRID MOUNTING.

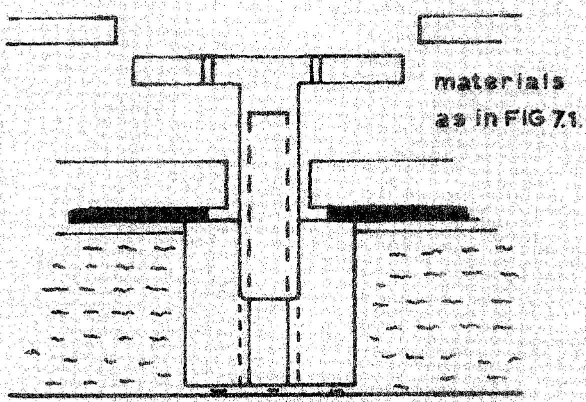


FIG.7.7 FLIGHT MODEL STUD MOUNTING.

lowered onto the base, the seal being made by a Neoprene 'O' ring which needed only to be cleaned with Alcohol before each use. A pneumatically operated sliding valve separated the chamber from the diffusion pump, and enabled the pumping system to be held at low pressures whilst adjustments were made in the open chamber. A large rotary pump was used both as a backing pump for the oil diffusion pump and also to reduce the system to a low pressure (approx. 10^{-3}mm. Hg) to enable the diffusion pump to be used, this it did in under five minutes allowing adjustments and modifications to be carried out without greatly interrupting work. This may be compared with a break of at least one hour involved in a similar adjustment with the vacuum apparatus in Durham.

The chamber itself was 33" high, had an internal diameter of 20" and was raised and lowered on a hand winch to a maximum height of 36" above the base. On this baseplate, within the inside diameter of the chamber, there were three vacuum sealed sub-miniature coaxial plugs, two of which were used for the mill output signals. There were also eight vacuum sealed electrode leads (unshielded) and these were used for motor power, filament power, and the leads to the grids and emitting filament baseplate. All except the motor power leads, which were below the earthed mill mounting assembly, were covered in screening

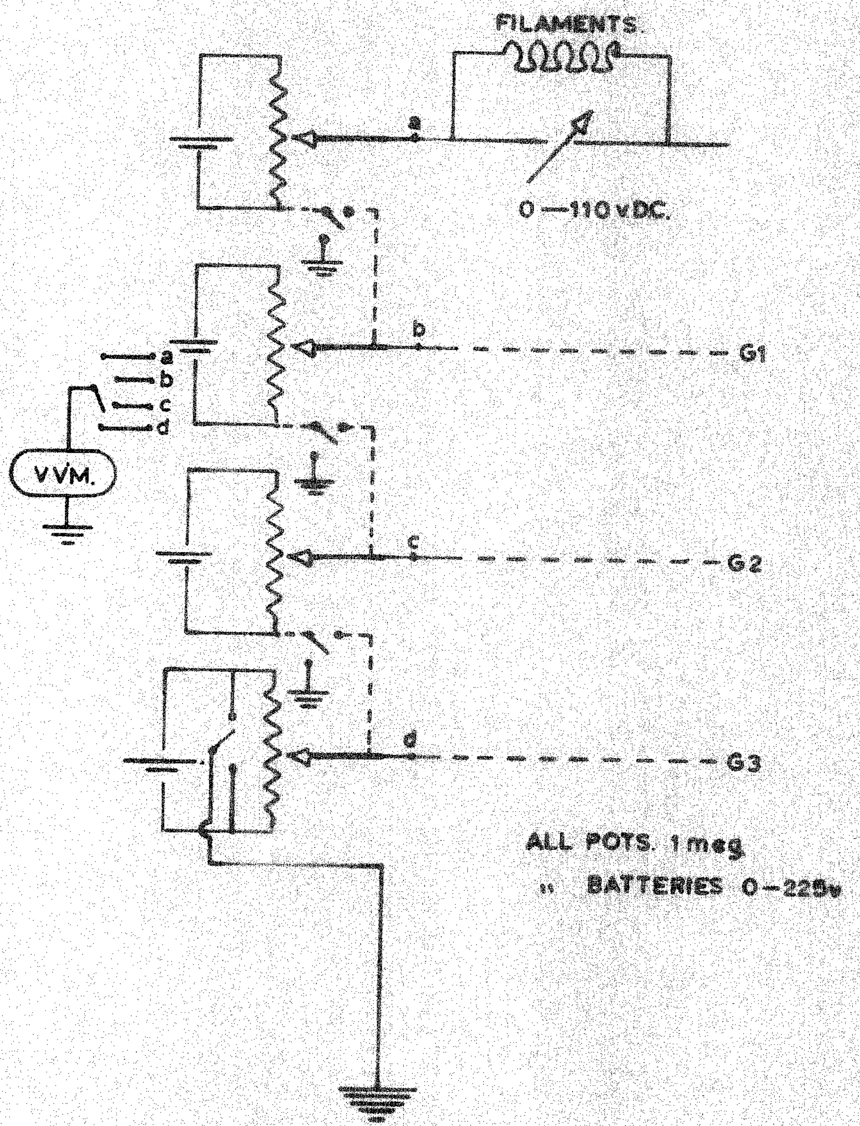

FILAMENTS.
a
0 —110 v DC.
b
G1
a
b
c
d
VVM.
c
G2
d
G3
ALL POTS. 1 meg.
" BATTERIES 0—225v

FIG. 710.

mesh which was earthed to avoid charge building up on the insulating sleeves of the leads.

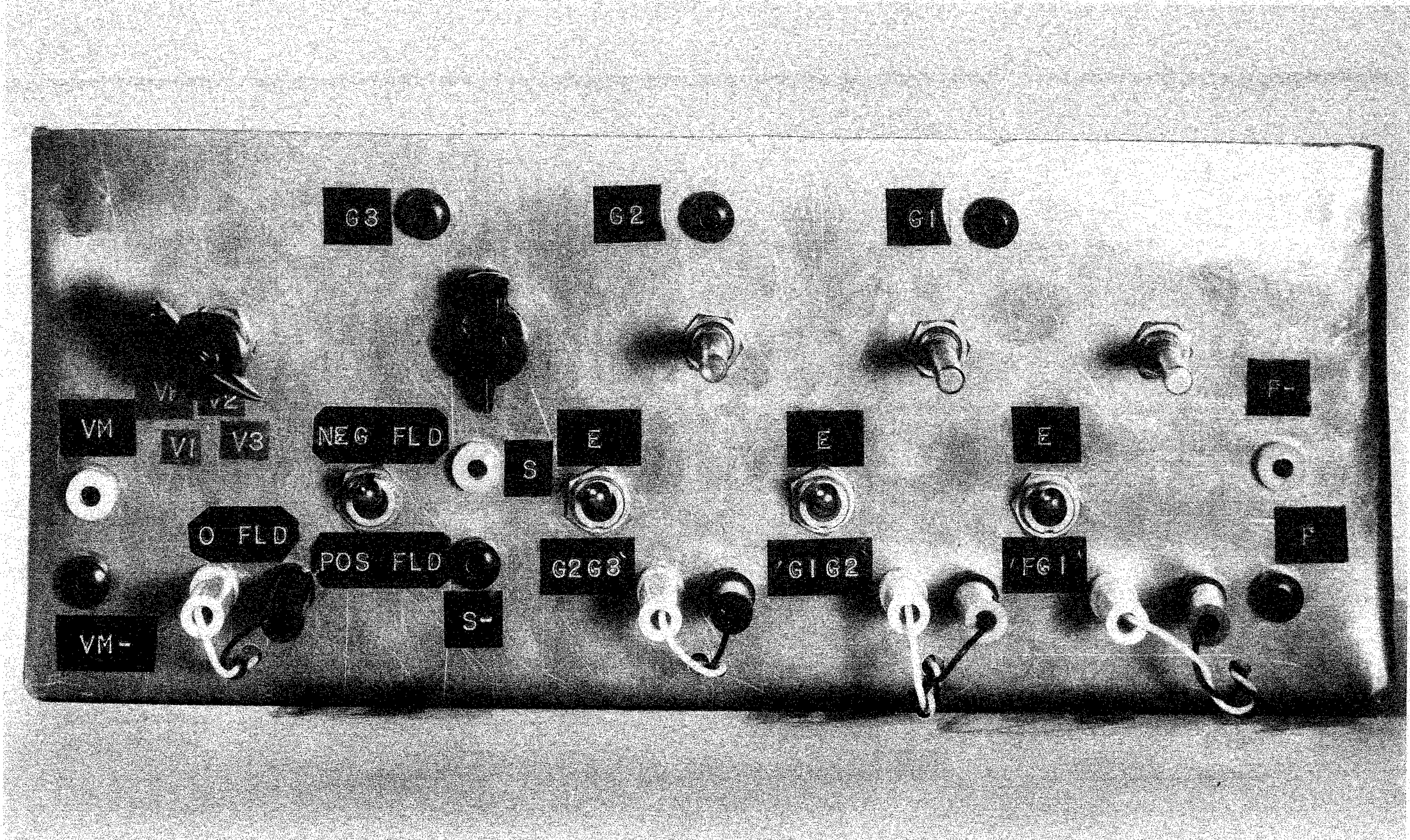
It may be argued that the presence of earthed conductors would distort the field, but this would be more consistent than varying amounts of charge on insulating sleeving. In any case these screens are close (approx. $\frac{1}{2}$") to the walls of the chamber which, unlike the isolated walls of the Durham chamber could not be varied from earth potential.

7.6. The control panel and circuit.

Figure 7.10. shows the circuit for the control of the voltages applied to the three grids, G1, G2, and G3 and to the emitter baseplate, and figure 7.9 shows the front panel of the chassis containing the switches, potentiometers, and batteries as needed.

It was in fact a more compact version of the circuit employed in Durham with the additional facility of being able to place the baseplate and the grids in series or independently, to earth.

Four 0 - 225v. dry batteries were connected, one across each 1 megohm potentiometer, and these rest in the tray formed by the base of the chassis, being connected to the potentiometers through the plugs along the bottom of the panel which are permanently connected to the potentiometers. The plug VM was earthed, VM- being connected to the output of



G3
G2
G1
VM
V1
V2
V3
NEG FLD
S
E
E
E
F-
O FLD
POS FLD
G2G3
G1G2
FG1
F
S-
VM-

Fig. 7.2.

the wafer switch shown in figure 7.8. The most negative point on the panel is F-, which is connected to the negative terminal of the power source of the emitting filaments. The extreme left hand switch in figure 7.9. applies a negative or positive field to the mill by earthing one pole or the other of the dry battery to which G3 is connected.

Typical values of the voltages applied to the accelerating grids were (Run I October 10th 1961);

$V_f = -200v$

$V_{G1} = - 80v$

$V_{G2} = - 75v$

$V_{G3} = 0$ (no applied field).

Chapter 8.

The calibration and performance of the flight model.

8.1. The estimated mill outputs.

If the same values of $\phi(x)$ as in Chapter 3 are to be retained, then the values of C must be known before R may be determined.

The capacity of each set of studs was measured with a Universal impedence bridge (General Radio model 1650-A) and when connected directly to the output plugs on the mill body, and the mill resting upon insulating material, these were measured to be 136 ∓ 2pF, for the inner set, and 229 ∓ 1pF, for the outer set. Removal of the rotor reduced both of these values by less than 10pF.

The capacitance of the leads from the mill to the input of the amplifying system, including the vacuum sealed electrodes, was measured in each case and found at first to be approximately 190 pF in both cases. The lead from the vacuum system output panel to the amplifying system was therefore lengthened to raise its capacity by about 40pF, so that for each channel the total input capacitance was approximately 400pF.

Thus if $x_1 = 0.75$, $\phi(x_1) = 0.81$, and since $f_1 = 1250$cps, $w_1 = 2500\pi$, thus $x = wCR$ gives;

$$7.5 \times 10^{-1} = 2500\pi \times 4 \times 10^{-10} R. \qquad \ldots 8.1.$$

$$R = 2.38 \times 10^{5} \text{ ohms.}$$

From equation 3.7. this would give a field signal when

$A_o = 10^{-3}$ meter^2 of;

$V_{E1} = 6.7 \times 10^{-6}$ volts/v/m. ... 8.2a

and for the lower frequency signal, using the same value of R, $\phi(x_2) = 0.97$, $f = 416$cps, $w = 833\pi$ giving

$V_{E2} = 2.65 \times 10^{-6}$ volts/v/m. ... 8.2b.

Similarly upon substituting in equation 3.9. the signal due to current for a current of 10^{-5} amps/meter^2 (10^{-9}amps/cm^2) will be;

$V_{C1} = 9.65 \times 10^{-4}$ volts ... 8.3a

$V_{C2} = 1.13 \times 10^{-3}$ volts ... 8.3b.

In the case of the field signals these are very small to handle, especially when the likelihood of a minimum 'noise' signal from the mill of as much as 1mV (as in Durham mill) is considered. It was therefore decided to use a resistor of 10^6 ohms. Without reducing the values of w and C, this gave;

$w_1C_1R_1 = 3.14$, therefore $\phi(x_1) = 0.30$ ... 8.4a

$w_2C_2R_2 = 1.05$, therefore $\phi(x_2) = 0.68$ ... 8.4b

Giving $V_{E1} = 1.04 \times 10^{-5}$ volts/v/m. ... 8.5a

$V_{E2} = 7.8 \times 10^{-6}$ volts/v/m. ... 8.5b

$V_{C1} = 5.57 \times 10^{-3}$ volts ... 8.5c

$V_{C2} = 3.32 \times 10^{-3}$ volts ... 8.5d

giving $V_{E1}:V_{E2} = 1.33$, and $V_{C1}:V_{C2} = 1.68$ ... 8.5e

Thus the overall values of the field sensitivities have been considerably increased, at the expense of the differentiation between them. The current signals appear to have been equally affected, but it will be shown that the current responses in practice bear little relation to those derived in Chapter 3, and above.

8.2. The calibration circuit, and procedure.

Accelerating voltages were applied to the various grids in the vacuum chamber by the circuit shown in figure 7.10. The connections between the mill itself were similar to those made in the laboratory in Durham and shown in figure 6.1. The coaxial leads from the mill were connected to screw on, sub miniature coaxial plugs on the base of the vacuum chamber, and from the lower side of this base coaxial leads went to the back of a panel fixed to the framework supporting the vacuum chamber. This panel also had connections for the leads to the filaments and the grids, and all connections to the batteries, to the amplifiers were made through it.

Two differences in the circuit used were that the mill amplifier gave a D.C. output which was connected to a Sanborn two channel pen recorder instead of an A.C. signal displayed on an oscilloscope, and also that the 10^8 resistor of the V.R.E was replaced by the Keithley D.C. amplifier, the output of this being fed to the other channel of the pen recorder. This pen recorder had a built in calibration and a range of sensitivities of 0.1, 0.4, 2.0, and 10.0, volts per cm. deflection, all with an accuracy of 1% of full scale deflection.

The calibrations may be divided into two parts.

8.3i. Field sensitivities.

The field sensitivities were determined for both sets of studs by disconnecting all grids except the lowest (G_3), and by placing this 10 cms above the upper surface of the mill rotor and its mounting. The application of voltages between $\mp$ 30 volts D.C. therefore, applied electric fields between $\mp$ 300 v/m and these voltages were monitored continuously on a valve voltmeter connected to the wafer switch in position 'd' (figure 7.10) (position V_3, in figure 7.9.).

No biassing was applied to the collector studs due to the upsetting effect that this would have on the currents collected, and as expected both zero outputs and both field sensitivities were very sensitive to the rotor-stator clearance. The actual value of this clearance was made so that the outer set of (smaller) studs were close under the rotor so as to give as great an output as possible since the smaller studs were found to be relatively less efficient (Chapter 6).. The inner, larger studs were then fixed so that the angle between the upper edge of the rotor hole and the upper edge of the studs was the same in both sets of studs.

A number of records were then obtained applying 50 v/m steps to the mill over the $\mp$300 v/m range and one 'typical'

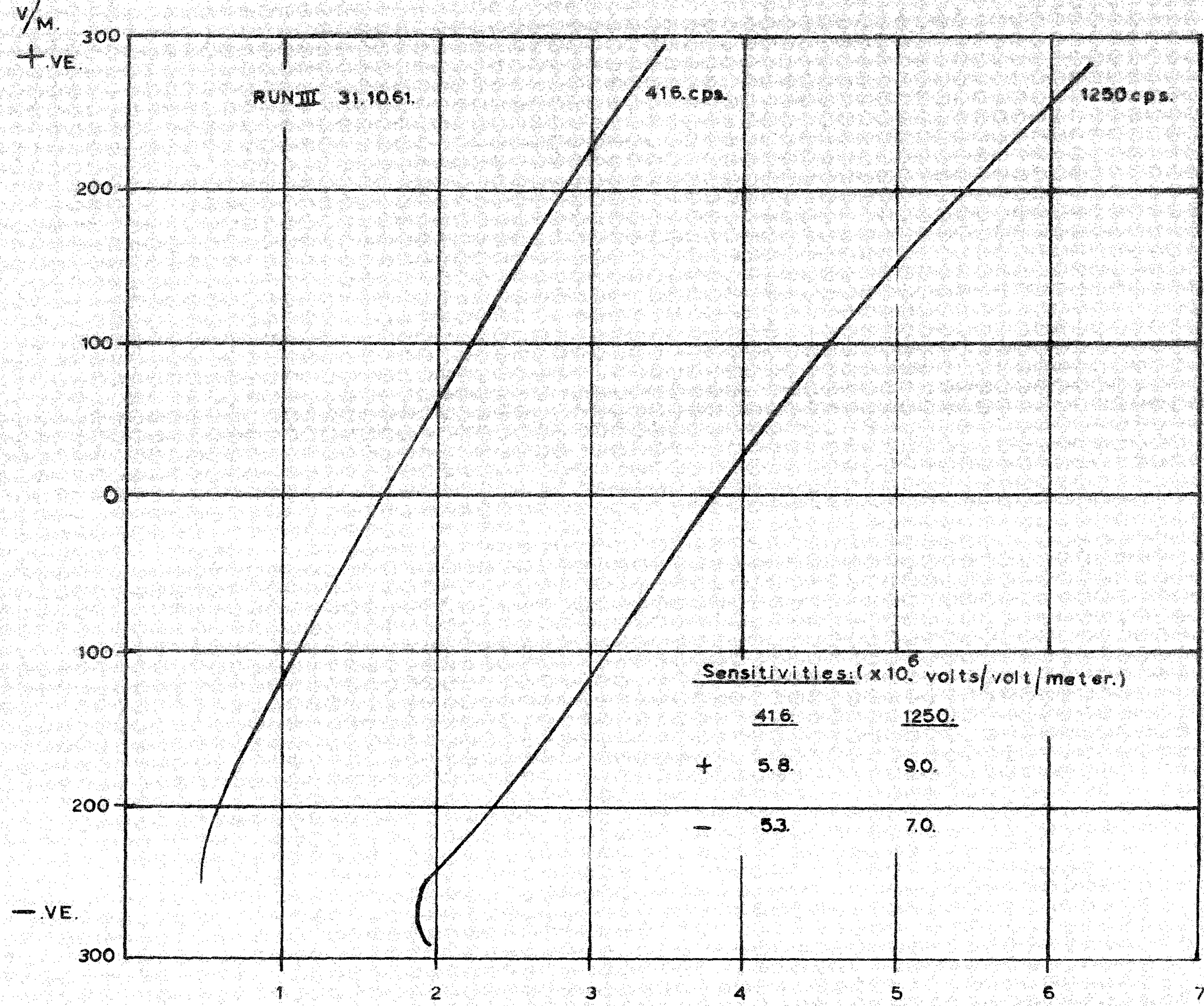

V/M.
+.VE.
—.VE.
300
200
100
0
100
200
300
RUN III 31.10.61.
416.cps.
1250cps.
Sensitivities:(x 10^6 volts/volt/meter.)
416.
1250.
+ 5.8. 9.0.
— 5.3. 7.0.
1
2
3
4
5
6
7
Mv. from Mill.

FIG. 8.1.

record is shown in figure 8.1. The gain of the amplifier was that as shown in figure 7.4. which was determined after a few preliminary applications of charged particle current.

The mill outputs are plotted here in terms of mV A.C. from the mill rather than D.C. output from the amplifier to enable the amplifier gain to be changed if necessary later. The output at zero v/m is the zero output of that particular set of studs since no biassing is applied, and it is this constant which appears in the expression for total output for field and current sensitivity given later.

It may be seen that the sensitivities that may be derived from the curves in figure 8.1. agree quite well with those calculated in equations 8.5. When the departure from the 50:50 solid/open ratio for the studs compared to the rotor is considered (42/50 = 0.725, in this case) then the agreement becomes even better. The D.C. Voltage from which the mill outputs are derived via figure 7.4. is smoothed thus concealing the periods where dA/dt is zero. The mean values of sensitivities for six runs of each set of studs are;

	415 cps.		1250 cps.
+ ve.	8.48 ∓ 1.8 volts/v/m.	+ ve	9.26 ∓ 0.68 volts/v/m.
- ve	6.49 ∓ 0.29 volts/v/m.	- ve	7.23 ∓ 0.57 volts/v/m.

The different apparent sensitivities for positive and negative fields may be due to contact potentials in the switch and battery connections to G3, which enable the polarity of the applied field to be reversed. No discontinuity was noticeable in one or two records obtained when a biassing field was applied to G3 to offset the mill zero output. This meant that fields were then applied taking this voltage of G3 as zero then minimum output occurs at 'zero applied field' and no sign discrimination is possible. Also, the amplifier sensitivity is lower with these smaller input signals resulting in a field sensitivity curve which is very flat and hence innaccurate for low values of field.

It is apparent from fig. 8.1. that if these zero outputs remain constant (1.7mV at 416 cps, and 3.8mV at 1250 cps), then they provide a means for determining the polarity of the applied field. This holds, in the present case over a range of $\mp$ 250v/m, but in the 1250 cps. case it may be seen that at around -250v/m the direction of the output is reversed. This is, a field somewhat greater than +250v/m is being cancelled out by the external field being applied.

8.3ii. Current sensitivities.

In this section the output from the mill amplifier is given when the Keithley Amplifier (K.A.) is at all times in-circuit (Figure 6.1.). This procedure had to be adopted despite the variable external resistance of the K.A. For the same reason the mill amplifier output is given since true mill output must be obtained by means of Figure 7.4, which would not apply under varying input impedance.

Ideally, if two current measuring devices (K.A's) had been available the current flowing simultaneously through both sets of studs for given grid and filament voltages could be noted; knowledge of either of these would allow the other to be determined even with that K.A. out of circuit. This would give a means of applying a known current density without disturbing the input resistance and capacitance.

Only one K.A. was in fact available and the procedure adopted is described later. A sensitive, battery operated V.R.E was available however, and this was connected to one set of studs with the K.A. in series with the other set. This enabled an estimate of the currents flowing to be obtained but the V.R.E would not operate the pen recorder, making accurate calibrations impossible.

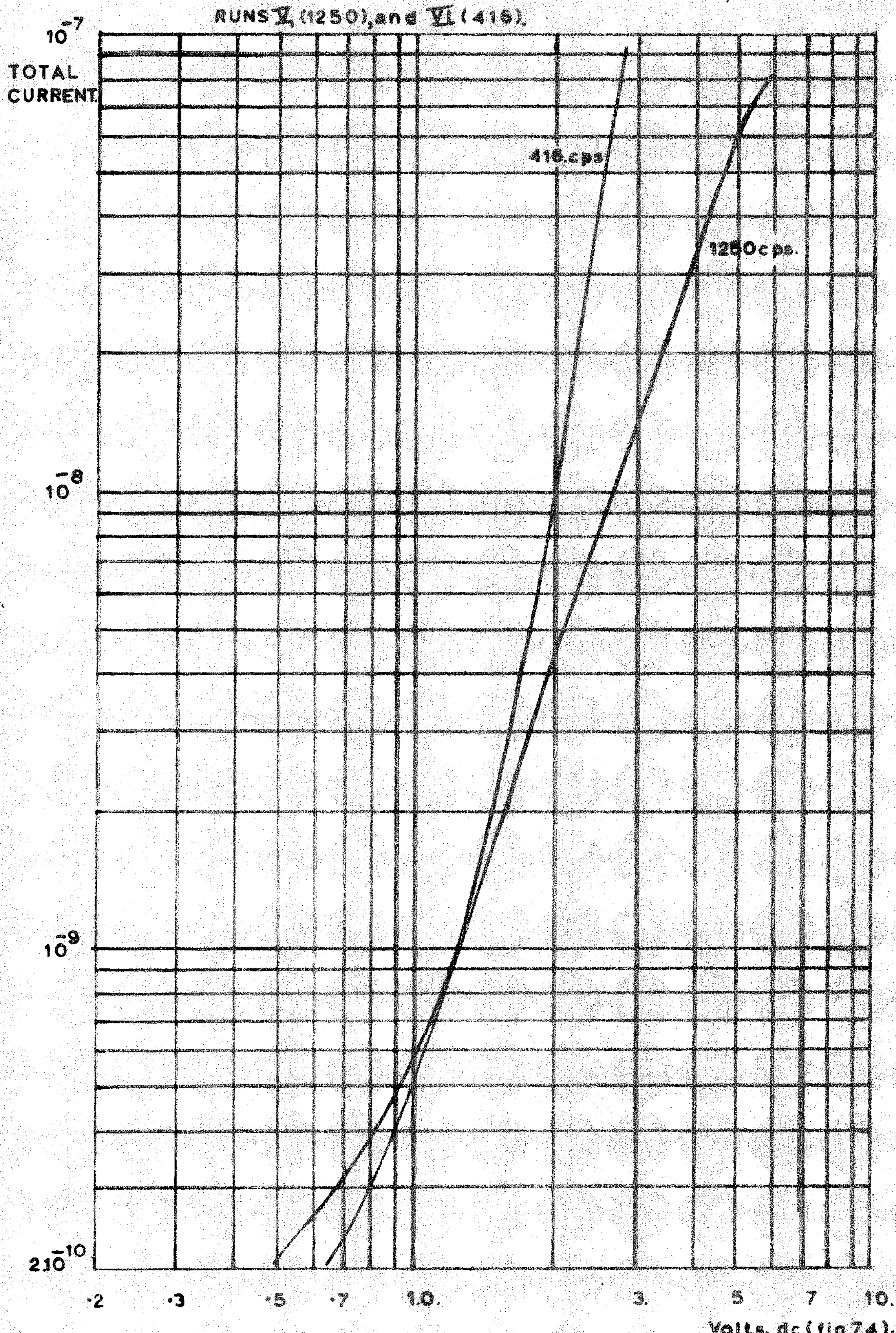
With this arrangement it was possible to show that, with the outer casing of the chamber earthed of necessity, then the current to the outer set of studs could not be made more than 40% of that to the inner set. This held whether the rotor was turning at its operating speed, or whether it was stationary with all studs fully exposed.

Some experiments were also performed where the 1 Megohm resistor of the V.R.E (10^{-2} volts, full scale deflection) was taken as the input resistor of the mill and amplifying system. Although the D.C. voltage, hence current, could only be monitored visually, an overall impression of current sensitivity could be gained. It seemed that, as noted in Durham (Chapter 6), the output was related to the one third power of the current applied.

To try and gain some idea of the effect of the varying K.A. impedance some records were taken where, for constant charged particle flux, the K.A. was disconnected for a short time and the studs connected straight to the input resistor of the amplifier. These records showed that, for both sets of studs, the K.A. seemed to have little disturbing effect when the total current flowing through it was greater than about 10^{-9} amps (10^{-10} amps/cm^2) but that below this, the value recorded when the K.A. was in circuit was greater than without it, indicating that the resistance of the K.A. was inversely related to the current flowing through. This may be seen in the lower portions of both curves in figure 8.2.

From these observations it was decided to assume that a calibration obtained with the K.A. in circuit would, for currents greater than 10^{-9} amps at least, give an accurate indication of the form of the mill current sensitivity, if not of the numerical constants involved.

A number of records were therefore obtained where no field was applied to the mill ($V_{G3} = 0$), where $V_{G2} = -30$v,



RUNS V (1250), and VI (416).
10^{-7}
TOTAL CURRENT.
416.cps
1250cps.
10^{-8}
10^{-9}
2.10^{-10}
·2
·3
·5
·7
1.0.
3.
5
7
10.
Volts. dc.(fig 7.4).

FIG. 8. 2.

$V_{G1} = -180v$ and $V_f = -225v$. In each 'run' the voltage supplied to the filaments was increased over a period of about five seconds from zero to about 18 volts, 4.3 amps. Since the filaments had a measured resistance at room temperature (23°C) of 0.4 ohms, the increase at maximum power to R = 4.25 ohms indicates from figure 5.3. a temperature of approximately 2050°C.

At such a power input the current to the mill, when rotating, was measured as about 10^{-7} amps at which the mill output was almost f.s.d. when on the 2.0 volts/cm range of the pen recorder. The pen recorder was run at 2 cms/sec. and one of these 'runs' is shown in figure 8.3. Only the rising current portion of the curve was used in plotting output current curves in an attempt to minimise the residual space charge effects, and surface contamination effects mentioned in Chapter 6. After each 'run' of little more than 5 to 10 seconds including reduction of power to zero, the mill was left running for about a minute to allow the zero to return its original value. The K.A. returned rapidly to an output indicating less than 10^{-10} amps total current which then slowly returned to its original zero, giving further proof to the idea of a slow leakage of free electrons to earth within the volume of the vessel.

Figure 8.2. shows another one of these 'runs' plotted in terms of current and mill amplifier output voltage, on log. log. axes. The straight lines indicate that the

mill amplifier output may be expressed as

$$(V_C - a) = (10^{10}\ I)^b \qquad \ldots\ 8.6.$$

where a is the amplifier output (extended back by dotted line) when $I < 10^{-10}$ amps the limit of K.A. sensitivity, below which no change in mill amplifier output could be detected either, effectively making $a = V_o$, and b is the slope of the log. log. graph. Equation 8.6. it should be noted holds only over the straight line portion of figure 8.2. that is where $I > 10^{-9}$ amps. Thus in solving the equations for electric field, occasional solution for current should be made to check that this minimum value of I is being exceeded. The rectified mill amplifer output is used since the amplifier calibration curves in figures 7.4. were obtained without the K.A. in circuit.

In all seventeen satisfactory 'runs' at 1250 cps, and seven at 416 cps. were obtained, and gave values for b_1 and b_2 of,

416 cps.	1250 cps.
$b_1 = 0.311 \mp .008$ $V_{C1} = a_1 + (10^{10}I)^{.311}$	$b_2 = 0.223 \mp .004$ $V_{C2} = a_2 + (10^{10}I)^{.223}$

The values of a_1 and a_2 must be obtained for each calibration individually.

If only a limited range of currents are required the straight line portions of the curves in figure 8.2. give a_1 and a_2 directly, and the bracket term becomes $(10^9\ I)^b$. In fact only that portion of the curve such that the output V is greater than the value of V at $I = 10^{-10}$ amps may be used in any case, though this is limited more by the K.A. than by mill characteristics.

8.4. The combination of field and current sensitivities.

It was then necessary to determine the way in which the mill output would behave when subjected to applied electric fields and charged particle fluxes simultaneously. In Chapter 3 it has been shown that at a given frequency, and with linear sensitivities for both current and field, then if the initial screening cycle is sinusoidal, the output will also be sinusoidal. If two field mills are considered, as in the present case, two simultaneous equations will result, which may be solved for applied current or for applied field.

In the present chapter however, it has been shown that the current signal is a sinusoidal signal contained within a power curve envelope. Thus for each half of the 'two frequency mill';

$$(V_E - a) \propto K_1 E \text{ Cos. } wt. \qquad \ldots.\ 8.7a.$$

$$(V_C - a) \propto I^{k2} \text{ Cos. } (wt + \theta). \qquad \ldots.\ 8.7b.$$

where, E is applied field in v/m.

I is applied current in units of (10^{-10}amps) see equation 8.6.

V_E and V_C are amplifier outputs for field and currents before rectification.

a is the zero output ($I < 10^{-10}$amps, see fig 8.2.) also before rectification.

K_1 and K_2 are constants denoting 'field only', and 'current only' sensitivities.

It should be noted that V_E, V_C and a. are in terms of amplifier output, and must be assumed to bear a linear relationship to the mill A.C. output, to allow the Cosine terms to be employed in equations 8.7.

From equations 4.12 it may be seen that Cos $\theta = 0$ ($\theta = 90^{\circ}$), the modulus of the total signal for each 'half' of the mill is of the form;

$$(V_T' - a) = (K_1^2E^2 + I^{2K_2})^{\frac{1}{2}} \qquad \ldots 8.8.$$

where the dashed terms indicate mill A.C. outputs, and are related to the amplifier outputs by equations of the form;

$$(V_T')^2 = p^2(V_T)^2 \qquad \ldots 8.9.$$

The constant p, as in equations 4.13, being the slope of the amplifier calibration curves.

Considering both halves of the mill and remembering that the field sensitivities are likely to be different for positive and negative fields.

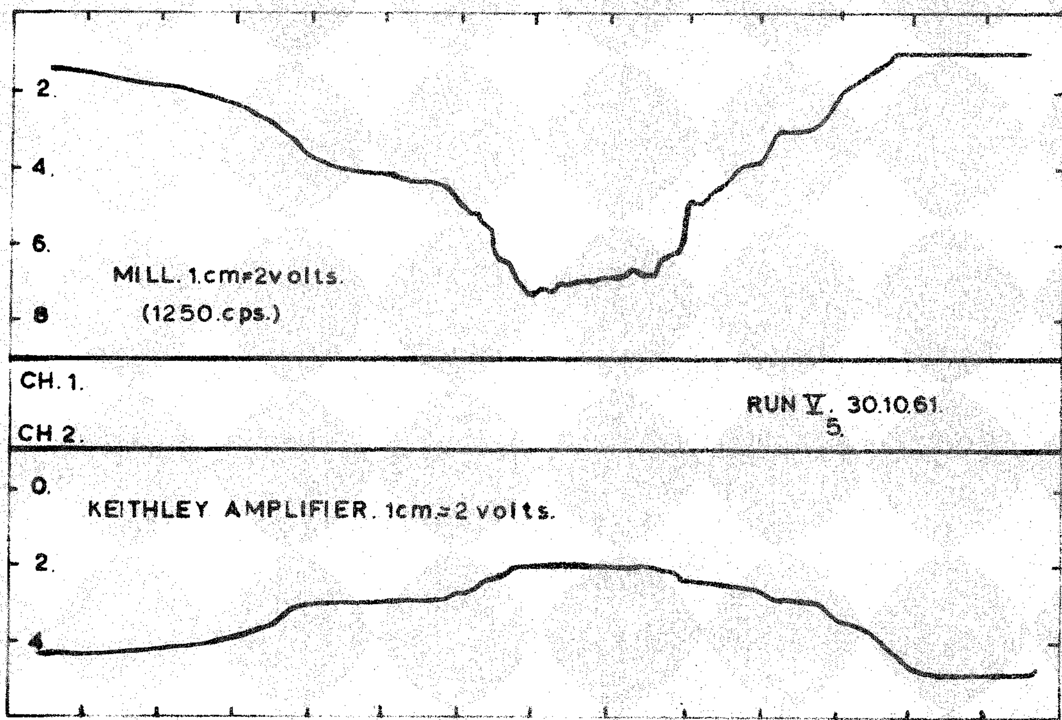

2.
4.
6.
8
MILL. 1cm=2volts.
(1250.cps.)
CH. 1.
CH 2.
RUN V. 30.10.61.
5.
0.
KEITHLEY AMPLIFIER. 1cm.=2 volts.
2.
4

FIG.8.3.

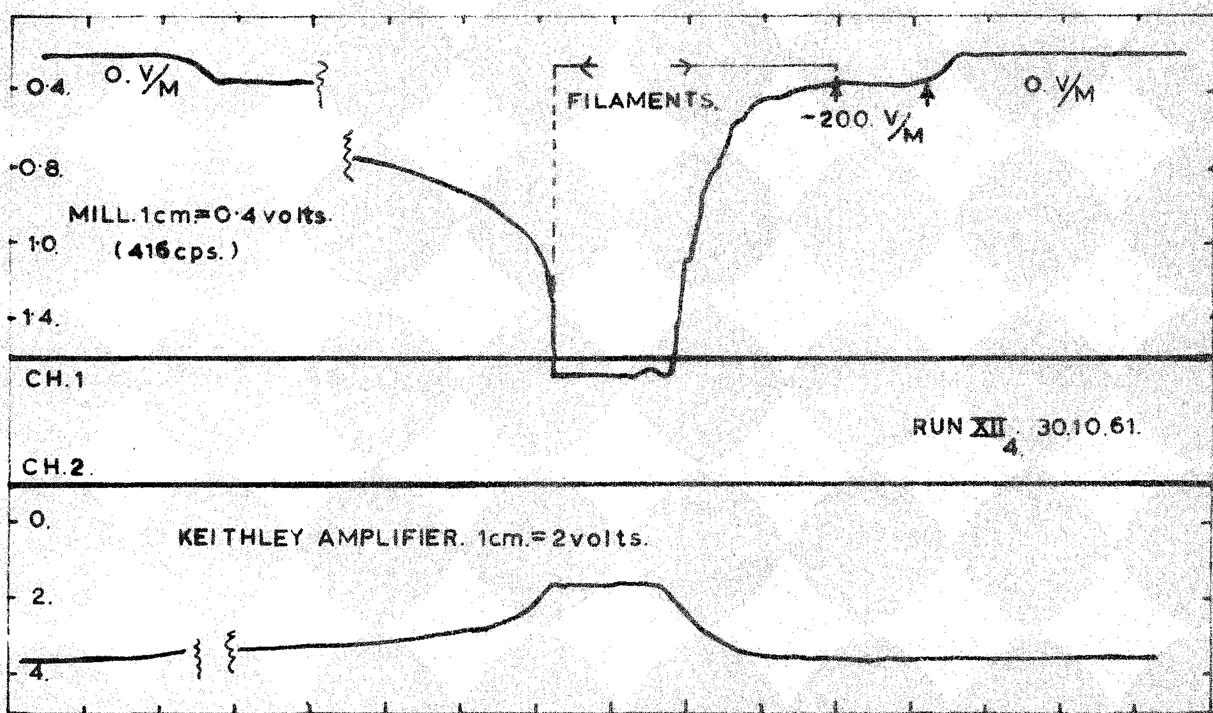

0·4.
0. V/M
FILAMENTS.
-200 V/M
0 V/M
-0·8.
MILL. 1cm=0·4 volts.
1·0.
(416cps.)
1·4.
CH.1
RUN XII. 30.10.61.
4.
CH.2.
0.
KEITHLEY AMPLIFIER. 1cm.=2volts.
2.
4.

FIG. 8.4.

$$(V'_{T1} - a_1)^2 = K_1^2 E^2 + I^{2K_2} \qquad \ldots . \; 8.10a.$$

$$(V'_{T2} - a_1)^2 = C_1^2 E^2 + I^{2C_2}$$

where C_1 and C_2 are the field and current sensitivities for the second set of studs. Also the values of K_1 and C_1 inserted depend upon whether a positive or negative field is applied, which condition may be expressed as;

If $(V_T - a)^2 > I^{2K_2}$ then field is positive, negative if it is less than I^{2K_2}, where the value of I has been obtained by solving equations 8.10 with an average value of K_1 or C_1.

Thus if a field is applied to the mill whilst a constant current is impinging upon it, then the total output from each channel will change by amounts K_1E' or C_1E', where E' is the change in field. Similarly with a steady field and varying current, the total outputs will change By $(I')^{K_2}$ or $(I')^{C_2}$, where I' is the change in current. Figures 8.3. and 8.4., are reproductions of pen recordings showing the mill amplifier output and K.A. output (d.c. current measurement). In figure 8.3. no field at all is applied and the current is slowly increased, and in figure 8.4. a field is applied, then a current and the straight-forward superposition forecast by equations 8.10. may be clearly seen.

The reverse procedure of applying a current and then a field could not be employed in the testing apparatus since the variation of the voltage on the lowest accelerating grid G3, required to vary the field greatly disturbed any current flowing to the mill.

The above procedures work only if one component or the other of each total signal changes at any time, but if both are continuously varying, this may be overcome by equalising either the field term or the current term from both total signals. Thus if K_2 and C_2 are known, then the current components may be equalised and eliminated to give a quantity directly related to applied field

$$Q(E) = (V'_{T1} - a_1)^{2x} - (V'_{T2} - a_2)^{2/x} \qquad \ldots 8.11.$$

Q(E), is a measure of field where $x = C_2/K_2$.

Chapter 9.

Conclusions and suggested further work

9.1. Conclusions.

The power curve form of the mill current sensitivity at a given operating frequency does not seem to have been noted by previous workers with electro-mechanical devices in either Lower, or the Upper Atmosphere. Some possible disturbing influences on mill output in the presence of space charge are considered below, but it is shown that at the current and charge densities used, they could not have a very large effect upon the forecast performance.

It has been suggested (Imyanitov 1957) that charge trapped between the rotor and stator of a field mill inhibits the modulation of the stator potential, there being insufficient time for it to leak away to earth. This charge has two portions, that which is 'bound' to the surface of the collectors at the time of screening, and that which is in the space between the stator and rotor, which must first diffuse to the stator surface.

In the first case, with operating frequencies of 416 cps and 1250 cps, the screening cycle times are approximately 2.4×10^{-3} secs, and 8×10^{-4} secs, and a time constant R.C. of the mill, its leads, and amplifier first stage of $R = 1$ Meg. and $C = 4 \times 10^{-10}$ pF, R.C. $= 4 \times 10^{-4}$ secs, therefore any charge already attached to the collector surface will leak away in less than one half or one sixth of the screening cycle. This means that the potential of the collector (mill output) will drop to at least 2/3 of its maximum value during half of the cycle that it is being screened. In any case such an effect has no dependence upon the current causing this potential, it is a property only of the time constant of the system and the screening cycle frequency and thus will not cause the output curve shown in Figure 8.2. though it would reduce the sensitivity by a constant factor through the input range.

In the case of those electrons or positive ions which must first drift to the stator let us assume a rotor-stator gap of 0.1 cms, and electron and positive ion (rare) temperatures both of $1000^{\circ}K$, which are low both for this experimental set up and for observed Ionospheric values. The velocities corresponding to this temperature are 2.3×10^7 cms/sec. and 7×10^4 cms/sec. (equation 5.8.), thus the times for them to reach the stator are negligible in both cases, when compared with R.C.

Another possible cause of innaccuracy would be the space charge fields caused at the surface of the mill, by the electrons in transit towards it. Since the mill rotor is mounted flush with an extensive conducting surface which is earthed, it is reasonable to assume that since a steady current reaches the mill and this plane, then no quasi-static space charge exists between G3 and the plane of the mill beyond that supplying the observed current to the mill and mounting plane, and also to the conducting walls of the chamber, which are earthed. The maximum total current which reaches the plane of the mill ($\sim 1000cm^2$) and is measured by that current passing through the collector studs of the mill, is of the order of 10^{-5}amps (10^{-8}amps/cm^2). This is at least two orders of magnitude less than the currents observed flowing to the accelerating grids which both at Durham (Chapter 5) and at A.F.C.R.L, were measured to be a few mA's.($I_{G1} > I_{G2} > I_{G3}$). This will be referred to again later, but for the moment we will consider the charge densitites that would give rise to such currents at the mill.

Before these charge densities may be determined the energies of the electrons impinging upon the mill must be considered. It has been stated (Chapter 6), that the current flowing to the collecting studs of the Durham mill was unaffected by the application of a voltage to these studs, until a value of approximately −1.0 volts was reached. Naturally the output signal from the mill increased since with a rotor stator gap of 0.1cms, this corresponded to an applied field of +1000v/m, but the D.C. current registered by the V.R.E soon returned to the pre-existing value after the disturbance caused by the displacement current as the bound charge on the studs is altered.

$$dI = C^2\, dV/t. \qquad \ldots\ 9.1.$$

Where dI is the displacement current

C is the capacitance of the collector system

t is the time to charge the voltage on collectors.

dV is the voltage change involved.

When observing the current in such a way the collectors are being used as a crude electrostatic probe, and in fact when the currents to the 'flight model' of the mill were measured (at A.F.C.R.L) with a V.R.E then it was possible to measure diminished currents with collector potentials as high as -100 volts, indicating that at least some of the incident electrons had energies of 100eV, once again these potentials resulted in very high A.C. outputs from the mill, equivalent to 10^5v/m.

Nevertheless the problem remains that since the baseplate containing the emitter filaments is put at $V_F \approx -200$ volts then all incident electrons at the mill, which is earthed, should have an energy of 200 eV upon which is superimposed their thermal (Maxwellian) energy distribution of emission.

Now from examining the power required for the emitting filaments to produce current densities between 10^{-11}amps/cm^2 and 10^{-8}amps/cm^2, correspond to filament temperatures between 700^{o}K and 2050^{o}K. (Figure 5.3.). From figure 2.1. these correspond to energies of 9×10^{-2} eV and 3×10^{-1} eV respectively, (average velocities of 1.8×10^7 cms/sec and 3.1×10^7 cms/sec). Thus these are the minimum values of electron energy and average velocity and the small effect of a -1 volt potential applied to the collectors would suggest that they are exceeded in practice. Nevertheless if we calculate the values of the fields that these will cause at the mill they will be seen to be negligible.

To obtain the greatest charge density;
at 2050°K, $\overline{w}$ is 3.1×10^7 cms/sec, and j the current density is 10^{-8} amps/cm^2 then the charge density

$$n = j/e.\overline{w}. \qquad \ldots 9.2a.$$

giving

$$n_{max} = 10^{-8}/1.6 \times 10^{-19} \times 3.1 \times 10^7$$
$$= 2.05 \times 10^3 \text{ electrons/c.c.} \qquad \ldots 9.2b.$$

The lowest charge density is given by 700°, $\overline{w}$ is 1.8×10^7 cms/sec, and j is 10^{-11} amps/cm^2 giving

$$n_{min} = 10^{-11}/1.6 \times 10^{-19} \times 1.8 \times 10^7$$
$$= 3.5 \times 10^{-1} \text{ electrons/c.c.} \qquad \ldots 9.2c.$$

If these charge densities are assumed to exist between the lowest grid, and the plane containing the rotor, which are separated by approximately 10cms, then the field, dV/dx at the surface of the mill, provided the grid and mill are at the same potential, will be, (Vonnegut and Moore 1958)

$$\frac{dV}{dx} = -\frac{\rho x}{2.\varepsilon_0} \qquad \ldots 9.3a.$$

where ε_0 is the permittivity of free space.

ρ is the charge density (per meter^3)

x is the rotor-mill separation.

Substituting 9.2b in 9.3. this gives;

$$\frac{dV}{dx} = -\frac{1.6 \times 10^{-19} \times 2.05 \times 10^{9} \times 10^{-1}}{2 \times 8.86 \times 10^{-12}} = 1.85 v/m. \qquad \ldots 9.3b.$$

Since this is a maximum value it is unlikely that the space charge fields are a cause of the anomalous current response of the instrument.

In actual practice for much of the time that a total current is being collected (figure 2.5, see also Bourdeau, Serbu, et al. 1961) that current is positive and although much of this is composed of photoelectric emission, there will also be environmental positive ions. Since in Chapter Two, vehicle potentials of the order -1 to -10 volts have been forecast after taking into consideration observed Upper Atmosphere ion and electron temperatures, then from figure 2.1. if these ions reach the collector of the vehicle having been accelerated through a sheath potential of 1 volt their velocity will be at least 2.5×10^5 cms/sec. This will not cause any interference in the theoretical current sensitivity due to charge trapped in the rotor-stator space, and since in 'flight' a true positive ion sheath is obtained then the field that this causes with a sheath voltage of 1 volt is very small since sheath thickness S in cms is,

(Guthrie and Wakerling 1949c)

$$S = 3 \times A \times 10^{-2} \times \frac{V^{\frac{3}{4}}}{j^{\frac{1}{2}}} \text{ cms.} \qquad \ldots 9.4.$$

Where A is a constant such that $1.0 < A < 1.36$

V is the sheath voltage drop in units of 100 volts.

j is the +ve ion current density in $amps/cm^2$

Taking V as 10^{-2}(1.volt) j as $10^{-8} amps/cm^2$, and A as 1.0, then;

$$S = 3 \times 10^{-2} \times 10^{-3/2}/10^{-4} \approx 30 \text{ cms.} \qquad \ldots 9.5.$$

Thus from equation 2.30, when the current carrying charges are positive, the field E, at the charge receiving electrode (mill) is,

$$E = \frac{4}{3} \times \frac{V}{S} = \frac{4}{3} \times \frac{100}{30} = 4.35 v/m. \qquad \ldots 9.6.$$

Therefore even with space charge controlled currents of moderate values the disturbing fields are calculable.

It is worthwhile noting here that under the conditions of calibration, with charge densities as great as 10^4 electrons/ c.c, the field intentionally applied to the mill by V_{G3} is very little screened by the intervening space charge. The concept of Debye screening length may be used in electron volume charges (Pines and Bohm 1952) and for an ion or electron temperature of $1000^{\circ}K$ at a density of 10^4/c.c.

$$D_L = \left[\frac{kT}{4\pi e^2 n}\right]^{\frac{1}{2}} = \left[\frac{1.38 \times 10^{-23} \times 10^3}{4\pi \times 1.6^2 \times 10^{-38} \times 10^{10}}\right]^{\frac{1}{2}}$$

$$= 2.1 \times 10^3 \text{ meters.} \qquad \ldots 9.7.$$

9.2. Interpretation of results.

The value of the field E, at the surface of the vehicle is derived by means of Q(E) in equation 8.11. and is also the quantity E_p in Chapter 2 from equation 2.29 onwards. The part of the theory most open to doubt is that in Chapter 2 concerned with the assumption of axial symmetry of the ion sheath surrounding a cylindrical vehicle. There would be little doubt about this assumption if,

(a) There were no ambient electric or magnetic fields.

(b) The vehicle were stationary.

(c) The vehicle were not exposed to solar UV and X-rays.

If we have an axially symmetrical vehicle rotating once every few seconds as is the case in some satellites (Explorer VIII, Bourdeau, Serbu et al. 1961) it will rotate within a sheath system that is stably oriented in space, since the sheath surrounding an isolated symmetrical shape will change only due to external influences. If the field sensitive device is placed so that the normal to its sensitive surface rotates perpendicularly to the axis both of symmetry and motion then the complications due to space charge build up will be avoided, and we can consider the variation of the field at the surface of the vehicle as it rotates, neglecting magnetic fields.

If the field F, (or E_p) is considered acting along the normal to the mill in the first instance, the diameter of the vehicle being 2n. meters then if the vehicle surface is taken as an equipotential the potential difference which the sheath will contain will vary between ($V_o \mp nF$), where V_o is the vehicle potential in the absence of any ambient electric field. It is reasonable to assume that during the course of one vehicle rotation the ambient ion electron, and neutral particle temperatures and densities do not change. The sheath thickness and hence the field and the vehicle surface will vary due to this potential difference of, 2nE volts.

Now according to equation 9.4. , the sheath thickness S, in a space charge controlled current, is proportional to $V^{\frac{3}{4}}$, where V is the potential difference across the space charge region. Since from equation 9.6., the field E, at the surface of a vehicle is directly proportional to V, and inversely proportional to S, (when the current carrying charges are positive, and the vehicle is negative with respect to its surroundings) then;

$$E \propto V^{-1/3} \qquad \ldots 9.9.$$

Thus when V changes in the course of one half rotation from $V_1 = (V_o + nF)$ to $V_2 = (V_o - nF)$ then E_1 and E_2 the corresponding fields at the vehicle surface have the relation;

$$\frac{E_1}{E_2} = \left(\frac{V_2}{V_1}\right)^3 \qquad \ldots 9.10.$$

But from equation 8.11.

$$\frac{E_1}{E_2} = \frac{Q(E)_1}{Q(E)_2} \qquad \ldots 9.11.$$

Therefore;

$$\frac{Q(E)_1 - Q(E)_2}{2n} = f(F) \qquad \ldots 9.12a.$$

or;

$$\frac{E_1^{-1/3} - E_2^{-1/3}}{2n} = F \qquad \ldots 9.12b.$$

since Q(E) may be related to E, (Chapter 8).

9.3. Further work.

If further models of the two frequency mill are to be constructed and flown, more attention should be paid to the accurate calibration of the flight models and their amplifying systems, in their 'in flight' state. The amplifying system should be calibrated separately so that it would be possible to determine the actual mill output as well as the whole system output.

The dimensions of the present model were derived considering a theory of current sensitivity which was not upheld in practice and which need not, therefore determine the configuration of further models. The total areas of two sets of charge collecting studs need not be exactly equal and could be adjusted to give absolute total signals by using as great a collecting area as was compatible with giving reasonable field signal differentiation.

The field sensitivities reported in Chapter 8 would indicate, that despite the results obtained with the electrolytic tank, the field sensitivity is limited by the solid/open ratio of the rotor.

As far as the calibration is concerned, with two current measuring devices, the applied current at any time could be known by cross calibration between the two channels with no applied fields, in the first instance. The current measuring device (V.R.E?) could then be removed from the set of studs under investigation and the current passing through it at any time inferred from that still being measured through the other set of studs. The input resistance of these current measuring devices should not exceed say 10^7 ohms, this would avoid raising the stud potential to a value where the electrons were repelled to any extent.

The limit of sensitivity of V.R.E's. (few x mV's) gives further reasons for improving the electron emission system. If the idea of a mono-polar charged particle stream is retained then if higher accelerating voltages could be conveniently employed the electrons impacting upon the mill would have a higher energy due to the lower density of space charge accumulating in the regions of the vacuum chamber close to the emitting filaments.

The only remaining source of innaccuracy seems to be that the current registered by the V.R.E's or K.A's is not a true indication of the current density at the plane containing the mill. This could be due to the measuring device itself or due to diminished current density of the collecting studs due to field reduction. The latter explanation seems more likely since the currents were measured with both sorts of instruments, and in both cases with the mill rotating and also with the rotor stationary and all studs fully exposed, to avoid any innaccuracy due to a change in V.R.E or K.A. properties when operating with an intermittent D.C. current of a few hundred cps. In all cases the intermittent current was approximately one third of the current reaching the studs when continuously fully exposed.

Since the current reaching the lowest grid (Chapter 5) was found to be a few mA's, it is reasonable to assume that the current reaching the plane of the mill ($10^3 cm^2$) is somewhat less, say 1mA, giving a current density of 10^{-6} amps/cm^2. This is two orders of magnitude greater than those assumed earlier, and will therefore result in space charge fields proportionally larger, thus from equation 9.3b.

$$\frac{dV}{dx} \approx 200v/m. \qquad \ldots 9.8.$$

Although large this is a maximum condition which would be associated with a large current signal, and if there were field distortion causing anomalously low current readings, this would also act as a reducing, exposure factor for 'bound charge' induced by the field given in equation 9.8.

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