were very disappointing, and the tube did not seem to behave according to any definite law at all. It is, of course, quite an old experiment to vary the hardness of a tube by putting patches of earthed tinfoil on the outside in suitable positions. Mr. Phillips asked about the Gaede pump. I have had it for eighteen months and it has never given any trouble until to-day, and now its failure is only due to the fact that in the course of its removal to this room a certain amount of mercury has been allowed to pass down the U tube and consequently the passage is impeded. It is otherwise an admirable pump. It can be connected to a little motor and left running by itself without giving any trouble, and one may fracture a tube and let the air in suddenly without breaking the porcelain. On the question of the diamonds, the point of my first experiment was that the diamond was not burned away like fuel as in the case when it is carbonized in the electric arc. It was wholly turned into coke. It is not the destruction of a diamond but its conversion that we carry out in our experiment. The reconstructed rubies of commerce are made in the oxy-acetylene flame, and I have no doubt that they can be made much better in that way. Probably the reason why our rubies are not optically clear is because gas has been continually driven into them while melting. I do not know much from practical experiment about the coloration of sapphires, but so far as I read in books it is believed that the different colours of sapphires are all due to chromium in various degrees of oxidation. If we take either blue sapphires or rubies and keep them a little above the melting point of alumina the colour, being apparently more volatile than the alumina, disappears. The amount of chromium required to make the ruby *look* red by ordinary light is quite large, but the amount required to make it *fluoresce* red under cathode ray bombardment is very small indeed. Mr. Glew suggested, with regard to the effect with the blackened tube, that the conducting coating on the tube's interior impeded the circulation of the gaseous contents. I must confess, however, that I have not now altogether the same faith in the diagram I showed at the Royal Institution in 1898 as I had at the time. The matter has turned out to be not quite so simple as it appeared then. We may put it generally, however, that in the case of the blackened tube we have a conducting surface inside the tube which alters the distribution of the electric force and thus increases the hardness.

## ORDINARY GENERAL MEETING.

An ORDINARY MEETING was held on April 1st, 1909, the President, W. DEANE BUTCHER, M.R.C.S., in the Chair.

The minutes of the previous Meeting were read and confirmed.

A ballot was taken for Dr. RAYNER, who was elected a Member of the Society.

The HON. SECRETARY announced that the Council, under the rule empowering them to do so, had elected Professor E. RUTHERFORD, of the University of Manchester, an Honorary Member of the Society.

The following paper was then read by the author :—

# THE ORIGIN, HISTORY & DEVELOPMENT OF THE X-RAY TUBE.

*By J. H. GARDINER, F.C.S.*

The fact that the collection of historical apparatus that has occupied the attention of the Council of this Society for some time past is now completed, and the valuable selection of tubes has been handed over to the authorities of the Albert and Victoria Museum for public exhibition, has given a favourable opportunity to review the history and development of one of the most remarkable pieces of apparatus that has ever been placed at the service of the physicist and the medical man.

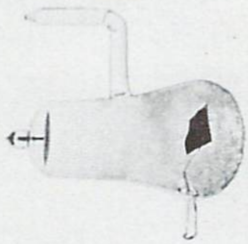
Thirteen years have now passed since the scientific world was startled by the announcement by Prof. Röntgen of the discovery of a "new kind of rays," and the vacuum tube in which alone they can be generated has passed from a piece of delicate apparatus, little known and rarely seen outside the laboratory of the "élite," to an every-day article of commerce that can be safely manipulated by any moderately skilful person. To trace the origin and development of the X-ray tube is to the speaker (and he will endeavour to make it so to his audience) a matter of very considerable interest. But, before commencing to deal with the tube itself, I may perhaps be permitted to say a few words as to the name by which we call the now well-known apparatus.

At the time of Prof. Röntgen's discovery, and for several years afterwards, it was usual to call it a "Crookes' tube" in honour of the one to whose classic researches in high vacua the discovery was largely due; but as the term "Crookes' tube" also applies to many other forms of vacuum tubes that produce effects quite apart from Röntgen radiations, this term has not been universally applied. "Röntgen tube" has been proposed, and is often used, but the discoverer of the rays has taken little or no part in the origin or development of the tube, therefore this designation is hardly suitable. "Jackson tube" has been suggested because the form of tube now universally used was first pointed out by our past President, Professor Herbert Jackson, but it seems to me that it is better to avoid making invidious distinctions and adopt the term X-ray tube which immediately conveys the sense of what one is speaking about.

In following the development of the X-ray tube through the many stages that lead up to the present efficient and beautiful piece of apparatus, I find that I shall have continually to refer to the researches of that veteran savant whose name will always be associated with that of Röntgen and X radiations. I refer of course to Sir William Crookes, for in almost every instance of advance that has been made in the X-ray tube up to the present time, the seed from which that advance sprang will be found in the work of that indefatigable investigator.

The Crookes' tube, with which Prof. Röntgen's famous discovery was made, was pear-shaped, having a flat circular cathode at its narrow end, and an anode in a small tube at the side. The cathode rays, or, if you prefer the more modern term, the stream of negatively charged electrons, fly off at right angles to the surface of the flat cathode plate and strike against the large end of the tube, producing there vivid phosphorescence, heat, and X-rays. The life of these tubes, as everyone who worked in the early days has sad cause to remember, was very brief; a few exposures at most and the tube was either pierced by a spark or cracked on account of the heat generated by the bombardment of electrons. Many devices were suggested to prolong the life of such tubes, and one of the earliest that I remember, which was really the prototype of the water-cooled electrode, was made by our first President, Prof. Silvanus P. Thompson, for in a letter written to me in March, 1896, he gave a sketch of what he then considered would be the ideal form of tube for producing X-rays. The large end of the pear-shaped tube when in use was to be kept in water contained in a thin celluloid dish, and the photographic plate placed below. At that time it was generally thought that the production of X-rays was dependent upon the phosphorescence of the glass, and it is interesting to recall that this idea, although a false one, was the means that led to the discovery of radium and radio-activity, and all that has been built up on that discovery. For the suggestion was thrown out by M. Poincare, in France, that if X-rays were generated in the phosphorescing walls of a vacuum tube, was it not possible that X-rays would be produced by other phosphorescing bodies! As is now well known the idea was put to the test of experiment by the late Henry Becquerel, and resulted in the discovery of

*To Illustrate Mr. Gardiner's Papers.*



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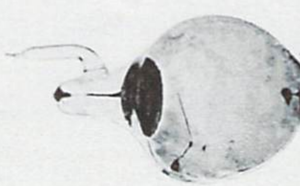

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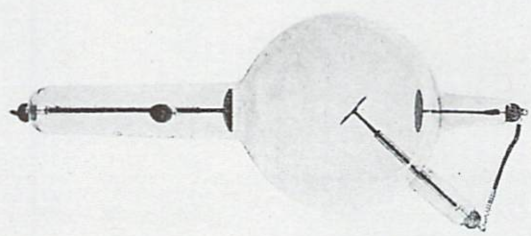

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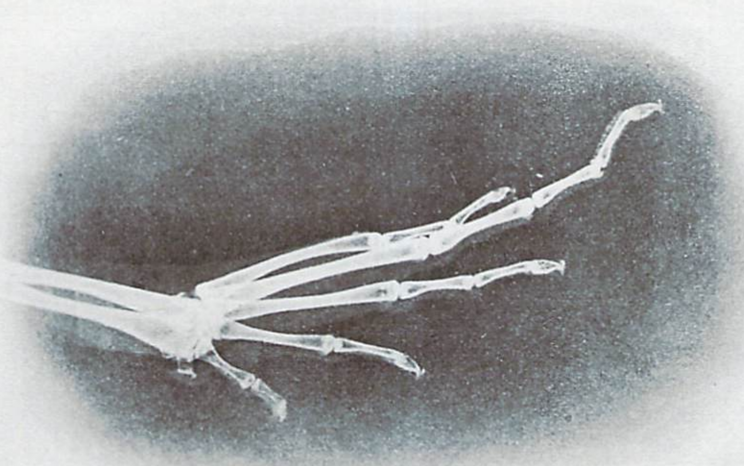

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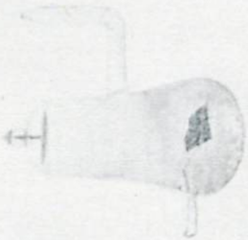
PLATE V.

*To Illustrate Mr. Gardiner's Papers.*



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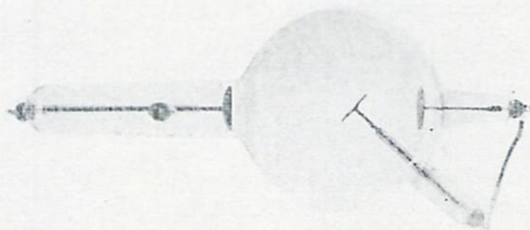

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PLATE V.

the radio-activity of the compounds of uranium, followed quickly by the discovery and isolation of radium by Madame Sklodowska Curie and the recognition of the other radio-elements.

But to return to the X-ray tube. Just about this time an exceedingly interesting tube was devised by our Vice-President, Mr. A. A. Campbell Swinton, which is fortunately safely included in the Society's collection. This tube illustrates how very near it is often possible to get to a mark without actually hitting it. (Fig. 1, plate V.) The Cathode rays were received not on the glass end of the tube, but upon a sheet of platinum supported a short distance from it. It only needed the cathode to be curved to have anticipated by some months the tube proposed by Prof. Jackson, which marked the greatest advance that has been made since Röntgen's discovery.

The radiographs produced in these early days, before the so-called focus tube came into use, were, of course, lacking in sharpness, and long exposures were needed; but one will never forget the creepy sensation experienced when looking for the first time at a photograph of the bones of the hand and wrist of a living person. The first radiograph of the kind exhibited in England was the work of our Vice-President, Mr. A. A. Campbell Swinton, and it was exhibited at the meeting of the Royal Photographic Society and immediately afterwards at the Royal Institution. Through the kindness of Mr. Swinton I am able to show you a slide of what I suppose was the best radiograph ever produced before the introduction of the focus tube. (Fig. 2, plate V.)

One can have no hesitation in saying that exact radiography dates from the time when Professor Herbert Jackson advocated the employment of a tube in which the cathode-rays were brought to a focus on to a plate of platinum, which could be either an independent pole or the anode itself.

That the cathode-rays could be brought to a focus by curving the cathode had been amply demonstrated years before, and the tube which is the prototype of our present X-ray tube was fully described in a paper by Sir William Crookes that appears in the philosophical transactions of the Royal Society for 1874. Sir William has generously presented the Society with the actual tube which was used in that research. (Fig. 3, plate V.)

You may well wonder why the discovery of X-rays was not made by Crookes in 1874 instead of by Röntgen in 1895. I can only say that there appears to be a psychological moment when and where only a discovery is possible. Again and again the same thing has occurred in other directions than molecular physics. The atmospheric constituent, argon, was actually isolated and handled by Cavendish a hundred years before its discovery by Lord Rayleigh and Sir William Ramsay.

It was now quite an easy matter to produce radiographs of almost any part of the body, showing structure and details with wonderful sharpness; and the science of radiology came into existence. And from then until the present time the form of tube proposed by Professor Jackson has never been superseded.

Slight modifications in the shape and form of the electrodes were made by various manufacturers, each one claiming some special advantage for his particular form of tube; and it soon became a matter of much perplexity for the busy practitioner to decide upon the particular make of tube to invest in. As the prices ranged from ten shillings to about five pounds, this was a somewhat serious matter. The then President of our Society, Dr. J. Macintyre, decided to offer a gold medal to "the maker of the best practical X-ray tube for both photographic and screen work."

A committee of experts was formed to act as judges, and some 28 tubes were sent in by manufacturers, both at home and abroad. Of course, as in every case of this kind where only one of the competitors is made happy and all the rest disappointed, there was a good deal of grumbling when the award was made to Mr. C. H. F. Müller, of Hamburg. And it has always appeared to me a pity that the very elaborate tests through which the tubes were passed was not made public. I refer to this matter now because I wish to show you the test plate that finally decided the award, as it illustrates how under identical conditions the output of X-rays from a selection of apparently faultless tubes can vary both in quantity and quality. By quality I mean chiefly the power of giving sharply defined shadows.

By a series of preliminary tests the number of tubes was reduced to six, and the final test was made photographically. Under absolutely identical conditions of electrification exposure, distance, and development, both the density and sharpness of shadow varied considerably. The two best were selected, and a still more searching test was made upon these two, with the result that the cheaper of the two was awarded the prize. It afterwards turned out that both of these tubes was by the same maker.

The actual tube is in our collection, and is shown in fig. 4, plate V.

It may occur to some here that such minute degrees of definition are quite unnecessary, and for the usual purposes of medical work it may be so, but there are some purposes for which X-rays are used that demand the greatest possible sharpness of shadow. As an instance I wish to show a radiograph that was made to settle an obscure point in zoological research, the foot of a very small frog. (Fig. 5, plate V.) You will notice that there is a curious hooked nail at the tip of each toe that is shown in perfect detail. When I tell you that this object or really microscopic being is not more than a tenth of a millimeter across, you will see that in such a case definition of a very high order is alone of any value.

Now that the X-ray tube had become an instrument in constant use, a difficulty that had always been noticed became a serious source of trouble. I refer to the gradual increase in hardness or electrical resistance of the tube. At first it was the practice to lower the resistance by the application of heat from a spirit lamp or gas burner; it was even proposed to bake the tube in an oven, but the lowering of resistance that followed such treatment was only temporary, and soon numerous devices came into use whereby the resistance could be lowered by the introduction of a small quantity of gas. Generally there are two ways of doing this, either by liberating gas accluded in various substances contained in the tube itself, or by letting in gas from the outside. The former method was employed by Sir William Crookes in his experiments in 1874, and I am able to show you the photograph of the tube he actually used which he has kindly added to our collection. (Fig. 1, plate VI.) The vacuum tube which in this case is cylindrical has a small tube attached containing some caustic potash—application of heat by a lamp immediately liberates gas and lowers the vacuum. This device has been utilised by various makers and is in use at the present day.

A novel and ingenious plan was patented by our member of Council, Mr. Harrison Glew, and we are fortunate in having a specimen tube in our collection. A narrow tube (Fig. 2, plate VI.) was connected, containing a number of very small pieces of iron coated with sealing wax; it was only necessary to isolate one by means of a magnet and heat it with a flame to liberate sufficient gas to lower the vacuum.

Very soon this acclusion method was made to work automatically. The substance containing the gas was mounted in a small tube attached to the main bulb, and, as the resistance increases, sparks pass to the small bulb, liberating sufficient gas to lower the resistance. These tubes are now in every-day use and one of the earliest forms by Messrs. Queen & Co. of Philadelphia is shown in fig. 3, plate VI.

The next method for introducing gas was by what was called the Osmosis method, which was the device of Prof. Villard of Paris. A small tube of palladium closed at one end was sealed into the bulb and the closed end allowed to project outside. Palladium has the property of being transparent to hydrogen at a red heat; if, therefore, the little palladium tube is heated by a gas flame, hydrogen immediately enters the tube, so lowering the resistance. This is a very convenient and practical method, but the latest and most ingenious plan is that known as the Bower valve, which has so recently been described here that I will not weary you by repetition; in this case it is only necessary to "press a button" and a minute quantity of air is allowed to enter the tube.

The gradual increase in the resistance of a tube by use is a matter of very considerable interest, and it is invariably accompanied by a darkening of the glass walls of the tube, due chiefly to a deposit of matter torn off from the electrodes by the electrical excitation. This disintegration of electrode matter takes place at the cathode only, and the property, called by Sir William Crookes "electrical volatilization," is possessed in varying degree by all metals. The matter was the subject of a paper by Sir William Crookes that appeared in the proceedings of the Royal Society in 1891, and in that paper the following list is given showing the relative volatilities of a good many metals:

The following Table of the comparative volatilities was obtained, taking gold as = 100:—

| | |
|---|---|
| Paladium ... ... ... ... ... | 108·00 |
| Gold ... ... ... ... ... | 100·00 |
| Silver ... ... ... ... ... | 82·68 |
| Lead ... ... ... ... ... | 75·04 |
| Tin ... ... ... ... ... ... | 56·96 |
| Brass ... ... ... ... ... | 51·58 |
| Platinum ... ... ... ... ... | 44·00 |
| Copper ... ... ... ... ... | 40·24 |
| Cadmium ... ... ... ... ... | 31·99 |
| Nickel ... ... ... ... ... | 10·99 |
| Iridium ... ... ... ... ... | 10·49 |
| Iron ... ... ... ... ... | 5·50 |

It was also found that of all the metals then tested two only, magnesium and aluminium, under the conditions of the experiments were non-volatile. I shall have to refer to this matter again later on.

Various explanations have been given as to the true cause of the increase in hardness of an X-ray tube by constant use. We know that the hardness of a tube varies with the degree of vacuum—or more correctly the pressure of the residual gas—the lower the pressure the harder the tube; and much speculation has been made as to what becomes of the gas originally left in the tube by the manufacturer. Disregarding some of the wilder theories (and there have been many), we may take it that at the present time there are two explanations either or both of which may turn out to be true: one that has been ably advocated here by our valuable member, Mr. Swinton, might be called the "HAMMER IT IN" theory. According to this view the gaseous constituents of the tube under the electrical impulse are actually driven and embedded into the walls of the tube, and Mr. Swinton has shown us by very beautiful photographs how its presence can be demonstrated by heating fragments of the impregnated glass walls to the softening point.

The other theory, which is advocated by our past President, Mr. Frederick Soddy, might be called the "PLASTER IT ON" theory. According to this view, the cathode discharge consists not only of torrents of electrons from the gaseous contents of the tube, but also by what might be called clots of metallic matter shot off from the electrodes themselves. The action of the current, as far as I understand it, is to subject the inside walls of the tube to a sort of rain of electrons, which may be likened to hard marbles, and clots of metal, like large lumps of cement. The pattering on to the walls of the tube of this mixture of hard electrons and sticky metal would result in producing a coating of metal in which would be embedded a great number of the electrons, so reducing the number of free electrons, and in short increasing the vacuum.

It is not my business to discuss the merits of these two theories, but I wish to point out that there is another cause for the increase in the resistance of the tube quite independent of the pressure of the gas contained in it.

I must again refer to the researches of Sir William Crookes, who, in an address to the Institution of Electrical Engineers in 1901, showed that the electrical resistance of a highly exhausted vacuum tube could vary enormously according to the physical condition of the inside walls of the tube. If these walls were easily phosphorescent, as in the case with clean soda glass, then the resistance was comparatively low. If, on the other hand, the gaseous pressure remaining unchanged, the walls could be coated with a metal—a conducting or non-conducting powder—or in fact anything that would interfere with the phosphorescence, the resistance was immediately increased.

I would like to show you a modification of this experiment. I have here a tube (Fig. 1),

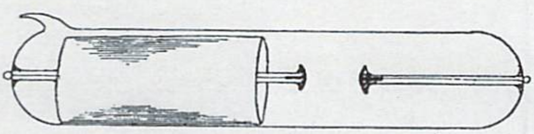


Fig. 1.

with two electrodes facing each other, and surrounded by a clean cylinder of soda glass in a very phosphorescent condition. The resistance of this tube is very low and corresponds to an alternative spark gap of $\frac{1}{10}$ of an inch, equivalent to about 2,300 volts. Inside the tube there is a cylindrical sleeve of aluminium foil that can be made to slip down and so inclose the electrodes in a metallic chamber. Under these conditions the resistance of the tube is very much greater and corresponds to about 23,000 volts. We see then that the resistance of an X-ray tube may be increased, apart from any change in the volume of the residual gas, simply by the deposit on its interior of metallic matter from the electrodes.

You will understand the reason for this apparent digression from my subject presently, but for the moment I must return to the X-ray tube.

Recent advances in X-ray work have made it necessary to employ much heavier currents than formerly, and now instead of one to two milliampères as much as 20 to 30 milliampères are often passed for short periods. With such heavy currents it has been necessary to introduce more or less complicated devices for preventing the anticathode surface from over-heating. Two methods are in use at the present time: one, first adopted by Mr. Swinton, is to back up the anticathode surface with a mass of metal so as to dissipate the heat generated by conduction; the other is to make the anticathode form the end of a box or tube that can be kept full of water from the outside. A third plan is to make the anticathode of a metal with a higher fusing point than the platinum generally used. A very early instance of this was the introduction by Mr. Mackenzie Davidson of the omium anticathode. A photograph of one of these tubes, presented to the Society by the inventor is seen in Fig. 4, Plate V. Very good results were obtained by these tubes, but the difficulty in obtaining the metal prevented their general adoption. One of the two methods just described, cooling by water or by a mass of metal, are now used.

Before proceeding to discuss the latest stage in the evolution of the X-ray tube, it will perhaps be well to briefly review the work of the past thirteen years. The old pear-shaped Crookes tube, that sometimes produced a hazy radiograph and always cracked, is a thing of the past. The advantage of the curved cathode bringing the rays to a focus, not upon the glass walls of the tube but on to an infusible target, has been recognised. The rapid "hardening" of the tube has in a great measure been overcome, partly by the introduction of an auxiliary electrode and partly by various devices for introducing successive quantities of gas into the tube. Successful methods have been introduced to prevent in very great measure the over-heating of the anticathode. The electrodes have been made heavy and substantial so as to enable comparatively large currents to be passed through the tube, wonderful advance has been made in glass blowing, and now the interest is centred in the form and material of the anticathode.

The spot, generally not more than one or two millimetres in diameter, where the cathode rays impinge upon the target—where one form of energy with all its wonderful properties is transformed into a totally different form of energy having properties that have not yet ceased to be astonishing or are yet fully understood—is a centre that cannot but be of the greatest interest to the physicist. There the material particles that constitute the cathode stream—call them molecules, atoms, electrons, or whatever you like—travelling with enormous velocity clash together under electrical impulse, producing conditions such as we have never before met.

We are all familiar with the fact that, accompanying the evolution of X-rays, both heat and mechanical force are generated. We have seen platinum and even rubies melted like wax. We have seen little mill wheels spun round, and driven up inclined railways; but for all that I cannot help thinking that we often under-estimate the magnitude both of the heat and force that accompany the transformation of cathode-rays into X-rays.

But I must return to the X-ray tube. It has long been recognised that the material of the target should be one that possessed both a high fusing point and a high atomic weight. These conditions at once confine us to a comparatively small number of substances, and for practical reasons the metals of the platinum group have usually been selected; but even in the early days, when comparatively small currents were used, it was quickly demonstrated that unless great care was taken the heat generated was sufficient to fuse and so destroy the target.

This trouble has only been partly overcome, and even in our most modern tubes, where the anticathode forms part of a great mass of metal with special arrangements to conduct away the heat, or by the more complicated system of water-cooling, there is always very great danger of destroying that particular spot on the anticathode surface where the cathode focus strikes.

The fact is that the heat, generated as I have already pointed out, is of an order and degree such as we have never before had to deal with. We know that if we take a tin kettle and keep it full of water we may expose it to a hot gas flame without any fear of burning out the bottom, but the heat in the focus of the cathode is of a far different order to that of a flame, and it is peculiar, in that it is absolutely local. It is generated where the focussed rays bombard the anticathode surface and ceases *absolutely* the moment the rays cease.

Through the kindness of several members of the Society I have been able to examine quite a number of anticathodes that have been fused. An early one made from a thin plate of platinum is quite a beautiful object under the microscope. The platinum has been rendered plastic by the heat and a hollow depression has been forced in the plastic metal with curious lines of fusion radiating in all directions. Fig. 1, Plate VII., is a micro-photograph of the specimen.

The cost of platinum has led manufacturers to introduce an anticathode of nickel with a very superficial coating of platinum, a proceeding which is essentially bad for two reasons: one because the atomic weight of nickel is very low, 58·7, and the other because the thin coating of platinum is quite unable to resist the enormous heat generated. Fig. 2, Plate VII., is a photograph of the effect produced upon such a target: both platinum and nickel are completely pierced.

A very great advance has undoubtedly been made in the introduction, by Messrs.

Siemens Bros. & Co., of the tantalum anticathode. Tantalum is an exceedingly interesting metal. Its elementary nature was recognised over a century ago, but it is only recently that it has been found possible to produce it in a compact form. This triumph in metallurgy is due to two members of the scientific staff of Messrs. Siemens Bros., and the introduction of the tantalum incandescent lamp has made its name familiar to everyone. The metal is now being produced in ingots, sheets and wire, and has many very valuable properties. It is very hard and tough, and has an atomic weight of 181 (platinum is 195) and a fusing point of no less than 2,300 as against 1,700 for platinum. The metal is peculiarly suited for the anticathode of the X-ray tube, and Messrs. Siemens Bros. have very kindly furnished me with sufficient of the valuable material to experiment with. They have also lent me specimens of tantalum plates, that have been used as anticathodes, which show in a remarkable manner the effect of the cathode focus. One of these specimens demonstrates very forcibly the truth of what I have said as to the magnitude of the heat and force generated and also the almost incredible suddenness with which the heat and force ceases on stopping the current. Fig. 3, Plate VII., is a micro-photograph of the focus spot in a plate of tantalum. This photograph was very kindly made for me by Sir William Crookes and shows clearly the remarkable effect produced when the current is of considerable magnitude. In this case, I believe, it was something like 30 milliampères. You will see that the metal has been liquefied and the puddle of molten metal has been blown up into a mound on the side furthest removed from the focus; but so absolutely local and momentary was the effect that the plate, nearly one millimetre in thickness, was totally unharmed on its under side, and the cooling on cessation of current was so sudden that the hill of molten metal solidified as it was, leaving a permanent record of the magnitude and novelty of the forces that were at work. Fig. 2 is a magnified section of the

Fig. 2.

plate across its long axis, showing the cavity and mound; the thickness of the plate is 0·98 millimetres, the height of the mound 0·11 millimetres above the surface, and the depth of the hollow about 0·1 millimetre.

In addition to its high atomic weight and fusing point, tantalum possesses another property that makes it of the greatest possible value, not only for the anticathode of an X-ray tube, but for vacuum tubes generally. You will recall what I brought before you earlier in the evening as to property possessed by metals of volatility under the cathode discharge in vacuo, and of the harmful result of the metallic electrode matter being deposited upon the interior of the tube. The only two metals that Sir William Crookes found were not volatile, under the conditions of the experiment, were magnesium and aluminium, and it is for this reason chiefly that this latter metal is universally used for vacuum tube work. Metals of the platinum group on the other hand are freely volatile and quickly disintegrate under the cathode discharge, and coat the walls of the tube causing a rise in the resistance. Tantalum has the remarkable property of being absolutely non-volatile under the conditions that exist in an excited X-ray tube. This negative property is of such great value that I have made a special experiment to demonstrate it. From the material kindly placed at my disposal by Messrs. Siemens Bros. I prepared a rod, 12 millimetres long and 0·5 millimetre thick, and also two exactly similar rods of platinum and copper. Fig. 3 shows the arrangement: a vacuum tube closed at the top by a flat plate fixed by cement; the anode is at one side and the cathode is in

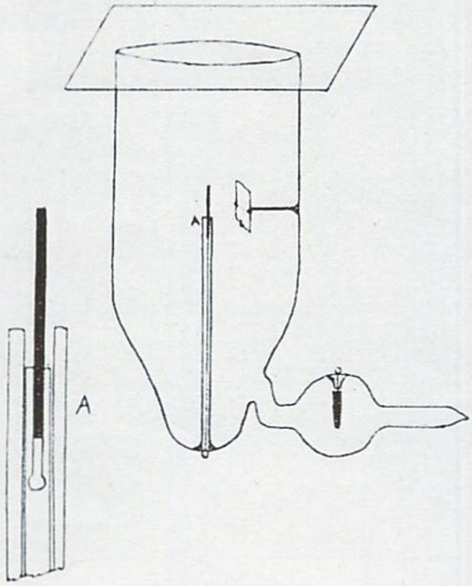



Fig. 3.

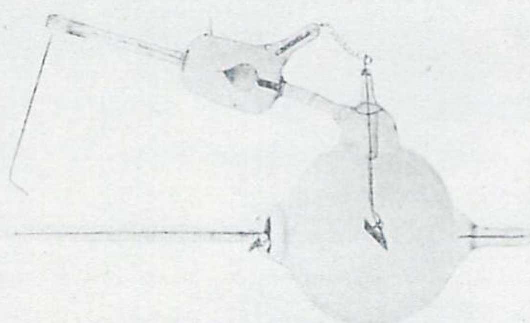
the form of a spring clip completely shielded by a glass tube which projects a millimetre beyond it. Into this clip the specimen rod can be forced with a pair of forceps so that it projects about a centimetre above the glass. Opposite this rod there is fixed a little glass claw and into this can be dropped a square of microscopic cover glass. In the experiment the three metals were taken in succession, exhausting the tube to the same point and passing the same current for five minutes in each case. Photographs of the three little windows are shown in Fig. 5, Plate VI., and you will see that platinum has given a good dense deposit, copper a less dense, while the glass square that was exposed and the tantalum rod is perfectly clean. The excitation was then continued in the case of tantalum for an additional 15 minutes without any visible effect whatever. The rods during excitation were bright red hot.

From what I have brought before you I think you will agree with me that a distinct advance has been made by the utilisation of tantalum for the anticathode of an X-ray tube; but we have not by any means reached finality, for we have seen that the heat generated in the cathode focus can be so great and so sudden that even in a plate of tantalum a millimetre thick it is possible to leave a puddle of liquid metal on one side while the under side is not even tarnished, making it clear that cooling the back of the plate either by water or a mass of metal cannot save the surface. And it is essential for a good definition that the surface where the *focussed rays strike* should be quite flat and if possible polished. As it is only this small spot of about one millimetre in diameter that is responsible for the production of X-rays, the obvious step is to make it possible to shift the plate so as to expose a fresh surface to the focus when one has been destroyed. In this way the life of a very costly tube could be very greatly prolonged. But there is another and even more simple means of lengthening the life of an X-ray tube. It is so simple that I almost hesitate to bring it before you, and yet I have never seen it adopted, and that is instead of moving the anticathode to expose a fresh surface to the focus, *to move the point of focus*. I have set up a little experiment that shows how easily this can be done. I have taken the anticathode plate out of an old X-ray tube and replaced it by a very thin sheet of platinum foil, so as to show the focus point more easily. On the end of the tube that holds the curved cathode I have fixed a loose block of wood that can be moved up and down and rotated at will. There is a hole in this block of wood into which can be slipped a little bar of magnetised steel. Fig. 4, Plate VII., shows the apparatus.

Now to illustrate its use. First of all, use your tube without the magnet until you have spoilt your anticathode surface. Then slip the magnet into its place, and use your tube. The focus will now be lifted up or pushed down as the case may be, and you will have a clean spot to work upon. When

1.

2.



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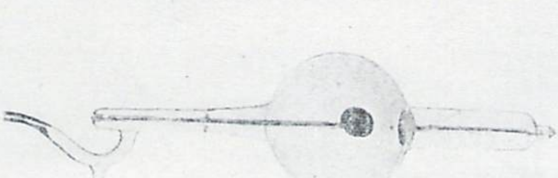
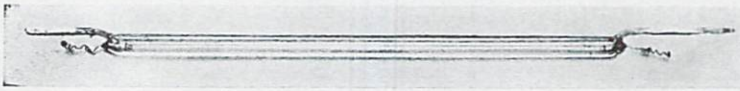


4.

TANTALUM. COPPER. PLATINUM.

5.

PLATE VI.



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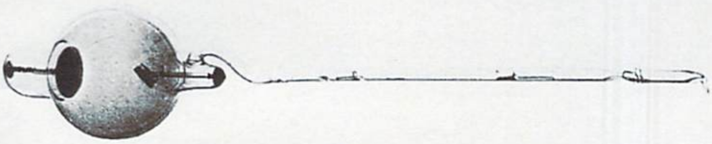

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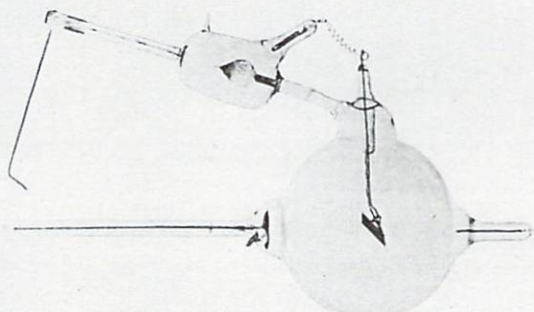

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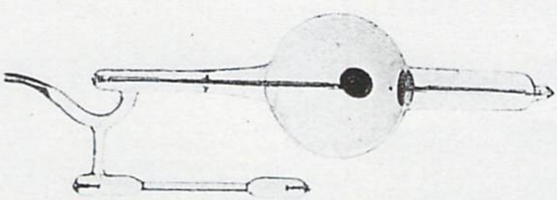

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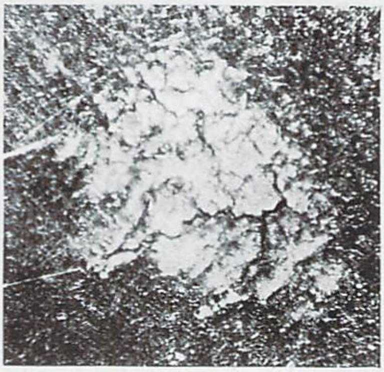
PLATE VI.



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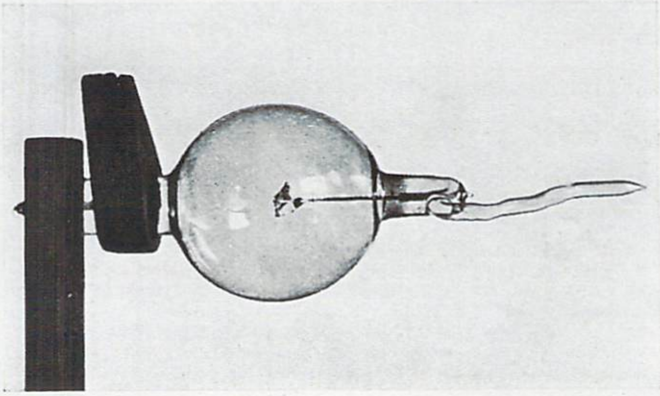

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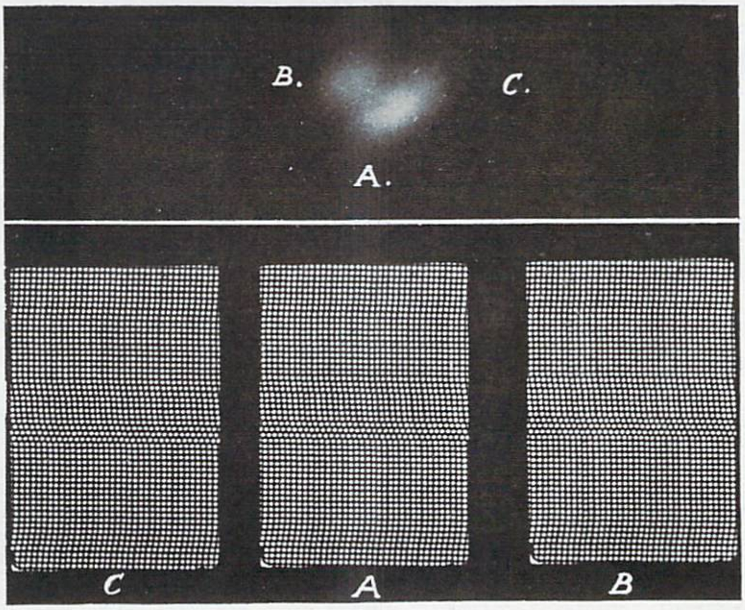


5.

PLATE VII

that has been spoilt rotate it half-an-inch and you have another clean place; and so you can go on all round, having a new place for each movement. When that ring of anticathode surface is finished, push the magnet a little nearer the cathode and your deflection will be greater, and you can rotate again until you have formed another ring, and so on. In this way it ought to be easily possible to greatly prolong the life of your tube. And when that apparatus runs into three or four pounds, this is no mean advantage.

Although the production of metallic tantalum is at the present time very properly the exclusive privilege of Messrs. Siemens Bros., it cannot but be expected that a metal of such value will soon become an article of commerce. There are great quantities of the ore available in many parts of the world, and I have very strong hopes that before long we shall see not only the anticathode but the whole of the internal electrodes of vacuum tubes made of this metal. Then we shall, I think, be able to construct X-ray tubes through which we can with safety pass 50 milliampères or more, and produce results far in advance of anything that we have yet seen or dreamed of.

## DISCUSSION.

The PRESIDENT said: We may congratulate the Society upon this most interesting communication. It deals with a matter upon which the Society has done good work in the past, and upon which it will, no doubt, do better work in the future. We may also congratulate ourselves upon having Mr. Gardiner as an exponent of this subject, than whom no one knows more about the focus tube or its predecessor, the Crookes' tube. The only point upon which I should like to have some further elucidation has regard to the cause of the increased resistance in the tube with the aluminium cylinder. Can Mr. Gardiner explain the physics of the phenomenon?

Mr. C. E. S. PHILLIPS: I feel sure I shall be voicing the feeling of the meeting when I say how pleased we are to see Mr. Gardiner fit and well again. His interesting paper has taken me quite by surprise. Of course, I came here knowing that anything Mr. Gardiner would have to say would certainly be interesting, but I had the idea that we were to listen to an oration on a subject about which we thought we already knew everything that was to be known. Mr. Gardiner has infused a splendid amount of enthusiasm into his paper, and the number of new subjects he has touched upon has been remarkable. One thing that strikes me is the question of the extraordinary force of the cathode streams. I know from my own experience that the anticathode will actually bend under the influence of the streams of particles from the cathode, but I have always felt that this might be due to some irregular shrinkage in the anticathode itself or to some weakness in its support. I have seen one tube in which the anticathode was bent right back, apparently by the force of the discharge. This is a line of investigation which ought to be followed up and threshed out to the bitter end. There is very little else to discuss, except to say how simple and ingenious is Mr. Gardiner's arrangement of the magnet on the end of the tube. The whole thing is so self-evident that it is astonishing we should not have hit upon it before. I should like to ask Mr. Gardiner whether he knows what is the behaviour of black glass from the point of view of fluorescence. If a tube were made of opaque glass, what would be the appearance of the glass when the discharge is sent through it?

Mr. A. A. CAMPBELL SWINTON: I should like to join in the praise of this most valuable and interesting paper. With regard to the experiment with the moving shield of aluminium, Mr. Duddell asked me a question at the last meeting upon that very point. I have tried quite a number of experiments with a very similar apparatus, but I am afraid I have not obtained the uniform results arrived at by Mr. Gardiner. I found that the size and shape of the tube made a great deal of difference and that the diameter of the aluminium cylinder relatively to the distance between the two electrodes was a factor to be taken into account. Absolutely different results were obtained when we used a battery discharge from those which were obtained when we used an induction coil. Obviously the result depended upon the character of the discharge. Replying to Mr. Duddell, I said that the results as a whole were very perplexing and indefinite, and I do not think the matter is as simple as it appears to be from the very nice experiments Mr. Gardiner has shown us. I should like to know whether he has tried other tubes, or whether he is pinning his faith entirely to the one which so excellently shows just what he wishes it to show. With regard to his last experiment in which he deflects his cathode rays on to another part of the target with a magnet when the old part is worn, I should like to ask whether such a procedure makes any difference to the results in point of sharpness. When using a battery discharge I should say it would not, but when using an induction coil with which the voltage is varying all the time, I should expect a result analogous to Birkeland's cathode ray spectrum. Birkeland found that the narrow patch of phosphorescence produced where the intensity of a cathode ray beam fell on the glass, when deflected by a magnet, was split up into several distinct patches, giving rise to what he called the magnetic spectrum. As a result of this, instead of getting a well-defined image, we may probably get a series of images, or at any rate a fuzzy image. I quite realise that it is only a certain portion of the cathode ray beam that gives the X-rays, and that with the deflected beam we might get a spectrum which would not give out the X-rays for its entire length. But between the extreme limits we should probably have X-rays proceeding not from a point but from an oval or a line, thereby interfering with the sharpness of the result. I am glad to hear what Mr. Gardiner has had to say with regard to tantalum. In some of the experiments in which we have been dealing using large powers—Mr. Gardiner has mentioned 50 milliampères, but we use a good deal more than 50 milliampères on occasion—one of the difficulties is due to the melting of the cathodes. It is no unusual experience to find the aluminium red hot. The difficulty in using platinum cathodes is that we get a deposit all over the glass, while magnesium which had not this disadvantage has about the same melting point as aluminium. If we can make the cathodes of tantalum it will be of very great importance, as the melting point of tantalum is very high, and cathodes of that metal should stand very large discharges without danger.

Dr. G. Rodman: Mr. Gardiner deserves congratulation upon his excellent photomicrographs, and I should like to ask him what magnification was given, and whether there were any great difficulties in obtaining such good results as those we saw on the screen. In the case of these anticathodes affected by the cathode rays, we have practically the same appearance as in that of the arc discharge. The positive carbon terminal, as the arc passes, becomes hollowed out into a luminous crater-like shape, having a considerable resemblance to that shown in Mr. Gardiner's photomicrographs of the anticathode. Another similarity between the two is that the light coming from the arc comes from the centre of the crater, and I take it that the X-rays also come from the centre of the crater that we have seen so admirably depicted on the screen. So that we have practically the same thing that we get with the ordinary arc lamp.

Mr. W. Duddell: I should like to join in complimenting Mr. Gardiner upon his most admirable paper, which will be one of great service to the X-ray industry. His suggestion of moving the point of the focus about the anticathode is certainly a most ingenious one. It appears, however, not to be of much use unless one is dealing with a metal like tantalum, and it is only in connection with the more modern tubes that it can be properly applied. A word of congratulation also is due to Dr. Rodman upon his photographs of the X-ray tubes, and I hope that at the next meeting we shall hear something further from him about them.

Dr. G. B. BATTEN: We have to thank Mr. Gardiner for his past and present researches into this question. A good many of us besides Mr. Duddell have not realised how much we owe to Mr. Gardiner. With regard to the experiment with the cylinder, although Mr. Campbell Swinton has shown that the effect is not a very constant one, I should like to know whether it would not be possible to use the device as a means of hardening tubes. The usual trouble in working X-ray tubes is that they get too high, but sometimes they get too low, and we require to harden them. The ordinary devices for hardening a tube are not very satisfactory, and if we could have a movable metal coating inside, or perhaps outside, the tube, it would help us in that direction. The mention of osmium used for the anticathode reminds me that I had a good tube made by Cossor on Mackenzie Davidson's suggestion in which the anticathode was made of this metal. It was a small tube and it gave beautiful definition. Ultimately, however, it became too hard, and I asked the maker whether he could not put it in an Osmo regulator. He replied that this had been tried but it was unsuccessful. Although osmium is rare there was a supply of it, and probably many of us have got tubes with osmium anticathodes lying on our shelves. With regard to the most pleasing and simple device for prolonging the life of X-ray tubes, it seems possible, as has been suggested, that there would not be such good definition when the rays are thrown out of their principal focus. We must thank Mr. Gardiner for showing the way to manufacturers for making smaller and simpler tubes. Many of the tubes at present made are good examples of glass-blowing rather than examples of the most convenient instruments for practical use. The medical man has to use his tube, not only for photography, but also for treatment, and it is often a difficult matter to get protecting devices which will properly fit the weird shapes of tubes now upon the market. If two or three different makes of tubes are employed a protecting device which will fit all in turn must be a huge contrivance, and even then if the opening is properly arranged for one tube it is quite out of place for another. With tantalum inside the tube and with an Osmo regulator or this new Bauer air-valve, or better still a Bauer valve and an automatic regulator also, we ought now to get more convenient tubes, and I would suggest that if these are not forthcoming, Mr. Gardiner should read the "Riot Act" to the manufacturers.

Mr. F. H. GLEW: The introduction of tantalum may ultimately explain some of the theory of the generation of X-rays in the tube. I remember a paper by Mr. Mackenzie Davidson, in which he traced the source of the X-rays by means of pinhole photography. He made a hole in a sheet of lead, and of course the pinhole photograph gave the seat of the X-rays. The first demonstration enabled one exactly to note the area made alive on the target. It is theoretically explained that the origin of the X-ray pulse is a pulse in the ether, resulting from the bombardment of electrons stopped at the target with great suddenness. The more suddenly they can be stopped, as Sir J. J. Thomson explains, the more intense is the character of the radiation. This, however, is really a kind of mechanical explanation, and if what takes place is merely mechanical we should expect something like the recoil of a gun to take place at the cathode. In Mr. Mackenzie

Davidson's experiments I do not think we had any evidence of the cathode itself being a source of X-rays. It would be extremely interesting to push the matter to its conclusion and see whether this is possible. It may be that this recoil effect, if it exists, is masked by the fact that aluminium is a poor target and therefore a poor source of X-rays, and it seems to me that the introduction of tantalum cathodes would settle that point, as we would get away from the low atomic weight of aluminium which might nullify the possible effect. Mr. Raffety has brought us this evening a most interesting tube in which it is possible to get the focus either on to platinum or aluminium and to see the difference between the two. The introduction of tantalum cathodes, tantalum having such a high atomic weight as 181, would probably enable us to see by this pinhole method whether the cathode is really itself a source of X-rays due to the recoil as the electrons leave it. It would seem as though there must be a recoil at the cathode, and something like X-rays formed, although they may be of a low order of penetration. Has Mr. Gardiner made any experiments along those lines? In connection with this most ingenious method of moving the spots on the target by magnetic deflection, although it is likely to be very useful under certain circumstances, yet the proper method seems to be the first that Mr. Gardiner suggested—*i.e.*, the movement of the target. If we had some means by which the target could be made to spin like a gyroscope, I think that, given a tube with a good, solid backing, we might pass some hundreds of milliampères through it. The target must, of course, always be rotated in such a manner that the plane is in the focus spot of the tube. A simpler method would be to have a pendulum inside and to put it into motion when the heavy discharge was coming through. Some years ago I pointed out this effect of the magnetic field at the moment of generation, and proved it in a simple way by using a choking coil in circuit with the primary coil, the choking coil being brought up to the tube in different positions; by this means the focus was altered and we obtained a line instead of a point. Evidently during the generation of the pulse, or rather during the flight of the electrons, there is time for the magnetic field to change, but the magnetic effect is really existing after the X-ray pulse has ceased. It takes time to die down. The same effect can also be seen when working a tube close to the coil.

Dr. A. H. Pirie thought that the effect with the cylinder might correspond with that which had been noticed in the case of some X-ray tubes having a great deal of deposit upon their inner surface. He thought that it might be possible to have some regulating device upon the same principle. With regard to the use of the magnet for the deflection of the focus of the cathode rays, Dr. Pirie thought that very much depended upon the square of the distance between the magnet and the electrons of the cathode rays. He would like to hear whether Mr. Gardiner had found that for sharp focus work with a big tube such arrangement did affect sharpness of the focus. For therapeutic work, if not for radiography, the plan might be of much service.

Mr. C. W. Raffety: I should like to join in expressing appreciation of Mr. Gardiner's excellent paper. With regard to the experiment with the metallic cylinder in the vacuum tube, it occurs to me that the increased resistance of the tube may be due to an electrostatic action of the metal in drawing off the discharge from the direct path between the electrodes, rather than to the fluorescence of the glass. Mr. Glew has suggested avoiding the overheating of one point of the anti-cathode by keeping the latter oscillating in its own plane. Perhaps this could be done with a pendulum arrangement, the oscillation being secured by the action of an electro-magnet outside the tube, the circuit of which was alternately made and broken with suitable frequency. Mention was made of the possibility of a form of "X" radiation from the cathode itself, owing to some sort of recoil action due to the starting of the electrons from its surface. This, however, seems to assume an explosive action in the metal of the cathode—a kind of artificially produced radio-activity. I see no reason to expect such an action, as the acceleration of the electrons is comparatively gradual, the velocity being acquired under the electrostatic field existing in the region between the cathode and anticathode. The electrons are presumably liberated from the cathode by the action of the positive ions which are continually streaming in towards it, and their acceleration appears to be analogous to that experienced by a falling body. In this way there is a continual relieving of the cathode potential. The method of altering the position of the focus of the cathode stream is exceedingly interesting, and I should imagine, as Dr. Pirie has pointed out, that it would be most useful in therapeutic work where sharp definition is unnecessary; but I think that the dispersion of the components of the cathode stream will, in any case, be so small that the method would be suitable for ordinary radiography without loss of definition. In very critical work, however, the slight enlargement of the radiant area might prove an obstacle.

Mr. J. H. GARDINER: I must apologise for having omitted to say that the slides showing the historical apparatus were the work of Dr. Rodman. We shall have an opportunity of hearing Dr. Rodman at the next meeting, and for that reason I have avoided as much as possible the subject which he will discuss in his forthcoming paper. Dr. Butcher asks for an explanation of the effect with the metallic cylinder. The reason for the increase in resistance is very obscure and as to-night I am anxious to avoid theoretical discussion and confine myself to experimental facts, I am afraid I must ask Dr. Butcher to hold his question over for the moment and be content with the experiment, which shows that if the discharge takes place in a metallic chamber the resistance of the tube is very much greater than if the chamber is composed of phosphorescing glass. Mr. Phillips asked about the phosphorescence in the case of opaque glass. I have not tried any specimens of opaque glass, but it is quite certain that a great many substances which are opaque will phosphoresce quite beautifully. A block of corundum, for instance, which is a dull mineral, brown in colour, will phosphoresce the colour of ruby. (Mr. PHILLIPS: My meaning was that owing to the phosphorescence being on the inner surface I take it that the glass will appear quite dark from the outer side.) With regard to the point raised by Mr. Swinton as to the possibility of the definition being less satisfactory on the magnetic deflection of the focus, I have not yet had an opportunity of making any tests, but the magnetic power necessary to cause the slight displacement of focus is so very small that the effect analogous to the Birkeland spectrum, of which Mr. Swinton speaks, would not I think be appreciable. I only brought the idea forward as a simple method by which, perhaps, a tantalum anticathode could be made to last longer than it otherwise would do. With regard to Mr. Swinton's point about the difficulty involved in making tubes of variable resistance, I may refer him to the researches of Sir William Crookes, described in his address to the Institute of Electrical Engineers in (I think) 1891; a very great number of tubes have been made in all possible kinds of ways to show the same effect. So long as the glass is coated with anything that stops the phosphorescence it will immediately increase the resistance. Several details have to be observed in the making of such devices. The electrodes must be covered with glass over their whole length; and only the front surfaces where you wish the discharge to take place left exposed, and then the whole of the current produces effects that immediately act upon the glass. If these precautions are taken there will be no difficulty in getting a tube exceedingly soft in the glass envelope and while in the metallic envelope exceedingly hard. I think that it has been established most clearly that the resistance of the tube under these conditions depends entirely upon the phosphorescing material. We may have, for instance, a soda glass tube that will fluoresce quite easily, and we obtain a certain resistance to the current, but if, instead of soda glass, we have some other glass that does not fluoresce so well, the resistance will go up. In reply to Dr. Rodman the magnification of the little photomicrograph was under 100. With regard to the osmium tube, the use of osmium would have no effect whatever upon the definition of the tube. The only advantage is that osmium has a slightly higher melting point. Osmium belongs to the platinum group, and an osmium anticathode would not be much better than a platinum or an iridium one. I quite agree with Dr. Batten as to the inconvenient shapes of tubes that are sometimes put before us; they are often "wonderfully and fearfully made," and I cannot help thinking that the X-ray tube of the future will be a smaller and simpler one, firmly and substantially constructed. It was my intention to have constructed an X-ray tube that would have settled the point that has been raised by Dr. Batten. I think it might be possible to make a tube on these lines that would give rays of any degree of hardness without any alteration whatever in the vacuum.

## X-RAYS FROM A MAGNETICALLY DEFLECTED CATHODE FOCUS.*

*By J. H. GARDINER.*

At the conclusion of the paper on the "Origin, History and Development of the X-ray Tube" read at the last meeting, I made the suggestion that the life of an X-ray tube might be lengthened by the simple device of attaching a small magnet outside the tube close to the edge of the cathode. By this means, when one spot on the anticathode surface had been fused, the focus could be made to fall on a new place and the tube used again.

In the discussion that followed the paper, several speakers expressed a fear that the proposed displacement of the focus would destroy the "radio-graphic definition," on account of the fact that the cathode rays are not homogeneous, some of them being more deviated in a given magnetic field than others, and that the displaced focus would be no longer a point but more or less oval in shape.

At that time I had not made the actual experiment, but merely showed by a hastily constructed tube how weak a magnetic field was necessary to distinctly affect the cathode focus; and I was only able to express an opinion that the proposed displacement was so small that any effect due to this cause was likely to be negligible.

As the matter seemed of some importance, I have now made the experiment and propose to briefly describe the result.

The tube that I showed last month (Fig. 4, Plate VII.) was opened and the thin screen removed, and replaced by a substantial plate of platinum. When the tube was excited the normal focus, without any magnetic deflection, fell nearly on the centre of the plate in the position marked A (Fig. 1). With the magnet in place, the focus was drawn about three millimetres to one side as shown at B, and then by rotating it 90° it was deflected about the same distance the other

* Read May 6th, 1909.