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The Absorption of Neutrons

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NOTE

This paper gives an account of work done during the University Session 1938-1939 at the end of which it became necessary to undertake work of national importance and of a secret nature. In agreement with Professor M.L. Oliphant this paper is therefore presented together with an account of part of the work done during the Sessions 1939-1941 in the form of a Secret Report.

PART I

The Velocity Dependence of Neutron Absorption In Matter

THE VELOCITY DEPENDANCE OF NEUTRON ABSORPTION IN MATTER

There are three main types of nuclear reactions which may occur with reasonable probability when matter is irradiated with neutrons. These may occur in addition to ordinary elastic scattering. The elastic scattering cross sections for most of the elements have now been measured and the values obtained range from 2×10^{-24} cm^2 to 12×10^{-24} cm^2. The highest value has been observed for hydrogen and this process is used, as will be seen later, for slowing down neutrons to thermal energies. This large scattering cross section enables one to perform the curious experiment of "leading" a beam of slow neutrons down a tube made of paraffin and to some extent of "leading" them round a corner.

The first type of reaction consists of simple capture of the incident neutron by the nucleus forming an isotope, the surplus energy being radiated in the form of γ rays thus :-

$$Z^{A} + n^{1} = Z^{A+1} + \gamma \text{ -------------- (1)}$$

The isotope Z^{A+1} formed may or may not be radioactive and the formation of a non radioactive isotope can only be inferred from the fact that the neutron has been absorbed.

The γ rays formed in accordance with equation (1) have been observed in a number of cases experimentally and since the original discovery of this type of reaction by Fermi[1] and others at least 100 radioactive isotopes have been formed in this way.

The second type of nucleor reaction that is known to occur involves the emission of an α particle thus :-

$$Z^{A} + n^{1} \rightarrow Z^{A+1*} \longrightarrow (Z-2)^{A-3} + He^{4} \text{ --------- } (2)$$

The reaction is seen to take place in two stages with the intermediate formation of an unstable isotope containing the original neutron which breaks down with the elimination of an α particle. This type of reaction is only known to occur in two cases, namely with lithium or boron

$$Li^{6} + n^{1} = He^{4} + H^{3}$$

$$B^{10} + n^{1} = Li^{7} + He^{4}$$

The observed cross section for these reactions are very large being $3000 \times 10^{-24} cm^{2}$ for B and $900 \times 10^{-24} cm^{2}$ for Li in the case of thermal neutrons, and in consequence they are often used as sensitive detectors of neutrons.

The third type of reaction causes the emission of a proton and may be written thus :-

$$Z^{A} + n^{1} = (Z - 1)^{A} + H^{1} \text{ ----------- } (3)$$

This has only been found to occur in the case of nitrogen, i.e. :-

$$N^{14} + n^{1} = C^{14} + H^{1}$$

and it is probable that other reactions of this type, except perhaps with boron, will not occur owing to the following energy considerations.

The mass difference between the combined neutron and a proton is known to be equivalent to only 0.8 MV., the neutron being heavier. Thus the reaction (3) is only possible if the mass difference between $(Z - 1)^{A}$ and Z^{A} lies between zero and 0.8 MV. That this mass difference will lie in this comparatively small region is in itself improbable, and in the case of the heavier nuclei the emission of a proton is even more unlikely as the proton, whose energy must be less than 0.8 MV, will be unable to penetrate the potential barrier of the nucleus.

Other than as a means of detecting neutrons, only the first type of reaction is of interest to us, as it is this type which gives rise to the large values of capture cross section.

Fermi and his co-workers describe experiments[2] on the artificial radioactivity induced in various elements under neutron bombardment and found that in the case of silver the intensity of activation appeared to depend on the proximity of various objects to their particular experimental arrangement. On surrounding the radon - beryllium neutron source with a large block of paraffin or water the activation of silver was enormously increased where the interposition of substance not containing hydrogen did not give a comparable increase. This was found to hold for specimens other than silver but not for all elements.

This effect was explained on the hypothesis that the neutrons were being slowed down by elastic collisions with hydrogen nuclei and that the resulting slow neutrons are more easily captured by some nuclei, e.g. silver, than the fast ones.

It can easily be shewn that, on account of the approximate equality of the masses of neutrons and protons, a collision between these two particles will, on the average, reduce the neutron energy to 1/e of its original energy. It follows that less than 20 collisions would serve to reduce the neutron from about 4 million volts energy to thermal energies when they will be in equilibrium with the hydrogen atoms. The time for which the neutron remains in equilibrium in the paraffin depends upon the relative cross sections for scattering and capture by the protons, and may be shewn to be of the order of 10^{-4} seconds which allows of approximately 100 collisions.

On these assumptions one is led to the belief that the collision cross section for neutron capture is greater for slow neutrons than fast, and the fact that the neutrons are actually absorbed was verified by Fermi by shewing that the neutrons responsible for the activation of the specimen are most strongly absorbed by that element. The absorption coefficients of a number of elements were also measured using as a detector the activation produced in a silver or rhodium plate after irradiation for a standard length of time.

Large values of absorption cross section for slow neutrons were obtained for a number of elements notably 3000×10^{-24} cm^2 for boron and $10,000 \times 10^{-24}$ cm^2 for cadmium. The figure for boron when fast neutrons are used is at least 1000 times smaller than that given above.

An attempt to measure the mean energy of the slow neutrons producing the activity was made by Fermi (loc.cit.) by measuring the activity produced in a rhodium or silver detector immersed in a bath of hydrocarbon mixture at two different temperatures, i.e. $200^{\circ}C$ and $20^{\circ}C$. The composition of the two mixtures was adjusted so that the concentration of hydrogen atoms was the same at the two temperatures, but no effect could be found.

Moon and Tillman[3] suggested that this negative result might be explained in three ways. It may be (i) that there are no thermal neutrons there, (ii) that the capture cross section of silver is low for both thermal and high energies but has a maximum at some intermediate energy; or (iii) that at thermal energies the capture cross section is independent of velocity.

An unsuccessful attempt to prove (iii) by rapidly moving the detector and source between two large water tanks, the detector preceding the source, can be explained by the short lifetime $\sim 10^{-4}$ sec. of neutrons in water. Apart from this, if the neutron velocity had been of the same order as that of the motion of the detector and source, i.e. 3×10^{3} cm/sec, a decrease in the activity of the specimen should have been observed.

Moon and Tillman then measured the activation produced in a specimen of silver, rhodium or iodine by slow neutrons which had passed through a cylinder of paraffin, wall thickness 1.6 cm, at room temperature 290°K and at liquid oxygen temperature, 90°K. With silver the activity at 90°K was 1.26 ± 0.04 times that at 290°K shewing that a considerable fraction of the neutrons were slowed down to thermal energies by their passage through the paraffin. This figure of 1.26 depends very greatly, however, on the actual geometrical arrangement in use. Owing to the absorption of the neutrons in the silver specimen the average activity, which is measured with a Geiger Muller counter, will depend on the thickness of the specimen. It was also shewn that the temperature effect will depend very considerably on the thickness of the wax layer that is cooled and the fact that Fermi in his temperature experiments used a fairly large thickness and a small temperature change compared with Moon and Tillman can be used to explain the lack of any measurable effect in Fermi's experiments. The absorption of neutrons in paraffin was also found to increase with decreasing temperature more rapidly than the absorption in silver.

Both groups of workers noted that when measuring absorption coefficients, higher values were obtained when the detector and absorber were of the same material shewing that the absorption was accompanied by activation and that different elements absorbed most strongly in different energy ranges.

Theoretical treatments of the absorption of neutrons were provided by several workers, including Fermi (loc.cit) and Bethe[4] , in which the bombarded nucleus was considered as a simple potential hole and interaction between the neutron and nucleus only takes place when the neutron is inside the nucleus or very close to its boundary.

The mathematical treatment consists of making the wave functions of the neutron inside and outside the nucleus fit at the boundary, i.e. the wave function and its derivative should be continuous at the boundary.

The calculated values of the capture and scattering cross section for slow neutrons are given respectively as :-

$$\sigma_c = \frac{\lambda \lambda_0}{23000} \cdot \frac{1}{\sin^2 \phi_0 + \lambda_0^2/\lambda^2} \quad \text{-------------------} \quad (4)$$

$$\sigma_s = 4\pi \left(ctg.\, \phi_0 + r_0 \right)^2 \quad \text{-------------------} \quad (5)$$

where λ and λ_0 are the de Broglie wavelengths outside and inside the nucleus respectively, and ϕ_0 is the phase of the neutron wave function at the nuclear boundary r_0

Since in general $\lambda_0 << \lambda$; λ_0/λ can be neglected, for slow neutrons compared with sin ϕ_0 We then have

$$\sigma_c \propto \lambda$$

i.e. $\sigma_c \propto 1/v$ ------------------- (6)

This theory serves to explain the increased absorption of slow neutrons and the wide variation of the capture cross section from one element to another may be ascribed to the resonance term $1/\sin^2\phi_0$.

However, it can be seen from (4) and (5) that an element which has a large capture cross section, i.e. small ϕ_0, must also have a large scattering cross section as ctg ϕ_0 will also be large. The theory demands in fact that the capture and scattering cross sections for slow neutrons shall always be of the same order. The observed scattering cross sections for cadium is, however, less than 1% of the capture cross section. The theory, while shewing that a large variation in the cross sections from element to element could occur, fails to enable one to say which elements should have the larger cross section.

The experiments on selective absorption of Fermi, and Moon & Tillman definitely disprove the theoretical prediction that the absorption should be inversely proportional to the velocity for any capturing nucleus.

These experiments, however, are of great importance in that they led Bohr[5] and Breit and Wigner[6] to what is now considered the correct theory of neutron capture.

This theory explains the greater probability of neutron capture over and above the probability of the re-emission of a neutron, i.e. scattering, in the following manner. On the entry of a neutron into the nucleus, its original kinetic energy is distributed among the constituent particles of the nucleus, and is frequently transferred between the various particles. Although the nucleus is now, as a whole, in a highly excited state, it is unlikely that sufficient energy will be concentrated in any one particle to cause the re-emission of a neutron. There may well be, however, sufficient energy present in the compound nucleus so formed to cause γ ray emission, when the nucleus may settle down forming an isotope which may possibly be radioactive.

The expressions for the capture and scattering cross sections given by the Breit-Wigner theory are difficult to interpret except in restricted velocity ranges which fortunately are those of greatest practical interest, namely, for very low (thermal) velocities and in cases of near resonance.

After making some simplifying assumptions the capture cross section is given as :-

$$\sigma_c = \frac{\pi \lambda \lambda_r \cdot A \cdot B}{(E - E_r)^2 + \frac{1}{4} C^2} \quad \text{--------------------(7)}$$

and the scattering cross section as :-

$$\sigma_s = \frac{\pi \lambda_r^2 \cdot A^2}{(E-E_r)^2+\frac{1}{4}C^2} \qquad \text{---------------------(8)}$$

where $2\pi\lambda$ & $2\pi\lambda_r$ are the de Broglie wavelengths for the neutron and for resonance respectively,

E and E_r are the corresponding energies

and A, B & C correspond to the width of various possible energy levels in the nucleus by which the emission of various types of particle or radiation is governed.

On substituting likely values for the widths A, B & C, for the case where $E \rightarrow E_r$ (near resonance) it is found that σ_s is only a fraction of σ_c in agreement with observations.

In the case where the neutron energy E is small compared with the resonant energy E_r or where $E \ll C$, the width of this resonance level; the capture cross section will depend only on λ , i.e. will be inversely proportional to the velocity of the neutron.

If the velocity is sufficiently small, therefore, we should expect the $1/v$ law to hold for all elements. The velocity at which this law begins to break down will depend on the widths C and relative spacing of the energy levels in the nucleus. For the lighter nuclei both these quantities will be large and we should expect, therefore, that the 1/v law will hold up to energies of a few thousand volts for elements such as Li., B, or N, but for elements such as Cd. it would only hold in the thermal regions of about 1/40 volt.

If the 1/v law for Li, or B, does hold over so wide an energy range, measurement of the absorption coefficient in boron gives a very useful method of estimating neutron velocities and a number of experiments have been performed to verify this law.

The experiments of Rasetti[7,8] consist of passing a beam of neutrons, slowed down by paraffin, through a steel disc near its edge at an angle of about 25° to the surface of the disc. The surface of the disc was coated with a layer of the material under investigation, and could be rotated so that the linear speed at the edge was about 140 m/sec. This velocity could be either added to or subtracted from that of the neutrons by reversing the direction of rotation. If the 1/v law holds for the neutrons in use no change in the number of neutrons emerging from the disc should be noted when the direction of rotation is reversed but if, for instance, the cross section were independent of velocity one would find more absorption when the disc moves against the neutrons than when it moves with them.

The measurements made with a cadmium layer on the disc did shew a change on reversal shewing that the 1/v law does not hold. When the cadmium was replaced with silver or boron carbide no change was observed and so it is to be concluded that the 1/v law holds for these elements in the region of thermal energies used.

That the neutron beam from a paraffin shielded source does contain thermal neutrons at room temperature was demonstrated by Dunning, Fink and others[9,10,11,12.] by means of a mechanical velocity selector. This consisted of four duralumin discs each fitted with 50 cadmium sectors of width equal to the spaces between the sectors. Two of these were mounted on a shaft 54 cm, apart and could be rotated at a speed up to about 5000 r.p.m. Behind each of the rotating discs were fixed the other two stationary discs, the separation of rotating and stationary discs being about 5 mm. Each pair of discs represents a shutter for the neutrons that are absorbed by cadmium, and from observations with a boron ionization chamber on the change in the number of neutron counts with change in speed of rotation a velocity distribution curve of the slowed neutrons absorbed in cadmium can be obtained.

This is on account of the fact that neutrons of a particular velocity which are let through the first shutter system will, at one particular speed of rotation of the discs, be prevented from passing the second cadmium shutter. The curve obtained corresponds well to a Maxwellian distribution at room temperature. A shift in the distribution curve maximum towards lower velocity was also observed on cooling the paraffin in liquid air. In addition, these experiments prove that boron is a good detector of thermal neutrons.

Owing to mechanical limitations the resonance absorption of neutrons cannot be investigated with the mechanical velocity selector as the energies involved here range from about 1 volt to several hundred volts and less direct methods of velocity measurement have to be used.

Amaldi and Fermi[13] have separated the neutrons slowed down by paraffin into various groups or energy ranges. Using the terminology of Amaldi and Fermi these groups are :-

(C) Strongly absorbed in cadmium, thermal energies.

(D) Strongly absorbed by Rh. and In. but not by Cd.

(A) Strongly absorbed by Ag. and activates Ag. and Ir.

(B) Moderately absorbed by Ag. and activates Ag.

(I) Strongly absorbed by I.

These groups can be arranged in order of velocity in several ways. A homogenous group can be converted into a group containing neutrons of a lower energy group by passage through paraffin wax and may be detected by the activation produced in a specimen of the appropriate material.

Since the energy of the C group is known to be thermal from the mechanical velocity selector experiments a comparison of the absorption of C neutrons in boron with that of any other group in boron will give the energy of the other group. This depends on the assumption that the 1/v law holds for boron in the velocity range to be measured. Experiments of this nature have been performed by Goldsmith and Rasetti[14] and Weekes and others[15]. The estimated energies of the various groups are :-

Group	C	D	A	B	I
Volts	0.037	1.6	4	7	36

In view of the large amount of information about the capturing nucleus which can be obtained from the Breit-Wigner theory a number of workers have directed their efforts towards some means of directly measuring the velocity of the resonance neutrons and to verify the 1/v law for the light elements. This latter is important not only to prove the Breit-Wigner theory for light nuclei but also to justify the measurement of neutron velocities by their absorption in boron. It was with this end in view that the construction of the apparatus described in the second section was undertaken and since, owing to the commencement of hostilities, only the high tension supply for the artificial neutron source was completed, it seems advisable to describe two somewhat similar velocity selectors which are at present in use in order to give some impression of the ultimate design of the apparatus.

Both groups of experimenters, namely Alvarez[16] and Fertel, Gibbs, Moon, Thomson and Wynn-Williams[17] were using a direct measurement of velocity of the neutrons by measuring their time of flight from an intermittent neutron source over a known distance.

Alvarez used as the neutron source a target of beryllium bombarded with fast deuterons from a cyclotron. The deuteron beam was modulated at 120 cycles per second by grid modulation of the cyclotron oscillator valves. The neutrons were slowed down with paraffin wax in the usual manner and pass down a cadmium tube about 8 metres long to a BF_3 filled ionization chamber. The cadmium tube ensures that only those neutrons which travel in straight lines will be detected and that no slow neutrons are either formed or reflected at intermediate points. In order that fast neutrons shall not be counted in addition to the slow ones the amplifer, to which the ionization chamber is connected, is arranged to be insensitive during the half cycle when the cyclotron is working and sensitive during the remaining period of 1/240 second or for a known fraction of this period. From the point of view of the recording instruments therefore it is as though the beam consisted of a nearly monochromatic neutron beam the temperature of which can be varied by altering the distance between detector and source or the phasing between the modulations of cyclotron and amplifier. The amount of the deviation from complete monochromatism is obviously a function of such things as the duration of the neutron pulse and sensitive period of the amplifier and the time of response of the ionisation chamber. It was proposed by Alvarez to use velocities corresponding to a maximum temperature of 300°K and when measurements are attempted at lower temperatures such as 90°K it is necessary to have a period following the neutron pulse during which the amplifier is insensitive in order to allow the higher temperature neutrons to pass through the detector without being recorded. When this precaution was taken it was found possible to verify the 1/v law for boron down to 30°K.

The second method used by Thomson, Moon and others (loc.cit.), to which the apparatus under construction bears a greater similarity, is somewhat different from the Alvarez method in that neutrons of all velocities are recorded in the same experiment and the different velocity groups are afterwards picked out from the photographic records. Here again the sphere of usefulness of the apparatus was restricted to thermal energies and it was hoped that by the incorporation of various improvements in the new apparatus under construction here the velocities of resonance neutrons up to 1 or 2 volts could be measured.

The source of neutrons in this case was provided by bombarding a target of heavy ice with deuterons of energy between 150 and 250 k.v. in a discharge tube of the Oliphant type[18] (Proc.Roy.Soc. 141, 259, 1933). The deuteron source, which was situated at a high potential above earth, was modulated in the form of short pulses of duration 5×10^{-4} seconds 200 times per second through the intermediary of an intermittent beam of light. The beam of light fell on a photo-electric cell which operated the modulator through an amplifier, all being situated at the top of the discharge tube. The neutrons were slowed down in paraffin, and since the mean lifetime of the neutrons in paraffin is about 2×10^{-4} seconds and the deuteron pulse lasts for 5×10^{-4} seconds the length of the neutron pulse should be about 7×10^{-4} seconds. This was in close agreement with the measured duration obtained with a boron lined ionization chamber near to the target. Thus with a repetition rate of 200 cycles per second the maximum possible resolving power of the apparatus is 7. The optimum distance between source and detector will be such that the average neutron will occupy most of a cycle in its time of flight. It must be borne in mind however, that very slow neutrons will be indistinguishable from fast ones leaving in the succeeding pulse.

The neutrons pass down a cadmium tube 5.3m. long to a boron lined ionization chamber where the presence of a neutron is indicated by the ionization produced by the particle which is emitted when a neutron is captured by a boron nucleus. It is important that the detector should indicate the arrival of a neutron to within a time interval less than the duration of the neutron pulse. In order to have sufficient sensitivity it was necessary for the chamber to be rather large with consequent increase in electrical capacity and decrease in rapidity of response. This was to be overcome in the new apparatus by the use of a smaller chamber filled with boron trifluoride under pressure and a considerably higher collector voltage.

The chamber was connected to a linear amplifier and cathode ray oscillograph, the screen of which was photographed on a small scale on a moving strip of bromide paper. The time of generation of the neutrons was also marked by applying the deuteron current pulse to the target, after suitable amplification, to the oscillograph. The last stages of the linear amplifier were used for this purpose. The photographic record then consisted of an uneven trace due to amplifier noise, etc., interrupted at intervals representing 5 x 10^{-3} seconds by the deuteron current. Occasional large kinks in the trace represented the arrival of a neutron at the detector and from its position relative to the previous time mark its velocity can be determined. The absorption of any material interposed between source and detector can be determined by noting the relative abundance of neutron kicks in the trace that occur at given intervals after the timing marks. It should be noted that it is the beginning of the neutron kicks that marks the true time of arrival of the neutron as current begins to flow to the detector electrodes immediately the ions produced begin to separate.

The improvements which it was intended to incorporate in the new apparatus under construction to allow of an increase in the velocities which could be measured included a more powerful neutron source. This was to be obtained by working the discharge tube at 600-700 k.v. instead of 150-250 k.v. as in the above apparatus. This necessitated the construction of the apparatus described in detail in Section II. The range of the apparatus cannot be extended indefinitely by increasing the distance between the source and detector as the solid angle subtended by the detector at the source becomes small and the absorption of neutrons in air due principally to the nitrogen is by no means negligible. The absorption in air could be obviated by evacuating the cadmium tube through which the neutrons pass. Greater sensitivity and speed of detection involved the use of the high pressure high voltage BF_3 chamber already mentioned and it was not expected that any great difficulty would be experienced in making measurements at 1 or 2 volts energy and there was some possibility of reaching 5 or even 10 volts.

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PART II

Construction of Apparatus.

GENERAL DESIGN.

Of the various possible methods of generating the 600-700 k.v. required for the neutron source the voltage multiplying circuit developed by Cockroft & Walton[1] was chosen. This was chosen in preference to the electrostatic belt generator of Van de Graaff[2] as it was felt to be less dependent on atmospheric conditions and was capable of delivering much larger currents. Also since the H.T. generator will eventually be required to run with little or no attention freedom from mechanical complexities is very desirable. The cascade transformer method was ruled out on the grounds of available space and cost. The alternating potential provided by this system would be a considerable disadvantage because it would only be possible to modulate the ion source in the discharge tube at the supply frequency or submultiples thereof. This would considerably limit the flexibility of the system as a whole.

An important point to bear in mind in the design of H.T. apparatus is that the capacity to earth of various parts of the generator system itself and its associated load is by no means negligible and that if very high alternating potentials are applied the capacitative currents become quite large. This current flow certainly provides a wattless load on the transformers used but the copper and iron losses in these neccessitate an unneccessarily high K.V.A. rating for the transformer. As will be seen with the circuit used parts of the apparatus are subjected to no greater alternation of potential than the ripple, which of course depends on the D.C. load taken and none of the apparatus fluctuates in potential above earth by more than twice the transformer voltage, i.e. about ½ of the total voltage for a four stage circuit.

A diagram of the circuit is shewn in Fig 1.

For a theoretical voltage multiplication of four, four rectifiers are required and these are represented by $R_1 - R_4$. An alternating voltage of peak value V is applied between A & B, B being connected to earth. During the half cycle when the point A is positive with respect to earth the condenser C_1 will be charged to a potential less than V by an amount equal to the potential drop across the rectifier R_1 which will depend on the emmission from the rectifier filament. In the circuit shewn the lower plate of C_1 will be charged positively with respect to the upper, so that on the succeeding half cycle the potential of the anode of R_1 and therefore of the cathode of R_2 would rise to a peak value of nearly 2V, if it were not for the fact that the condenser C_2 will share the charge on the condenser C_1. In practice, it is convenient to make the capacity of C_1 double that of C_2 as the condenser C_1 has to withstand only half the voltage of C_2. During subsequent half cycles the charge on C_2 cannot leak back through R_2 but can pass through R_3 and be shared by C_3 and likewise the charge on C_3 can pass through R_4 to C_4. These transferences of charge can only occur from the condenser C_1 to condenser C_2 when the potential difference across C_2 is less than that accross R_1. Now the maximum negative potential on the anode of R_1 and cathode of R_2 is equal to twice the peak transformer voltage and in the absence of any load across the output terminals P Q the potential of C_2 will rapidly reach the limiting value of 2V. Also in the static case when no further transference of charge occurs from C_2 through R_3 and R_1 to C_3 the condenser C_3 will have a potential difference across it equal to 2V. Again the maximum negative potential of the upper plate of C_3 above earth will equal the sum of the potential differences

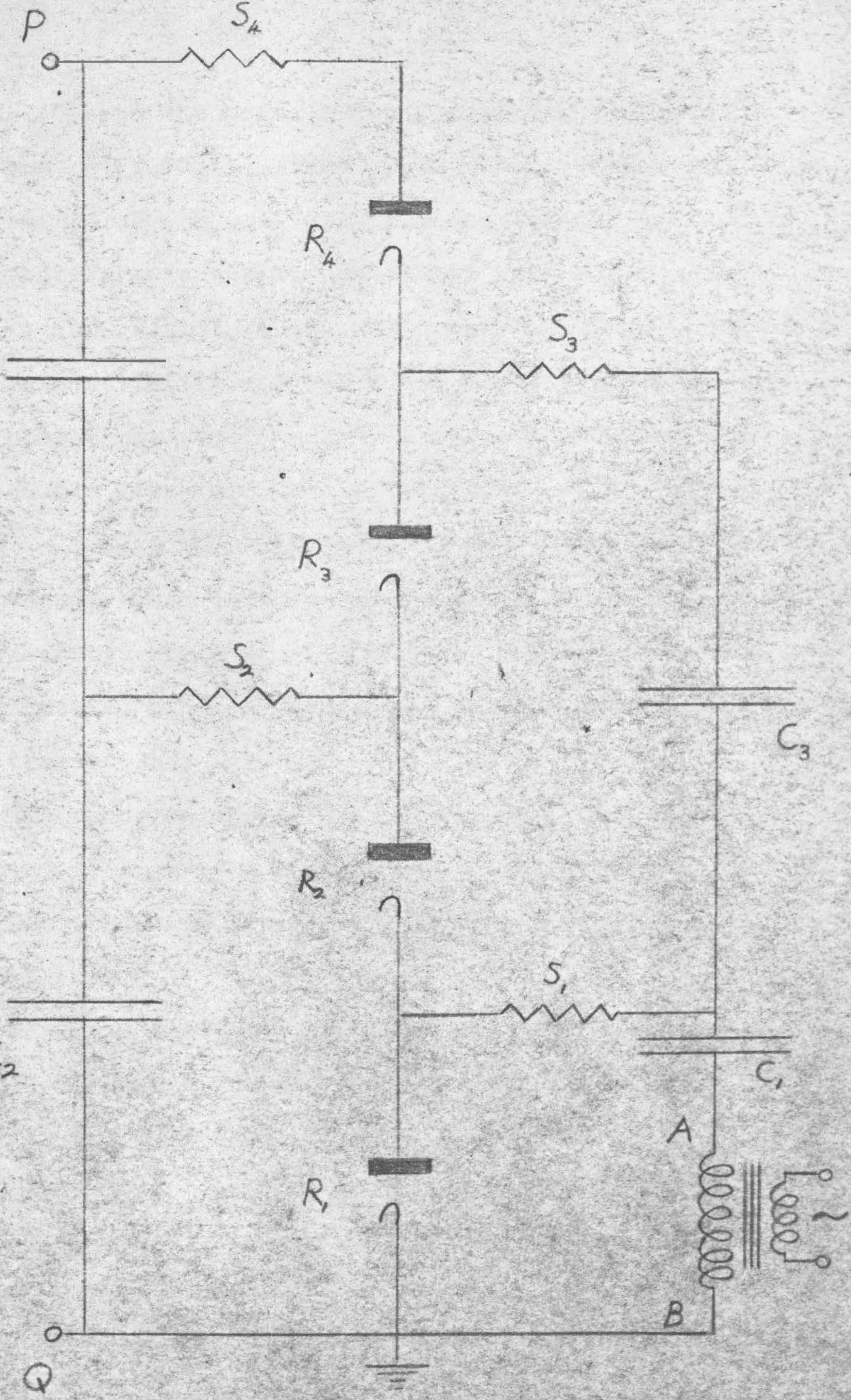


Fig. 1

across C_3, C_1 and the transformer secondary, namely 4V, so that the point P will reach a potential of 4V. The resistances S_1, S_2, S_3, S_4 are included for the protection of the rectifiers as during the period when these are conducting the rectifiers will be operating under conditions of temperature limited emmission and the sudden application of high potentials would result in large heating of the anodes and the liberation of gas and it is well know, v. Gossling[3], that the initiation of flash arcs in high voltage vacuum tubes is greatly minimised by the reduction of the reservoir capacity connected to the tube, or by the introduction of some impedance between this capacity and the tube itself.

The operation of the circuit when a load resistance of value S is connected across the output terminals P Q is more complex and may be imagined somewhat as follows.

During a cycle of period t the condenser C_4 will lose charge $Q = \frac{2Vt}{S}$ and in some subsequent small fraction of a period this charge Q will be received from the condenser C_3. During the same initial period t the condenser C_2 will lose a charge Q to the load and an equal charge to C_3 making a total loss of 2Q. This loss must be made up by a transference of charge 2Q from C_1, in other words by an amount of power from the transformer equal to 2 Q.V. An expression for the amount of ripple superimposed on the direct potential of P may now be found in terms of the load, period and the capacities C_2 and C_4.

The drop in potential occuring during the period t will be given by

$$\Delta V = \frac{Q}{C_4} + \frac{2Q}{C_2}$$

and when $C_4 = C_2$

$$\Delta V = \frac{3Q}{C} = \frac{6Vt}{CS}$$

The load current $I = \frac{4V}{S}$ so that the percentage ripple is

$$\frac{\Delta V}{V} = \frac{3}{2} \frac{It}{VC} \times 100$$

Thus for a load current of 1 ma. at 600 k.v. using a 500 c.p.s. supply the ripple will be 0.25% for a condenser capacity of 0.01 μfd. It can be seen that a high frequency supply is desirable and that a square topped wave form from the transformer will give a longer fraction of a period during which charge may be transferred from C_1 and C_3 to C_2 and C_4 for any given small drop in potential of P. than would a sinusoidal wave form. In the present apparatus 500 c.p.s. was used and the alternator that supplied the power gave an approximately square waveform.

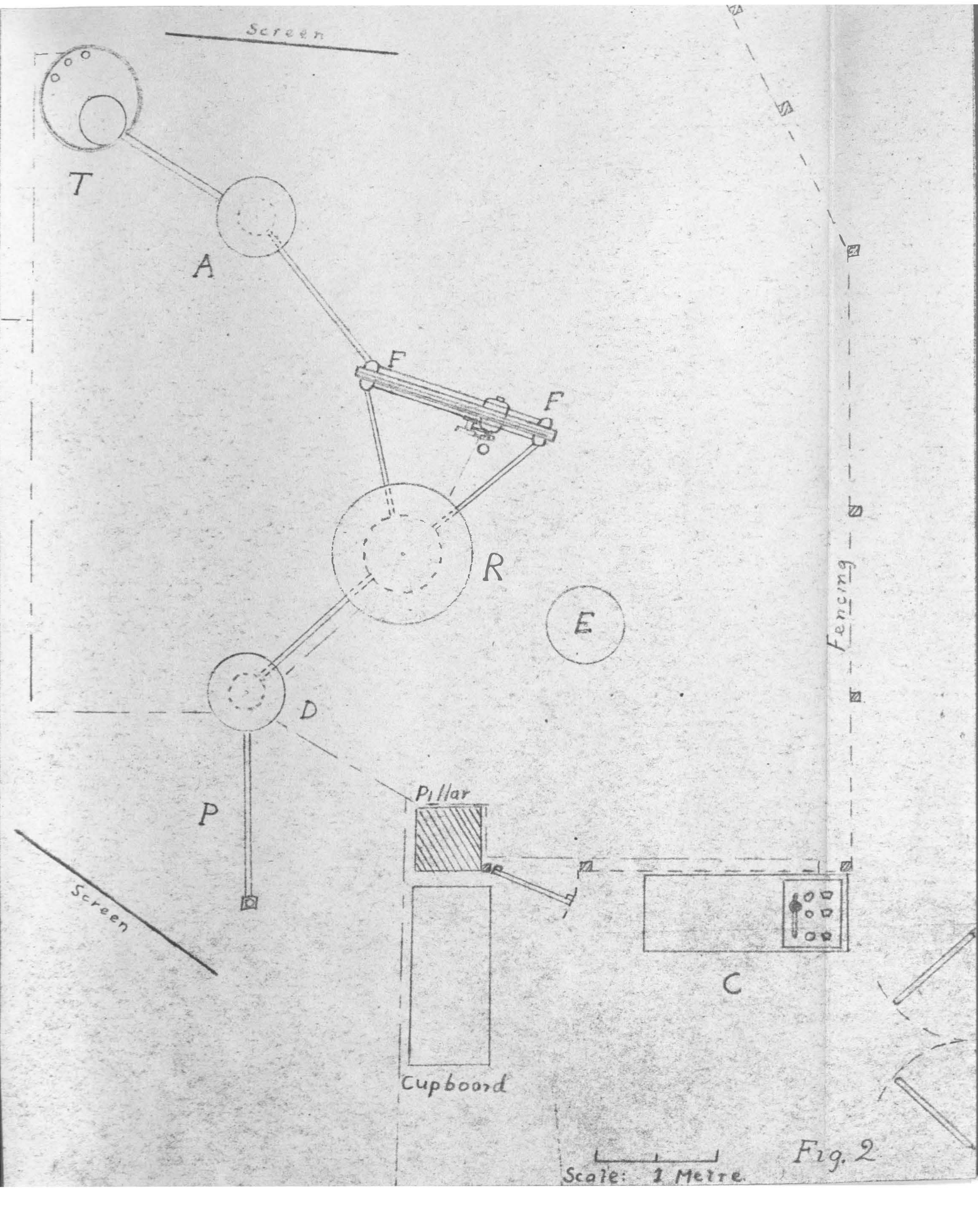
As it was known that continuously pumped rectifiers could be made to stand up to 400 k.v. without great difficulty it was decided to use a transformer capable of giving 200 k.v. peak voltage, which in view of the fact that each rectifier must withstand an inverse voltage of double this figure, neccessitated the circuit shewn in Fig 1. using four rectifiers. Condensers, made by Philips, were available with capacities of .01 μfd and a safe working voltage of 200 kv, one of which was used for C_1 and the capacities C_2, C_3, and C_4 which as previously noted need to be no more than half the capacity of C_1 but to work at 400 kv. were each made up of two condensers connected in series. At sufficiently high voltages, such as are in use here, there is no need to use bleeder resistances across each condenser to equalise the voltages when two are used in series as the shunt path provided by corona discharge will produce a stabilising effect. At lower voltages the consenser with the higher internal resistance will be subjected to more than half the voltage across the pair but where corona can occur it will do so across the higher internal resistance condenser, thus increasing the potential on the other, and if the corona leakage paths are approximately equal in the two cases the potential distribution will be fairly uniform.

As can be seen from Fig. 1 the most convenient mode of disposing the various components is in the form of three vertical stacks, the four condensers forming C_2 and C_4 generally known as the D.C. condenser stack, the four rectifiers and the three condensers forming C_1 and C_3 known as the A.C. condenser stack. Cross connections between the various stacks are made by the resistances $S_1 - S_4$. A further structure is required for supporting the power supplies for the filaments of R_2, R_3 and R_4 as these are all at a high potential above earth.

The approximate positions of these components in the room available is shewn in plan in Fig.2. T is the transformer; A the A.C. condenser stack; F the filament heating supply frame; R, the rectifier stack; D, the D.C. condenser stack. This arrangement was neccessitated by the pillar P which could not be removed as it formed part of the main steel frame of the building.

The control table is shewn at C behind the wire fencing which provides a safe passage along one side of the room. E represents the situation for the proposed acceleration tube and ion source.

Owing to the restricted height of the ceiling of



Screen
T
A
F
F
R
E
D
P
Pillar
Screen
Fencing
C
Cupboard
Scale: 1 Metre

Fig. 2

the room most of the lighting fittings had to be removed and various metallic projections were covered with tinplate sheets with turned up edges to avoid possible sparkover troubles.

The floor originally consisted of untreated wooden blocks and was a potential source of considerable amounts of dust which it was feared would be precipitated all over the high tension generator and would lower the maximum voltage at which the set would safely work. The floor was greatly improved by treatment with several coats of linseed oil and little trouble was subsequently caused by dust precipitation.

Since, with the material available, the rectifier stack was to be about 7 feet in length without the high tension electrode at the top it was necessary to drill a hole some 5" diameter through the floor to the room below and to pump out the rectifier by means of pumps suspended from the ceiling of the lower room. This expedient was resorted to to allow ample clearance between the rectifier stack main electrode and the ceiling. The floor was found to be 14 inches thick of reinforced concrete and the hole was eventually bored with an electric hammer rather similar in action to an ordinary pneumatic road drill.

Rectifier Construction

The design of the rectifier stack was centred round some large porcelain insulators which were available. One of these is depicted in Fig.3(a) which is a detailed drawing of one section of the stack.

Each rectifier entails one of these insulators which are made of white porcelain of high electrical breakdown strength. Both inner and outer surfaces of the porcelain are glazed, the glazing of the inner surface being very important in enabling a good vacuum to be obtained easily. The insulators are 20 inches long with an internal diameter of 10 inches. The wall thickness is 1 inch and the cylinders are provided externally with two flanges moulded integrally with the body bringing the overall diameter to $15\frac{1}{2}$ inches. The anode A and cathode B are both identical in all four rectifiers and consist of lengths of steel tube $2\frac{1}{4}$ inches external diameter, soft soldered into steel end discs D, which are large enough in diameter to protrude over the edge of the insulator by about 1 inch all round. These end discs are circular and about $\frac{3}{8}$ inch thick turned flat on both faces to seat on the ends of the insulators, Fig.3(a).

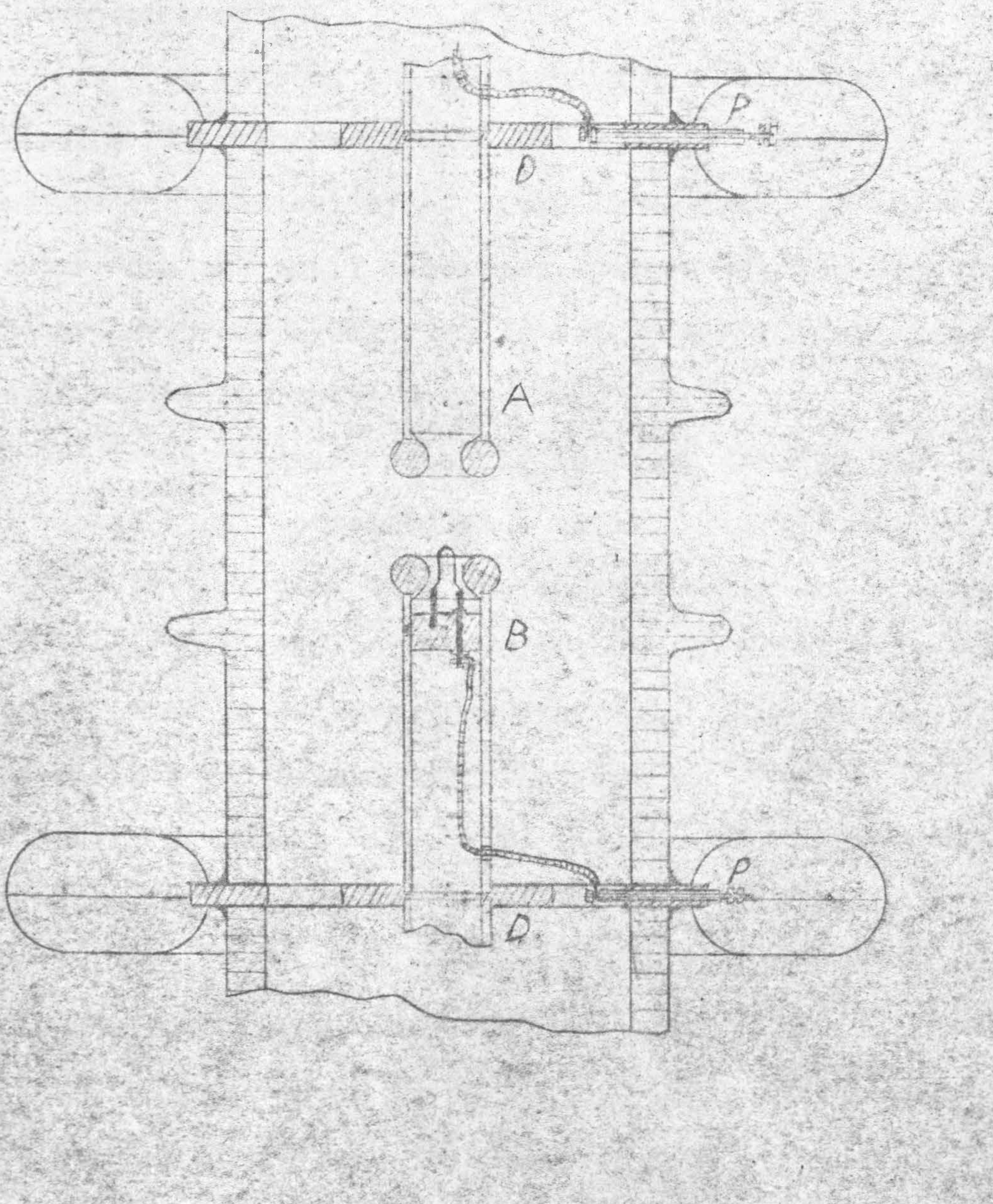
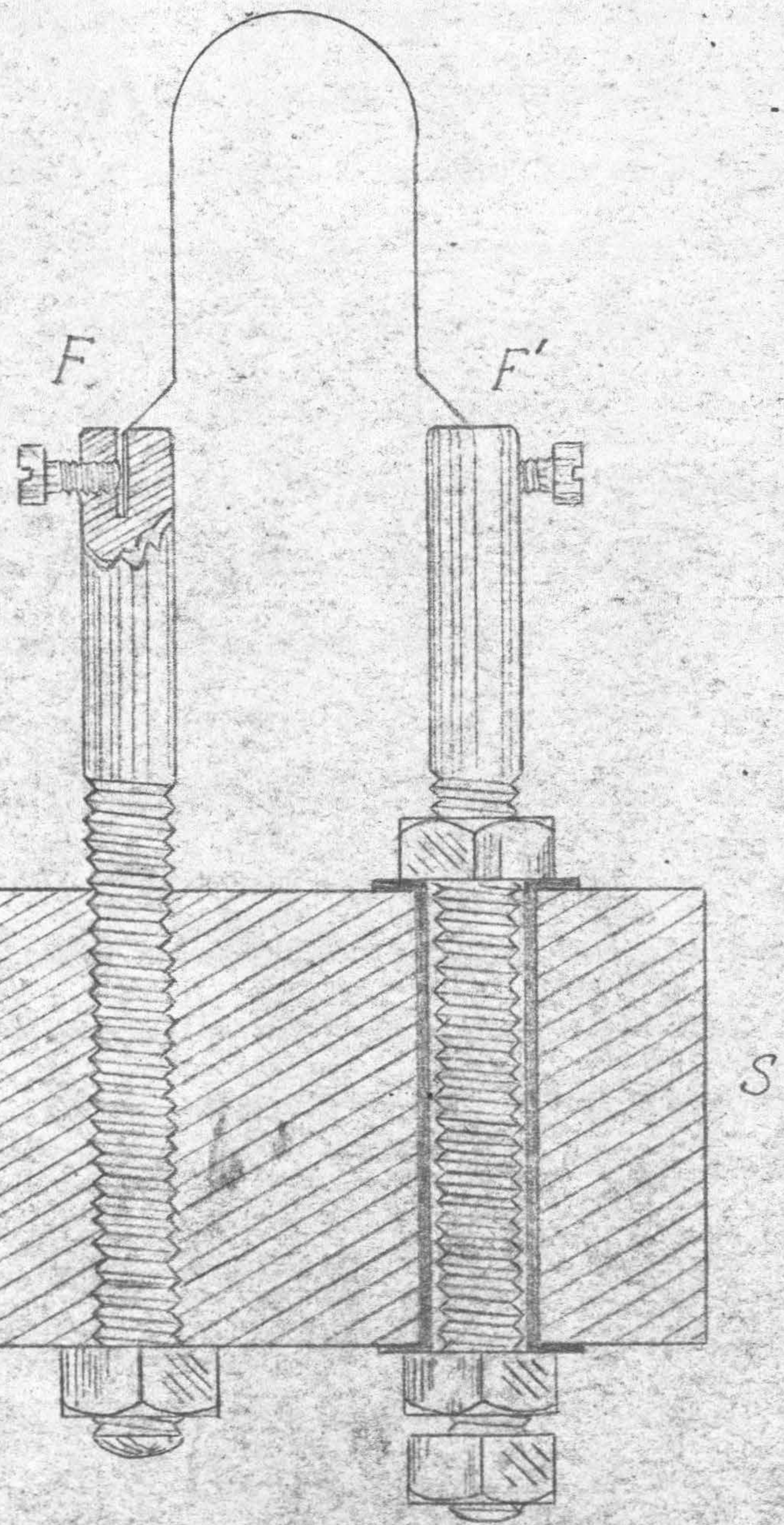


Fig. 3a.

A total of five discs are required but the top and bottom ones of the stack are of slightly different construction and do not contain the three large diameter holes for pumping.

The ends of the electrodes are formed by toroidal steel turnings pressed into the ends of the tubes to reduce the possibility of field immersion that might occur with the small electrode spacing of 2 inches. This inter-electrode spacing will, after initial degassing, stand 400 kv. without difficulty.

The filament assembly is shewn in Fig 3(b). The filament itself consists of a single loop of tungsten wire 0.75 m.m. diameter, the ends of which are clamped by means of small set screws into holes drilled in the steel filament supports FF', Fig.3(b). One of these supports F is screwed directly into the steel block S which is of such a size as to slide easily inside the cathode tube B, Fig.3(a), where it can be clamped at any height by a set screw in the side of the cathode tube. The head of the set screw is of course below the surface of the cathode tube, which it-self has a wall thickness of ½ inch. The other filament support F' is insulated from the block S by a mica sleeve and is held in position



Scale: Twice Full Size

Fig. 3b.

by nuts under which are mica washers. One end of each filament is then seen to be connected electrically to the corresponding end disc of that rectifier section. A copper wire, about 18.s.w.g., insulated with "fish spine" porcelain beads, is connected to the lower end of F' and passes through a hole near the lower end of the cathode tube where it is connected to the lead out P. This lead P consists of a length of 6.B.A. screwed brass rod passing through a radial hole in the end disc and insulated from the disc by means of a glass tube. The inner end of this lead is arranged to come about in the centre of one of the pumping holes in the end plate and a vacuum tight joint is made with sealing wax for a length of about 2 inches at the outer end of P.

The amount by which the filament protruded above the negative toroidal electrode can be adjusted by raising or lowering S in the cathode tube. The usual projection of the filament was about 8-10 m.m.

The above filament assembly was chosen on the grounds of simplicity and since it was necessary to dismantle the whole rectifier stack to renew the lowest filament and corresponding amounts for the other filaments. the heating current was kept as low as possible to give long filament life. Other workers have used ingenious designs to enable the filaments to be renewed without any dismantling. In one of these the cathode tubes are bent round in a gentle curve so that the filament assembly may be drawn down this tube and removed from a hole in the side of the stack, but owing to the fact that a space of nearly 3 inches would be required between the ends of one insulator and the next the overall height would have been increased by about one foot which could not be tolerated here.

The weight of the rectifier stack is taken by three wooden blocks beneath the bottom end plate D, Fig.4. This end plate must be accurately horizontal to prevent the stack being unstable.

The bottom section filament lead is brought out similarly to the previous ones except that the radial hole through the plate is not drilled parallel to the face and so penetrates the upper surface of the disc. This is necessary because of the omission of the three pumping holes in the lower plate. A pumping tube A, $2\frac{1}{2}$ inches in diameter and just long enough to protrude through the ceiling of the room below, i.e. 20 inches, is attached to the centre of the base plate immediately under the foot of the cathode

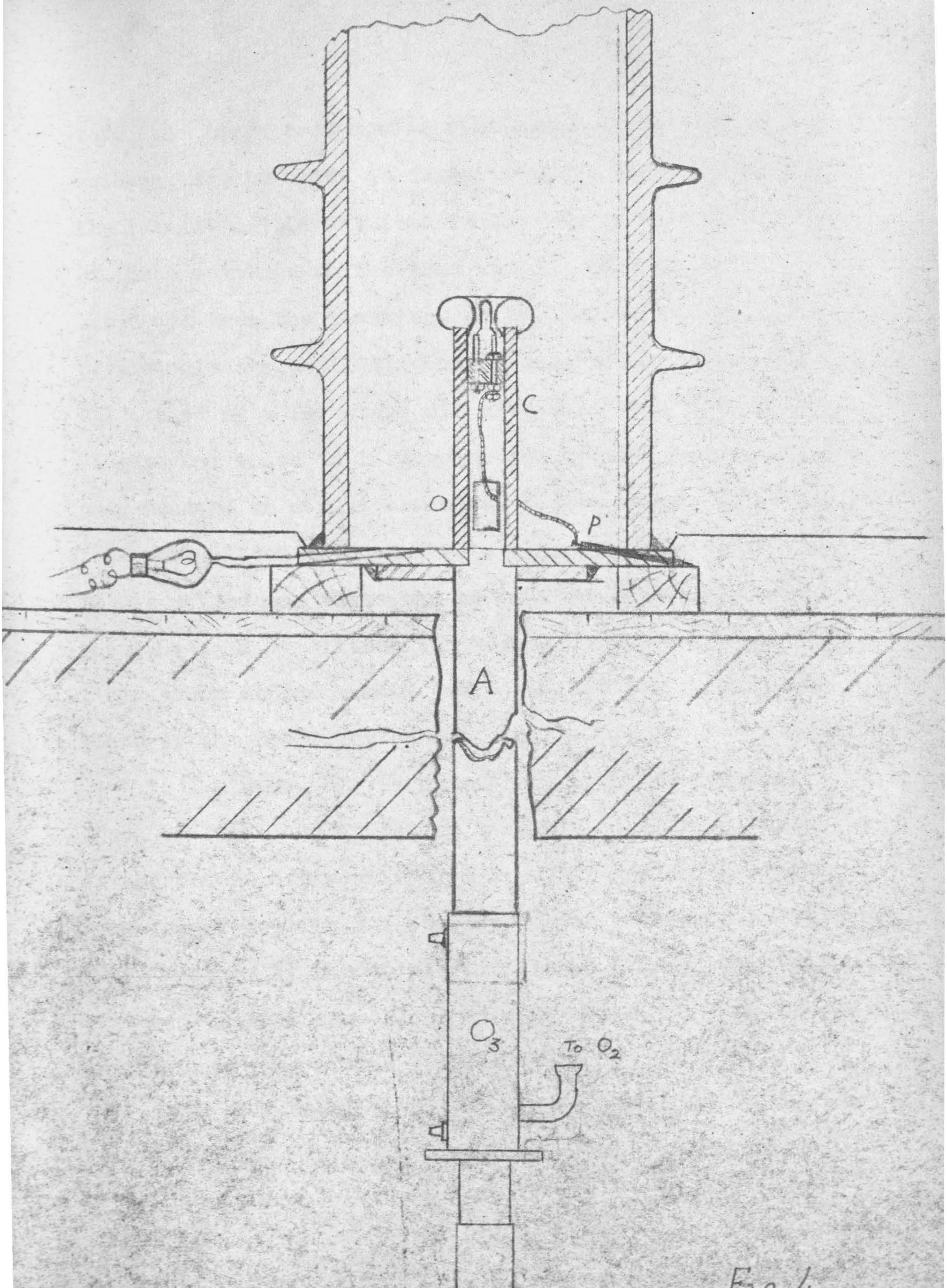


Fig. 4

tube C. Large rectangular openings O are cut in the cathode tube to allow as fast a pumping speed as possible. The insulated filament lead is also brought through one of these openings to the lead out P. The pumps are suspended from the lower end of the tube A and consist of a single stage oil diffusion pump (Metropolitan Vickers, O_3) backed by a two stage oil diffusion pump (Metropolitan Vickers O_2) which is in turn backed by a Hyvac rotary oil pump mounted on a platform about 6 feet below the ceiling. This combination of pumps has a rated pumping speed of 25 litres per second while the calculated pumping speed of the tube A is 30 litres per second. A connection for a Pirani or McLeod vacuum gauge is provided on the base plate of the rectifier column.

A diagram of the assembled rectifier stack is given in Fig. 5 and it can be seen that each steel disc is surrounded externally by a toroidal shaped aluminium spinning, 2 feet in diameter, which is made in two halves held together by three internal wooden blocks, Fig. 3(a). A large removeable metal earth plate, about 5 feet square covers the edges of the lower disc.

Before assembly all the steel parts are polished brightly with fine emery cloth and then, together with

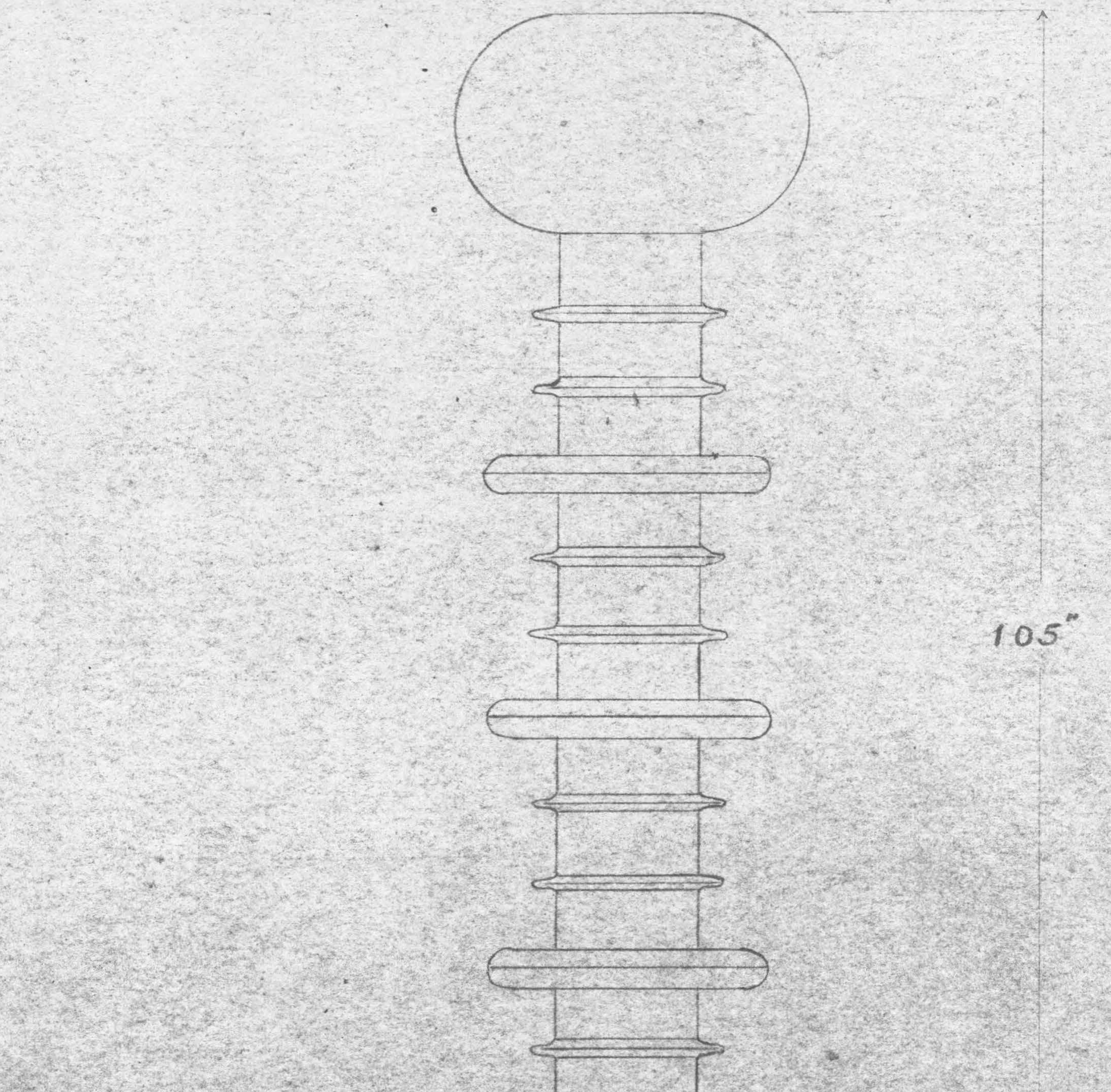


Fig. 5.

the porcelain insulators, are carefully cleaned with carbon tetrachloride, or some other such solvent, taking care not to leave specks of cotton, etc., from the cloth used for cleansing. The base plate together with the attached pumping tube, filament, etc. is then carefully levelled up on the wooden blocks. A porcelain cylinder is then placed over this and accurately adjusted central by measuring the distance of the edge of the porcelain from the edge of the steel disc with calipers. This joint is now roughly sealed with "Apiezon Sealing Compound Q", usually known as vacuum plasticene. One half of an aluminium spinning is then dropped over the insulator and the next disc with the anode tube and cathode tube for the next section placed in position and centred as before. This ensures that both electrodes in the lower section are correctly aligned. The joint between disc and porcelain is again roughly sealed and the assembly continued as before.

The technique of completing the sealed joints to render them really vacuum tight is as follows. The plasticene is first rolled into cylinders about 5/16 inch in diameter with the hands and pressed round the join with the fingers in the usual manner. It is then smoothed with the fingers and the surface, if at all rough, should be rubbed with a little vacuum grease or oil. In a good plasticene joint the plasticene should be thinned down to nothing at the edges where it meets the metal or porcelain surfaces. This is most easily done with a tool made from a polished steel ball, a ball bearing for instance, about $\frac{3}{8}$ inch in diameter, soldered to a metal rod fastened into a handle. This is pressed into the plasticene and pushed right round the joint. A large amount of the plasticene is removed by this means, leaving a very neat and reliable joint. The temperature of the plasticene is important for the successful use of this tool, as if it is too cold a rough finish is produced and if too warm it is liable to stick to the ball. It is desirable to have a reduced pressure inside the apparatus while the sealing is being performed.

In a vacuum system of this size numerous leaks are almost certain to occur. Two methods of tracing these were used,both involving the use of a Pirani gauge. The rate of leak, in terms of the gauge galvanometer reading, is taken with the pumps shut off, or the pressure with the pumps running is noted. In one method the suspected parts are painted over with water or vacuum oil and the rate of leak or equilibrium pressure will fall when the leak is covered. With the other method which is perhaps quicker but less reliable a stream of coal gas or hydrogen is directed from a glass jet at the suspected parts when the apparent rate of leak or steady pressure will rise due to the greater rate of diffusion of hydrogen through the leak than air. If a Pirani gauge and not a McLeod gauge is used the effect will be accentuated by the higher thermal conductivity of hydrogen than air, thus giving a greater cooling effect on the Pirani gauge filament.

The rectifier stack is completed with the addition of the high tension electrode at the top. The construction of this electrode involved some serious consideration as an aluminium spinning of the size required, namely an oblate spheroid 2½ feet in diameter and 1½ feet high, would have proved very expensive and some considerable time would have been needed for manufacture. An electrode built of sections of thin wood carefully fitted and shaped was discarded as being too complicated to construct and the material finally decided upon was ordinary brown paper. A wooden frame made of two discs of plywood for the top and bottom separated by vertical wooden pillars was made and six or eight strips of plywood about 1 inch wide were bent to shape and nailed to the two discs. Carefully cut "gore" shaped pieces of brown paper were then glued onto this frame and the edges sealed with gummed brown paper tape. This electrode proved completely satisfactory in operation and corona was never observed even at 700 kv. The reason for its success is not very clear but would appear to be in part due to its very poor conductivity as the various corners and creases in the surface would almost certainly have given rise to trouble had they been on a metallic electrode. That the electrode really does rise to a high negative potential, i.e. the same sign as that of the top plate of the rectifier, is shewn by that fact that one electrode which was insufficiently heavy floated away from the top of the stack when the potential was sufficiently high. Any connections made to the top of the stack for the purpose of conducting any appreciable current must of course be made direct to the top steel plate under or through the paper electrode. The only other disadvantage of a paper electrode is the danger of fire should a flashover occur, but no trouble of this kind was experienced. Brown paper electrodes were also used at the tops of both the D.C. and A.C. condenser-stacks, and two corners of the room which contained fittings likely to cause too much corona leakage were shielded with brown paper screens, a technique introduced by Messrs. Philips of Eindhoven, hung from the ceiling. A possible explanation for the success of these screens, and also for that of the electrodes, is that they become charged to a potential intermediate between that of the wall or ceiling, i.e. earth, and that of the source of corona discharge. The greater the corona current the nearer will the potentials of the paper and the apparatus become resulting in a lowering of the field and a consequent stabilising effect. The operation of these paper screens and electrodes did not appear to depend on weather conditions, but the operating room was always kept in the neighbourhood of 65^{o}F. in temperature.

Filament Heating Supplies.

Since the apparatus is designed to produce a negative potential the filament in the lowest rectifier is connected to earth. This enables this filament to be heated by means of an ordinary auto-transformer. It is scarcely practicable to heat the filaments of the remaining three rectifiers by means of transformers with insulation capable of working at up to 800 kv. as the clearances involved would make them extremely bulky. It would have been quite simple to use accumulators in insulated corona shileds but the need for frequent charging when delivering a current of about 8 amperes at about 8 volts, which is the approximate load provided by each filament, renders this method troublesome.

The alternative scheme of separate small alternators for each filament driven by insulating belts was adopted. Belt drive was used in preference to a direct drive to all three alternators by means of an insulating shaft, as by the latter method it was impossible to obtain sufficient clearances between alternators and yet keep each alternator at about the same ehight as the appropriate filament leads on the rectifier stack. The alternators were accordingly mounted on an insulating framework as seen at A, B, C, Fig. 6(xx). giving adequate clearances without increase of height. The alternators themselves ran at 1500 r.p.m. and were of somewhat unusual design, having been originally designed to run immersed in oil. They were of the four pole, salient pole, permanent magnet rotor type thus eliminating all slip rings, etc., and the stator was wound with asbestos insulated wire. The spaces between the rotor poles were filled in solid with bakelite to improve

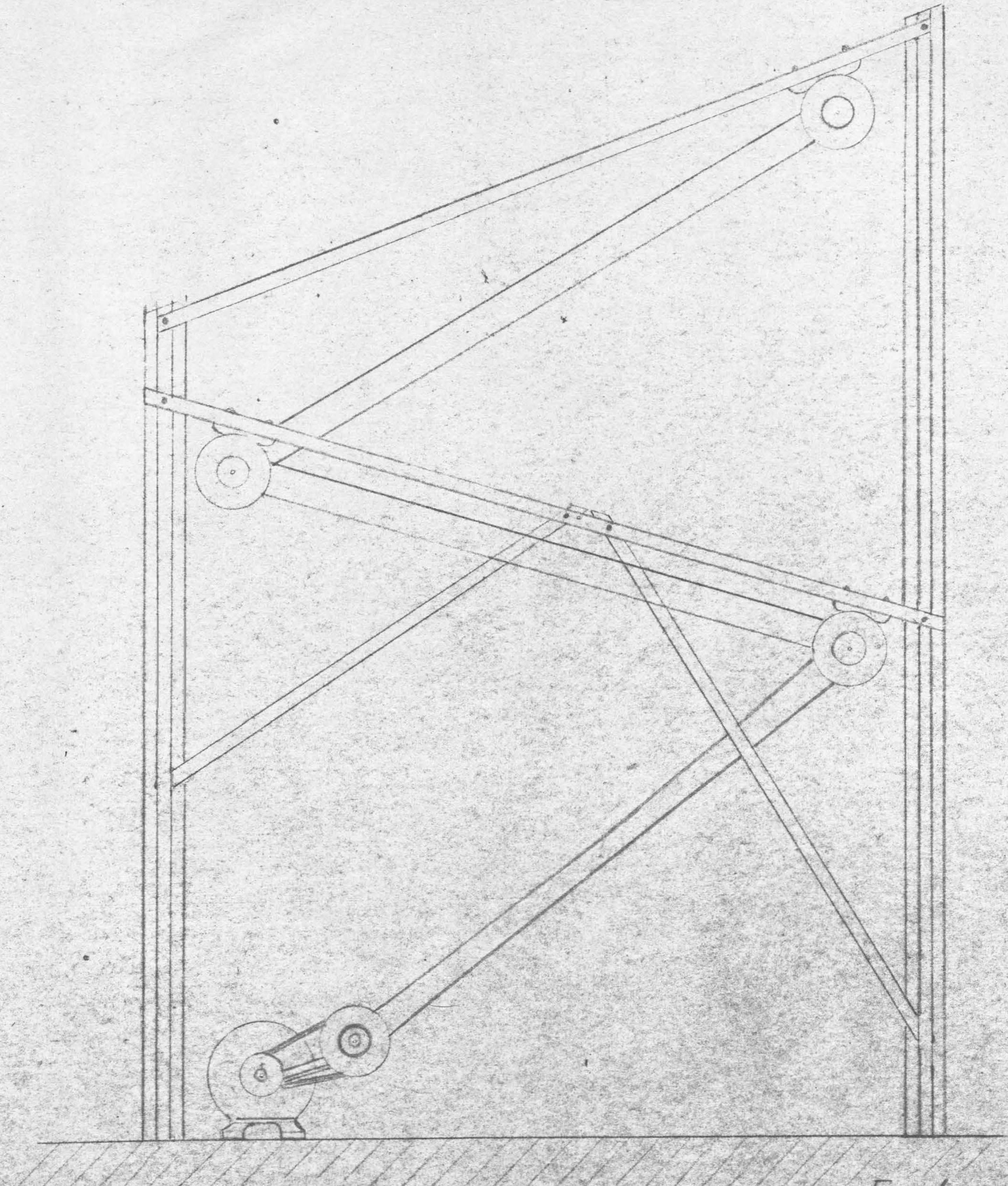


Fig. 6.

streamlining when running in oil. Wooden V rope pulleys 3 inches in diameter were attached to each end of the rotor shafts of A and B and to one end only of C, and aluminium spinnings with a re-entrant end were used to prevent corona from both ends of the generators, see Fig.7. The belts, which were ordinary rubberised canvas V belts, passed through slots cut in the sides of the spinnings, the edges of the slots being turned inwards to avoid corona.

The insulating frame was constructed of strips, 2 inches x 1 inch, of well seasoned mahogany, which had been heated in molten paraffin wax for ten or twenty hours, or until all bubbles had ceased to appear. Whilst no measurements on the insulating properties of this material were made it proved very satisfactory in use and appears to have a very high leakage resistance, both volume and surface, when tested by so sensitive an instrument as a charged gold leaf electroscope.

The vertical members of the frame were made of T section by screwing two of the strips together and each of the diagonal cross members consisted of two strips bolted, one each side, to the vertical supports. The lower cross members were braced to the vertical strips by two further pieces of paraffined mahogany and diagonal struts served to maintain the whole structure vertically on the floor to which it was screwed. This triangulated design gave a very rigid structure which proved almost completely free from vibration when running, even though some whip of the belting did occur.

The speed of the driving motor, which was 1.2 B.H.P. 110 volt D.C. shunt machine running at 3,000 r.p.m. was reduced to 1,500 r.p.m. by means of a countershaft pivoted on one bearing housing of the motor. This arrangement allowed adjustment of the lower belt tension. The other belts were adjusted by moving the alternators B and C along the frame which was provided with slots for this purpose.

The motor speed was maintained constant with the aid of a stroboscope consisting of a number of black and white lines on the motor pulley in front of which, on the floor, was fixed a neon lamp running off the 50 c.p.s. supply mains. Owing to the uncertain speeds of the three alternators due to the belt slip with the series type of belt drive used, it was necessary to provide means to adjust the filament current.

The leads from the alternator to the filament terminals on the rectifier stack were run through pieces of brass tube $1\frac{1}{2}$ inches in diameter with 1/32 inch thick walls. This diameter of tubing seemed sufficiently large to prevent brush discharge. These filament lead tubes project into the re-entrant portion of the aluminium shields on the filament alternators which thus serve to support one end of the filament lead. The other end is carefully cut to fit the curvature of the corona shield on the rectifier stack, and is supported by two small steel pins soldered into the brass tube, and which project into two small holes drilled in the corona shield. The filament leads may thus be removed by sliding them about $\frac{1}{4}$ inch into the alternator corona shield when the two steel pins will be withdrawn. The tubes contain the actual filament current leads and a variable resistance which is set to pass the correct heating current when the driving motor is running at 3,000 r.p.m. The current leads are of ordinary twisted flex and are made some 50% longer than the brass tube so that the resistance may be removed from the tube easily and for removal of the tube itself some extra length in the flexible leads inside is obviously necessary. A diagram of this arrangement is shewn in Fig.7 and the filament leads can also be seen in the photograph of Fig.8.

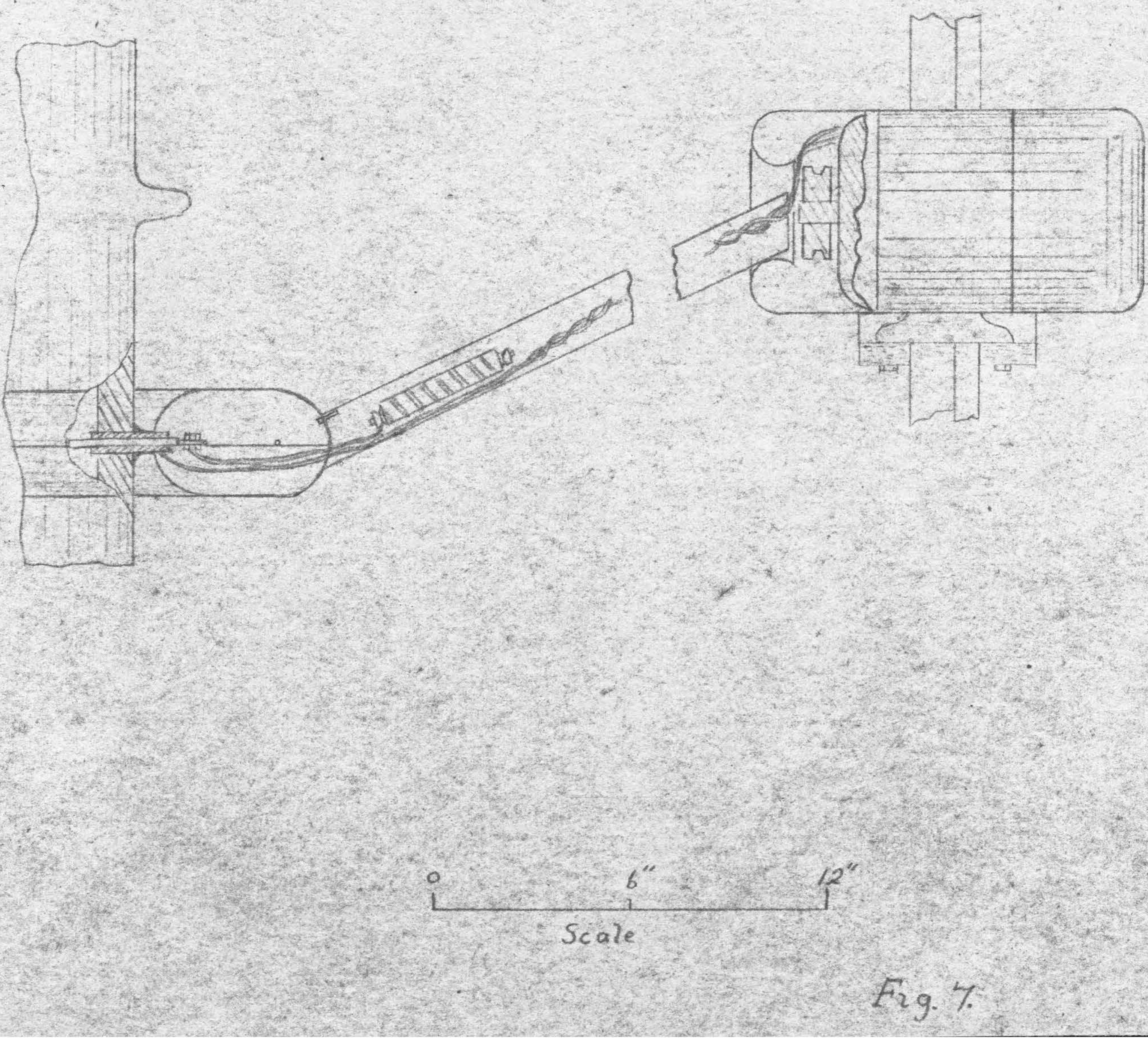


Fig. 7.

Fig. 8.

General view of high tension generator taken in the light of a 600 kV. spark.

Condenser Stacks.

The high tension condensers available were constructed by Philips and are remarkable by virtue of their small dimensions for their high voltage and capacity rating namely 200 kv. and 0.01 ufd. see Fig.9(a). They are made of a synthetic resinous compound, known as Philite, containing only a small proportion of high quality "filler" and each condenser really consists of five condensers each of 0.05 ufd. capacity. Each elementary condenser has a construction similar to the familiar glass unspillable office inkwell as shewn in Fig.9(b). The condenser plates are metallic coatings sprayed on to the Philite cone shaped dielectric. This type of construction greatly simplifies the manufacture of such high voltage condensers as each elementary condenser has only to withstand 40 kv. and the set of five when assembled as one unit gives a nearly uniform distribution of potential along its length. How successful is this construction is shewn by the fact that no flashover has ever occurred along any part of the condenser stack. In the condensers as supplied these five units cannot be separated and and four insulating fins are provided on the outer surface at points opposite the dielectric layers of the elementary condensers so that the

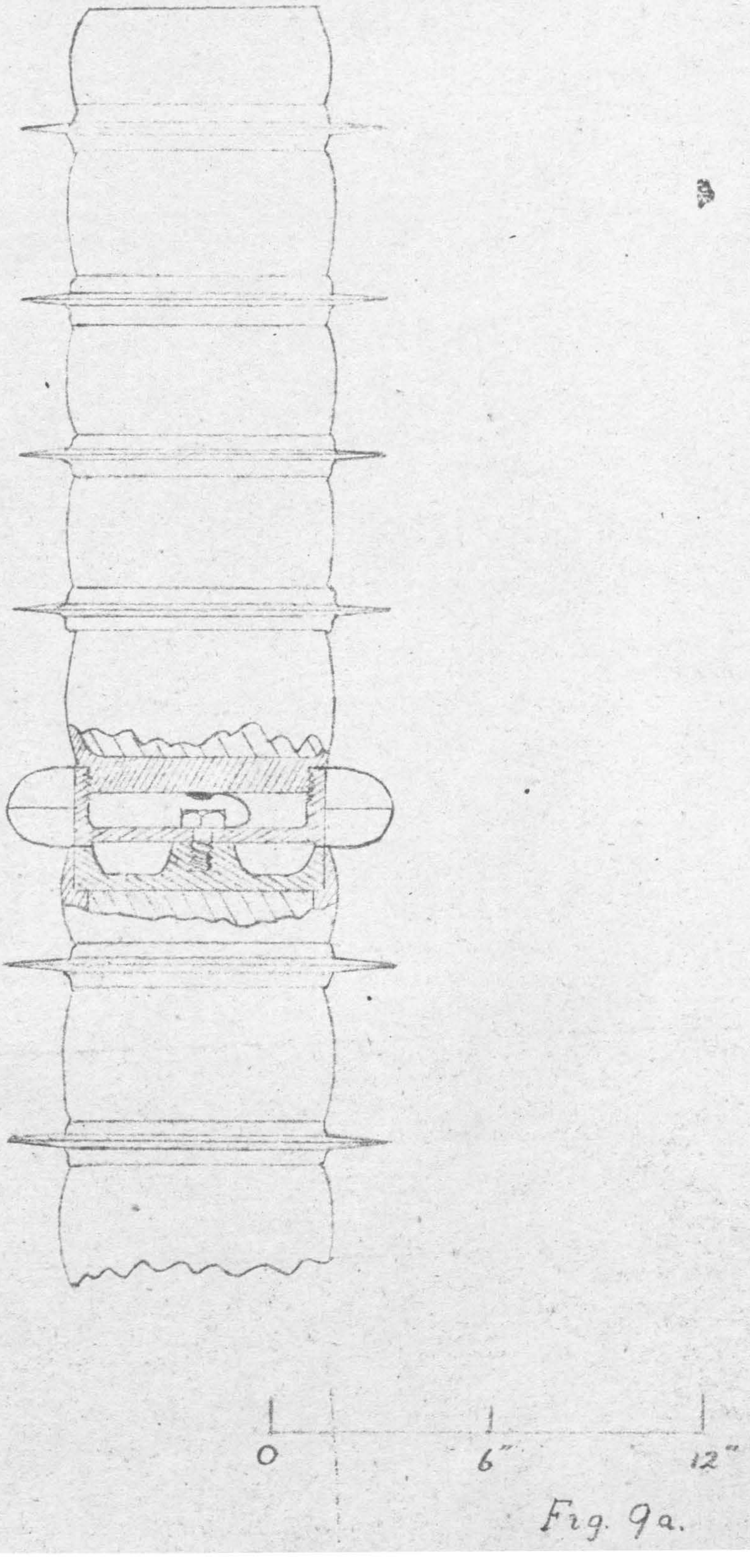


Fig. 9a.

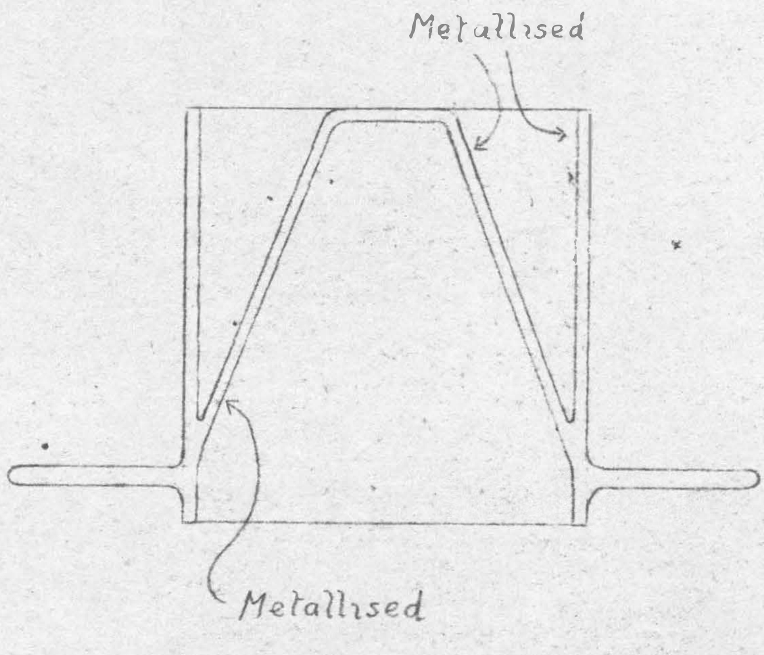


Fig. 9b.

possibility of insulation breakdown round the edges of the condenser plates is further reduced. The lower end of each condenser has a screwed thread moulded in the outer surface, and the electrical connection at this end is brought out by means of a small central terminal. The upper end consists of an aluminium plate containing a central hole screwed $\frac{1}{2}$ inch Whitworth, which serves for both electrical and mechanical connection.

A number of bronze castings were made with an internal thread to screw onto one end of each condenser, and a hole to take a $\frac{1}{2}$ inch bolt to attach them to the other end of a condenser. These castings were about 2 inches deep and had the same external diameter as the body of the condenser, namely 7 inches. With the aid of these castings it was possible to assemble any number of condensers in a vertical column.

A number of aluminium spinnings were made in the workshop such that two, when assembled together, would just contain one of the bronze castings without leaving any appreciable gap round the edge.

The D.C. condenser stack is now built up as follows. An aluminium spinning is put, edge upwards, on the floor and a bronze casting, which in this case has three $\frac{1}{4}$" holes, is screwed to the floor, thus fixing the spinning in place. A second half spinning is then dropped over the casting and the first condensers screwed in place. A further upturned spinning is then placed on the metal end of the condenser and a bronze casting bolted on. The next condenser is then screwed in after the second half of the aluminium spinning has been put into position. This process is repeated until all four condensers have been assembled. A spring contact is attached to the lower terminal of each condenser so that it makes electrical contact with the inside of the bronze casting below it. The completed stack is surmounted by another brown paper electrode shewn approximately to scale in the schematic drawing of Fig.10.

The A.C. condenser stack consists of three condensers mounted on a steel plate which is supported on a porcelain insulator similar to that used for the rectifiers. The steel plate is surrounded by an aluminium corona shield also identical with those on the rectifier stack as is the electrode on the top of the A.C. stack. This top spinning is supported on a thin sheet iron disc and is covered with a brown paper cone, which seemed to improve its performance, see Fig.10. A free circulation of air was allowed through the insulator supporting the A.C. stack by means of three wooden blocks under the lower edge and several ventilation holes in the steel plate above. This was to avoid the possibility of internal flashover due to condensation occurring on the inner surface of the porcelain.

The assembly drawing of Fig.10 shews the positions of the various interconnections between the different columns. R_1, R_2, R_3 and R_4 represent the resistances S_1, S_2, S_3 and S_4 of Fig.1 and are constructed of lengths of pyrex glass tube 1 inch external diameter having a wall thickness of about 3 m.m. The ends of these tubes were closed with rubber bungs through which passed a stout copper wire some 3 m.m. diameter. The tubes were filled with a dilute solution of copper sulphate of such a strength that the resistance measured between the two copper wires is about ¼ megohm. The value of this resistance does not appear to be critical under the conditions of light loads such as the apparatus has so far been called upon to deliver. It will be seen from Fig. 10 that all the tubes are inclined to the horizontal in order to allow gas bubbles due to electrolysis to rise to one end where a vent is provided for their egress. It

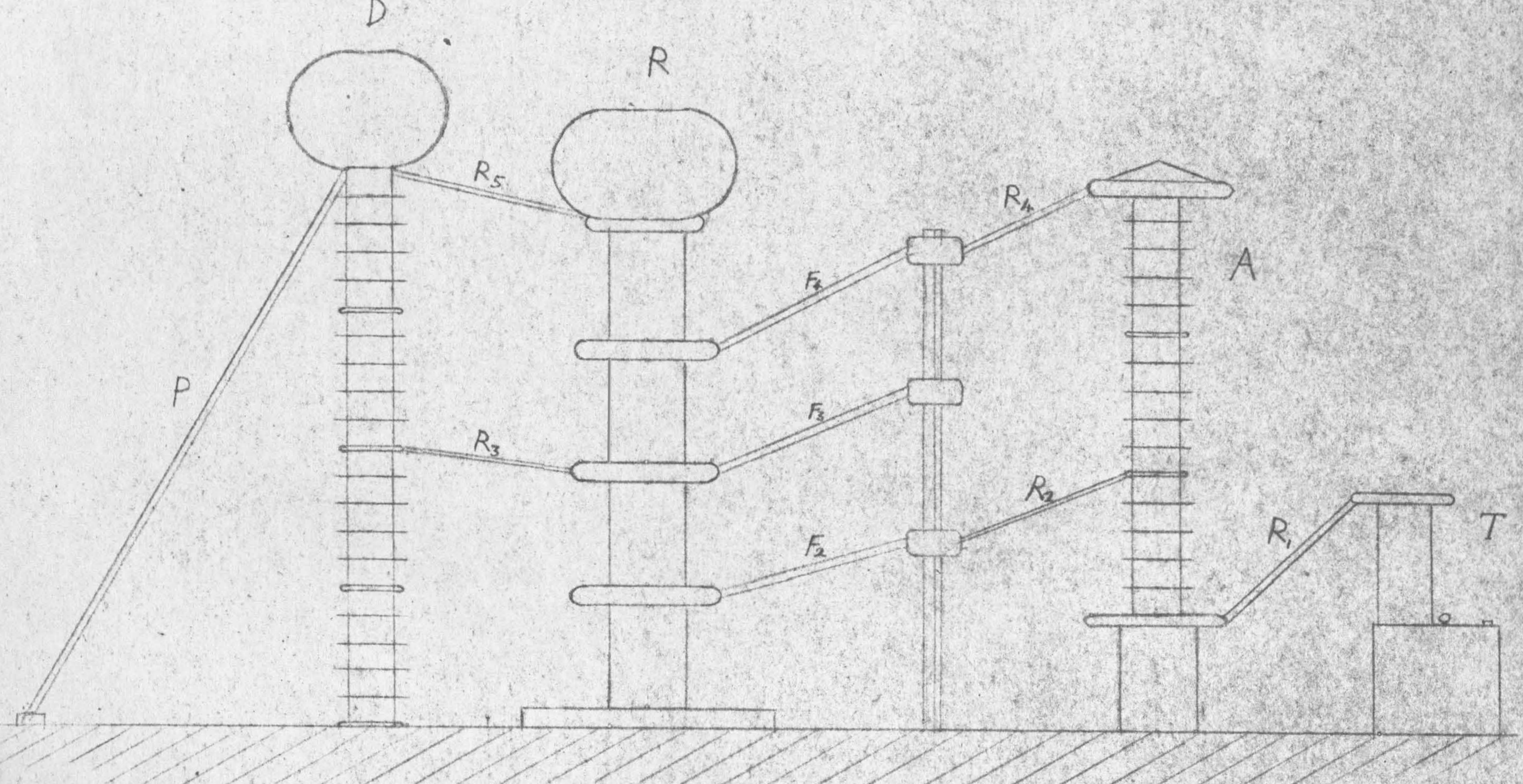


Fig. 10.

is important to check the level of the solution in these resisters as if the upper copper wire fails to make proper contact violent sparking will occur and the glass tube will in general be cracked. The tubes rest in holes with turned in edges, formed in the aluminium corona shields on the various columns, and are sufficiently short to enable their removal taking place by sliding further into one shield until the further end is free.

F_2, F_3, F_4 in Fig.10 correspond to the brass filament lead tubes already described.

The transformer T, will deliver a secondary voltage of 200 kv. peak and a current of 70 ma. and is rated at 10 kva. 400 volts primary voltage, 500 c.p.s. One end of the secondary is brought out to an insulated terminal on the top of the transformer tank and is meant to operate at nearly earth potential. The other end is brought up through a solid bushing to the disc shaped high tension electrode, which is supported by an oil filled insulating tube about 28 inches in height. The high tension electrode is connected through a resistance R, which is of 2 inch diameter glass tube containing copper sulphate solution giving a resistance of 0.1 megohm to the lower end of the A.C. Condenser stack.

Control Gear and Wiring.

After a few initial experiments with the completed apparatus it was soon made obvious that very special care was needed in the disposition of supply leads to the various components, in order to avoid breakdowns when a flashover on any part of the apparatus occurred. In the original layout, lead covered twin cable was run directly from the supply points on the walls to the place where it was needed such as the foot of one of the stacks or the transformer, or the control table. Earth leads of heavy copper wire were similarly run to a fire hydrant on the wall and the lead covering on the cables was earthed at convenient points. When an external flashover did occur the main fuses of the building were blown and pieces of the lead covering were blown from adjacent cables on the floor, and occasionally the main circuit breakers were tripped in the local power station. On another occasion a number of odd lengths of lead composition tubing had been left lying about the floor in contact with the case of an electric radiator. Here large holes were blown in the tubing where various pieces made contact and the radiator fuses together with the main fuses were blown. On examination of the wires it was found that the lead covering of the cables had been earthed, intentionally or otherwise, at more than one point, forming a closed circuit of low resistance and that part of the wiring itself formed effectively a large loop around the apparatus.

The wiring was accordingly altered to that shewn by the broken lines in Fig.2, where no closed loops of appreciable area were formed and all cables, so far as was possible, were run close together and close and parallel to the earth lead, which was now made of copper strip. The lead sheathing of the cables was earthed at one point only and the windings of all motors, pump heaters, etc., were bye-passed to earth by means of small non-inductive condensers of capacity between 0.1 ufd. and 0.5 ufd. This re-arrangement removed all breakdowns due to surges and proved completely satisfactory in use.

A circuit diagram of the control panel is given in Fig.11 and requires little explanation.

The 500 cycle alternator was situated in the basement of the building, whereas the high tension generator was on the first floor. It was driven by a 3 phase 50 c.p.s. motor equipped with a star-delta type of starter also situated in the basement, as it was only necessary to start the alternator once each morning. The 500 cycle

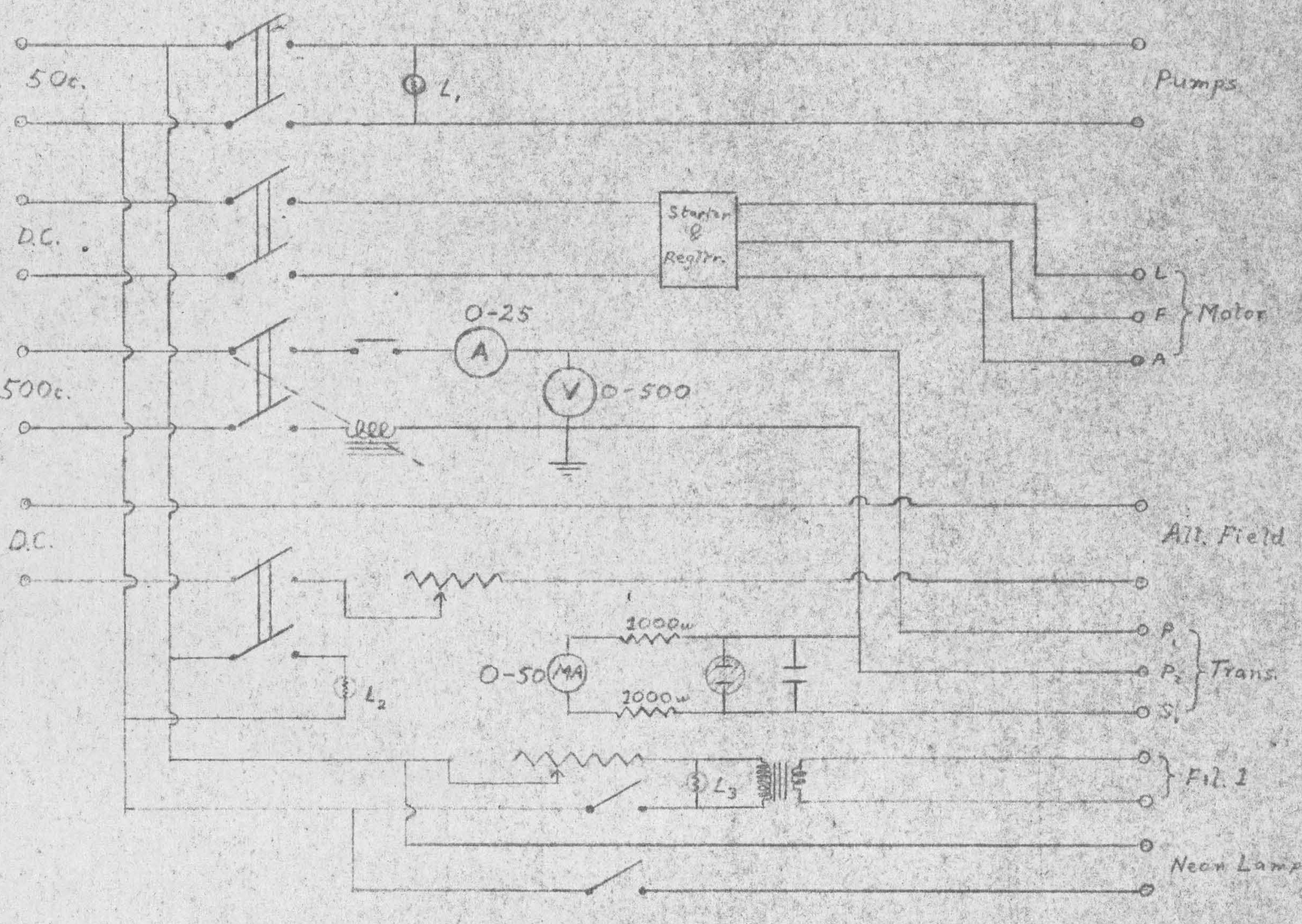

230v. 50c.
110v. D.C.
400v. 500c.
80v. D.C.
L1
Pumps
Starter & Reg'tr.
L
F
A
Motor
0-25
A
V
0-500
Alt. Field
1000w
1000w
0-50
MA
P1
P2
S1
Trans.
L2
L3
Fil. 1
Neon Lamp

Fig. 11.

output was brought up through fuses to a two pole circuit breaker switch on the front of the control table, and thence through an ammeter to the H.T. transformer primary. The switch-breaker was set to trip at about 30 amps. thus effectively protecting the transformer and alternator should the rectifiers go soft. A 0-500 v. voltmeter was connected in parallel with the transformer primary as by this means a rough estimate of the secondary voltage and also of the final potential reached on the set could be made. This potential was controlled by means of the field excitation current of the 500 cycle alternator which was supplied from a 110 v. battery of accumulators situated in the basement. The field current was regulated by means of a variable resistance on the control table and the field current switch also actuated a red warning lamp to indicate that the high tension was available on closing the breaker switch. The 500 cycle supply to the transformer also went through a switch actuated by the door allowing extrance into the area enclosed by wire netting. A long earthing lever was situated by this door in order to discharge the D.C. condenser stack in such a way that it was impossible to open the door before discharging the condensers and also impossible to close the door and switch on before removing the earth on the condensers. An insulating rod about 4 feet long with a steel spike at one end connected to earth by means of heavy flexible cable was used to discharge individual parts of the apparatus before approaching closely.

Two further warning lights were situated on the panel to indicate that the diffusion pump heaters were on and that the bottom filament was hot. Sufficient indication of the operation of the remaining three filaments was given by the fact that the driving motor and belting were running. The starter and field regulator for this motor were also situated on the control panel and the stroboscope disc on the motor pulley could be observed from the operating position.

The secondary current from the transformer was measured with a milliammeter on the control panel connected between the earthy end of the secondary and earth. The meter was protected from surges by being shunted with a condenser and having in series with it two resistances such that the small argon discharge lamp connected across the ends of the resistance would light and shunt out the meter when the current reached nearly double that required for full scale deflection, see Fig.11.

CONDITIONING OF RECTIFIERS

When the vacuum gauge indicates that the rectifier column is reasonably free from leaks the initial "degassing" of the electrodes and porcelain insulators may be undertaken. For this, all connections between the rectifiers and the condensers were removed and the high tension transformer was moved near to the rectifier stack. The top plate of the stack was then connected through a large water resistance of about ¼ megohm, and of the construction already described, to the high tension electrode if the transformer and the potential increased until breakdown was about to occur. Periodic bursts of gas will probably be released with the result that the circuit breaker will be tripped but after some time, perhaps hours, of pumping, the full 200 kilovolts may be applied indefinitely. When this point is reached the transformer is connected to the centre electrode of the stack and the top plate is earthed and the process repeated. The maximum potential that can now be applied to each interelectrode gap is 100 kilovolts. The connections are again altered when this point is reached so that the full 200 kilovolts can be applied to each rectifier section in turn. The time taken to obtain a vacuum sufficiently good to withstand this potential difference may run into several days, but running the apparatus with a glow discharge, of sufficiently low intensity to avoid overheating, greatly hastens the process.

After removal of the high tension the filaments themselves may be degassed by applying to them a voltage approximately 50% higher than their normal running voltage for about a quarter of an hour. This is most easily done by increasing the speed of the motor that drives the filament alternators.

The resistance tubes connecting the rectifiers to the two condenser stacks may now be replaced and the apparatus after further degassing is ready for operation. It will be found at first that the maximum output obtainable will not exceed about 400 kilovolts as the rectifiers have only been degassed up to 200 kilovolts per stage and then only with cold filaments. The potential may, however, be gradually increased until 700 or even 750 kilovolts can be obtained over lengthy periods and the apparatus can be run continually at 650 kilovolts. At the highest potential, when thoroughly degassed, external breakdown usually occurs over the surface of the porcelain insulators of the rectifier column or directly between the aluminium corona shields on this column. This usually results in the breaker being tripped immediately but occasionally long self sustaining arc-overs have lasted for two or three seconds.

A potential in excess of 1,000 kilovolts has been obtained on one occasion by spraying a jet of carbon tetrachloride from a "Pyrene" type of fire extinguisher on to the ceiling above the rectifier column. This greatly increases the breakdown strength of the resulting atmosphere, but it was of course necessary to overrun greatly the high tension transformer to obtain one million volts output. This procedure is a very dangerous one on account of the production of large quantities of phosgene, $COCl_2$ by oxidation of the air - carbon tetrachloride mixture by the brush discharge that occurs. The characteristic "musty" smell of this poisonous gas was noticeable in a very few minutes, and it was necessary to vacate the laboratory for some considerable time.

On reassembly of the rectifiers, after renewing a filament, for instance, the degassing process is nowhere near so lengthy, even though parts of the apparatus have been cleaned with some grease solvent or left exposed for a day or more.

MEASUREMENT OF FINAL POTENTIAL

The final potential difference developed across the D.C. condenser column was measured by means of an electrostatic voltmeter connected to a high resistance potentiometer having a ratio of 350:1. This potentiometer shown at P in Fig.10 and in greater detail in Fig.12 consists of a long Pyrex glass tube 2·5cm internal diameter 320cm. long, having a wall thickness of 0·3cm. This contains a liquid consisting for the most part of carbon tetrachloride with the addition of a small amount of alcohol to lower the resistance to about 10^9 ohms. The liquid also contained a small amount of phenol and picric acid to lower its temperature coefficient of resistance.

An electrode, consisting of a spiral of platinum wire was sealed through each end of the glass tube and at its upper end, where it protrudes into the high tension electrode of the D.C. condenser stack, a small glass reservoir, to allow for expansion of the liquid,

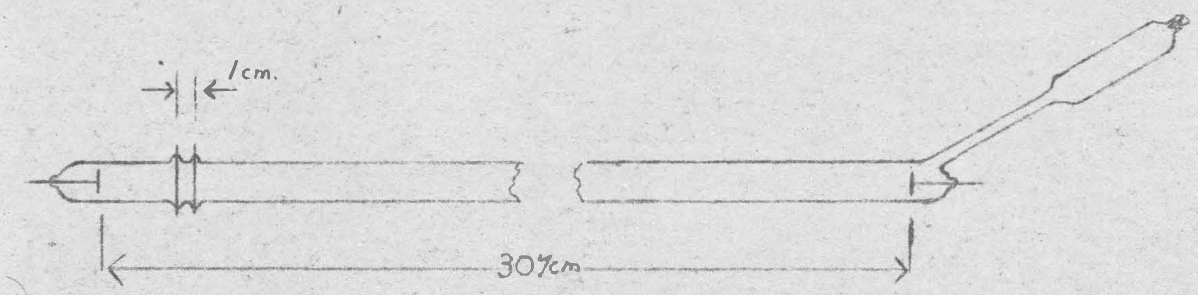


Fig. 12a.

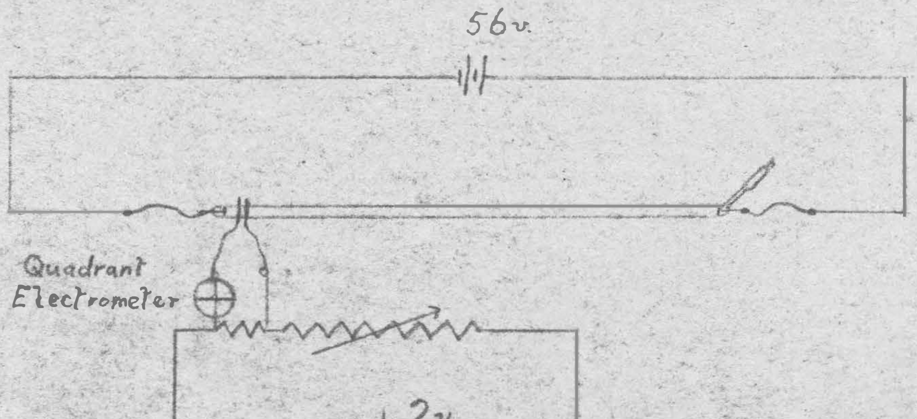


Fig. 12b.

is attached.

Close to the lower earthed electrode, two parallel platinum wires about 1 cm. apart, are sealed through the glass and to these is connected the small electrostatic voltmeter reading up to 3,500 volts. As the case of this meter is connected to one of its terminals it was stood on a paraffin block on the floor and it, together with the lower portion of the potentiometer, about 1 foot in all, was screened by means of a metal sheet from the rest of the apparatus. The meter was read through a telescope near the control table.

The ratio of the potentiometer was measured by applying about 56 volts to the potentiometer and measuring the potential difference between the two platinum spirals by means of a quadrant electrometer and a potentiometer insulated from earth by a paraffin wax block, Fig. 126. The measured ratio was found to be 350:1 whilst the geometrical ratio was 307:1.

This method of measuring the voltage generated by the apparatus cannot be regarded as free from error owing to the unknown temperature distribution along the length of the glass tube and the possible shunting effect of corona discharge occurring from the surface of the comparatively narrow tube. This corona current would, however, have to pass radially through the glass walls of the tube and may well be quite small.

PROPOSED ION SOURCE AND ACCELERATING TUBE

Fig. 13. gives a diagrammatic representation of the proposed design of accelerating tube and modulated ion source. The final details of this design were never fixed and its construction not commenced owing to the fact that at this time, about three weeks before the commencement of hostilities, the writer was requested to undertake work of greater national importance.

The accelerating tube was to be built of two porcelain insulators similar to those used for the rectifiers. The accelerating potential is equally divided by the two gaps FG and DE. This is ensured by connecting not only the top of the accelerating tube to the top of the D.C. condenser stack, but also the centre electrode to the centre of the D.C. stack. The potential difference across each gap will then be no more than the maximum potential difference occurring across each rectifier gap in the non conducting direction.

The tube is supported on an iron stand of sufficient height to accommodate the diffusion pumps P below the base. There are four oil diffusion pumps in all; two Metropolitan Vickers O_3 pumps as shewn in the diagram and each O_3 pump is backed by a Metropolitan Vickers O_2 two stage pump. The tubes between the O_3 pumps and the base plate of the tube are kept as short and wide as possible to allow of the maximum pumping speed. The pumping speed here is far more important than that of the rectifier stack as a continuous stream of hydrogen or deuterium is allowed to enter the ion source situated in the lower electrode D.

The ion source consists of three concentric steel tubes A, B and C, having steel flanges at their lower ends which are insulated from one another by plate glass rings. The joints between the steel flanges and the glass rings are rendered vacuum tight by means of sealing wax. The flange of the outer tube C was attached by means of another insulating ring to the flexible metallic bellows thus allowing the ion source to be moved about inside the lower accelerating electrode D. The

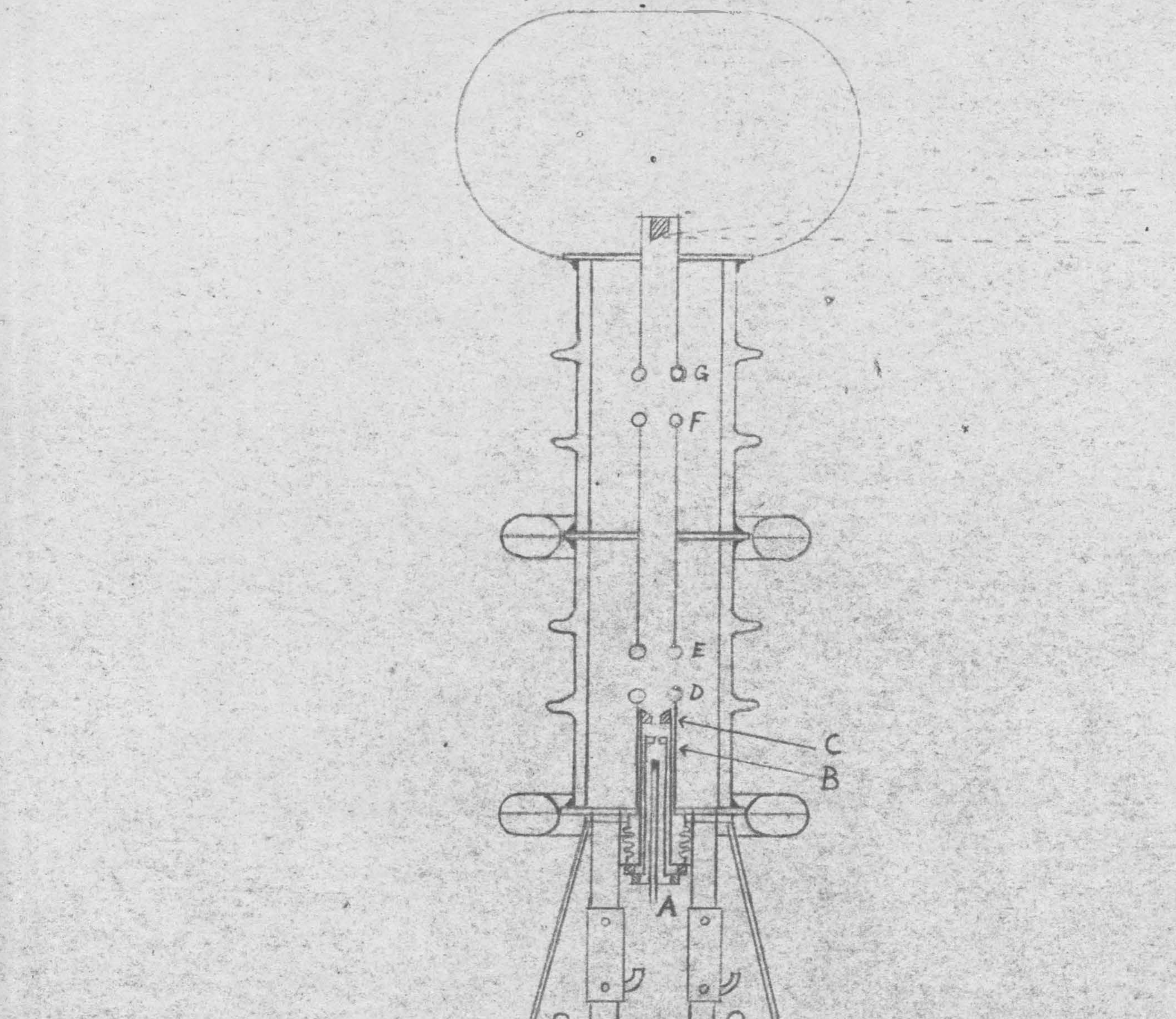


Fig. 13.

upper end of the electrode B is closed by a steel plug through which is bored a fine hole and owing to the low pumping speed through this hole a gas pressure of about 10^{-2} mm of mercury can be maintained in the ion source whilst a pressure sufficiently low to avoid breakdown of the accelerating gaps can be maintained in the tube proper. The rate of entry of gas into the ion source, and consequently the gas pressure therein is controlled by means of an adjustable needle valve. The central tube A is arranged that it can be water cooled internally if required.

In operation A & B form the anode and cathode respectively of a low pressure gas discharge. The discharge takes place between the closed upper end of A and the lower face of the steel plug in the end of B as the annular gap between the surfaces of the tubes A and B is too small, i.e. less than the mean free path of an electron in the gas, for the discharge to occur there.

When the gas pressure and discharge current are correctly adjusted a stream of positive ions will emerge from the capilliary in B and may be accelerated or decelerated initially by means of the electrode C which also contains an aperture in the steel plug forming the upper end.

It is obvious that if the electrode C is given a sufficiently high positive potential with respect to B no positive ions will emerge from the aperture C so that the number of ions passing to the first main accelerating gap DE can be controlled at will. By suitable choice of the dimensions of the aperture in C and its separation from that in B, it may be arranged that the application of a negative potential to C will cause the positive ions to be collected by C, but this would probably be a less convenient method of modulating the ion beam. It is probable that the first type of modulation would be used and here the control electrode C would be held normally at a positive potential and made negative or less positive for short periods of time at regular intervals, thus allowing short bursts of positive ions to travel up the tube to the target.

An alternative form of ion source was also under consideration. In this type the gas, instead of being ionised by a high tension discharge, was ionised by an electron beam of low velocity (one or two hundred volts).

The positive ions are extracted from the discharge by means of a hollow probe electrode held at a negative potential. The possible advantages of this type of ion source are that lower operating voltages may be required and that since the ions emerging from the probe may be of quite low velocity the modulating voltage applied to the control electrode C could also be quite low. However, the source of the ionising electrons in this type of ion source has usually been an oxide coated thermionic cathode which may need rather frequent renewal due to the high probability of it being poisoned by impurities in the entering gas.

The construction of the target from which the neutrons were to be produced has scarcely received any attention except that it was to be mounted above the top plate of the accelerating tube inside the high tension electrode. This electrode would certainly have been made of brown paper and would be similar in size to that on the rectifier column. If the target needed cooling this could be done by leading ordinary tap water through a long glass tube to the top of the accelerating tube. This is permissable on account of the great purity of the water supply in Birmingham and conduction down the water tubes would impose but a small additional load on the high tension supply.

The neutrons generated at the target were to be slowed down in the usual manner by surrounding the target with paraffin wax inside the high tension electrode which, if made of paper as intended, would be quite transparent to the neutrons.

As already mentioned at the end of Part I of this paper, the methods of recording the arrival of neutrons at the distant target were to be very similar to those used by Thomson, Moon and others (Proc. Roy. Soc. 175, 331, 1940) with the addition of the improvements suggested in Part I.

In conclusion I should like to express my gratitude and appreciation for the valuable assistance and advice given by Prof. M. L. Oliphant and Dr. P.B.Moon, both on points of design and in the actual construction of the apparatus, and I am also much indebted to Mr. M. P. Edwards for technical assistance.

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