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X-Ray Technology

The Production, Measurement and Applications of X-Rays

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1830  1930

CHAPMAN & HALL'S
CENTENARY YEAR

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PREFACE

It has been the purpose in preparing this book to present the practical rather than the theoretical aspects of X-ray measurements as they are inevitably encountered by all who choose to work in the X-ray laboratory. Much of the contents is devoted to problems which are common to all X-ray laboratories but particular attention has been given to the quantitative measurements involved in X-ray therapy and in industrial applications.

A considerable portion of the contents may be properly classified as X-ray engineering. Much space has been given to the description of instruments and apparatus and methods of using them, since it is recognized that in the X-ray laboratory it is often necessary to make use of special equipment which cannot be obtained except by constructing it in the laboratory workshop.

The authors are conscious of the help they have received from many sources. They are so deeply indebted to the researches and publications of Coolidge, Hull, Wood and Duane especially, that adequate acknowledgment would be impossible. They are also indebted to the catalogues and bulletins of manufacturers of electrical apparatus and equipment. The assistance given by Mr. L. F. Ehrke in the preparation of a number of the illustrations and radiographs is especially appreciated.

H. M. TERRILL
C. T. ULREY

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X-RAY TECHNOLOGY

CHAPTER I

Properties of Moving Electrons

Electrons in motion in a vacuum tube under the influence of an electrical field applied to the electrodes are usually called cathode rays. The name is derived from the fact that they were originally produced at the cathode of Hittorf tubes, gas-filled X-ray tubes, and similar devices whose conductivity depended upon the residual gas in the "vacuum." Modern methods, however, require a tube with a much higher vacuum and a cathode from which the emission of electrons is caused by heating it as in the common radio tube.

The term "beta rays" was originally applied to high-speed electrons emitted spontaneously from radio-active substances. It is sometimes also used for electrons of more moderate speeds, especially when these are produced outside the vacuum tube, as for example, the electrons emitted by a substance placed in a beam of X-rays or in the rays from a radio-active substance.

Many substances possess the property of electron emission while absorbing light. Such electrons are properly called photo-electrons and the term has been extended to include the electrons emitted under the influence of ultra-violet rays, X-rays, gamma rays and cosmic rays.

When a beam of electrons falls upon a substance other electrons are ejected at low speed. The number of these secondary electrons, or "delta rays," as they are sometimes called, depends upon the nature of the substance emitting them

and upon the velocity of the primary electrons. For the velocities corresponding to several hundred volts many substances emit more secondary electrons than are contained in the primary beam.[1]

Cathode rays travel in straight lines, are stopped by heavy objects but have the power of penetrating exceedingly thin ones, affect photographic plates, excite fluorescence in certain substances, and are deflected by magnetic or electrostatic fields.

Velocity

The velocity of the cathode rays depends on the voltage applied to the electrodes of the tube. The following table gives velocities in centimeters per second corresponding to various voltages expressed in kilovolts; the third column headed β, giving the velocities as a fraction of the velocity of light.

kv.	cm./sec.	β
25	9.05×10^9	.302
50	12.42×10^9	.414
75	14.67×10^9	.489
100	16.45×10^9	.548
150	19.1×10^9	.637
200	$20\ 9 \times 10^9$	.695
250	22.3×10^9	.743

Text books often give the relation

$$E = \frac{Ve}{300} = \tfrac{1}{2}mv^2, \qquad (1)$$

which is correct for low velocities where the increase in mass with velocity is small enough to be neglected. At high velocities the increase in mass can not be neglected and in this case the longitudinal mass is given by the relation:

$$m = m_0(1 - \beta^2)^{-3/2}$$

where m_0 is the mass of the electron at low velocity. Substituting this value in

$$E = \int_0^v mv\,dv,$$

[1] H. E, Farnsworth, Phys. Rev., **25**, p. 41 (1925).

and integrating we get:

$$E = c^2 m_0[(1 - \beta^2)^{-\frac{1}{2}} - 1]$$

Introducing the values of the constants gives

$$V = 2.830 \times 10^{-16} v^2(1 + .83v^2 \times 10^{-21} + .77 v^4 \times 10^{-42} + \ldots) \quad (2)$$

Throughout this work, velocity of electrons will ordinarily be expressed in terms of the voltage through which the electron must fall in order to acquire such velocity. This notation is open to criticism since velocity and voltage are not dimensionally equivalent, but it at least has the justification of com-

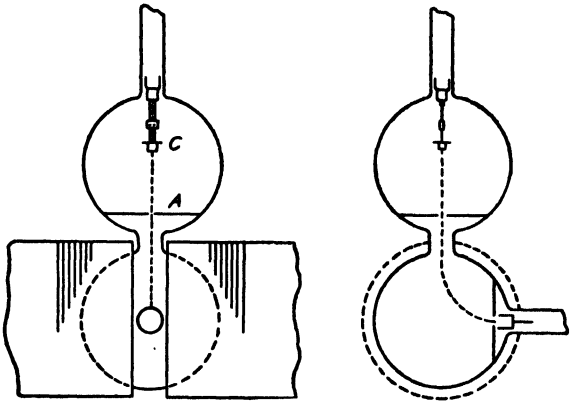


FIG. 1.—APPARATUS FOR VELOCITY SPECTRUM.

mon usage. Furthermore, in the determination of velocity the only quantity which is ordinarily measured is the voltage.

When all the electrons in a beam of cathode rays have the same velocity, the beam is said to be homogeneous, or uniform. Such a beam is produced by an unvarying voltage. If the voltage is varying, such as the output of an induction coil, or switch rectified a. c., the velocities will not be uniform.

The fact that the rays are deflected in a magnetic field can be used as a means to measure the velocity of these rays. Intense fields are not required, and a stream of electrons entering a field such as the interior of a solenoid can be bent at right angles to its original direction with a few amperes flowing through the coils. Figure 1 shows such an arrangement.

The electrons produced at the cathode C under the influence of a voltage difference between C and the perforated anode A pass through the opening in the anode and into the interior of a solenoid which is so long that the effects due to its ends are negligible. The dotted line shows the path of the electrons.

This serves as a method of analyzing the velocity. If the beam is not uniform, the electrons of different speeds will be deflected by different amounts and the beam spread out in a velocity spectrum.

Current Carried by Cathode Rays

The moving electrons carry electricity and the stream of electrons acts similarly to a flexible conductor through which a current is passing. The charge on one electron is 4.77×10^{-10} electrostatic units so that it would take 6.3 billion billion electrons (6.3×10^{18}) to make a coulomb, or this number passing in one second to equal a current of 1 ampere. When cathode rays strike a solid object, if it is insulated, it acquires a charge of electricity, while if it is connected to earth, a current of electrons flows from it.

The energy of a beam of electrons striking a solid body manifests itself principally as heat. The amount of energy depends not only on the number of electrons, but also on the speed with which they strike.

Secondary Electrons

When a beam of electrons strikes a thick metal target, most of the electrons are absorbed in the metal; some of them are scattered or diffusely reflected, and some secondary electrons, not in the incident beam, are ejected from the target. The scattered electrons have all velocities up to almost that of the primary beam, while the secondaries are all of low velocity. It is this difference in velocity distribution which makes it possible to distinguish scattered or reflected from true

secondary electrons. The term "secondary electrons" usually includes all electrons escaping from the target, including the scattered, as well as true secondaries.

A considerable amount of experimental work has been done on the investigation of secondary electrons from various metals, with primary velocities of several hundred volts, but not much has been done with higher velocities. The number of secondary electrons depends upon the nature of the metal, the conditions of the surface and the kind and amount of residual gases in the tube and increases with primary velocity up to about 300 or 400 volts where there may be twice as many secondary as primary electrons.

To measure the number of secondary electrons, a collecting electrode must be inserted into the tube in such a way that it can collect all the secondaries without intercepting any of the primary beam. The collecting electrode must be kept at a positive potential with respect to the target. Such apparatus does not distinguish between true secondaries and scattered or reflected electrons directly, but this can be done by determining the velocity distribution of the electrons coming from the target to the collecting electrode.

The collecting electrode may be in the form known as a Faraday cylinder. Such a cylinder traps all the secondaries, provided it is deep enough, and therefore the current flowing to the cylinder as measured with a milliammeter or other current measuring instrument gives an accurate measure of all the electrons entering it. Usually the depth of the cylinder is made three or four times its diameter and the electrons are allowed to enter through an aperture in the end.

The velocity distribution of the secondary electrons can be determined by placing retarding potentials on the Faraday cylinder so that only those electrons having velocities sufficient to move into the cylinder against this potential are collected. When dealing with high voltages it is sometimes desirable to keep the Faraday cylinder at ground potential. In this case the accelerating or retarding field can be secured by using a second larger cylinder concentric with the other,

but insulated from it and applying the desired potential to this auxiliary cylinder.

The curve in Fig. 2 shows how the number of secondary electrons varies with the velocity of the primary beam in a typical case.

For primary velocities above 1,000 volts the difficulties of measuring the secondaries increase and this region has not been thoroughly studied. It appears however that the ratio of secondaries to primaries decreases at higher voltages and with primary voltages of from 30 to 100 kv. the number

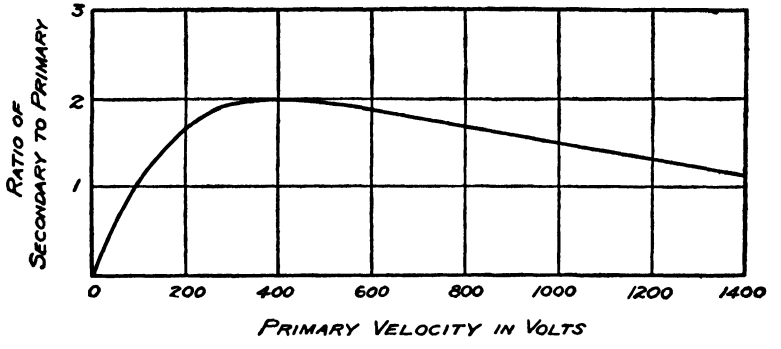


FIG. 2.—THE RATIO OF THE NUMBER OF SECONDARY ELECTRONS TO PRIMARY ELECTRONS.

of secondaries is about 25 to 35 per cent of the primary beam and does not vary much with the voltage.

Coolidge has estimated that the X-rays coming from the parts of an X-ray target outside the focal spot have an intensity of approximately 20 per cent of that coming directly from the focal spot. He attributes these extra-focus X-rays to electrons striking the target after being scattered from the focal spot and this conclusion is in substantial agreement with that obtained by direct measurements of secondary electrons under similar conditions.

Reflection

When a fine beam of cathode rays is projected onto a metal target the scattered electrons in general rebound from the

target in all possible directions in the manner known in optics as diffuse reflection. Davisson and Germer [2] have discovered in addition to this diffuse reflection and superimposed upon it a type of regular reflection, but this occurs only when the target consists of a large metallic crystal and then only for certain definite angles of incidence for a particular velocity of the incident beam. The optical analogue of this phenomenon in optics and X-rays is known as diffraction. As in the case of diffraction of X-rays by crystals, the reflection angles can be determined by assigning a wave-length to the electron. The wave-length to be associated with an electron depends upon its speed and is determined by the quantum relation,

$$\lambda = \frac{h}{mv}.$$

Passage through Matter

The fact that cathode rays can pass through thin sheets of solid matter has long been known, but the phenomenon is very complicated. Consider a beam of electrons striking a thin sheet of metal foil. A very small part of them is reflected or scattered back while a certain fraction is absorbed in the foil, from which current must be continually conducted. The kinetic energy of these stopped electrons is transformed into heat. Another fraction gets through the foil, but the velocity is diminished and no longer uniform. This fraction has suffered some scattering and many electrons are traveling at an angle to the original direction. Over all is the fog of secondaries, on both sides of the foil, rendering precise measurements difficult.

Absorption

Measurements of the absorption of cathode rays in aluminum foil have been made by Terrill [3] over a range of voltages from 20 to 50 kv.

[2] Davisson and Germer, Phys. Rev., **30**, p. 705 (1927).
[3] Terrill, Phys. Rev., **24**, p. 616 (1924).

When a beam of cathode rays strikes a sheet of thin metal foil, the fraction that penetrates depends on the velocity of the rays. Figure 3 gives the fraction getting through for various initial velocities in the case of aluminum foil .00031 cm. thick. The dotted curve gives the apparent value of the transmitted fraction, when the secondaries on the emergent side of the foil are not excluded from the measurements.

The fraction of a beam of cathode rays of uniform velocity that passes through a sheet of metal foil depends also on the thickness of the foil and follows the usual exponential law of absorption: $I/I_0 = e^{-ax}$ where x is the thickness and a depends

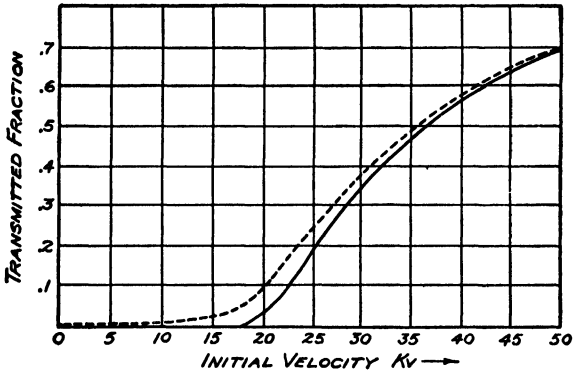


FIG. 3.—TRANSMITTED FRACTION AS A FUNCTION OF THE INITIAL VELOCITY.

on the density of the material and the velocity of the rays. The constant a may be called the absorption coefficient of the material for the particular velocity. It is evident that the velocity of the rays is continually changing as they are passing through the foil and that some sort of average or effective velocity will have to be assumed. For present purposes, it will be sufficient to define the effective velocity as the arithmetic mean of the velocities on entering and leaving the foil, experiments showing this method to be satisfactory as long as the foil is not too thick nor the velocity too low. The most probable velocity on leaving the foil can be found from the results of the next section. For example, with foil .00093 cm. thickness, this method of approximating the effective velocity

will give fair accuracy for cathode rays of initial voltage of 43 kv. or more. In general, the method can be used as long as the velocity loss, as determined by methods to be described in the next section, is not more than 30 per cent of the initial velocity expressed in volts.

The following table gives the value of a/ρ where ρ is the density of the material.

Effective Velocity, kv.	a/ρ, 10^3	Effective Velocity, kv.	a/ρ, 10^3
22 2	1 815	39 8	0 645
26.4	1.289	44 1	0 530
31 3	0 960	48.3	0 449
35 3	0 786		

It must be emphasized that the velocities in the first column refer to effective velocities, and not initial velocities.

According to an expression derived by J. J. Thomson, the values of a/ρ may be taken as approximately inversely proportional to the fourth power of the velocity expressed in centimeters per second. Thus, to a still rougher degree of approximation, these values are inversely proportional to the square of the voltage. This law should not be used to extrapolate the above table for the law holds only for a limited range.

Velocity Loss

After emerging from the foil the velocity of the rays has suffered a considerable change. Not only is it in general diminished, but the rays that were of uniform velocity on entering the foil, have, on leaving, a mixture of velocities. This mixture can be analyzed by spreading it with a magnetic field. Figure 4 shows the distribution of velocities of uniform cathode rays having an initial velocity corresponding to 33.9 kv., after passing through a sheet of aluminum foil .00031 cm. thick. In this diagram and throughout this section, all

the velocities will be given in terms of corresponding voltages.

Of course, after passing through the foil, the beam has suffered some scattering and is more diffuse, and the velocity distribution in the diagram was determined for that portion of the beam that continued in the original direction.

To speak of the emergent velocity has not much meaning since the emerging beam is a mixture and there is no single velocity, but for certain purposes it is desirable to have a single velocity that can be used in computations, and the velocity corresponding to the highest point on the curve may be taken.

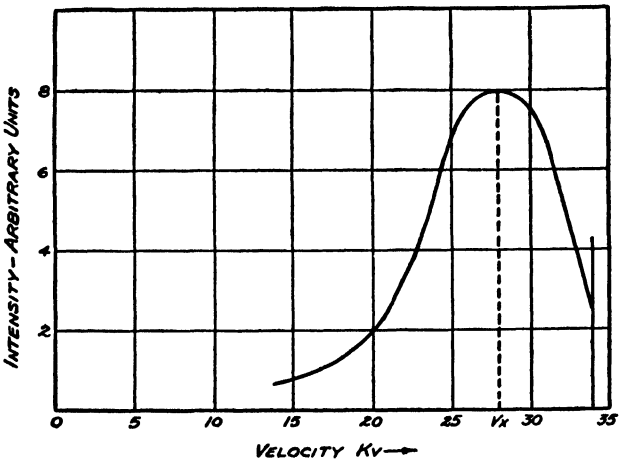


FIG. 4.—VELOCITY DISTRIBUTION CURVE.

This may be called the most probable velocity, and the symbol for it, expressed in volts is V_x. J. J. Thomson has derived an approximate relation connecting V_x with the initial voltage V_o. If the thickness of the foil is x, the relation is $V_o^2 - V_x^2 = bx$, where b is a constant for a particular metal, depending on its density. The value of b has been determined experimentally by Terrill[4] for a number of metals. Taking the mean of several experiments, with different metals, the value b/ρ is $.40 \times 10^{12}$. Thomson's equation seems to hold over a range of voltages, up to at least 50 kv., the highest voltage used in these experiments.

[4] Terrill, Phys. Rev., **22**, p. 101 (1923).

When passing through a thin foil, the rays lose both intensity, i.e., number of electrons, and velocity. The loss of intensity takes place at a more rapid rate and the intensity can be reduced to a few per cent of the original before the velocity, i.e., the most probable velocity, falls to half value. Figure 5 shows the intensity and velocity distributions of uniform cathode rays having an initial velocity corresponding to 45.6 kv., after passing through aluminum foils of thickness .00031, .00062 and .00093 cm., respectively. The curves are

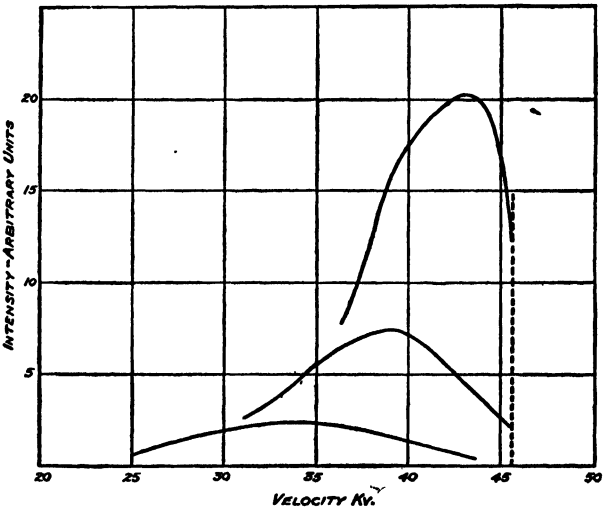


FIG. 5.—VELOCITY DISTRIBUTION AT DIFFERENT DEPTHS BENEATH THE SURFACE OF THE TARGET.

only approximations, but serve to show, in a general way, the number and velocity of the electrons at various depths.

Range

If the velocity of the electrons is diminished on passing through a thin foil, it is evident that a foil can be found so thick that the velocity would be reduced to zero. This thickness is calculated from the equation by placing $V_x = 0$, whence $x = V_0^2/b$. This thickness is usually called the range corresponding to the given velocity, V_0. Thus if V_0 is 18.4 kv., the

range in aluminum is .00031 cm. and we should expect this velocity to be the limit below which no electrons get through the foil. Referring back to Fig. 3, it will be observed that such is the case.

It should be noted that the range refers only to transmitted electrons and that secondaries can still be observed on the far side of the foil, even when the thickness is greater than that given by the range. These secondaries are possibly photo-electrons liberated by X-rays generated in the foil.

Electron Emission

A common source of electrons is a heated tungsten filament or wire. To get an appreciable amount of electrons the filament must be heated to the same order of brightness as that of an incandescent lamp. Following is a table given by Dushman showing the variation of emission with filament temperature.

Absolute Temperature	Current from 1 sq. cm.
1800° K.	0.2 milliamperes
1900	1.0
2000	4.2
2100	15.1
2200	48.3
2300	137.7
2400	364.8
2500	891.0
2600	2044.0

It is important to observe the extremely rapid rate at which the emission increases with the temperature. In a later section will be given a table of the electron currents emitted by a filament for various heating currents in the filament, and it will be noticed that small fluctuations in the heating current can cause enormous fluctuations in the emission.

Richardson deduced the following equation for the thermal electron current on the assumption that the electrons in

a metal have a thermal distribution of velocities like the molecules of a gas or liquid and when the temperature is raised the velocities increase so that some of the electrons escape through the surface against the attractive force of the metal:

$$I = AT^n e^{-b/T}$$

in which b depends upon the surface work function constant for a particular metal.

In radio tubes, the cathodes are often coated with oxides of the alkaline earth metals and other substances so that they emit an appreciable amount of electrons at a dull red heat. Such cathodes have not been developed to a satisfactory state for use in high voltage tubes because ion bombardment during exhaust and the excessive electrostatic forces disintegrate the coating. Much improvement has been made recently, however, and they are being employed in higher voltage tubes than was possible with the older types of oxide cathodes.

A layer of thorium on the surface of a tungsten filament also gives it the power of emission at lower temperatures. Although this property has not been employed in high voltage tubes up to the present, it may hold possibilities for future development. X-ray tubes having thorium targets, but ordinary tungsten filaments have been used by the authors. These tubes operated with normal tungsten emission for normal power input, but when such a tube was heavily overloaded so that the target melted at the focal spot, some thorium was deposited on the filament and its emission was increased so that the normal tube current was then obtained with the filament at a much lower temperature than before.

Space Charge

Referring to the table given in the previous section, it will be observed that the applied voltage was not mentioned. That table gave the amount of current that could be obtained, provided the voltage was sufficient to drive from the filament all the electrons that were emitted. If the voltage is not suffi-

ciently high, the electron current will be limited by space charge. This is due to the mutual repulsion of the electrons, somewhat as if those first emitted formed an electric field around the filament and prevented the others from crossing to the anode.

At low voltages, then, instead of getting all the current corresponding to the filament temperature, it is found that the current depends on the voltage, and under certain conditions varies as the 3/2 power of the voltage over a limited range. Of course, as soon as the voltage gets sufficiently high, the current becomes constant, for the current then consists of all the electrons that are being emitted by the filament.

In the diagram, Fig. 6, the current corresponding to various voltages is plotted for a given filament temperature.

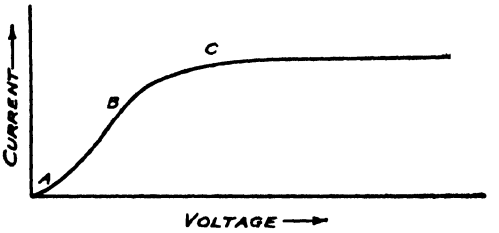


FIG. 6.—VARIATION OF CURRENT WITH VOLTAGE FOR CONSTANT FILAMENT TEMPERATURE.

On that portion of the curve between *A* and *B*, the voltage is low and the current follows the 3/2 power law, and the tube is said to show space charge characteristics. On the part of the curve beyond *C*, the current is approximately constant.

With tubes used as rectifiers, the effects of space charge are important for it is desirable to have the voltage across these tubes as low as possible, possibly not over 500 volts in the case of rectifiers suitable for X-ray use. With X-ray tubes, the normal operating voltage is usually far above this, but even at 15 kv., the current of an X-ray tube is often limited, no matter how hot the filament becomes. There is, however, another factor entering into this case. In the rectifiers, the filament is unenclosed and there exists a clear path from the

filament to the anode. With X-ray tubes, the filament is partially enclosed in a focusing shield and it requires a much greater voltage to withdraw all the electrons in such a case.

For example, suppose a tube built as in Fig. 7 with the filament enclosed in a hollow sphere which has only a small opening. It would require very intense fields to get many electrons out through the opening and this would mean not only a high voltage across the tube, but also that the anode *A* be brought close to the cathode.

The effects of space charge are exhibited only in a high vacuum. In the case of a pure electron discharge, such as that in a high vacuum X-ray tube, the electrons must get across the tube without an appreciable number of collisions with the molecules of the residual gas. If there is sufficient residual

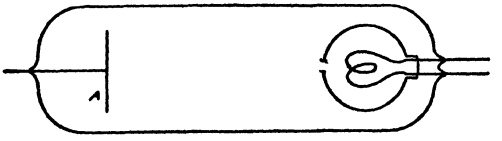


FIG. 7.—DIAGRAM OF TUBE WITH FILAMENT TOO MUCH SHIELDED.

gas in the tube, there will be ionization and neutralization of the negative space charge by the positive ions. This allows more current to flow and at the same time the cathode is bombarded by positive ions causing its temperature to rise so that the tube may be destroyed. From measurements of the gas pressures in X-ray tubes it is found that the positive ions play no appreciable part when the tube is exhausted to a pressure of several bars, under which conditions each cubic centimeter may still contain more than ten million million molecules.

Electron Emission from Cold Cathodes

It has been observed that when very intense electric fields are employed, it is possible, under certain conditions, to obtain an electric current from a cold cathode in a high vacuum. In

order to produce an intense electric field at the cathode, this electrode may be in the form of a sharp needle-point or a wire of small diameter and the electrodes must be separated by only a small distance. If the anode is smooth and free from sharp edges a unidirectional current flows when alternating voltage is applied to the electrodes. The phenomenon has been attributed to the extraction of electrons from the cathode by the intense electric force.

Lilienfeld has constructed an X-ray tube based on this phenomenon. He used a cathode consisting of a tungsten point placed several millimeters from the target, and a vacuum of the same order as that of a Coolidge type X-ray tube. Ruben has made use of carborundum points for cathodes in this type of Lilienfeld X-ray tube. These tubes operate at voltages such as are ordinarily employed for X-ray tubes, i.e., 50 to 60 kv. Such tubes have current-voltage characteristics somewhat similar to the old type gas X-ray tubes and the discharge is subject to fatigue effects if operated for a long time, so that they have little practical value in their present state of development.

Considerable experimental work has been done on the investigation of the principles underlying this type of electron emission but many of the results are contradictory.[5] On one point, however, all are in agreement, and that is that the magnitude of the electron emission decreases as the electrodes are freed from gas by heat treatment. This fact is suggestive as to whether the emission may not vanish altogether when the electrodes are entirely freed from gas.

The manner in which this type of discharge is affected by gas pressure is shown in the results of some experiments conducted by Rentschler and Ulrey in 1921. They employed a pointed tungsten cathode, which could be heated by passing a

[5] Millikan and Shackelford, Phys. Rev., **15**, p. 239 (1920). Lilienfeld, Phys. Ber., **2**, p. 1350 (1921); Phys. Zeit, **23**, p. 506 (1922). Schottky, Zeit F. Phys., **14**, p. 80 (1923). Gossling, Phil. Mag., **1**, p. 606 (1926). Millikan and Eyring, Phys. Rev., **27**, p. 51 (1926). del Rosario, J. Frank Inst., **203** p. 243 (1927). Lauritsen and Bennett, Phys. Rev., **32**, p. 850 (1928). Millikan and Lauritsen, Phys. Rev., **33**, p. 598 (1929).

current through it, spaced several millimeters from a molybdenum anode which could be heated by high-frequency induction. The exhaust system and methods of evacuation of the tube were essentially the same as that used in exhausting Coolidge type X-ray tubes. A charcoal trap was sealed in the exhaust line between a McLeod gauge and the experimental tube, and a mercury cut-off was inserted between the pumps and the gauge. After thoroughly baking the glass and heat treating the electrodes and with the charcoal trap immersed in liquid air, the mercury cut-off was closed. The pressure in the tube was too low to give an indication on the gauge which was sensitive to .01 bar. A potential of 50 kv. applied to the terminals of the tube caused no current that could be read on the milliammeter. Upon lowering the Dewar liquid air flask so that it no longer completely covered the charcoal in the trap a current of several milliamperes was obtained as the pressure in the tube increased to a magnitude readable on the gauge. Upon raising the liquid air flask the gas was again absorbed in the charcoal and the current decreased simultaneously to a value too low to be read. This cycle could be repeated indefinitely and clearly indicates that in this experiment the electron currents, large enough to be read on the milliameter, were entirely due to gas.

In the experiments referred to here, the discharge was silent and continuous and accompanied by bright fluorescent spots on the anode but no visible radiation from other parts of the bulb. The pressures at which such a discharge could be obtained ranged from less than .01 bar to 0.8 bar and the current obtained at a given voltage always increased with the pressure. At pressures above 0.8 bar the silent continuous discharge changed to an intermittent discharge accompanied by hot sparks.

It is obvious that at such low pressures and with such short spacing between electrodes the current can not be due to ionic conduction as in the more common type of gaseous discharge. The fact that the current decreases with time but returns to the original value when the tube has been allowed

to stand a short time without impressed voltage suggests that the phenomenon may be due to the formation of an adsorbed surface layer of gas molecules on the electrodes.

Electron emission from cold sharp points has also been observed during the exhausting of high voltage thermionic rectifiers, in which "cold emission" of several milliamperes was obtained. In nearly every case the discharge ceased as the degree of exhaustion proceeded, the only exceptions being in tubes where magnesium had been vaporized for the purpose of maintaining a vacuum, and in one tube in which the anode was known to contain traces of calcium. It appears from these observations, that this type of discharge can be more readily obtained in tubes containing small amounts of magnesium, calcium, or similar metals. Ruben also found that rubidium caused an X-ray tube of the Lilienfeld type to function more satisfactorily.

No satisfactory explanation has been given for the enormous increase in cold cathode emission caused by gases and the metals mentioned above. While Richardson's work function of such elements is much less than for metals like tungsten and platinum it does not offer a complete explanation.

When tungsten which has been heated to a high temperature in a very high vacuum is used as a cold cathode, a potential gradient of more than a million volts per cm. is required to produce an electron current which can be measured with a microammeter.

Lenard Ray Tubes

Lenard[6] constructed a tube which allowed the cathode rays to emerge from the tube through a window of thin aluminum foil and observed that they caused blue glow of the air in the neighborhood of the window, blackening of a photographic plate, phosphorescence of calcite, uranium glass, etc. Figure 8 shows Lenard's original cathode ray tube in which the rays were produced by means of the ionization of the rarefied

[6] P. Lenard, Ann. d. Phys. u. Chem., **51**, p. 225 (1894).

gas in the tube when a sufficient voltage was applied between the electrodes. Similar tubes in which the source of electrons was a heated tungsten filament have been constructed by Eisenhut [7] and others.[8]

Electrons which have been projected from a tube into the atmosphere are properly called Lenard rays. Although X-rays were not discovered by Roentgen until a year later, it is now known that X-rays were necessarily produced in Lenard's experiments as well as in those of a large number of others who were experimenting with cathode rays in vacuum tubes.

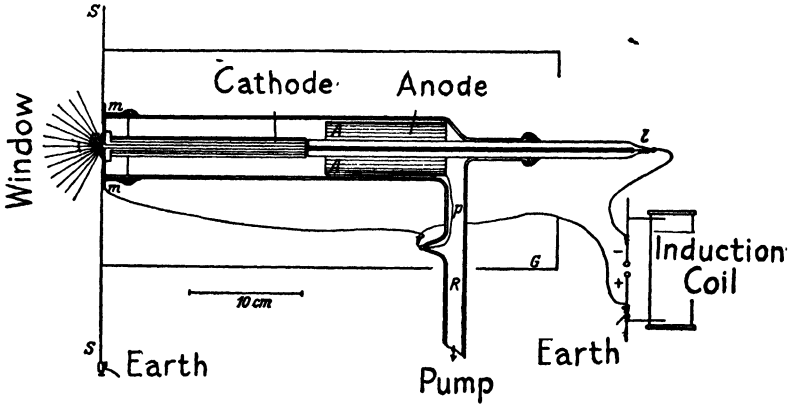


FIG. 8.—LENARD'S ORIGINAL TUBE.

Coolidge [9] has described a tube designed for high voltages so that cathode rays of very great velocity can be ejected through a metal window. The cathode is similar to that in a Coolidge X-ray tube except that sharp edges are avoided and the support wires are inclosed in a metal tube to prevent discharges from regions which would otherwise be subjected to too high a potential gradient.

[7] O. Eisenhut, Heidelberg Diss., (1921). Lenard states that this tube was constructed in 1913 and that the family of curves showing the relation between electron current and filament current at various tube voltages, plotted by Eisenhut from the data of this tube in 1913, was the first experimental proof of the now familiar space charge laws. (Handbuch der Expermentalphysik, XIV, pp. 70–74.)

[8] Kruger and Utesch, Ann. d. Phys., **78**, p. 113 (1925).

[9] W. D. Coolidge, J. Frank. Inst., **202**, p. 693 (1926).

A diagram of the tube is given in Fig. 9. The window is made of nickel foil 0.0127 mm. thick and 7.5 cm. in diameter, supported by a honeycomb structure of molybdenum. The window is soldered into the end of a hollow invar tube which is sealed to the end of the glass anode arm. A copper tube, electrically connected to the window, extends from the window to within a few centimeters of the cathode. This tube shields the glass from bombardment from both direct and scattered electrons.

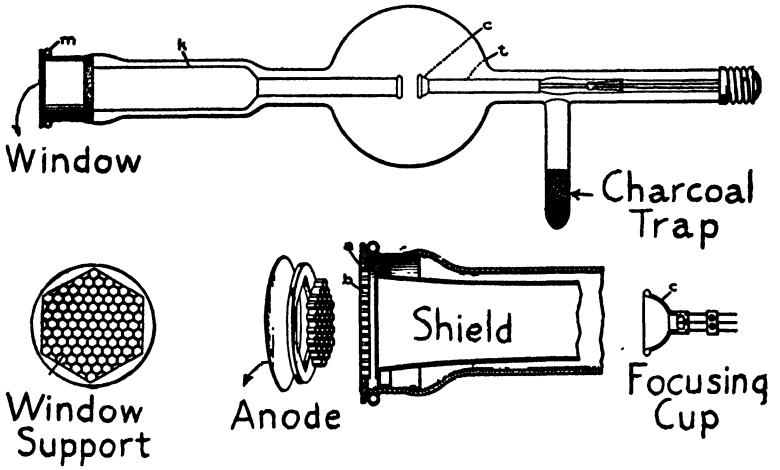


FIG. 9.—COOLIDGE CATHODE RAY TUBE.

Although the tube is given a thorough exhaust, it is necessary to provide a side tube containing charcoal which can be immersed in liquid air after sealing from the pumps. An alternative method of maintaining the vacuum after sealing the tube from the pumps has also been employed by Coolidge. Instead of charcoal, a rod of calcium, held within a tungsten heating coil, is placed in the side tube and used to clean up the gas when necessary.

Such tubes have been operated up to 350 kv. By constructing the tube in three sections and applying an accelerating voltage to each section, Coolidge has been able to produce cathode rays having velocities corresponding to nearly a million volts, i.e., about 95 per cent of the velocity of light.

A Lenard ray tube with a thin glass window has been described by Slack.[10] This feature simplifies the construction and makes possible a tube in which the vacuum is maintained without the use of pumps, charcoal traps, or other means. By using a concave spherical surface for the window it may be of

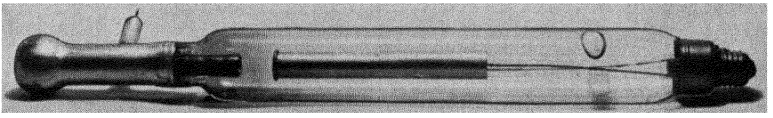


FIG. 10.—WESTINGHOUSE LENARD RAY TUBE, LOW VOLTAGE.

remarkable thinness and still support atmospheric pressure. The tubes shown in Figs. 10 and 11 have glass windows of about .001 cm. thickness. Figure 12 is an X-ray photograph of two such windows. Glass has about the same absorption coefficient for cathode rays as aluminum and therefore Lenard rays can be produced at lower voltages than when windows of denser metals such as nickel or molybdenum are used.

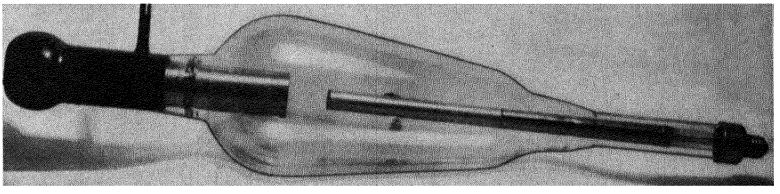


FIG. 11.—WESTINGHOUSE LENARD RAY TUBE, HIGH VOLTAGE.

It has been observed that most of the fluorescent and chemical effects produced by cathode rays are also produced by X-rays, although the action of the cathode rays is greater due to the greater energy absorbed in a small volume of the specimen radiated. This indicates that the effects caused by X-rays are not due directly to the X-rays themselves but to photo-electrons liberated within the specimen.

A calcite crystal will glow with a reddish light after a short

[10] C. M. Slack, Jour. Opt. Soc. Am., 18, p. 123 (1929).

exposure to cathode rays. The same effect can be produced by exposure to intense X-rays.

The chemical action caused by cathode rays and X-rays is primarily a reduction or dissociation of the molecules. As an example the yellow trioxide of tungsten, WO_3 is changed

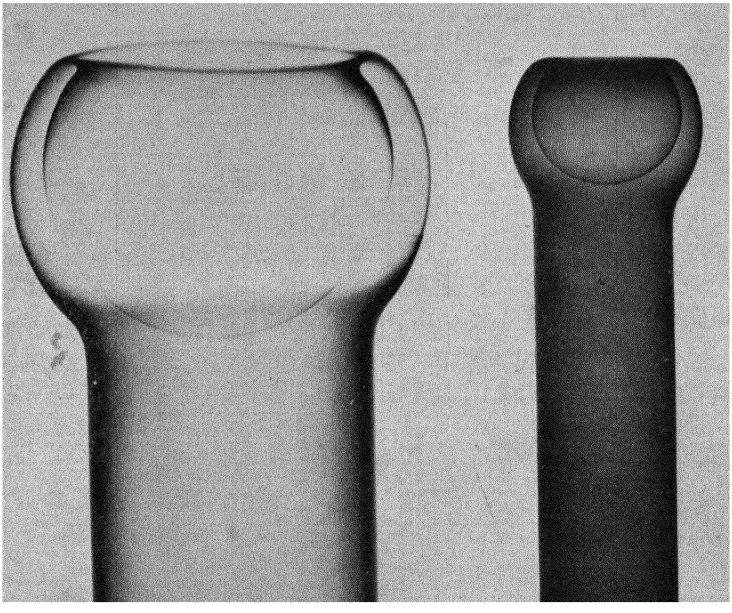


FIG. 12.—X-RAY PHOTOGRAPH OF THIN GLASS WINDOWS.

to the lower blue oxide when radiated by either cathode rays or X-rays.

X-rays

X-rays are produced when cathode rays strike a material body. There is no general agreement as to the complete theory of this action, but the main facts concerning it are comparatively simple.

The cathode rays strike a block of metal; they penetrate a few microns into its interior but are ultimately absorbed and

give up their energy in the form of heat. A very small part of their energy, one or two tenths of a per cent, comes out in the form of X-rays. The exact fraction depends on the voltage of the original electrons and with certain limitations, varies as the square of this voltage. The fraction also depends on the material that the electrons strike, and varies approximately as the atomic number of the target metal.

These factors affect also the quality, i.e., penetration, or more accurately, wave-length of the X-rays produced. The penetrating power of the rays increases with the voltage and while the output of X-rays consists of a mixture of wave-

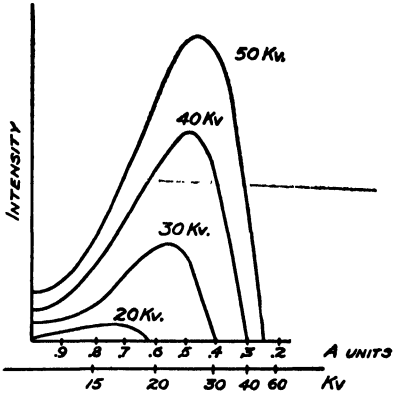


FIG. 13.—SPECTRAL CURVES FOR TUNGSTEN TARGET.

lengths the mean or effective wave-length varies approximately inversely as the voltage.

The effect of target material on the quality of the radiation is more complicated. Each element produces a certain amount of radiation concentrated in definite wave-lengths similar to the spectral lines in the region of visible light. The wave-length of this characteristic radiation depends on the atomic number of the element producing it. The amount, however, is small in proportion to the total amount of radiation produced.

The general energy distribution of a tungsten target for various voltages from 20 to 50 kv. is shown in Fig. 13. These

curves were obtained by Ulrey,[11] using a crystal spectrometer and an ionization chamber filled with ethyl bromide vapor. Practically total absorption was secured, so that, save for minor corrections, these curves represent approximate energy distributions. The values for the wave-lengths were transformed to kilovolts by the relation kv. $= \frac{12.35}{\lambda}$ and plotted on a separate scale for the sake of comparison with Fig. 5, which shows an interesting analogy.

X-ray Tubes

Since X-rays are produced when cathode rays or high-velocity electrons strike a material object, it follows that any form of hot cathode vacuum tube will function as an X-ray tube if sufficient voltage is placed across its terminals. However, certain features of design are necessary if the tube is to operate properly. For example, there is a large amount of heat produced at the anode, and if this were a thin metal plate it would be quickly melted through and ruined.

The X-ray tube known as the Coolidge tube was developed by W. D. Coolidge. The cathode consists of a heated spiral of wire within a focusing shield, while the anode or target is designed to dissipate a large amount of heat, and in one form consists of a massive block of wrought tungsten. The glass bulb is exhausted to the highest possible degree and the current is carried entirely by electrons emanating from the hot filament, there being no appreciable ionization within the tube. The focusing shield affects the direction of the electric field so that the electrons are drawn toward one spot in the center of the anode which is called the focal spot. The focusing shield is very important for it prevents any electrons from flying out toward the sides of the tube where they would strike the glass bulb and heat it so that it would quickly be melted.

The essential parts of such a tube are shown in Fig. 14. The cathode is a molybdenum tube surrounding the fila-

[11] Ulrey, Phys. Rev., 11, p. 401 (1918).

ment and the paths taken by the electrons are indicated by the dotted lines drawn from the filament and converging on the focal spot. The size of the focal spot is governed by the distance between cathode and anode, and also by the shape of the focusing shield and position of the filament.

In the diagram it will be observed that electron paths are drawn emerging from the focal spot, and curving around to strike the target at other places. These are scattered and secondary electrons. Little is known about the number and directions of these electrons, but some idea of their relative importance can be gained from the observations of Coolidge that about 20 per cent of the total X-radiation comes from the

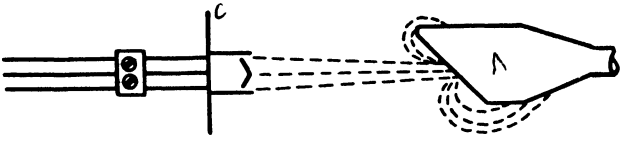


FIG. 14.—CATHODE, ANODE, AND ELECTRON PATHS.

back of the target, the anode support, and the part of the target face outside the focal spot.

Stray Electrons

It is known that there always are a few electrons that take other paths than those leading directly from the cathode to the focal spot. Some of these probably emanate from the cathode, and, while moving in the general direction of the anode, get past it and strike the glass upon the anode arm. Others, probably scattered or back diffused from the anode are to be found in all portions of the tube. Ordinarily these stray electrons do little harm, if their number is small, although, if striking the glass, they may stick to it and charge up its surface, and so distort the electric field within the tube. For example, an experimental tube was made with narrow straight sides instead of the large bulb. The cathode and anode were quite far apart, and a very small current was used. It was found that the focal spot would not stay fixed in posi-

tion, but would move around on the face of the target as the glass charged up in various places and repelled the electron stream. In another tube where the cathode was placed in a side tube of about 1.5-cm. diameter, no appreciable current could be forced through the tube when 50 kv. was applied.

This charging up of the glass may, in the high voltage tubes, be a cause of puncturing. Furthermore, these stray electrons are the cause of other difficulties. When they strike the glass they seem to scour or abrade it. Such action is particularly noticeable in kenotrons or rectifiers. Sometimes these are found with a small patch on the inner surface of the bulb, a millimeter or two in diameter, that looks as if it had been cut into with a sand blast.

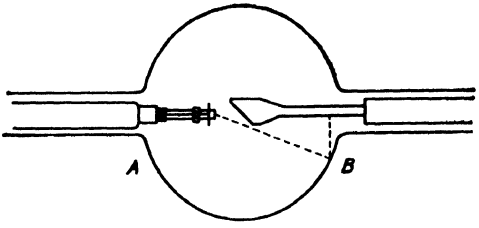


FIG. 15.—ELECTRONS STRIKING GLASS IN VICINITY OF ANODE.

The heating of the glass is probably the most harmful effect. Since the current may be carried off by secondaries, a considerable number of electrons can strike the glass in certain portions of the tube. In Fig. 15 the glass in the vicinity of the cathode, say at *A*, would soon become charged up and repel further electrons, but this would not be the case at *B*. Electrons striking at *B* would release secondaries which would be attracted to the anode. Thus the glass at *B* would be at a potential of only a few hundred volts higher than the anode and high-speed electrons could strike it, and give up their heat, while the current carried by them would all ultimately escape to the anode, either by slow-moving secondaries or by conduction along the glass.

CHAPTER II

X-RAY TUBES

In the early type of tube the cathode rays were produced in the same manner as in Lenard's cathode ray tube, that is, as a result of the ionization of the rarefied gas in the tube. The cathode rays were focused upon the anti-cathode or target by means of a concave cathode. This type of tube has practically disappeared since the advent of the Coolidge tube, due to the more stable and reliable operating characteristics of the latter.

In the Coolidge tube the electrons are liberated at the cathode by thermal electron emission. The tube is exhausted to such a high vacuum that there is no appreciable current carried by gas ions and therefore the tube current is independent of the voltage and can be varied by regulating the filament temperature. This type of tube is self-rectifying when operated at low enough power that the target is not raised to electron emitting temperature.

The Vacuum

Coolidge [1] found that for an X-ray tube to operate with a pure electron discharge it was necessary to evacuate it to the highest attainable vacuum. Such a vacuum is often referred to as a "Coolidge vacuum" and represents a pressure not greater than a few hundredths of a bar.

The bar is the unit of pressure in the C.G.S. system and is the pressure due to a force of 1 dyne per square centimeter. Standard atmospheric pressure is:

$$76 \times 13.596 \times 980.6 = 1{,}013{,}250 \text{ bars.}$$

[1] W. D. Coolidge, Phys. Rev., 2, 409 (1913).

The bar is therefore approximately one-millionth of standard atmospheric pressure. Another unit which is often used in measuring low pressures is the micron of mercury and it is the pressure due to a column of mercury 1 micron (.001 mm.) high. This unit, the micron of mercury, is often contracted to "micron" by those who are indifferent to the meaning of units. Since the micron is a recognized unit of length it is incorrect to use it as a unit of pressure. It is sometimes ambiguous to use the expression "microns of mercury" when referring to gas pressures since this may be interpreted as referring to the vapor pressure of mercury. The wide use of the McLeod gauge is responsible for measurement of low pressures in terms of the length of a column of mercury but such gauges can be calibrated to read directly in bars as well as any other unit. The bar and the micron of mercury are of the same order of magnitude,

$$1 \text{ bar} = 0.75 \text{ micron of mercury.}$$

It should be observed that vacuum is only a relative term. At atmospheric pressure and 0° C. each cubic centimeter of gas contains about 2.7×10^{19} molecules. Therefore, at a pressure of one bar, each cubic centimeter contains about 2.7×10^{13} molecules and in the highest vacuum attainable today (about 10^{-4} bar) there are still over a billion molecules in each cubic centimeter.

Mean Free Path of Electron

But even with so great a number of molecules present the electrons in a highly evacuated X-ray tube pass across the space between cathode and anode with practically no probability of collision with a gas molecule. The chance of an electron colliding with a gas molecule in its flight from cathode to anode depends upon the distance between the electrodes and the mean free path of the electrons in the gas. The mean free path is the average distance an electron moves without collision with a molecule. The table below gives the mean free path of an electron in various gases at 0° C. and at a pres-

sure of 1 bar, calculated from the gas laws, assuming that the mean free path of the electron is 5.6 times the mean free path of the gas molecules.[1a] There is some evidence that the mean free path of electrons is greater than the tabulated values, especially when voltages as high as those used for operation of X-ray tubes are used. The mean free path is inversely proportional to the gas pressure.

Air	48 cm.
Argon	50 cm.
Carbon Dioxide	31 cm.
Hydrogen	90 cm.
Helium	141 cm.
Neon	95 cm.
Nitrogen	47 cm.
Oxygen	51 cm.

When electrons travel over a path which is 1/10th the mean free path, 10 per cent of them will make collisions with the gas molecules, while if the path is 1/100th of the mean free path, 1 per cent will make collisions. It is therefore necessary in an X-ray tube that the mean free path of the electrons be large compared to the actual paths in order that ionization resulting from collisions may be negligible. But it would appear from the above table that this condition would be fulfilled in an X-ray tube at pressures far in excess of the minimum which Coolidge has found to be necessary.

It should be remarked that the vacuum in an X-ray tube is not fixed and stable. For instance, if a tube were pumped to 1 bar and sealed off, on operating under certain conditions there would be some clean-up and the pressure would be lowered as gas was absorbed or driven into the walls.

The opposite effect can also take place, and quantities of gas can be liberated from the glass walls and metal parts when these have not been properly treated.

In X-ray tubes that have been operated for some time, probably some sort of equilibrium takes place. The vacuum

[1a] For other values see Van Der Bijl's "Thermionic Vacuum Tube," p. 88.

for ordinary X-ray tubes usually averages from .05 to .01 bar.

If the vacuum is not sufficiently high, the tube may still operate, although fluorescence and gas discharge are likely to occur. One of the effects of small amounts of gas in the tube is to poison the filament and cause it to become brittle and also more likely to take up a permanent deformation under the electrostatic strain. When old X-ray tubes are broken open, it is sometimes found that the filaments will fall to pieces at a touch. Also, gas gives rise to positive ions which bombard the cathode and cathode stem. This raises the temperature of the filament and causes more current to flow and is thus responsible for unsteady operation of the tube.

With still further amounts of gas, the vacuum will break down entirely, and the tube will be filled with glow and fluorescence and operate as a gas tube. When such gas discharges take place suddenly, they can cause considerable damage to the milliammeters or other instruments that are a part of the installation.

Experimental X-ray Tubes

There have been described in the literature, various types of X-ray tubes for laboratory use in X-ray spectroscopy and similar experimental work. These have usually been operated while connected with the pumps, since in many cases it is necessary to change the electrodes frequently and this can be most easily accomplished by using ground glass or metal joints or by sealing the joints with a good hard wax.

In many investigations, however, it would be desirable to have a tube sealed off from the pump, but there seems to be a prevailing opinion among research workers that such tubes cannot be made in the laboratory. In order to dispel such apprehension a rather complete account of the methods of construction and exhaust are given in another section. Suffice it to say here that any laboratory equipped to make and oper-

tial equipment necessary to make tubes which can be sealed off from the pumps. It is an established fact that an X-ray tube will operate with stability, even if the vacuum is considerably below the limits mentioned, provided, however, that the metal parts are thoroughly degassed. If the residual gas is pure helium or neon the pressure may be considerably greater since fewer ions are produced in these gases than in air.

Janitsky [2] has made an extended series of investigations along this line, using a tube which had been thoroughly pumped and degassed, and to which then, pure helium had been admitted to the desired pressure. Helium was selected in this case, because it does not clean up, i.e., disappear upon the operation of the tube, like some of the more familiar gases. It thus permits the pressure to remain fairly constant over a more extended series of experiments.

There have been manufactured abroad Müller tubes to which a small amount of helium has been admitted after the usual exhausting and degassing. These so-called helium filled tubes operate in all respects like Coolidge tubes.

Cathodes

The function of the cathode is to liberate electrons and to focus them upon the target under the influence of the electric field. In the choice of an electron emitting material, the question of efficiency is of only secondary importance, since the power consumed in the filament is insignificant when compared to that used in other parts of the power supply.

Tungsten filaments are generally used on account of their ability to withstand the force of the electric field without deformation. Tantalum has also been used and in one respect it has an advantage over tungsten since its electron emission is not so much affected by gas liberated by electron bombardment of the target. Unless the anode has been very thoroughly treated to free it from gas, a slight amount may be

[2] Janitsky, Zeit. für Phys., 31, 277 (1925).

liberated by bombardment and seriously reduce the electron emission of a tungsten filament. This decrease in tube current is only temporary and the filament will usually recover in a short time when bombardment of the target is stopped.

Cathode Design

The cathode comprises the filament, focusing shield, and the supporting wires which also act as leads. The features to seek for in a cathode are:

1. Control of size of focal spot
2. Distribution of energy uniformly over focal spot
3. Reduction to a minimum of stray electrons

The size of the focal spot is governed by the diameter and shape of the spiral filament and that of the focusing device and also by the relative positions of these with respect to the target. In tubes where a fine focus is desired the filament is placed farther back in the focusing cylinder or cup. In tubes designed for therapy the electron stream has been made divergent by Coolidge by projecting a molybdenum pin through the center of the filament.

The smallest and most uniform focus is given by a hemispherical focusing shield placed close to the target as in Fig. 16.

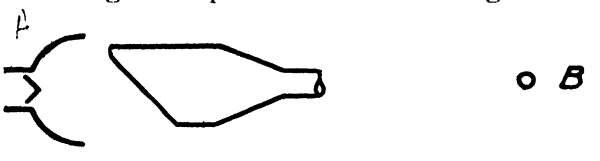


FIG. 16.—HEMISPHERICAL CATHODE.

The relative positions of target and cathode are shown at *A*, while the size of the focus is shown at *B*. Note that the target distance is a factor in the size of the focus and consequently should always be mentioned in the description of any cathode. The universal type cathode is shown in Fig. 17. The approximate size of the focus is shown at *B*. It is possible to vary the size of the focus by adjusting the position

of the filament within the tube. The diagram shows a broad focus. For a fine focus, the filament is set back within the tube about 1/16th inch farther and the spiral is made in a flatter taper.

Note the skirt *S*. This has nothing to do with the focusing, but is for the protection of the glass back of the cathode while the tube is being exhausted, or in case the tube should gas slightly during use. It is not essential and tubes can be made without it.

When voltage is applied across the tube, the electrostatic field exerts a pull on the filament spiral, and under very high voltages, the wire may bend a little, thus changing the focal spot, although the wire usually recovers its shape when the voltage is lowered. If, however, the filament had been run-

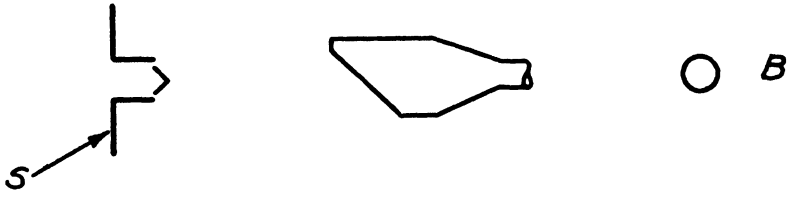


FIG. 17.—UNIVERSAL CATHODE.

ning very hot, or had been poisoned by gas in the tube, the deformation may be permanent. If one should attempt to use a small size universal tube at the high voltage supplied for deep therapy, say 180 kv. or more, the filament may be pulled entirely out of the shield.

For radiography, the focal spot should be small to give approximately a point source and hence sharp pictures, but no smaller than necessary for the required sharpness since the allowable energy input on a small spot is low. To get the maximum input in a given size, the intensity must be uniform over the area covered by the focal spot. The usual size is about 3/32 inch in diameter, while for very rapid work 5/32 inch diameter or more may be used. Particularly undesirable are focal areas in the shape of a ring, or a ring with a small intense spot in the center, and these are extremely likely to occur unless the cathode is well designed.

For therapy, the focal spot should be very large, in fact, as large as possible without having an undue proportion of electrons get past the edge of the target. The use of a projecting pin in the center of the filament may spread the beam of electrons so much that many pass outside the edge of the target.

One means of obtaining a large focal spot is to use a cathode similar to the universal type, but larger, so that the area covered will be larger. In this case it is necessary to use heavier wire for the filament to enable it to withstand the electrostatic force. The electron stream may also be dispersed over the face of the target by interposing a coarse meshed grid, electrically connected to the cathode, between the target and cathode. Certain tubes of French manufacture use a cathode of the same general size and shape as the universal cathode, save that the taper on the filament spiral is pointed away from the anode. See Fig. 18.



FIG. 18.—FRENCH CATHODE.

Anodes

The anode, sometimes called the anticathode, serves as a target into which the electrons are shot from the cathode. The target is that part of the anode which receives the electron stream and from which the X-rays are emitted. The main body of the anode serves as a reservoir for the heat generated by the impact of the electrons and as a means of dissipating this heat by radiation or conduction. Since the efficiency of a metal as a source of X-rays is greater for elements of higher atomic number, the choice of a target material is limited, for most purposes, to those elements of high atomic number which have high melting points, high thermal conductivity and low vapor pressure at high temperatures. Only a few common metals such as tungsten, tantalum and platinum, possess these properties and of these tungsten is superior.

The principal requirement for the anode is that it shall

be able to dissipate the heat generated by the electron impact, and anodes may be classified according to the special features of the design directed toward this end. Uncooled anodes, such as those of the universal tubes, depend entirely on radiation, for very little heat escapes down the stem. In the radiator anodes, the heat is conducted down the thick copper stem to a set of fins outside the tube. These so-called radiator tubes are strictly not radiators, since the cooling is mostly due to air coming in contact with the fins. Water-cooled anodes have many advantages but the constructional difficulties so increase the cost that some of these advantages are partially offset.

The face of the target of the universal tube is cut off at a 45 degree angle. The target of the water-cooled deep therapy tube is inclined at a little flatter angle, i.e., the angle between the face of the target and the electron stream from the cathode is about 70 degrees. One possible reason for this angle is the influence it has on the number of secondary and stray electrons. A target cut square across at 90 degrees to the cathode stream would be most satisfactory in this respect, but for conditions of practical use, to permit the full size cone of X-rays being utilized at right angles to the axis of the tube, some inclination of the target is necessary, and for this purpose 75 to 70 degrees would appear to be ample.

Another means of cutting down the number of stray electrons striking the glass is to use a larger surface for the face of the target. A tube designed by Ulrey has a target consisting of a 4 inch disk inclined at an angle of 65 degrees. Very few electrons get past the edges of this disk to strike the glass in or near the anode arm, and it has the further advantage of a large surface to radiate the heat. If the difficulties of manufacture could be overcome, there is no doubt that further advantages could be secured by the use of a rim or turned-up edge. See Fig. 19.

Such a rim would stop still more secondary and stray electrons and furthermore, if rolled in a smooth curve, would have the additional advantage of reducing the potential gradi-

ent that exists at the sharp edge of the ordinary disk. This would diminish the liability to puncture or would permit smaller bulbs to be used.

X-ray tubes built for special purposes may have the target cut square across at full 90 degrees. An example is the

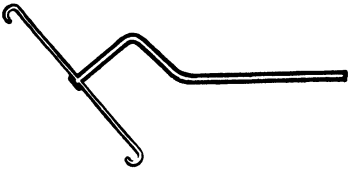


FIG. 19.—DISK ANODE WITH ROUNDED EDGE.

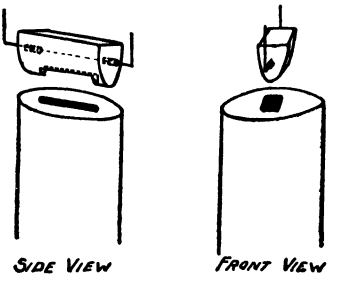


FIG. 20.—GOETZE LINE FOCUS.

molybdenum target tube used with the powder diffraction apparatus. From a point a little above the plane of the target, the focal spot appears foreshortened to a narrow ellipse so that it is thus possible to produce a narrow beam of X-rays suitable for the spectrograph by the use of but one slit.

This foreshortening principle is also carried out in a tube of European manufacture in which a line focus, attributed



FIG. 21.—CONE-SHAPED TARGET.

to Goetze, is used instead of the usual circular focus. A long coiled filament is mounted near a focusing slit so that the electron stream is focused in a line on the target. The target face is at an angle of about 80 degrees to the axis of the tube and the cathode focusing shield is placed fairly close to the target and has a long narrow opening, as in Fig. 20.

The actual shape of the focal spot is an area about 2

mm. wide by 16 mm. long. From the front this appears foreshortened to a small spot 2 mm. square. By using the X-rays which emerge at a small angle with the target face, the radiographic definition is the same as that obtained with a small focal spot, but the current capacity of the target is considerably increased by the fact that the electron stream is spread over a greater area.

The advantage of this arrangement for photographic use is obvious. The effective size of the spot being small, sharp pictures are secured, while the true area being large, greater energy can be used.

It is even possible to carry the foreshortening principle a step further. Thus targets are made in which the electrons strike in a cone-shaped hole as in Fig. 21.

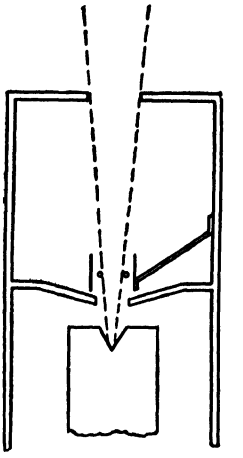


FIG. 22.—DIAGRAM OF PHILIPS TUBE, WITH CONE TARGET.

In one type of tube manufactured by the Philips Co. of Holland the X-rays are taken from the tube through the cathode in a direction along the axis of the target. In this tube the filament consists of 1½ turns of wire wound in a circle of sufficient diameter that the X-rays may pass through it. See Fig. 22. The electron stream is focused

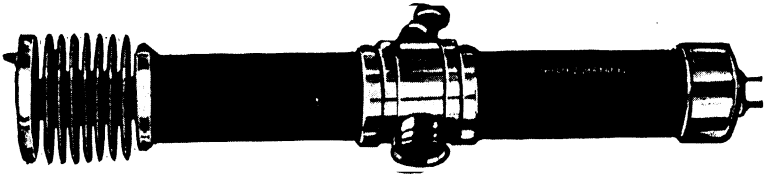


FIG. 23.—PHOTOGRAPH OF PHILIPS TUBE.

into a conical recess in the target so that a greater surface of the target can be used without losing the radiographic definition of a small focal spot. Figure 23 gives a photograph of a Philips tube and Fig. 24 shows a radiograph of the same tube.

Choice of Metal for Target

Tungsten is the metal generally used for the target because of the properties:

1. High melting point
2. Low vapor pressure at high temperature
3. Good heat conductivity

With water-cooled targets, the first two of these properties are not so essential and tubes have been constructed with, for example, copper or silver targets that work per-

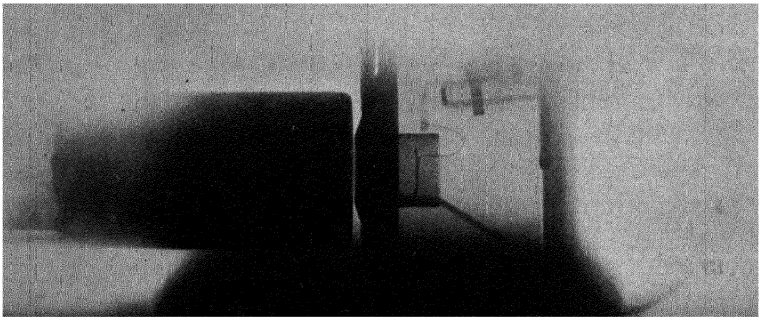


FIG. 24.—X-RAY PHOTOGRAPH OF PHILIPS TUBE.

fectly, although perhaps not at very high voltages nor with extra large energy inputs. Even with water-cooled targets, however, vapor pressures have to be considered, and zinc, which has a comparatively high vapor pressure is particularly unsuitable. Brass, on account of its zinc content, is also barred, and in fact, in the regular manufacture of radiator anodes, to avoid contamination, the copper is of specially selected stock that has not been melted in any of the equipment used for brass manufacture.

The kind of metal used for the target also governs the efficiency or output of X-rays, and in a general way, the output increases with the atomic number of the target metal. The

exact law, however, relating output and atomic number is more complicated.

X-Radiation and Atomic Number

Kaye [3] measured the intensity of X-radiation from twenty targets of various metals at about 25 kv. and found that this was roughly proportional to the atomic weight of the metals. Ulrey[4] has compared the X-ray energies in the continuous spectra of chromium, nickel, molybdenum, palladium, tungsten and platinum at 35 kv. and found that while the total intensities are more nearly proportional to the atomic numbers than atomic weights, there appears to be dependence upon the position of these elements in the periodic table. Duane and Shimizu [5] found that for the elements iron, cobalt, nickel and copper the total X-ray intensities are in the order of atomic numbers and not of atomic weights.

To get the fullest advantage from the increase in efficiency with atomic number, we should choose as high an atomic number as possible. The atomic number of platinum is slightly higher than tungsten and its efficiency therefore somewhat greater, but this advantage is not sufficient to offset its higher cost and lower melting-point. Targets have been constructed of thorium and uranium and although these metals have melting points only a little higher than platinum their efficiencies are relatively high. The element rhenium, of atomic number 75, has not been produced in quantities sufficient to determine its properties as an X-ray target.

For certain purposes it is not the total efficiency of X-ray production that is desired, but a large amount of radiation of a particular wave-length. In such cases advantage is taken of the characteristic radiation of the elements. In X-ray crystal analysis, the K-series of molybdenum is especially suitable and this is the metal commonly used for targets in X-ray

[3] Kaye, X-Rays, p. 36.
[4] C. T. Ulrey, Phys. Rev., 11, 401 (1918).
[5] Duane and Shimizu, Phys. Rev., 11, 491 (1918).

tubes for this purpose. For superficial X-ray therapy a very soft radiation is desirable and the characteristic rays of carbon and aluminum have been used. For deep therapy the characteristic rays from uranium and thorium, having the shortest wave-lengths of all the elements, would appear to be most suitable.

Cooling

One of the greatest obstacles to be overcome in an X-ray tube is the difficulty arising from the enormous amount of heat generated at the target surface, compared to the energy radiated in the form of X-radiation. In order to have a tube which can emit one watt in the form of X-radiation, it is necessary to dissipate over a kilowatt in the form of heat by conduction or radiation from the target surface. The problem is all the more serious when it is considered that there is no known method of focusing or concentrating the X-rays and therefore only a small part of the emitted X-radiation can be used. Furthermore, in radiographic tubes, the cathode-ray energy is concentrated in a small focal spot and unless the cooling is efficient the target will be melted at this point.

The most efficient cooling is obtained by having a stream of water circulate through the anode and coming in close proximity to the focal spot. Unless the anode is at ground potential, this method necessitates an insulated water system, or a sufficient length of rubber hose leading to and from the anode, so that the electrical leakage through the water is negligible. Where maximum cooling is not necessary the heat may be conducted from the tube by a rod of good conductivity such as copper, terminating in a set of fins for air cooling.

For intermittent operation large heat capacity of the anode is important, though where the operation is continuous over long periods, it is only the conductivity that is important. Certain types of tubes depend upon radiation for cooling. The

targets of these tubes are made of tungsten which can be operated at a temperature of 2000° C. or more where the efficiency of radiation is high. Cooling by radiation can be applied best to tubes which do not require a fine focus. Ulrey has applied this method in a tube where the target consists of a large tungsten disk and the electron stream is dispersed over its surface. Such a tube has the advantage that it may be operated at high power without roughening the target surface.

Size of Bulb

The general proportions of the tube are governed by the voltage at which it is to be used. Obviously, a high operating voltage requires that the tube have long arms, so that the possibility of sparking over the outside of the tube will be minimized. Higher voltage also necessitates a larger bulb, to lessen the chance of puncturing, but the size required depends to some extent on other factors, such as the distance between anode and cathode. If the cathode distance is large and the bulb is small, the glass may charge up in patches and cause the focal spot to wander. A water-cooled anode permits the use of a smaller bulb, since there is less danger of the glass becoming hot.

Except for the small 90-degree tubes, X-ray tubes are usually made with the two arms in the same straight line. This seems to be the logical design, since it keeps the high-voltage terminals as far apart as possible, and simplifies the construction of tube holders and shields. A few deep therapy tubes of European manufacture have been made in a V-shaped design, probably with the object of keeping the high-voltage terminals away from the patient.

Manufacture

A description of the manufacture of modern X-ray tubes properly starts with the manufacture of tungsten. Without this

valuable metal, and the somewhat similar element molybdenum, there is little doubt that the X-ray art would have never advanced to its present high degree. The manufacture has been described by Arnold [6] and others.[7]

Much of the tungsten ore comes from Boulder County, Colorado. The extraction depends on the kind of ore used; for example, if wolframite is used, tungstic oxide is obtained by fusing with sodium carbonate, dissolving out the sodium tungstate with water, precipitating with an acid, and drying.

Commercial tungstic oxide is purified, dried and sieved, and then is ready to be reduced to the metal by heating in hydrogen. For this operation, the oxide is placed in porcelain tubes, through which the hydrogen is passed. The tubes are heated electrically and held at the proper temperature until the reduction is complete, when the current is cut off and the reduced metal allowed to cool in the hydrogen.

The result is a gray, metallic looking powder. This powder must be pressed into rods, which, for those that are intended for anodes, are about 11 inches long and 1 inch square. These rods are too fragile to be picked up, and can only be moved by sliding on a metal plate. Each of these rods is slid on to a temporary support of molybdenum and placed in a tube furnace through which hydrogen is passing. After firing for a while at 1600° C. the rod shrinks, and the particles of metal cohere more strongly so that the rod will bear handling.

It is then ready for sintering. This is accomplished by heating it in hydrogen at a temperature close to its melting point by the passage of a heavy current. The rod is held vertically in a treating bottle, which is a sort of metal bell jar with a mercury seal at the bottom, the upper end of the bar in a heavy water-cooled clamp of copper, the lower end fastened to a piece of copper which in turn dips into a water-cooled pool of mercury, thus permitting the rod to shrink.

The rod as it comes from the treating bottle is ready to be made into wire, anodes or whatever is required. Tungsten

[6] Arnold, Victor Service Suggestions, **27**, 17 (1927).

[7] Coolidge, Jour. Roent. Soc., **17**, 23 (1921).

is very heavy, having a density of about 19.3 grams per c.c. It is brittle when cold, and so hard that it cannot be hack-sawed, filed, or otherwise machined, but it can be brought to a desired shape by grinding, and it can be cut by a rubber wheel using carborundum powder.

At a high temperature it can be forged and drawn into wire. It does not tarnish upon standing in air, but at a bright red heat oxidizes rapidly and the oxide volatilizes so that the metal seems to smoke. It is thus very important that forging operations be conducted as rapidly as possible, so that the hot tungsten need be kept in the open air for only a few seconds. It is often worked in an atmosphere of forming gas, a mixture of nitrogen and hydrogen. At temperatures below a red heat, or where the supply of oxygen is limited, various blue oxides are formed on the surface which chemically are mixtures of W_2O_5, WO_2 and WO_3. These are sometimes noticed on the anodes of punctured X-ray tubes.

To form a tungsten rod into the shape for an anode, it is heated in an electric tube furnace, seized with a pair of tongs and quickly inserted into a swaging machine. This machine hammers the metal between a pair of hardened dies carried in a revolving spindle. The dies are struck rapid blows by a series of steel rolls which are held in an annular steel rack within which the spindle revolves. Fig. 25 shows the essential parts of the machine. The square rods are swaged until they are round, and by repeatedly passing through the machine, the diameter is reduced to the proper size and one end is then tapered down to the diameter of the stem. The anode head is swaged on to the molybdenum stem and finished by grinding.

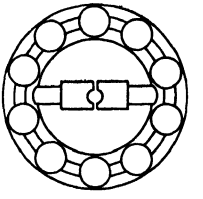


FIG. 25.—SWAGING DIE.

The tungsten wire for the filaments is produced in the same manner. The rod of pressed powder can be made of smaller cross-section to start with, say $\frac{3}{8}$ inch square. It is swaged round and its diameter is reduced by passing through a series of swaging machines until it is about the size of a

No. 18 wire. From then on it is reduced by hot drawing through diamond dies, the wire passing through a heater just before it reaches the die and a certain amount of aquadag being used as a lubricant. The wire used in X-ray tube filaments is usually between 28 and 31 B. & S. gage.

Wrought molybdenum is made by the same process as wrought tungsten, but differs from it in that it can be machined while cold. It can be drilled and tapped if care be used. The focusing shields for the cathodes are made of molybdenum.

In making anodes for the universal tubes, the stem is fixed in an iron collar which just fits in the end of a split tube rolled up out of sheet steel. This split metal tube is of such diameter as to make a tight fit when forced over a projecting glass tube in the anode arm, and supports the anode rigidly in its place in the glass bulb.

Anodes for radiator tubes are more complicated in construction. A round flat button swaged out of tungsten is placed in a carbon mould in a vacuum furnace and copper melted over it. It is essential that the copper wets the tungsten. The head thus made is welded on a longer stem of copper. In the water-cooled deep therapy tubes, a copper and tungsten head made in the same way is silver soldered to a close coil of copper tubing which forms the backing for it. Smaller water-cooled anodes with targets of molybdenum are made about the same size as the radiator anodes, save that the stem is hollow, to provide space for the water cooling.

It may be observed that in all the water-cooled tubes at present constructed, the tungsten is backed with copper. When such a tube is overloaded, the copper backing is liable to melt and pull away from the tungsten just behind the focal spot. Without the copper to conduct away the heat, the tungsten button gets still hotter and is quickly ruined.

A suggested construction to avoid this difficulty is shown in Fig. 26. Instead of a flat button, a cup-shaped piece of tungsten is used. The copper is melted over the tungsten in the usual

way; the shaded portion in the figure being filled with copper. After the head is welded on the hollow stem, this shaded portion is machined out, so that the cooling water can come in direct contact with the tungsten.

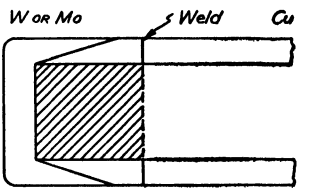


FIG. 26.—WATER-COOLED SAFETY HEAD.

In both the water cooled and the radiator anodes there is a metal sleeve which is sealed to the glass. In the universal type, it is only necessary to seal a small wire through the glass. Wire for sealing in glass is usually of dumet, a nickel steel overlaid with copper. The sleeve on the radiator anodes is also of this material. It is possible, by taking suitable precautions, to seal a tube of copper, or even iron to glass if the edge of the tube has been made thin and sharp, but the method has not yet been applied to X-ray tube construction in this country, although used abroad in the manufacture of valve tubes and X-ray tubes.

The large disk anodes for the tube described in another section were made as in Fig. 27. The stem, which is all

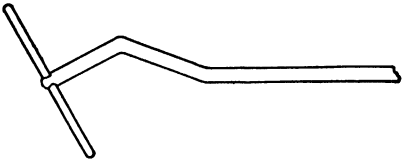


FIG. 27.—LARGE DISK ANODE.

tungsten, must be bent and offset to give the proper inclination to the disk. The stem has its end reduced in diameter before being bent, and the disk is hot riveted on, after the bending operation.

Cathodes

The focusing shield presents no particular manufacturing difficulties, as it is made of molybdenum which can be machined. Making the filament is a more delicate operation.

The tungsten wire is first wound in grooves cut on a cone-shaped mandrel of steel or molybdenum, shown at *A* in Fig. 28, after which the wire and mandrel are placed together in a hydrogen furnace and heated to ensure that the turns of the coil will not spring apart or the wire partially unwind from the form. The filament is then removed and placed on a second form, or rather clamped between a pair of forms shown in section at *B* and put back in another furnace at a higher temperature. The object of this second form is to shape the coil to a cone of the proper taper so that the focal spot will be the right size. It will be observed that the taper of the mandrel at *A* is rather long, so that when the spiral is

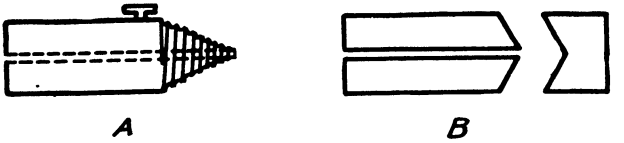


FIG. 28.—FILAMENT WINDING MANDREL.

pressed into form *B*, with its short taper, the adjacent turns of wire are brought nearer together, making a very close coil.

Filaments for experimental tubes are often made in flat coils and used without this heating on the forms which can only be done in a well-equipped factory. The great difficulty, however, is to wind a tight coil since tungsten wire is so springy that it will not hold its shape, unless heated after being wound.

Some grades of wire are softer than others and much time and trouble can be saved if a very soft grade of wire is used. On the whole, it seems impossible to get a really close coil without the forming treatment described above, but unless a very fine focus is wanted, a more open coil will do as well.

Glass Parts

X-ray tubes are usually made of ordinary soft lime glass. This is easily worked, and bulbs and other shapes can be ob-

tained ready blown in a very complete line of sizes. This glass has the further advantage that it can be sealed on to lead glass.

On the other hand, if the resources available include oxygen blast, the use of modern hard glasses like pyrex and nonex will be well worth the extra trouble. These glasses have a higher softening point and will stand baking-out temperatures perhaps 100° C. in excess of those used for soft glass.

For those cases where the tube being exhausted is of different glass from the tubing of the vacuum line, since pyrex and soft glass cannot be sealed together, graduated seals may be purchased, containing five different glasses in a few inches of tubing. Another method of joining two different glasses is to use a short piece of copper tubing, with a thin-edged seal to glass on each end.

Regarding the possibilities of fused quartz as a material for X-ray tubes, little can be said beyond mere speculation as to the future. While there have been occasional experimental tubes made of fused quartz, very little real research has been done in this line. The material has properties that would recommend it, especially for tubes to be used for large power inputs at high voltage. If fused quartz should, through improved production methods, become very cheap, it may well serve as the material for X-ray tubes of the future.

Assembly of the Tube

The essential point in the assembly of tubes is cleanliness. This is especially true for hand assembly or for experimental tubes built entirely by hand. The metal parts must be degassed as will be described in the following section, and they should be handled as little as possible. The anode is usually first put in place and the cathode is then sealed in, closing the tube.

Machine assembly is being rapidly developed and the machines are patterned somewhat after those used in the incan-

descent lamp and radio-tube industry. The essential feature of these machines is a means for rotating the work while a gas flame is playing on it. The operation of sealing the sleeve of a radiator anode to the glass has long been done on a machine. In this case, the machine is somewhat like a lathe, a gas flame taking the place of the cutting tool. The anode and the glass tube are both rotating, the one on what would correspond to the head stock, the other on the tail stock. The operator brings the sleeve into the flame and coats it with glass from a rod held in his hand, then by the motion of a lever brings up the glass tube and presses it against the sleeve, air for blowing out the joint being supplied through the center of the rotating spindle.

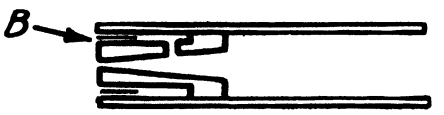


FIG. 29.—GAS BURNER HEAD.

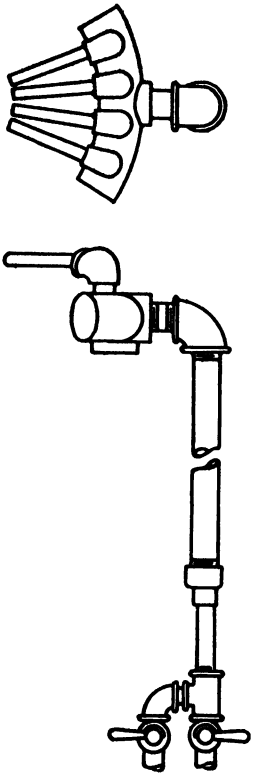


FIG. 30.—GAS BURNER MANIFOLD.

Automatic machines similar to lamp machines are made in the form of a large circular disk or ring carrying six or more operating heads, each of which rotates continuously while the ring slowly turns, indexes itself, and stops before a jet of flame long enough for one particular operation to be performed, and then turns on to the next.

For machine glass working it will not suffice to use burners like the ordinary laboratory hand blow pipes or blast lamps in which a jet of air blows out through a gas flame. A better type of burner head is shown in Fig. 29. The small passages at *B* are to prevent the flame from striking back. Usually several of these burner heads are placed on a single manifold as in Fig. 30.

The air and gas are mixed before entering the manifold and the mixture flows into the burners so that a jet of mixed gas blows out through a flame of the same mixture. One of these burners gives a sharp needle flame and the whole set in the manifold gives a flat band of flame which is all of very uniform temperature. Usually the pressure of the gas mains is not sufficient for these burners and it must be stepped up with a booster. About ½ lb. per sq. in. gas pressure and 3 to 5 lbs. per sq. in. air pressure are recommended.

With large disk targets, there are special problems involved in getting them into the bulb. To put a 4-inch disk into an 8- or 10-inch bulb requires an enormous hole in the side of the bulb which will take all the skill of a good glass worker to close.

The tube being assembled, it must be washed before exhausting. A tube in which the glass blowing has been done by hand is filled with condensed moisture and the glass may be in some places coated with carbonized films of organic material. Usually it will suffice to rinse out the tube with pure methanol. Machine-blown tubes are usually clean and do not require washing.

Exhausting

As mentioned in a previous section, the success of the exhausting all depends on getting the gas out of the metal parts. They are degassed before being assembled in the tube as this saves much time in the exhausting process. The parts, after having been washed with acetone or some cleansing agent to remove grease or finger marks caused by handling, are placed in tube furnaces from which the air is exhausted while they are heated to a high temperature. They are allowed to cool in the vacuum. It has been found that in some cases, a further treatment with hydrogen improves them still more. A certain amount of degassing can be done with hydrogen alone. The metal parts are packed in a tube furnace, and heated in an atmosphere of hydrogen for ten or fifteen min-

utes at a temperature of about 1000° C., and allowed to cool while the hydrogen is still passing over them.

It is thus seen that the exhausting process really begins before the tube is assembled. All during the assembly it is necessary to keep in mind the requirements of the exhausting process and avoid any accumulation of dirt or grease on the inside of the tube.

Having been assembled and washed, the tube is sealed on to the exhaust line. The pumping system usually contains three pumps in series, the first a mercury condensation pump, the second an intermediate pump which may be of the mercury jet, or of the rotary scraper type, and the third, a rough pump, or in large establishments, the house vacuum. In order to eliminate mercury vapor from the pumps a refrigerating chamber or trap immersed in liquid air is installed between the tube to be exhausted and the first pump. Figure 31 shows the pumps and set up for exhausting a high voltage X-ray tube.

In practice, a McLeod gauge may be connected to the vacuum line, but this is of value only during the preliminary part of the exhaust, mostly as a test to ensure that the pumps are working properly. Since the McLeod gauge contains mercury, whose vapor would contaminate the tube being exhausted, it cannot be connected directly to the tube, but is joined to the vacuum line in front of the freezing-out bulb. The gauge itself is always full of mercury vapor, but this condenses when the level is raised, so the measurement gives the actual pressure in the vessel, exclusive of the mercury vapor.

In the final stages of the exhaust, the McLeod gauge is of little value, save to detect the presence of a leak, as the vacuum reached is rather low for a precise reading on a gauge of this type. Indeed, the behavior of the tube itself, on operation, is the best indicator, and expert operators can tell how the exhaust is progressing by the disappearance of green glow, the fluorescent patches on the glass and other phenomena. After all, as has been previously explained, the actual gas pressure in the tube is not so important as the proper degassing of the glass and metal parts.

In experimental work, where actual pressure may be required to be known, an ionization gauge may be connected directly to the tube, or the parts of such gauge sealed inside the tube itself.

For baking-out, the tube itself is enclosed in an oven which can be brought to a temperature of 400° C. or more during

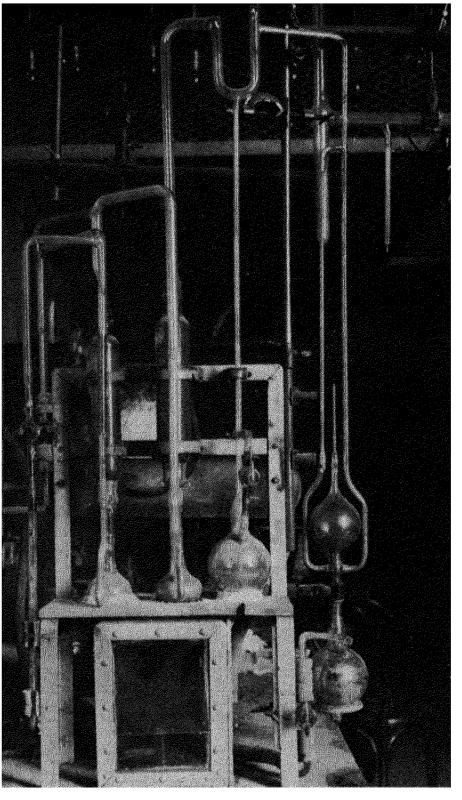


FIG. 31.—MERCURY VACUUM PUMPS.

the first stages of the exhausting process. This baking-out is for the purpose of driving out absorbed moisture and gases from the glass parts.

The baking-out oven should be built to fulfil two functions, i.e., to retain the heat and also to serve as a shield against the radiation while the tube is being operated during

the latter part of the exhaust. One style of oven is made on a steel frame, having an asbestos lining and an outer covering of sheet lead. Figure 32 shows a photograph of such an oven.

Small ovens are often made of transite or asbestos boards. An adequate lead covering makes the oven very heavy and often, full protection is not provided, but a portable lead shield is moved up in front of the operator when high voltage operation is commenced.

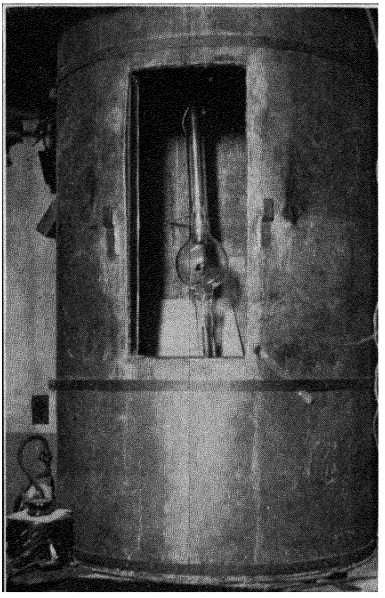


FIG. 32.—BAKING-OUT OVEN AND SHIELD.

The most convenient source of heat is electricity, although gas can be used. For electric heating, the heating elements, usually chromel or nichrome wires, are fastened to the inner walls of the oven. Lead glass windows are usually provided so that the progress of the exhaust may be observed, although, in emergencies, a pyrex pie plate makes a good substitute.

The exhaust being under way, the heating current is switched on and the oven slowly brought up to temperature. For soft glass, the proper temperature is from 350 to 400° C.

while up to 100° higher may be used with pyrex. Assuming a high voltage tube is to be exhausted, the baking-out will continue for two or more hours.

After baking, the tube is operated, first at low voltage but with heavy currents so that the anode is heated very hot in order to drive out any gas not removed by the previous treatments. This can usually be started before the oven is entirely cool.

Induction heating by a coil and a high-frequency set may be applied to the base of the anode and to the cathode shield.

In production work on the smaller tubes, the baking-out process is considerably cut and induction heating is not practised. However, the tube must always be operated for some time while on the pump to get the gas out of the anode.

The exhaustion of a tube designed for high voltage requires a tedious repetition of operating the tube until the metal parts become as hot as they can be safely allowed to get, and then waiting for them to cool off; always working at increasing voltages until the tube will run steadily without a trace of fluorescence at higher power input than it will be subjected to in actual use. This may take five or six hours in addition to the time required for baking-out.

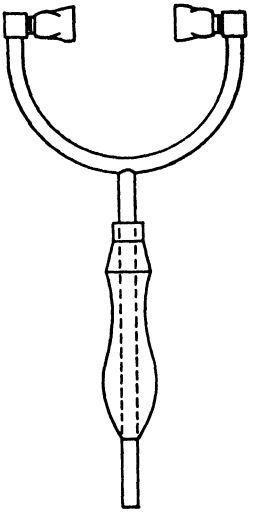


FIG. 33.—TIPPING-OFF TORCH.

While any sharp-pointed flame can be used for sealing off, a very convenient burner is shown in Fig. 33.

The gas and air are mixed in a fixture connected directly to the bench pipe lines, and the mixed gases are led through a rubber tubing to the tipping torch. The two needle-like flames meet at the center of the torch and a perfect tip can be drawn off.

In sealing off, Dushman recommends that the tubing be torched for a short while before the seal off is made. This

torching is supposed, by heating the glass to almost the fusing point, to liberate all the gas that will come out during the sealing-off process, and permit the pumps to sweep out this gas before the seal cuts the connection.

Some tubes are exhausted from the side of the bulb, and sealing off from the pump consequently leaves a tip which is always liable to be broken. Consequently tipless tubes, which are exhausted from the cathode end are considered an improvement. These have the tip concealed under the lamp base that finishes off the cathode arm.

The lamp base, and the ferrule which finishes off the anode arm are cemented in place with a special cement made by mixing bakelite varnish with an inert material such as Portland cement. The parts are heated in an oven or over a flame to 200 to 225° C. for a few minutes after which the sement hardens.

CHAPTER III

Practical Operation of X-ray Tubes

The subject of the operation of X-ray tubes is dominated by a very practical consideration. An X-ray tube is an expensive piece of apparatus and at the same time a very fragile one and the problem is to protect it from electrical and mechanical injury while it is being used.

The question of the tube holder or support, and the arrangement of filters and shielding may be all discussed together. The requirements are: the tube must be held rigid and protected from mechanical shock or chance of breakage and the support must be so designed as to avoid electric strain or causes of punctures. The shield may be part of the support, and must protect the operator from X-rays, allow for the circulation of air to carry off the heat, and be provided with suitable windows permitting the radiation to emerge after it has passed through the necessary filters.

Tube Holders

One of the oldest and simplest type of tube stands is the lead glass bowl with clamps gripping the two arms of the tube. This is simple and adequate for some purposes, but is not satisfactory for high-voltage therapy use.

Here it is necessary to support the tube by the ends only and it is common practice to enclose the whole tube in a lead lined metal container. Figure 34 shows the usual type. An air blast or exhaust must be used to draw air through the container to cool the tube. An exhaust should properly discharge out of doors, or into the ventilating system. Cylinders like this, when containing the proper amount of lead, are very

heavy, and mountings permitting them to be raised and lowered, swivelled, and inclined at various angles, so as to treat patients in various positions, have made such equipment very elaborate and expensive.

For a shield, it is possible to use a simple wooden box covered with lead, or to do without a shield entirely if the tube and generating plant can have a room to themselves with sufficiently thick walls. In this case, the tube must be controlled from the outside and the radiation emerges through a small hole in the wall or ceiling. Instead of solid insulators,

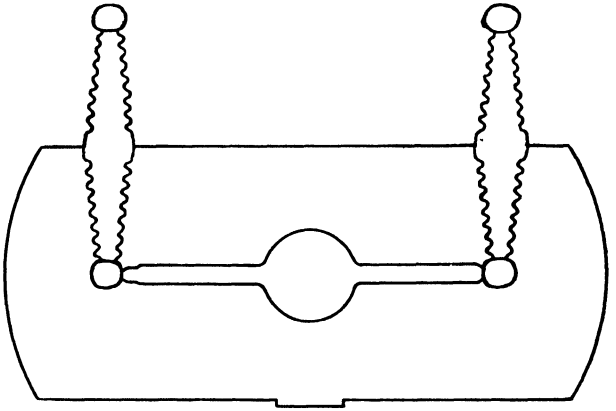


FIG. 34.—METAL TUBE SHIELD.

the tubes may be suspended by silk cords, preferably braided silk fish line.

For tubes run at moderate power inputs, it is possible to dispense with the air blast or suction, especially in case the tube is in a large box or open in a room as above described.

Whenever possible, a mirror should be placed so that a reflection of the tube may be observed. This is very convenient to watch for gassing and over-heating and avoids the temptation of looking directly at the tube.

Operation in Oil

Much of the liability to puncture can be avoided by operating the tube in a bath of transformer oil. It has some disadvantages; in particular, it is a nuisance to change the tube,

but these are inconsiderable when compared with the longer life secured.

The oil tank must be lead shielded, and it is preferable to use the lead for a lining, since lead can be soldered, and the tank thus made oil tight.

A tank used at St. Luke's Hospital was built of 1 inch oak, lined with ¼ inch lead, and had inside dimensions of 21 × 21 × 54 inches. These dimensions are larger than necessary for work up to 200 kv. but were purposely kept large in order to permit the use of experimental tubes and circuits. Its large size gave it the further advantage that no water cooling was required. The tube could be operated all day at 200 kv. and 5 ma. without the oil getting more than lukewarm.

The X-rays may be taken out from the bottom or sides, in which case, provision for a window will be necessary, or from the top, in which case, all that is required will be some sort of opening in the cover of the tank. It is, however, in some ways unsatisfactory to have the radiation emerge from the top, and the tank described had a sheet of ½ mm. copper soldered in the bottom as a filter, giving a window 15 cm. square. It is possible to use a thinner sheet for the window, but as the outfit was to be used only for high voltage, a filter of at least that thickness would always be required, and the installation had the advantage that the filter would never be forgotten.

The tube holder is shown in Fig. 35. It was constructed of soft dry white pine, which seems to become a good insulator when immersed in oil. Quartered oak has been advocated for its insulating properties, on account of the lesser chance of having electrical leakage along the grain, but the tube holders shown have given perfect service for several years and at present seem to be as good as ever.

The wooden stand has considerable buoyancy and the tube itself much more, so that weights must be used to sink the tube and holder in the oil. The projecting ends of the tube holder make convenient places to stand these weights, which may be cut from scrap pieces of sheet lead.

It will be seen that these holders support the tube so that the lowest part of the bulb is about 5 inches from the bottom of the tank. This would require the radiation to pass through at least 5 inches of oil before reaching the air and some type of oil cell must be placed between the tube and the tank bottom to provide a path through the oil for the X-rays to escape.

This cell may be of celluloid or glass and may be sealed, or may be open at the bottom on the principle of the diving

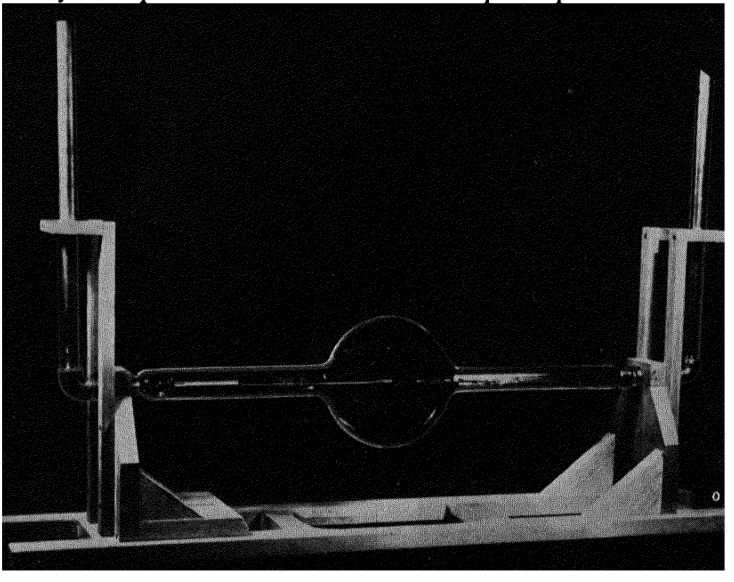


FIG. 35.—WOOD TUBE STAND FOR OIL TANK.

bell. There is no advantage in using an evacuated cell and such a one can cause real harm, for in a cell with an ordinary rough vacuum, glow discharges may occur that can cause punctures both of the cell and the X-ray tube.

The need for counteracting the buoyancy of the cell complicates its design. One type experimented with at the Institute of Cancer Research consisted simply of a beaker inverted in the oil, the trapped air providing the air space and the weight being supplied by strips of sheet lead which were wound around the beaker and resting on the flange.

It was a curious fact that the air in this beaker disappeared regularly over a period of months. Of course some air was lost the first time the tube was used, since it expanded and bubbled out as the oil warmed up, but in addition to this there was a steady loss due to some other cause. The cells needed to be blown out about once a week. On this account, they were replaced by cells having sealed covers.

One method of making an air cell is to use a beaker which has a piece of sheet aluminum cemented over its mouth. The beaker should be of thin glass, those of Kavalier make being quite satisfactory. The best shape to select is the Griffin tall form without pouring spout. The sheet aluminum can be somewhat less than ½ mm. in thickness. It should be well scored with sandpaper to give the cement a good grip. Cements with a pitch and Venice turpentine base, such as de Khotinsky, can be used, although they may soften if the oil gets very warm. A water-glass and powdered mica mixture such as Early's commutator cement is also good, but should be well covered with shellac after it has set, to ensure that it is oil tight. An all glass cell, hermetically sealed, is more desirable, but requires more skill to construct.

With oil tanks, there arise several minor problems that must be taken care of. One of these is the scattering. Since the oil scatters the X-rays that do not proceed straight for the window through the air cell, the emergent beam of radiation is accompanied by scattered radiation, proceeding from other angles. This should be suppressed by a lead ring, which may be within or without the tank. In Fig. 36 is shown a lead sleeve surrounding the air cell which has the double function of providing a weight to counteract the buoyancy of the cell and of preventing radiation scattered at wide angles from leaving the tank.

Water-cooled Tubes

Oil immersion is also of advantage in the case of water-cooled tubes. These tubes seem to have more gas in them, probably because of the unusual difficulties in their manufac-

ture, and the oil, by keeping the glass cool, helps to prolong the life. It is necessary to solder a foot or two of copper tubing to each of the leads at the target end of the tube, since no connections containing rubber or rubber packing should be placed under the oil.

Many water-cooled tubes are supplied with cooling water from an insulated pump and radiator system. This is not always necessary, and in many cases it is possible to connect

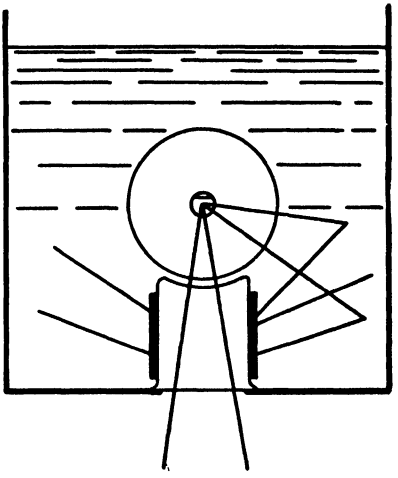


FIG. 36.—AIR CELL FOR OIL TANK.

the tube directly to the city supply mains through a length of rubber tubing. A water-cooled tube running at 100-kv. constant potential direct current was supplied from the regular New York City water supply through 100 feet of ¼-inch rubber tubing and tests showed that the loss through this line of tubing was only about 2/10 milliampere.

Dangers from X-rays

It has been learned from the experience of the early workers with X-rays that certain harmful effects are due to too long exposure to X-rays. Many of the pioneers have paid their

sacrifice to knowledge with suffering from severe X-ray burns, with the loss of fingers and hands and some even with their lives. It is now well known what precautions are necessary in order to avoid X-ray burns, and such disfigurement is no longer considered as a sign of martyrdom but rather as a stigma of carelessness or ignorance.

There are other harmful physiological effects, especially associated with very penetrating X-rays, and there is considerable divergence of opinion concerning the minimum protection necessary for this type of radiation. It is known that the composition of the blood undergoes variations, the white corpuscles particularly being decreased in number by the absorption of large amounts of penetrating X-rays. The red corpuscles are similarly affected but to a less extent. The absorption of small amounts of X-rays, however, may have an opposite effect.[1]

The glands are specially sensitive to the rays and absorption of radiation by the generative organs may result in temporary or permanent sterility.

It is not to be presumed from these effects that the absorption of X-rays in limited amounts is harmful, any more than it would be to presume that because sunlight, under certain conditions, causes burns, that sunlight is harmful in all amounts. There is much evidence which indicates that X-rays in small amounts may have a stimulating effect.

Protection from X-rays

Various protective devices, such as lead and lead-glass tube holders are supplied by the manufacturers of X-ray equipment but this has not been standardized. The Safety Committee of the American Roentgen Ray Society is working on this problem and if this Committee receives the co-operation of manufacturers and X-ray laboratories, a safety code based upon scientific principles should be universally adopted in the near future.

[1] Hirsch, Principles and Practice of Roentgen Therapy, Chapter XXVIII.

Safety Codes have been adopted in several European countries and Kaye [2] has given an excellent account of the progress made in the direction of protection in Europe. Estimates of the amount of X-rays that may be absorbed with impunity by those who are exposed daily in the routine of their duties vary from that intensity which would produce an accumulated dose of one erythema (480 R units) in 1800 hrs. to that which would produce this dose in 90,000 hrs. Based on a six-hour day these extremes would represent intensities which would give 1/100 erythema in two hours and fifteen days, respectively. Kaye concludes that the intensity should not be greater than that which would give 1/1000 erythema in every ten working days.

The recommendations of the English X-Ray and Radium Protection Committee specify the following protective shielding for X-ray tubes operated at the given voltages:

Voltages	Minimum Thickness of Lead
70 kv.	1.5 mm.
100	2 0
150	3 0
200	4 0

It is also necessary to provide a corresponding amount of shielding from the X-rays which are scattered by the beam emerging from the tube shielding. For fluoroscopic examinations the screen should be viewed through a lead-glass window or indirectly by means of mirrors.

A common method of testing the efficacy of the shielding is to place photographic films wrapped in black paper at various positions in the X-ray room while the X-ray tube is operated at normal conditions. Dental X-ray films are convenient for this purpose. The operator may also carry several dental films in his pockets during a normal working week. A lead foil stencil or a paper clip fastened on the film gives a shadow

[2] Kaye, G. W. C., Caldwell Lecture, Am. Jour. Roentgenology, 18, Nov. (1927).

by which to judge the blackening. With a self-rectifying X-ray tube operating at 60 kv. an amount of X-rays equivalent to 1/5000 of an erythema will cause definite blackening of an Eastman "regular" dental film, and about one-fourth this amount will show on the "extra fast" film.

A better method is to make ionization measurements with a standard ionization chamber as this gives the intensity of the X-rays directly.

It is advisable for those working with very penetrating X-rays to have a blood count made several times a year so that any changes which occur may be recognized at an early stage.

Where complete shielding from direct or scattered X-rays is not feasible in routine work, protective aprons and gloves may be worn. Bowen [3] has given some suggestions in regard to the use of lead rubber aprons. It should be recognized, however, that complete protection can not be afforded by such devices.

Operating Characteristics

If the filament is not lighted, the tube will not pass any current in either direction. Use is made of this property in locating the difficulty in case of trouble. If the voltage is gradually applied to a tube with a cold filament, any sign of current in the milliammeter or considerable fluorescence in the tube is an indication that the vacuum has become lowered, through evolution of gas, or because of a leak.

The filament being heated, the tube will pass current in one direction only, unless the target is incandescent. Accordingly, the tube will not operate unless the polarity switch is thrown so as to make the filament side negative.

With tubes of the universal type, the target, having no special cooling device, practically reaches incandescence after a few seconds' use and may attain temperatures approaching

[3] Bowen, Jour. Roentgenology, 16, 473 (1926).

that of the filament. It then becomes an equally good source of electrons, and if reverse voltage is applied, current will pass in the wrong direction and damage the tube. This may occur through an error in manipulating the polarity switch while the target is still hot from a previous run, or may occur during operation through the rectifier motor getting out of synchronism.

On the other hand, in tubes having specially cooled targets, i.e., radiator and water-cooled tubes, the target never gets hot enough to emit electrons and these tubes are unidirectional at all times unless overloaded. They may be used as self-rectifying, being connected directly across the terminals of the transformer. This results in eliminating one piece of apparatus and saving in cost, which is of especial importance in small units.

That there is a certain loss in efficiency in self-rectification is apparent from the oscillograph picture (Fig. 37) of the voltage wave form.

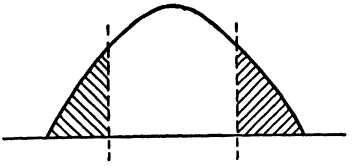


FIG. 37.—VOLTAGE WAVE FORM.

In the shaded area outside the broken lines, the current is passed at low voltage and contributes mainly to heating the target. This current is to a certain extent suppressed in machines having a mechanical rectifier. In the dental apparatus, and in the powder diffraction apparatus the loss in efficiency is somewhat compensated for by the elimination of the rectifier with its space requirements, noise, possibility of trouble, and extra cost. Of course this loss in efficiency, just mentioned, applies equally where rectifying tubes are used without condensers.

Current Limits

The current passed by the tube is limited, at low voltages, by space charge; at high voltages by filament temperature.

With a low voltage across the terminals, say less than

3,000 volts, the tube does not respond to changes in the filament temperature. In fact, the filament could be heated to the melting point, without much increasing the milliamperes passing through the tube. Under these conditions, the tube is showing space charge characteristics.

At high voltages, the tube current depends only on filament temperature, and is almost independent of the voltage. Figure 38 shows the current-voltage relations with the filament temperature constant.

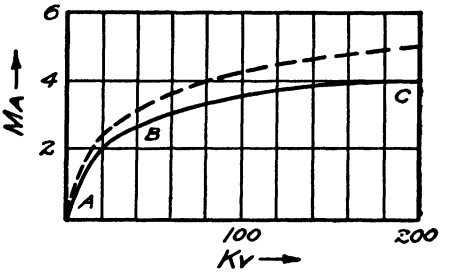


FIG. 38.—VOLTAGE-CURRENT RELATION.

From *A* to *B*, the tube shows the effect of space charge, while from *B* to *C* the curve is nearly flat. In this range, the current is completely under the control of the operator. Thus the dotted curve gives the relations for a somewhat higher filament temperature.

One factor responsible for a very slight upward slope between *B* and *C* is that, as the voltage increases, the electrostatic attraction pulls the filament closer to the mouth of the focusing shield, and more electrons escape. Another factor is that, as the voltage increases, the target gets hotter, and radiates more heat back on the cathode.

The power input is limited principally by the heat that can be dissipated by the target. The capacity of the tube is the energy it will carry safely, measured by the product of the voltage and the milliamperes, but there is a separate limit to the voltage, even when the milliamperage is diminished to keep the product constant.

In the radiographic tubes, the voltage is fixed by the pene-

tration required, and is never very high, but high current is desirable and the amount of energy that may be safely used depends on the size of the focal spot, the length of time the voltage is applied, and whether or not the target is still hot from previous use. The service is intermittent, and failure from overloading is usually due to melting or volatilizing the metal at the focal spot. It should be noted that the focal spot may attain a temperature high enough to damage it in a fraction of a second, while the rest of the target is still cold.

In the case of therapy tubes, the focal spot is broad, and the service continuous. The energy is limited by the heat that can be dissipated, not entirely by the target, but also by the glass of the bulb. Accordingly, blowing an air blast on the bulb, or immersing the tube in oil increases the limits at which it may safely run. With the glass thus cooled the target is again the limiting factor, although, even if excessive current is used, there is little chance of the metal being melted at the focal spot. Instead, the target and the bulb become heated to the point where some occluded gas is driven out, and this, at the high voltages used in therapy, causes failure through gassing.

With water-cooled, deep therapy tubes, assuming that the water supply is sufficiently increased as more energy is used, the limit depends on two factors. The tungsten face will get hot even though the copper back of the target is kept cold by the water, and if the face gets too hot, damage will ensue, either through gas being evolved, or the copper melting away just behind the tungsten. There is also the possibility of the glass being bombarded by electrons, either secondaries from the target, or primary cathode electrons. The glass will be heated, and gas liberated, although cooling the bulb with an air blast should be of help.

Effect of Wave Form on Power Limits

The amount of power which an X-ray target can dissipate is limited by the melting temperature of the target material.

A large mass of metal of such high thermal conductivity and melting temperature as tungsten can be melted at the focal spot in a fraction of a second, although the total input energy may be only sufficient to raise the equilibrium temperature of the target a few degrees.

If an X-ray tube is operated by a machine giving c.p.d.c., the temperature of the focal spot will rise until thermal equilibrium is established throughout the anode. The time required to reach thermal equilibrium will depend upon the size and shape of the anode, the thermal capacity, thermal conductivity and the method of cooling, as well as upon the power input. When thermal equilibrium is reached there will be no further rise in temperature at any point in the anode

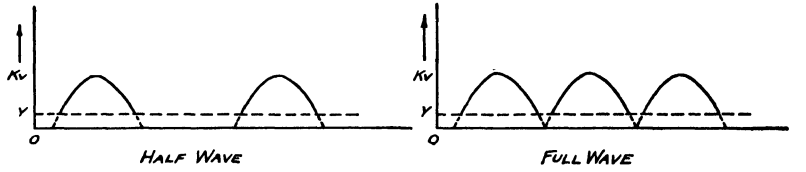


FIG. 39.—WAVE FORM WITH ONE AND TWO THERMIONIC TUBES.

but a temperature gradient will exist throughout the anode, the highest temperature, of course, being at the focal spot. Thus if the anode is made of a single metal such as tungsten and the tube is overloaded, melting will occur only at the focal spot. However, if the target is backed with copper, it is possible that the copper will melt first.

When the power supply is other than c.p.d.c., the temperature at the focal spot will fluctuate with each cycle and the maximum average power which the target can dissipate is quite different for different wave forms and different frequencies. Consider first the use of rectifying tubes without condensers. If one thermionic rectifier is used, or the X-ray tube is self-rectifying (half wave rectification), in the first case and two thermionic rectifiers are used (full wave rectification) in the second case the voltage forms will be approximately as indicated in Fig. 39, provided no capacity is added to the circuits.

The voltage represented by *OY* is the drop in the rectifiers. It is obvious that for the same average power in the two cases, the power per wave must be twice as much in the first case. Although the milliammeters and voltmeters read the same in the two cases, the filament heating current for the X-ray tube must be greater in the first case than in the second, since the tube current, averaged over a cycle, is twice as great in the first as in the second. Furthermore, the temperature fluctuations of the focal spot are correspondingly greater in the first case than in the second, and therefore the tube in the first case cannot be operated at as high average power input as in the second and in neither case can as great power be used as when c.p.d.c. is used. It should be noted also that the rectifier in the first case must be operated so as to be able to pass two times the current of either rectifier in the second case.

If we compare the condition of full wave rectification with thermionic tubes with that of mechanical rectification, Fig. 40, we see that for the same meter readings the power per cycle

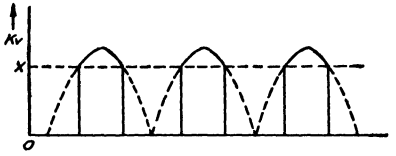


FIG. 40.—WAVE FORM WITH MECHANICAL RECTIFIER.

must be the same in both cases, but since the mechanical rectifier delivers to the tube only a part of the cycle, the tube current must be greater during the used part of the cycle. Hence, a tube cannot be operated at as high average power with mechanical rectification. Such a comparison, however, is of little value, since for the same power input, the X-ray output will be greater with mechanical rectification where the lower part of the wave which produces heating, but no useful X-rays, is suppressed.

From the standpoint of the maximum power which a target can dissipate, when the X-ray tube is excited with different

wave forms, it may be stated that the greater power can be used with those wave forms which approach more nearly the condition of c.p.d.c. excitation. Other advantages of c.p.d.c. excitation are discussed in another section.

Voltage Limits

Irrespective of the energy used, the voltage that may be safely employed across the tube is limited. With the small size universal tube, the voltage is limited by the distance between the cathode and the target. The electrostatic force at high voltages is considerable, and the filament, which is softened by the heat, may be pulled out of its place. With the deep therapy type, the distance is increased to prevent this, and the arms are lengthened to prevent sparking over the outside of the tube, a factor which becomes of especial importance in the rarefied atmosphere of high altitudes, and in humid weather.

In the deep therapy tube, provided it is free from gas and other impurities, the voltage limit is then probably the electrostatic strain the glass will stand, and if the voltage is increased beyond this, failure will occur by puncturing. This liability to puncture, which seems to be increased in the case of constant potential direct-current machines, is partly avoided by supporting the tube from its extremities by silk threads, well away from the wall or conducting sharp points. Still better protection is had by operating the tube in a bath of transformer oil. This not only keeps the glass cool, but seems in some way to relieve the electrostatic strains and reduces the liability to puncture. Coating the tube with shellac before placing in the oil is an additional safeguard.

With water-cooled deep therapy tubes, the peculiar difficulties in the exhausting during manufacture usually leave some gas or other impurities which becomes the limiting factor as the voltage is increased. In these tubes, on account of the copper back and stem, the target cannot, during the exhausting process, be thoroughly heated in order to degas it. As a con-

sequence, after exhaustion, the tubes must be run for a while at low power, so as to take advantage of the seasoning or cleanup. They are, therefore, never quite as free from gas as the universal type, and if operated at increasing voltage, soon show fluorescence in the stem and give evidence that failure by gassing is imminent.

The normal life of a tube operated at its rated capacity is between 300 and 1,000 hours. The reasons for failure under normal use are not completely understood. So many tubes fail from accident or overloading, that it is hard to get at the facts. Still, even if carefully protected from accident and abuse, tubes most decidedly do not last forever, and there must be some period of time which can be taken as the normal life.

Two facts at least seem to be clearly established. The lower the power input, the longer the life of the tube. When the end finally does come, it is often due directly or indirectly, to gassing.

In the case of deep therapy tubes, which are operated at high voltages, most failures are due to gassing or puncturing. When a tube is first built, it may have a slight tendency to gas at voltages considerably below its rated limit, but usually improves after a few weeks' seasoning at low voltage, and may then be operated at its regular voltage. But, where a tube develops gas after a normal life of several hundred hours, ordinarily, no amount of seasoning will help, although in some cases, its life may be prolonged by using it only at lower voltages.

In the case of punctures, these seem to be so much like accidents that it is questionable to consider a tube that has punctured as having given a normal life. It is true that many punctures are the result of unusual conditions that may be classed as accidental, usually increased voltage, or high tension surges induced by sparking, but punctures do occur in tubes operating under closely watched conditions and to which no known accidental causes can be ascribed. Some punctures seem to be connected with gassing, at least, punctures are more

liable to occur in tubes that have already given evidences of trouble by gassing, but of course, gassing is also responsible for violent voltage fluctuations which may be the direct cause of the punctures. Punctures may be made less frequent by taking proper precautions; by ensuring that the tube is supported away from sharp points, keeping the tube free from dust, using the tube under oil, etc., but in the present state of our knowledge, there is no way to entirely prevent them.

Output and Efficiency

The amount of X-rays obtained from a Coolidge tube increases directly as the number of milliamperes of current and as the square of the voltage. The increase of output with voltage is shown in Fig. 41, where, it should be noted, the output is measured as total energy and not ionization units.

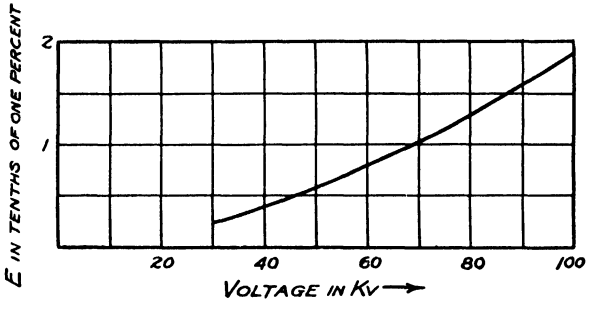


FIG. 41.—OUTPUT OF COOLIDGE TUBE.

At 100 kv., under best operating conditions, we get out in X-rays about .2 per cent of the energy supplied to the tube. Even this small amount is spread out over the whole hemisphere and only a small fraction goes through the port of entry. The filter still further reduces the usable amount by the fraction ½ or more. Even this small proportion is not entirely utilized, since only the fraction absorbed by the tissue can take effect.

At 200 kv. we would expect four times this amount. Thus it would seem that if voltages of the order of a million volts

could be utilized, much better yields of X-rays might be secured. Unfortunately, while increasing the quantity by using higher voltages, the quality is also changed and the X-rays produced at exceedingly high voltages are so penetrating as to be of little value in therapy, passing through the body with very small absorption, and consequently small effect.

The efficiency depends on the atomic number of the metal used for the target, but all Coolidge tubes using tungsten targets should have about the same efficiency, save for the effect of certain minor factors which will be noted. The output of two tubes run at the same voltage and current on different machines of the rotary rectifier type are not necessarily equivalent since the wave form may be different. This would also apply to the same machine with two different settings of the regulators, one using mostly auto-transformer, the other resistance, control. Of course, the point is, that with these machines the voltage is somewhat indefinite and can only be completely specified by determining the complete wave form with an oscillograph. On constant potential, direct current, the question of wave form does not enter, and two Coolidge tubes of the same type and in good condition should give the same output.

Two tubes of the same type, when new, should give about the same output, but may vary if one has been used much longer than the other, so that the target is roughened or pitted. The X-rays generated at the bottom of the pits in the target are lost, save the small proportion of them that can penetrate through a great thickness of metal (Fig. 42). In the figure the relative size of the hole is of course exaggerated for purpose of illustration.

Some deep therapy tubes that have been in service for a long time have cracks in the face of the target, others have deep holes at the focal spot with shreds of metal projecting, and these old tubes show a loss of output that may be as much as 25 per cent.

A coating of volatilized tungsten on the wall of the bulb would not ordinarily be thick enough to cause much loss by

filtering action, but such tubes may show low output, since there must have been some pitting in the target when the tungsten was volatilized.

Two tubes of different type will be slightly different in output for several reasons. Referring back to Fig. 14 (page 25), it will be seen that some electrons are reflected from or splashed out of the face of the target, only to be driven around to the back or stem. Coolidge and Moore estimate that as much as 10 per cent of the total radiation can come from these points. In tubes with copper-backed targets these electrons strike the copper and produce proportionately less radiation, so the total yield is less. This is no disadvantage in radiographic work, where all X-rays not proceeding from the focal spot are undesirable.

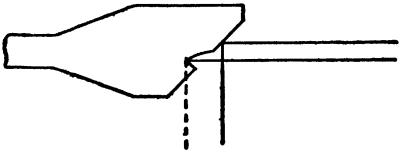


FIG. 42.—EFFECT OF FITTING OF TARGET.

In the water-cooled, deep therapy tubes, the focus is deliberately spread out by means of a pin in the cathode. If the spreading is overdone, some of the cathode electrons will strike the copper rim surrounding the tungsten button, resulting in a loss in efficiency. The slant of the face of the target, the cathode distance, the size and shape of the glass bulb, all have an effect on the electrical field within the tube and consequently on those electrons that come out of the face of the target, only to strike it in some other place, and so we should expect these factors to have some bearing on the total output.

In determining the output of a tube, it is understood that what is measured is the energy passing into the measuring apparatus through a small port of entry, and it is assumed that the intensity distribution is fairly uniform over a large range of solid angle. Coolidge has shown that if the surface of

the target is smooth, the intensity of filtered radiation is much the same over the active hemisphere until we get to within 10 degrees of the edge. Here it falls off a little, the radiation being somewhat more filtered, since it must be remembered that the rays are produced, not at the surface of the target, but at depths varying to some ten-thousandths of an inch below it.

Uniformity of Output

It is becoming of increasing importance to ensure that all tubes of the same type give the same output of X-rays in order that power measurements may be used instead of ionization measurements to determine dosage in therapy.

To do this there are two requirements that must be fulfilled:

1. Pitting of the target must be avoided.
2. A large and variable fraction of the electrons should not be allowed to get past the face of the target to strike it at the back and sides.

At the present time, there are only two tubes that fulfill these requirements to a high degree. One is a special type of the water-cooled deep therapy tube, built with a universal cathode instead of the projecting pin cathode. Being water-cooled, the target will not pit and because of the medium focus, the electrons are mostly confined to the center of a comparatively broad disk, and the number of strays is reduced to a minimum. Of course, this tube cannot be used with such high energy inputs as permitted by the regular type.

The other tube fulfilling the requirements is one with a target consisting of a tungsten disk 4 inches in diameter. In this tube, to avoid pitting, the focus must be spread with a pin in the cathode or by other means, so that the bulk of the electrons is received on a circle some 2 inches in diameter. This still leaves, however, a margin of 1 inch all around the target to catch the strays, and few electrons get past the edge.

nother factor which to a lesser degree, makes for uniformity of output, is a large bulb. In tubes having small bulbs, especially where the anode and cathode are well separated, the glass charges up and, in the worst cases, causes the focal spot to wander about, and in any case, has an effect on those electrons that get past the face of the target.

CHAPTER IV

High Voltage Generators

The general term, X-ray machine, refers to a combination of high-tension transformer, a means of rectifying the secondary output, and a control box or panel. There may be more than one transformer, or the windings may be divided into two or more sections on the same core and these transformers or sections may be separated by rectifiers so that the whole circuit can become very complicated.

Consequently, the design and arrangement of the various circuits is so much influenced by the method of rectification, that reference to the various circuit arrangements will have to be postponed until after the methods of rectification are discussed.

The alternating voltage supplied by an a.c. generator has the form of a pure sine wave, and this is practically the shape of the wave as it enters the primary of the transformer. Figure 43 shows such a wave. This is the fundamental shape

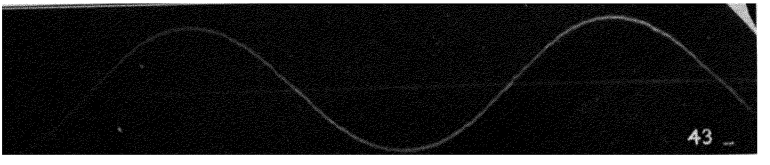


Fig. 43.—Line Voltage Wave.

for a.c. and it is on this shape that calculations are based, as for example, that the effective voltage is $\frac{1}{2}\sqrt{2}$ times the peak, etc.

Now practically all X-ray transformers distort the wave form somewhat, i.e., the secondary voltage, under load, dif-

ters considerably from the sine wave. Figure 44 represents the wave form of a medium-size transformer that is probably no worse than the average. It is apparent that this complicates somewhat the problem of voltage measurement.



FIG. 44.—DISTORTED VOLTAGE WAVE.

Rotating Switch Rectifier

The rotary switch rectifier, whose invention is usually attributed to C. S. Snook, has developed into a cheap and fairly efficient means of rectification and up till recent years was in almost universal use. The alternating current is supplied to the transformer primary and the rotary switch connects the terminals of the secondary alternately to opposite ends of the X-ray tube in synchronism with the alternations of the current. This is accomplished by mounting the switch on the shaft of a synchronous motor which is operated on the same current supply. As the motor, when started, may get in synchronism on either half-cycle, a polarity indicator is supplied on the control board, and in one type of construction, the transformer primary is connected with the line through a reversing switch which is thrown in accordance with the indications of the polarity indicator. Where only d.c. mains are available, as in parts of New York City, a rotary converter is used with the switch mounted on the converter shaft.

The contactors may be mounted on cross-arms or on a micanite disk. The cross-arms must be adjusted in relation to the motor armature to give maximum efficiency. This can be done by measuring the X-ray output for the different positions with an ionization chamber and selecting the position that gives the maximum reading.

The rotary switch reverses the connections to the tube

every half cycle, which would be depicted by showing the wave crests all rising above the zero line, but the current in the transformer secondary and connecting lines up to the switch is truly alternating as will be seen by referring to Fig. 64, which was taken at the mid-point of a transformer secondary.

If an oscillograph picture of the rectified current is desired, it would be necessary to run two X-ray tubes in series, placing the oscillograph between them, and grounding the line at that point.

Besides the actual rectification, the switch has another function. It makes contact during only part of the half-cycle, taking out the peak of each wave. This is shown at *A* in Fig. 45. Thus the tube passes current only during the high-voltage part of the wave, and does not get current at low voltage, which would serve only to heat the target, and not be efficient in the production of X-rays.

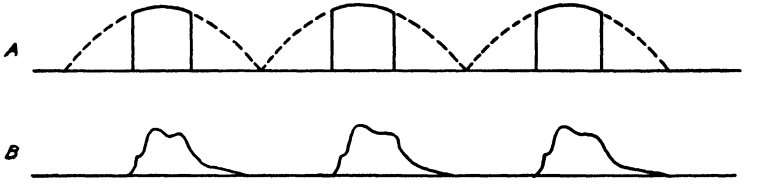


FIG. 45.—ROTARY RECTIFIER VOLTAGE, THEORETICAL AND ACTUAL.

This action, however, is complicated by the fact that there is a spark at the approach and recession of each contact, and by other factors, so that the vertical lines in the diagram are in practice replaced by curves sloping off on each side, as will be seen at *B* in the figure, and the rotary switch cannot be said to perform this part of its duty in such manner as to give complete satisfaction. In fact, oscillograms show that the rotary rectifier machine produces a considerable proportion of its output at comparatively low voltage. Naturally then, such a machine will not give as large an output of X-rays as a continuous current machine run at the same voltage and current.

From biological measurements, Dr. F. C. Wood and his associates have observed that a rotary rectifier machine at 120

kv. peak voltage and 5 ma. produced about one-half the output of a continuous current machine operating at the same voltage and current.

Wave Form

A pair of oscillograms, one of voltage, the other of current, taken under load conditions would define the wave form of the machine.

It will be apparent at once that the wave form is not constant for each machine, but will vary with load conditions, voltage, etc. This is especially true since the voltage is ordinarily controlled by a combination of auto-transformer and resistance in the primary and, for the same load, various combinations of the two methods of control may alter the wave form.

Further, the exact shape of the wave depends on many things. With two machines of the same model, run at the same load with the same control settings, it is reasonable to expect them to have about the same wave form, but even here, there are possibilities that they will not. For example, the setting of the rectifier switch may vary slightly in the two machines. This setting is always a matter of nice adjustment, and there is always the possibility that the factory adjustment may have been disturbed.

With machines of different design, the transformers will differ in size, shape of core, ratio of iron to copper, the cross-arms will be of different designs, etc., and the same wave form would not be expected.

It is apparent, then, that the only correct way to state the voltage of a machine of the rotary switch type is by specifying the complete shape of the wave form. From this point arises the chief disadvantage of the rotary switch method of rectification, i.e., the fact that the voltage is not determinate and reproducible. It has other disadvantages such as noise, vibration, production of ozone, etc., which are, however, to some extent, offset by its low cost and reliability; but as long as the

voltage cannot be accurately determined nor reproduced, there is no hope of determining or stating the X-ray output in terms of the voltage and current, and this disadvantage, added to the others, will no doubt ultimately cause the rotary rectifier machines to be replaced by a better type.

Tube Rectifiers

The use of vacuum tube rectifiers such as kenotrons presents many advantages over the rotary switch rectifier. They are noiseless in operation, there are no moving parts and consequently no vibration and no bearings to be oiled. There are no contacts to spark and so there is practically no ozone nor NO_2 generated. Their use in this country has not yet attained great proportions, but in Europe, especially in Germany, they are standard equipment.

They are particularly adapted for use with condensers to give c.p.d.c., which, from the point of view of measurement and reproducibility, is the ideal form of current, but of course, all installations using tube rectifiers do not give c.p.d.c. Some machines, for example those that give half wave rectification on 60-cycle current and have insufficient condenser capacity, have a wave form that makes their voltage almost as unsatisfactory as that of the rotary switch rectifier machines.

Tube rectifiers can of course be used without condensers, and a few experimental installations of this type have been tried, but they are not very satisfactory. For the greater part of the cycle, X-rays are produced at low voltage, as practically the whole wave is passed by the rectifier, and there is much heating of the target and little yield of penetrating radiation. This is also true when the X-ray tube is used without a rectifier and forced to do its own rectification.

Rectifying tubes, known also under the trade name of kenotrons, are made in two types for X-ray use. The two types differ only in the arrangement of the elements.

In the first type, *A*, Fig. 46, the plate is in the form of a cylinder surrounding the filament. This type passes large

currents with comparatively small voltage drop. In the second type shown at *B*, the filament consists of several hairpin loops of wire, and the anode is a cup or disk. This type is particularly suitable for use in high voltage units.

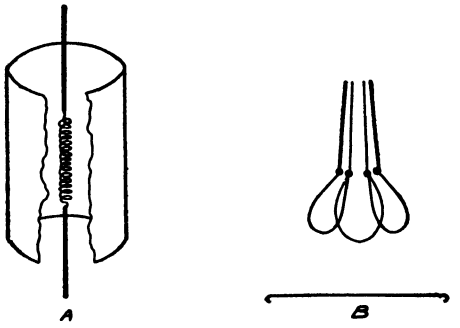


FIG. 46.—TWO TYPES OF RECTIFIERS.

The simplest circuit involving a single kenotron and condenser is shown in Fig. 47.

This circuit is not extensively used alone since for the same transformer, twice the voltage could be had by the use of a

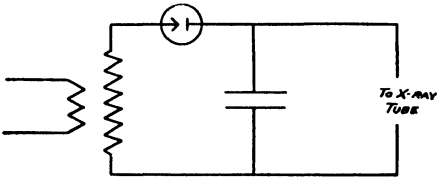


FIG. 47.—SINGLE TUBE CIRCUIT.

second kenotron and condenser. The circuit, however, often appears as a part of a larger combination.

The circuit diagram for the simplest form of installation employing two tubes each giving half-wave rectification is shown in Fig. 48. This arrangement supplies the X-ray tube with twice the transformer voltage and the rectifiers must be able to withstand this voltage. The capacity of the condensers required will depend on the frequency of the a.c. supplied to the transformer. In an experimental outfit built at the Hunt-

ington Memorial Hospital, in Boston, this circuit gave very satisfactory results on 2,000 cycles with condensers of .0081-mf. capacity. It can also be used with 500-cycle current if the capacity is increased or if too much current is not drawn by the X-ray tube.

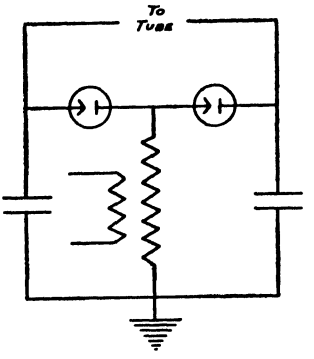


FIG. 48.—CIRCUIT USING TWO TUBES.

If supplied with 60-cycle current, no ordinary condenser capacity will suffice to suppress the ripple. The circuit may be used, of course, but the output will not be c.p.d.c.

Figure 49 gives an oscillograph tracing taken with a circuit of this type using 60-cycle current, and a condenser of .016-mf. capacity. Observe that the total voltage across the tube is equal to the sum of the voltages on the two sides of the line, and since the impulses are in opposite phase, the fluctuation in the total voltage is proportionately less than that of either side separately.

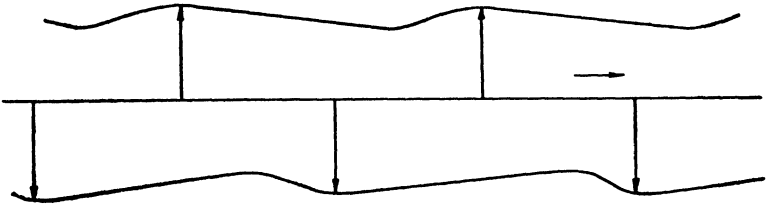


FIG. 49.—OSCILLOGRAPH TRACING OF VOLTAGE, TWO-TUBE CIRCUIT.

The condition is somewhat analogous to what is called in transformer practice, wabbling neutral. It has no particular disadvantage, however, except making voltage measurements more difficult.

As an example of the possible magnitude of these voltage fluctuations, suppose the condenser capacity to be .01 mf. and the current drawn by the tube to be 8 ma. Thus the condenser is discharging at the rate of .008 coulomb per sec. and in 1/60 second would lose 13.3×10^{-5} coulombs, so that the

voltage would drop 13.3 kv. on each side of the line, and the same amount on the total voltage across the tube.

Filter circuits containing inductance and additional capacity may be added to the circuit, as in Fig. 50. This has been done in an experimental plant built at the Bureau of Standards. Such an arrangement serves to further reduce the voltage ripples.

Two tubes may be used for full-wave rectification, but voltage of one sign only is obtained. This, however, is very convenient for some purposes, especially research investigations in physical laboratories.

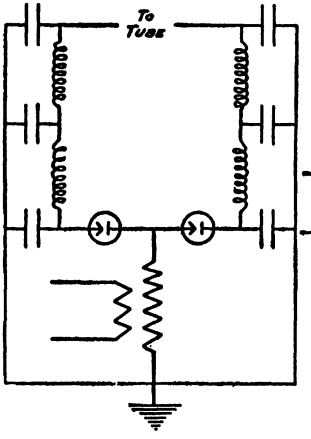


FIG. 50.—HALF-WAVE CIRCUIT WITH FILTERS.

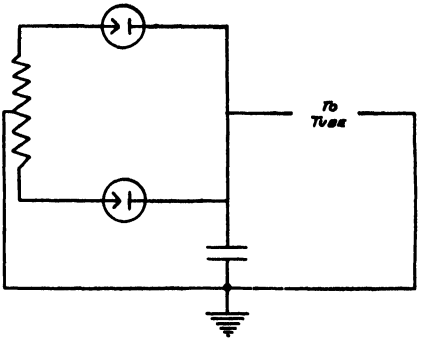


FIG. 51.—TWO-TUBE, FULL-WAVE CIRCUIT.

The circuit is shown in Fig. 51.

Voltage of either sign may be obtained, according to the direction in which the kenotrons are placed in the circuit. In this circuit the X-ray tube has one end grounded. Such an arrangement supplies the X-ray tube with half the transformer voltage. The rectifiers must be able to withstand the entire transformer voltage or twice that of the X-ray tube.

A circuit employing four kenotrons and giving full-wave rectification is shown in Fig. 52. This circuit has been employed for some years at the Institute of Cancer Research, working on 500-cycle current and using for condensers .01 mf.

It has the advantage of requiring only a single transformer. The rectifiers must be able to withstand the same voltage as the X-ray tube, i.e., the entire transformer voltage.

The current is supplied to the primary by a 500-cycle generator, direct-connected to a synchronous motor fed from the city mains. The primary current is thus independent of any chance voltage fluctuations which might occur on the power mains.

The constancy of the voltage as regards freedom from ripple of course depends on the load, but for ordinary purposes, the voltage is constant to within 1 per cent.

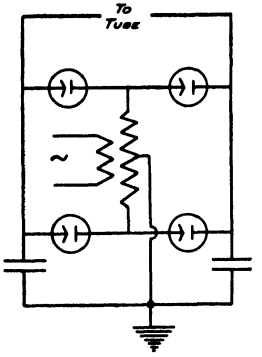


FIG. 52.—FOUR-TUBE, FULL-WAVE CIRCUIT.

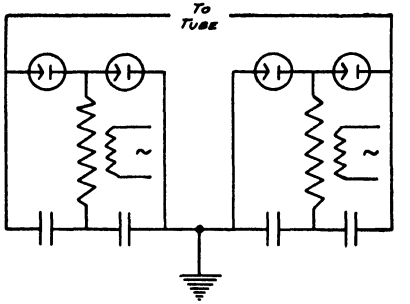


FIG. 53.—CIRCUIT USING TWO TRANSFORMERS.

Circuits using more than one transformer are common and some of them have special advantages. Taking the familiar half-wave circuit as a unit, two of these may be placed in series, as shown in Fig. 53.

A second circuit using three transformers is given in Fig. 54. This is built up from a half-wave circuit as a basis by putting a single tube booster on each side.

Dessauer Circuit

The Dessauer circuit is built up of small units or sections, each consisting of a half-wave set as in Fig. 55, although in some models, the sections contain only one rectifier tube.

Each section is designed to produce 30 ma. at 25 kv. and any number of sections up to twelve or more may be connected in series, the primary supply being carried through insulated transformers, one for each three sections. These insulated

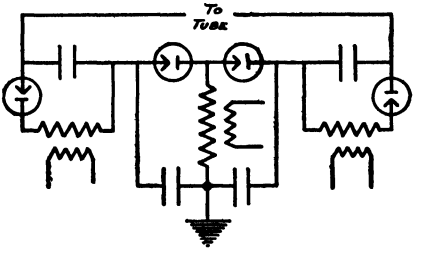


FIG. 54.—CIRCUIT USING THREE TRANSFORMERS.

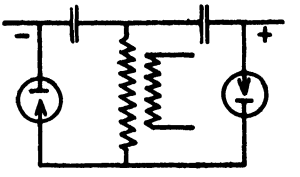


FIG. 55.—DESSAUER UNIT.

transformers are a fundamental part of the system and have been used by Dessauer for many years in various applications. They are usually of one to one ratio, but with sufficient insulation between the primary and secondary to withstand a difference of potential of 100 kv. or more. In Fig. 56 is shown a Dessauer circuit embodying four sections and one insulated transformer.

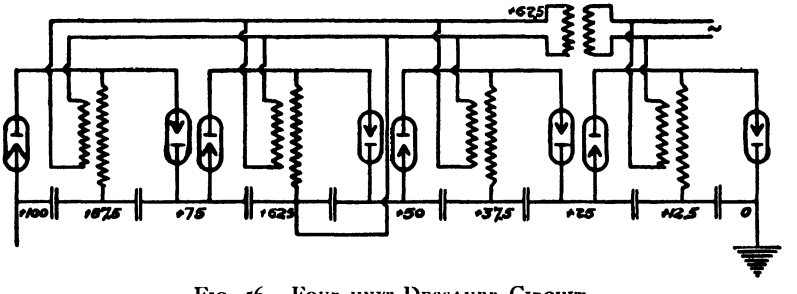


FIG. 56.—FOUR-UNIT DESSAUER CIRCUIT.

Multiphase Circuits

Three-phase transformer installations using kenotrons have been described by Hull and others, but these are hardly practical for use in X-ray therapy, except in special localities where three-phase current is available.

Two-phase current can be more easily obtained in most cities and a circuit could be devised in which the ripple would be considerably reduced by the use of two-phase current.

S. Ruben has suggested the use of phase-splitting devices, e.g., capacity in one lead and inductance in the other, to overcome the problem of 60-cycle rectification.

Tube-Rectifying 60-cycle Machines

Tube-rectifying machines now in use that operate on 60 cycles, while not giving c.p.d.c., have at least some of the characteristics of the c.p.d.c. machines. On the other hand, having a wave form or ripple, they partake of the nature of the rotary switch machines, and the objections urged against those, are true, in a somewhat lesser degree, for these.

The principal object in having a machine deliver pure c.p.d.c. is that results may be reproduced and dosage determined simply from the voltage and current. The importance of this has been mentioned in another section and can hardly be over-emphasized.

There may be sufficient other advantages in tube rectification to create a demand for tube-rectifying machines that do not give c.p.d.c., but there is no doubt that once machines giving pure c.p.d.c. appear on the market at a reasonable price, their obvious advantages will cause them to become rapidly adopted.

Circuits using 500-cycle current and full-wave rectification produce a voltage that is easily constant to within 1 per cent for normal X-ray tube loads. At the present time, no circuit has been developed that will give this constancy operating on 60-cycle current. No doubt, a combination of inductances and condensers can be devised that would suffice without running the cost and bulk up to an unreasonable amount; but any installation that is connected directly to the supply mains is always subject to the line fluctuations and still more apparatus would be required to suppress these if an X-ray plant capable of precise work is to be obtained. The

expense of suppressing the wave ripple would hardly be justified if line fluctuations were not also taken care of, at least for such machines where it is desired to determine accurately the output of X-rays by measurements of current and voltage. On the whole, the problem is not an easy one, and no doubt many machines using tube rectifiers but having more or less of a wave form will be used before a 60-cycle c.p.d.c. machine is generally available. Some further remarks on this point will appear in a later section.

Line Fluctuations

While it is true that line fluctuations have a tendency to average out during the course of a long exposure, still this cannot always be relied upon, and they are always a source of difficulty to the operator who is trying to adjust the machines to a given voltage. While small voltage stabilizing units that will suppress line fluctuations in the filament circuit are available, there is at the present time no simple means of securing a steady voltage supply to the main transformer.

One method that can be used is to employ a separate generator driven by a direct-connected synchronous motor. While the line voltage may fluctuate considerably, it is true in most cities, that the frequency is remarkably constant; so constant in fact that small synchronous motors are used to actuate various timekeeping devices such as wall clocks and recording meters. Accordingly the voltage output of such a motor generator plant is quite steady. This plan is followed in many research institutions. In some, but not all cases, advantage is taken of the opportunity to change the frequency and generators giving 500 cycles or even higher frequency are employed.

There seems to be no simple combination of static transformers that can be used to suppress fluctuations in the line voltage. Since practically all machines contain an auto-transformer as part of the control system, it would seem possible that additions or modifications could be made at this point.

Constant current transformers of the floating coil type formerly were built for the purpose of supplying arc lamps, but would hardly find application in the present instance.

The principle utilized in the construction of filament current stabilizers could hardly be applied here, as these devices are extremely inefficient. In the filament stabilizer the loss is only a few hundred watts and may be neglected. If a stabilizer were built for the main transformer, such loss might amount to 10 or 20 kilowatts, and aside from the expense, dissipating the heat would be a considerable problem.

Filament Current Stabilizers

Due to the extremely rapid increase in electron emission with filament temperature, a very slight increase in line voltage can cause an enormous increase in tube current. Under certain conditions, it is possible for a 1 per cent fluctuation in the line voltage to cause a 20 per cent fluctuation in the tube current. For this reason, the suppression of fluctuations in the filament circuit is even more imperative than in the main circuit. The necessity of preventing line fluctuations in the filament circuit has long been recognized and there are at present two types of apparatus on the market that can be used to insure steady filament current despite line fluctuations.

The Rieber stabilizer is a combination of transformers and inductances that maintains the filament current practically constant at any desired value, despite fluctuations in the supply voltage. The main features are shown in Fig. 57. In this figure, *A* is a transformer with a closed core which is so proportioned that it is saturated at a voltage somewhat below the normal voltage of the supply. Due to the saturation of the core, the output of this transformer has the voltage fluctuations considerably reduced, and the small remaining variations are completely nullified by the transformer *B*. This transformer has a relatively small potential in the secondary, which is connected with the secondary of transformer *A* in such manner that the windings are opposed to each other.

The magnetization in the core of transformer *A* is always above the knee of the saturation curve, and beyond that point, the magnetization increases for increasing voltage, just as if there were a large air gap in the core. Accordingly, the core of transformer *B*, as indicated in the figure, is made with an air gap, and is proportioned so as to insure that the fluctuations in *B* are just sufficient to nullify those in *A*.

It is necessary to provide means for adjusting the filament current to any desired value. If a resistance or inductance were simply placed in series with the output side of the stabilizer, the nice adjustment between transformers *A* and

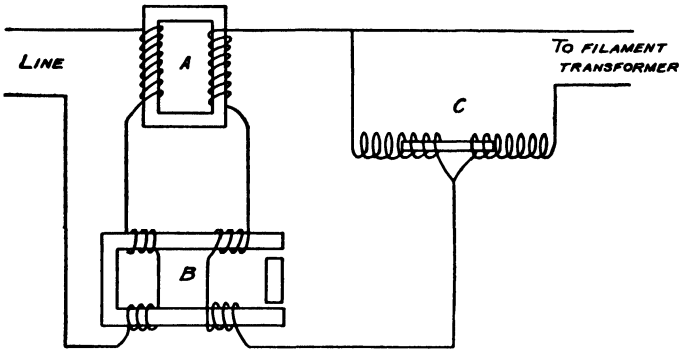


FIG. 57.—RIEBER STABILIZER CIRCUIT.

B would be disturbed, and the voltage fluctuations would no longer be suppressed. Accordingly, it is necessary to keep the load approximately constant, and this is accomplished by providing two variable inductances as shown at *C* in the figure. One of these is in series with the filament supply circuit and the other is parallel with it, and they are wound on opposite ends of the same spool with a movable core that can be slid from one end to the other, so that as the inductance of one is increased, the other is decreased. This sliding core is actuated by a gear wheel, the shaft of which, projecting through the front of the box, terminates in a bakelite knob moving over a graduated dial.

In the instruments as manufactured, the circuit is complicated by the fact that there are extra windings and taps

leading to a selective switch on the back of the control box in order to permit it being used equally well with supply mains of 110, 150 or 220 volts.

While the apparatus just described is patented, the general idea of using a transformer with a saturated core to give approximately constant output is comparatively old. Such a transformer with a certain amount of resistance in series with the primary has been used by one manufacturer to supply current to the filament transformer with the result that the filament current is quite steady regardless of line fluctuations.

The Kearsley stabilizer is a device which makes no attempt to hold the filament current constant, but rather, automatically varies it as required to maintain a steady current through the tube. It thus compensates for fluctuations that might be due to other causes than voltage fluctuations in the supply line, such as, for example, gassing of the tube.

Figure 58 gives a diagram of the principle upon which it operates. It will be seen that it has much similarity to the

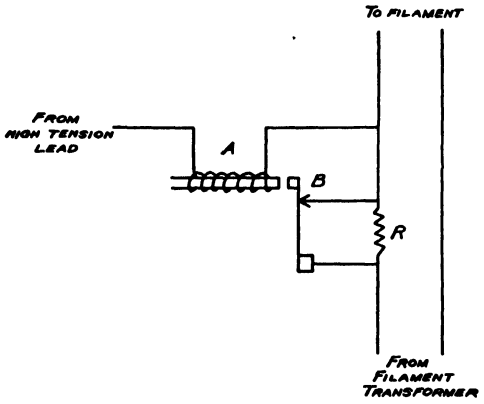


FIG. 58.—KEARSLEY STABILIZER CIRCUIT.

ordinary electric buzzer. The high-tension current supply to the tube passes through the electromagnet at *A*. The armature of the magnet is held back by a spring so that it rests against the contact at *B*. Suppose that it is desired to operate the tube at 5 ma. The armature spring is adjusted so that it

yields when only 5 ma. flows through the magnet. If now the current increases above 5 ma., the armature overcomes the tension of the spring and moves toward the magnet. The instant it moves, it breaks the contact at *B*, just as the armature does in the electric bell. In the present case, however, the filament circuit does not open entirely, for the resistance *R* is shunted across the contact, but the filament current is reduced because of this resistance, the tube current falls below 5 ma. and the armature comes back against its contact. With X-ray machines of the rotary switch rectifier type, there is a current impulse every half-cycle, and usually the armature is attracted and the contact opened at some time during each impulse. Thus the armature has the effect of vibrating back and forth regularly, and the small changes in the filament current made by cutting the resistance in and out follow each other rapidly and blend all together so that the pointer on the milliammeter simply indicates a constant current.

If it is attempted to operate the Kearsley stabilizer on c.p.d.c. the armature will vibrate but not very regularly. It will take up a rate of vibration governed by several factors; the natural period of the armature and its spring, the amount of lag between a change in the filament current and the corresponding change in the tube current, and the difference in the number of milliamperes between the setting of the armature spring and the number of milliamperes that would flow if the armature were forcibly held against its contact and not allowed to move. The rate of vibration can be increased by making the difference large, i.e., if the armature spring is set for 5 ma., the filament transformer regulator should be turned up to a position equivalent to say 30 ma.

On the whole, while the Kearsley stabilizer will operate with c.p.d.c., it cannot be said to work with the same success that it has attained on the switch rectified current.

Besides the vibrating relay described above, the instrument contains a second relay operating on the same principle. This second relay, which ordinarily performs no function, is designed to prevent heavy current surges passing through the

tube and so may come into action at the time of closing the X-ray switch.

Accessory Apparatus

The following paragraphs give some notes on the various pieces of equipment that go to make up a modern X-ray plant. They are given chiefly in the interests of research workers and those who are confronted with the problem of securing c.p.d.c. installations and wish to assemble their own plants. The kenotrons or rectifying tubes have been described in another section, and the present section offers a few notes on filament transformers, main transformers, motor generator sets and condensers.

Kenotron Filament Transformers

There are on the market filament transformers designed specially for kenotrons, but some of these are rather bulky and also very expensive. A smaller unit can be secured by using a regular X-ray tube filament transformer, built with a special secondary winding to take care of the larger current. However, too small a transformer should not be used, for it will overheat. The size will be governed partly by the insulation required between the primary and secondary, i.e., by the voltage for which it must be insulated. A rheostat or inductance should be provided in the primary circuit in order to have means of adjusting the filament temperature.

The manufacturers recommend that to ensure a long life, kenotron filaments should be run at constant voltage rather than constant current. To determine the voltage accurately, a fairly high resistance a.c. voltmeter is required, otherwise the meter will draw enough extra current to cause a considerable voltage drop. Certain a.c. meters of suitable range have too low a resistance to work well, but a Weston model 433, range either 15 or 20 volts, is quite satisfactory for this use. The lamp socket into which the kenotron screws may be shielded

with a spun metal ball to prevent corona, but provision should be made that the terminals are accessible so that the filament voltage may be measured.

The filament of the KR-1 tube requires 10 volts and the tube is so marked on its upper terminal.

Motor-Generator Sets

As has been mentioned, a very steady current supply is secured from an a.c. generator driven by a direct-connected synchronous motor. If such a set is used, it should be placed at a sufficient distance from the X-ray tube and control panel that the noise and vibration will not be objectionable, and yet it should be in a place readily accessible for inspection and lubrication. If the two units are securely bolted to a heavy cast iron or concrete base which rests on a layer of felt, little trouble from vibration will be experienced.

The direct current for exciting the generator field may be taken from storage batteries, from a d.c. generator also connected to the synchronous motor or from any source of very steady d.c. Voltage control of the a.c. output is secured by rheostats in the field circuit of the generator.

If the synchronous motor is of a self-starting type, it can be started by means of a regular starting compensator. If a d.c. generator is connected to the shaft as mentioned above, this may be used as a motor for starting purposes and the synchronous motor may be brought up to synchronous speed with the aid of a series of incandescent lamps shunted across the main switch. As synchronism is approached, the light and dark alternations grow slower, and finally become so slow as to permit closing the switch at an instant when the lamps are dark.

Main Transformer

The main transformer may be purchased from one of the regular X-ray manufacturers or from an organization doing

general work, such as the American Transformer Co. Since the main transformer is a rather expensive item, there is frequently a temptation to economize by ordering one of comparatively small size with low power and voltage ratings. A transformer that is overloaded at high voltage is liable to break down, and a failure of the transformer often requires more time and expense to repair than one occurring in any other part of the apparatus.

Transformer breakdowns usually occur in the insulation that separates the primary and secondary. Any means that will help to promote a free circulation of oil at this point will lessen failures. In some cases, two concentric tubes are used, held apart by spacers, so that the oil can circulate between the tubes. Current of 500 cycles and higher frequencies is much more severe on the insulation than 60-cycle current on account of the greater dielectric heating with high frequencies.

Since breakdowns may occur in spite of all precautions, the transformer should be designed so that it is easily accessible. It is well to have one of the yokes of the core removable (i.e., not interleaved) so that the coils and tubes may be easily taken off.

Most X-ray transformers are inclosed in tanks which have tops made of fiber or other insulating material, but some have metal tops and in such cases the lead-in insulators sometimes overheat and cause trouble, especially when higher frequencies are used. A simple remedy that may be effective is to discard the iron top of the transformer tank and substitute one of wood.

A simple and cheap lead-in insulator used by Duane consists of a glass tube about 3 inches in diameter, the lower end corked, and the conducting lead brought up through the center, the tube being filled with transformer oil.

The temperature of the transformer should be watched. It is not advisable to use extra high voltage at a time when the transformer is hot from long continued running. Breakdowns are more likely to occur when the transformer is hot.

Samples of the oil should be withdrawn periodically and

tested for moisture. The condition of the oil is usually tested with a spark gap. One type of gap consists of sharp edged brass disks, 1 inch in diameter, set to a 1/10-inch gap, and mounted in a cup of hard rubber or moulded composition. Oil in good condition will stand 25 to 30 kv. across this gap. Oil that shows a breakdown voltage of less than 16.5 kv. should be filtered and freed from moisture or replaced with a good grade of transformer oil.

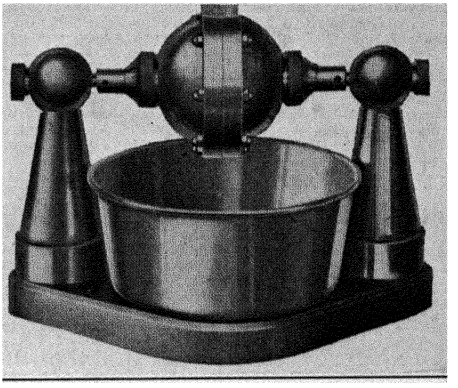


FIG. 59.—OIL TESTING GAP.

Figure 59 shows the gap and mountings made by the General Electric Co.

Aerial Wiring

To avoid corona on high voltage installations, conductors should be of large diameter tubing. Brass tubing ¾ inch in diameter is quite suitable for the fixed wiring. For flexible leads and temporary installations there are several substitutes. One plan is to use a close coiled spring, wound of brass wire on a mandrel having about the same diameter as the tubing. Perhaps a better material is flexible metal hose, or flexible metal conduit, preferably without asbestos packing. It can be had in galvanized steel or brass and in a wide range of diameters, ⅝ or ¾ inch being ordinarily sufficient. Joints

may be covered by spun brass balls such as used on bed steads or the ends of curtain rods.

Condensers

Obtaining a condenser having high enough capacity and sufficiently insulated for the high voltage is one of the problems of building a c.p.d.c. X-ray plant. There is no general agreement on the best type to use, and of the various types that can be bought in this country none is entirely satisfactory.

In a general way, we can classify the various types by the kind of dielectric used. Among these would be included compressed gas, high vacuum, solid and liquid dielectrics, and combinations of the latter two.

Condensers using compressed air or nitrogen were built some years ago by the National Electric Signaling Co. for radio use. They had fairly high capacity and at pressures of about 220 lb. per sq. in., were capable of withstanding 45 kv. There is no record of their having ever been used in connection with an X-ray generating plant, but they have been mentioned here since the type seems to present possibilities that may have been overlooked, especially in connection with reducing fire hazard by eliminating the oil.

A condenser consisting of concentric metal cylinders enclosed in a glass bulb which is exhausted to the same high degree of vacuum as the Coolidge X-ray tube has been described by S. Ruben. This was designed for X-ray work, but has never come into extensive use, probably because of the relatively high cost for given capacity and the especial difficulty of completely preventing discharges from the sharp edges of the metal plates, even when the bulb is exhausted to the highest possible degree.

Condensers with solid dielectric range from the old type glass Leyden jars, to plate condensers using glass, micanite, micarta or bakelite. They are sometimes rolled up in cylindrical form using shellacked paper or moulded material as the dielectric. Many German condensers are made this way.

Beside the possibility of puncturing there is always a chance of brush discharge or corona at the edges of the plates that might slowly destroy the dielectric. Those designs in which the metal plates are moulded in the dielectric suffer less from this corona effect, but on the other hand, the loss on puncturing is proportionately greater, if a unit contains many plates moulded together.

Condensers using only a liquid dielectric such as transformer oil have not been used extensively for very high voltage. The plates have to be so well separated that the capacity becomes small, and the electrostatic force of attraction on the plates requires them to be made of heavy sheet metal. This type, however, has possibilities for the future. The great advantage of a liquid dielectric is that in case of a breakdown it is not permanently damaged.

The most used types at present seem to be those having a combination of solid and liquid dielectrics. The solid material between the plates prevents trouble due to electrostatic forces and also permits the plates to be brought close together. The oil forms a seal against moisture and prevents corona at the edges of the plates.

A condenser built for X-ray use by the Wappler Electric Company consists of micanite sheets coated with metal foil and immersed in the same oil tank with the transformer. These seem to be very satisfactory, especially when used in circuits where the full voltage does not fall across a single condenser.

Condensers in small units are made commercially for industrial use as a means of power factor correction. The units have a paper dielectric which has been treated in vacuum to withdraw all moisture, immersed in oil and hermetically sealed in a light sheet metal container. One kind sold by the General Electric Company consists of units $4 \times 15 \times 15$ inches, each having a capacity of .05 mf. and a voltage rating of 10,000 volts.

When using units of small voltage rating it is necessary to connect a number of them in series. This introduces special problems. If the units have some uniform natural leakage, or

if the X-ray tube ionizes the air around them and causes a small amount of current to flow, the voltage will equalize itself over the series, otherwise unequal voltage distribution often causes breakdown of the dielectric.

It has been claimed that mica condensers are unsuitable for use in series as they have practically no leakage and consequently there would be no equalization of the voltage. To shunt them with a high resistance is impractical. Rods of clay and graphite compositions, or tubes filled with alcohol and xylol mixtures become unduly heated and a sufficiently high metallic resistance is too expensive.

A set of units of the paper and oil type used at the Institute of Cancer Research worked very well in series. There were ten units in each series and each unit was bridged by a point spark gap in series with graphite composition rod of about 1 meghom resistance. The gaps were set for about 11,000 volts. When ten units were placed across a potential difference of 100,000 volts, there would be an occasional spark across one of the gaps, but such spark would be very small and weak due to the high resistance, and never more than one gap sparked at a time.

The important point about these protective gaps is the use of the very high resistance. It is true that spark gaps without resistance will safeguard the condensers from puncturing, but they will do nothing to help equalize the voltage strain and ensure the regular operation of the circuit.

If the condensers themselves have little natural leakage, any attempt to use spark gaps without adequate resistances in series with them is liable to failure since the breakdown of one gap may start a surge that will cause the remaining gaps to spark over.

CHAPTER V

VOLTAGE AND CURRENT MEASUREMENTS

The measurements treated of in this section include measurements of voltage and current. In general, voltage measurement is much more difficult than current measurement. There is no satisfactory general method of measuring high voltage, but many special methods, including primary meters, resistance multipliers, spark gaps, electrostatic instruments and oscillographs; none being entirely satisfactory, but each partially adapted to some special case or type of apparatus. Partly as a consequence of this situation, there is a tendency on the part of users of X-ray plants to slight voltage measurements, while they may observe exaggerated precautions in reading the milliammeter. And yet, as a measure of intensity of radiation, or quantity of X-rays, voltage is more important than current, since the intensity varies as the voltage squared.

The methods of voltage measurement may be classified according to the system of rectification used.

Tube Rectifying Its Own Current

In those cases where a Coolidge tube is used as self-rectifying, there is ordinarily little need for precise voltage measurements. A knowledge of the transformer ratio and the primary voltage will usually be sufficient. It might be well to note that a spark gap in parallel with the tube would read the inverse voltage, so its indication would be definitely wrong.

Rotary Switch Rectifier, or Tube Rectifiers Giving Bad Wave Form

To measure the voltage of an arbitrary wave form is one of the outstanding difficulties of X-ray practice. Ordinarily, the peak voltage is measured and this can be done with a spark gap. The term peak voltage has real meaning in ordinary alternating current practice, but it has much less significance in X-ray work.

For example, compare the wave forms given at *A* and *B* in Fig. 60. They both have the same peak voltage, yet the one at *B* gives several times as large an output and a much greater proportion of hard radiation.

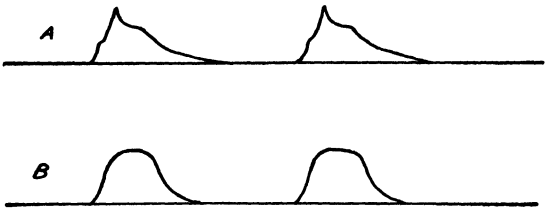


FIG. 60.—VOLTAGE WAVE FORMS.

Strictly speaking, the only reliable way to measure the voltage of a wave form is to take an oscillograph picture by the use of a non-inductive resistance. The oscillograph and resistance can be calibrated by c.p.d.c., or alternating current of pure sine wave form.

Another method of estimating the voltage is to determine the spectrum of the X-rays produced by it. This will give the peak voltage since that corresponds to the shortest wave-length in the spectrum produced. But it gives more information than that since by comparison of the spectrum with one taken from c.p.d.c., it is possible to gain some knowledge concerning the wave form. This method is not entirely satisfactory, but is least objectionable when used only for comparisons with other spectra taken on the same instrument. The uncorrected readings of a spectrometer do not, in general, represent the true

energy distribution in the radiation, and to supply the corrections, is for ordinary use, out of the question.

This objection also applies to spectrographs, despite the elaborate methods applied for measuring energy in terms of photographic blackening. Furthermore, the ordinary spectrographs crowd the whole spectrum into such a small space on the film that they are considerably wanting in sensitivity.

It will be observed that both the oscillograph picture and the X-ray spectrum are two-dimensional diagrams and it is apparent that to completly determine the voltage of a wave form requires such a diagram. If it is required that the voltage be stated in terms of a single number, that number can only be peak voltage. It does not seem possible to formulate a useful definition of effective voltage in the case of an irregular wave form. The first requirement would be that the same effective voltage would always give the same yield of X-rays, both in amount and quality, and this is not possible.

The quantity of X-rays produced may be assumed to vary as the square of the voltage and a root mean square value would give an effective voltage satisfactory as a measure of quantity of X-rays. The quality of the X-rays, however, for example, as indicated by the absorption coefficient in water or tissue, depends on a more complicated function of the voltage, and the root mean square value would not do.

Primary Meter

Manufacturers of commercial machines always supply them with an ordinary a.c. voltmeter connected across the primary of the transformer, or better, across an auxiliary coil wound alongside of the secondary. A compromise arrangement consists in connecting it across a few turns of the low voltage section of the secondary.

Its readings are of value, provided it is regarded simply as an indicating instrument, and it is calibrated by some other means. For complete accuracy, a separate calibration must be made for each setting of the control handles and for

each value of the current at which the tube is operated. Two points may be noted here. First, the calibrations must be in terms of peak voltage as that is the only thing that can be measured by a single number, and as mentioned before, the peak voltage of a wave form is not a reliable measure of the amount and quality of X-rays. The second point is that if the calibrations are made as described, the only use for the meter is to check the constancy of the line voltage.

An example showing the impossibility of placing any value on the readings of one of these meters without calibration may be had as follows: With the tube drawing large current, and the controls adjusted so that all the resistance is cut in, the meter is read, and the output of the X-rays determined by an ionization chamber. The resistance is now cut out and auto-tranformer steps cut in to bring the meter to the same point. The output of X-rays will be found to have increased, possibly even doubled.

Some manufacturers graduate these meters with an arbitrary scale so that the user will be able to calibrate the machine and meter himself. Others graduate the meters directly in kilovolts according to a factory calibration, and provide an approximate compensation by marking off the dial on the resistance control handle in milliamperes. If this handle is set according to the markings, resistance will be cut out as the current through the tube is increased and a rough kind of compensation effected.

Oscillograph Measurements

The moving coil type of oscillograph consists of a single turn coil stretched by means of a pulley between the poles of an electromagnet. A mirror is fastened to the wires and the moving system is immersed in oil for damping. The mirror throws a spot of light upon a rotating drum carrying photographic film and in some instruments a rotating mirror or other device is also provided for visual observation of the light spot.

The details of one of the elements or vibrators is shown in Fig. 61. Some instruments contain two and others three vibrators, all registering on the same drum, so that voltage and current readings may be taken simultaneously. For X-ray measurements, the principal requirement is high current sensitivity and the resistance of the moving coil is not important. The sensitivity depends principally on the moving coil system and usually vibrators of various sensitiveness can be obtained from the makers of the instrument. If the instrument at hand is not sufficiently sensitive, it is possible to obtain some increase in sensitivity by increasing the current through the electromagnet. If this happens to be designed for 110 volts, it can be connected across the 220 volt line for periods of a few seconds, with possibly some resistance in series with it.

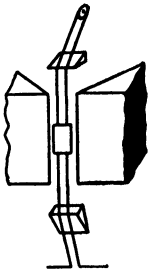


FIG. 61.—OSCILLOGRAPH VIBRATOR.

The machine must be supplied with a synchronous motor, but for ordinary wave form determinations need not have any of the elaborate electrically operated shutter systems required for photographing a single cycle or transient phenomena.

The wave form can be gone over and over and the shutter operated by hand, giving exposures of a second or more. In certain of the oscillograph pictures shown in this section, the exposure was twenty seconds.

Much difficulty may be caused by electrostatic charges affecting the sensitive element. It is always difficult to work with delicate apparatus near high tension circuits and the oscillograph is almost as sensitive to stray charges as a galvanometer.

The remedy is to ground all the metal parts, making sure that good contacts are secured and also to ground any large pieces of metal in the vicinity. If the instrument can be placed in a different room from the high tension circuit, so much the better. It is usually not necessary to cover the whole instrument with a metal shield, although this could always be done as a last resort.

If, instead of a clear photograph, a confused blur is obtained, electrostatic disturbances should always be suspected, and the grounding wires gone over carefully.

Voltage Measurement With the Oscillograph

The oscillograph with its motor and electromagnet is such a complex instrument that it is difficult to operate it at anything but ground potential. As a consequence, voltage measurements with the oscillograph will usually have to be made from one side of the line to ground.

A non-inductive resistance of several megohms is required and probably the simplest for this purpose is one consisting of 8 to 10 feet of glass tubing filled with distilled water to which a certain proportion of tap water or a few drops of sodium chloride solution have been added to secure the proper conductivity. Carborundum or graphite rods may also be used but they must not be run too hot for they change resistance rapidly with the temperature. On this point water has the advantage, for it gives warning of a rise in temperature by boiling. However, it requires only a second or two to take a photograph so that if care is taken not to run current through the resistance unnecessarily, no trouble from overheating need be anticipated.

The sensitivity of the instrument should be known, or can readily be determined by running measured currents through it by the aid of a dry cell, resistance and a milliammeter, and observing the deflections. Suppose that a deflection large enough to give a well-proportioned diagram requires 5 milliamperes, then this amount of current will have to be drawn through the resistance, and that can be adjusted for the voltage with which it is to be used. In the case of the tubes of distilled water, the connections to the tubes are made by wires dipping into the water. Accordingly, adjustment is readily accomplished by pushing the wires deeper into the water to lower the resistance.

The resistance connects the oscillograph to one side of the

line and as it draws a considerable current, possibly as much or even more than the X-ray tube, the circuit will be unbalanced. To remedy this an approximately equal resistance must be constructed and attached between the other side of the line and ground.

Figure 62 gives an oscillogram of the voltage of a rotary rectifier at 70 kv. and 9 ma.

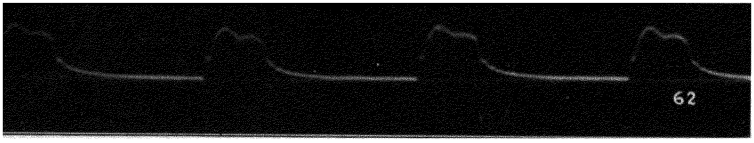


FIG. 62.—OSCILLOGRAM OF VOLTAGE WITH ROTARY RECTIFIER.

Care must be taken not to draw too much current, and whatever current is drawn must be added to the tube current when stating the load at which the picture was taken. Thus, if 6 ma. were passing through the tube and 5 ma. were being drawn off through the resistance to operate the oscillograph, the readings would give the voltage corresponding to a load of 11 ma. The 5 ma. that goes through the balancing resistance is of course not added, since the two resistances each get only half the voltage.

The voltage of a tube-rectifying plant at 500 cycles is given in Fig. 63, taken with and without condensers in the circuit.

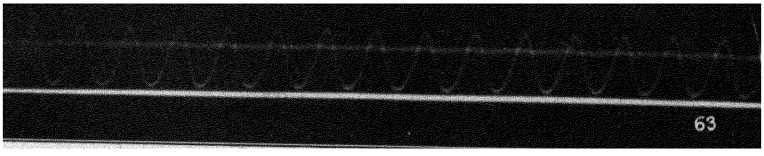


FIG. 63.—OSCILLOGRAM OF VOLTAGE WITH TUBE RECTIFIER.

Current Measurement With the Oscillograph

The fact that the oscillograph must be kept at ground potential complicates the methods of current measurement. Probably the best way to obtain the measurements is to place two X-ray tubes in series, with the oscillograph in the line be-

tween them and grounding the line on one side of the instrument. The tubes may be first placed in parallel and their filament heating currents adjusted until they both pass the same number of milliamperes, and then the connections may be changed, placing them in series.

With some machines using rotary switch rectifiers, a common method is to place the oscillograph in the circuit at the middle point of the secondary, which is grounded. This has the disadvantage that the transformer must be lifted out of the oil to get at the connections and the further disadvantage that the current is not rectified at this point. The shape of the wave form, however, may be obtained from the curve.

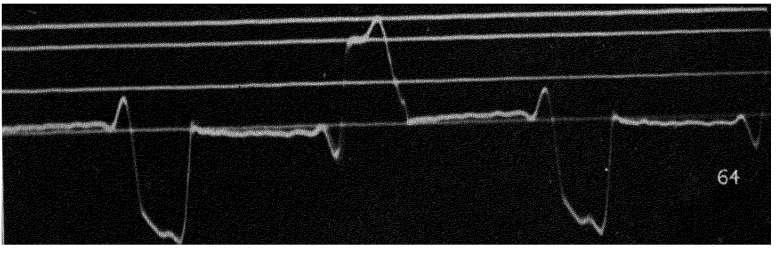


FIG. 64.—OSCILLOGRAM OF CURRENT WITH ROTARY RECTIFIER.

In those machines whose circuits permit the use of a milliammeter on the control box at ground potential, it is possible to connect the oscillograph at the same point. Also, in those cases where a single transformer, grounded at one end of the secondary, is used, the oscillograph is simply inserted between the secondary terminal and the ground.

A vibrator of very high sensitivity may require part of the current shunted around it in some cases, for it must be realized that a tube drawing 10 ma. according to the milliammeter may be passing as much as 40 ma. during the periods the rotary switch is making contact. If the sensitivity of the instrument is determined by passing current through it from a dry cell, lines corresponding to 10, 20, etc., milliamperes may be photographed on the same film. This was done in the picture shown in Fig. 64 where the lines correspond to 10, 20 and 25

ma., the milliammeter at the time the wave form was taken reading 8 ma.

Fig. 65 gives an oscillogram of the current in a tube used self-rectifying. The voltage was approximately 30 kv. and the reading of the milliammeter was 8.5 ma.

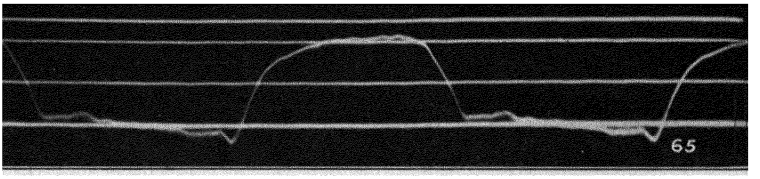


FIG. 65.—OSCILLOGRAM OF CURRENT WITH SELF-RECTIFYING X-RAY TUBE.

Cathode Ray Oscillographs

Since cathode rays are deflected by an electric or a magnetic field they can be used to show the wave form of the current in an a.c. circuit. Braun first applied this principle in the construction of a cathode ray oscillograph and such instruments are commonly referred to as Braun tubes. A fine pencil of cathode rays is obtained by directing the beam upon a diaphragm with a small aperture. After passing through the aperture the pencil of rays is acted upon by an electric or magnetic field by means of a pair of plates or coils which are connected with the alternating current circuit. The rays then fall upon a fluorescent screen placed in the end of the tube, and if this screen is viewed by means of a rotating mirror the wave form can be seen.

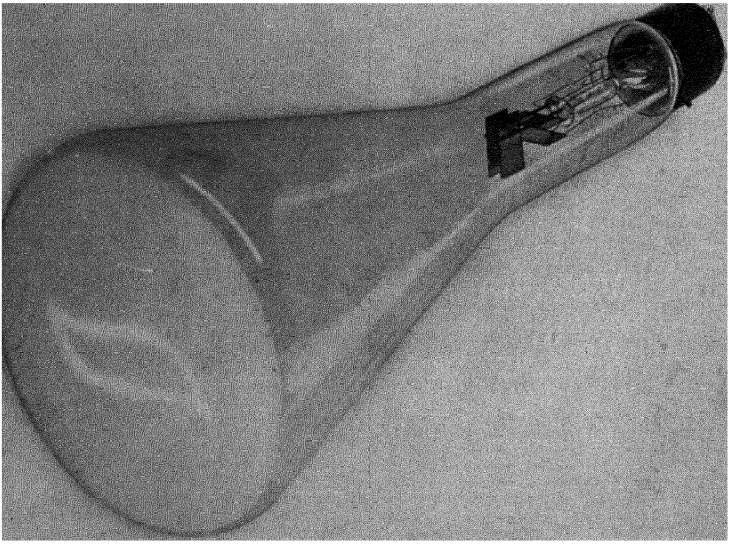
The cathode ray oscillograph will respond to all frequencies and it can therefore be used in the region of high frequencies where the Dudell and Einthoven types are insensitive, on account of the inertia of their moving elements. The moving coil type of oscillograph which was used in obtaining the oscillograms shown in the preceding section will determine accurately the wave form of the current in circuits of low frequencies but cannot be used for frequencies much above 1000 cycles per sec. Oscillations of over a million cycles per second

have been recorded by means of the cathode ray oscillograph. It has also been applied to the study of transient phenomena, the duration of which is measured in micro-seconds.

Various modifications of the Braun tube have been made, among which may be mentioned those due to Johnson,[1] Dufour[2] and Wood.[3]

Western Electric Oscillograph

J. B. Johnson of the Bell Telephone Laboratories has perfected a type of Braun oscillograph, which is simple in con-



(*Courtesy, Bell Telephone Laboratories*)

FIG. 66.—WESTERN ELECTRIC CATHODE RAY OSCILLOGRAPH.

struction and sensitive in operation. High sensitivity is obtained by operating the tube at lower voltage than was pos-

[1] J. B. Johnson, Jour. Opt. Soc. of America **6**, 701 (1922).

[2] A. Dufour, Comptes Rendus **158**, 133.9 (1914); L'Onde Electrique **1**, 638 and 699 (1923); **2**, 19 (1923).

[3] A. B. Wood, Proc. Phy. Soc. of London, **35**, 109 (1923); Jour. Inst. E. E. **63**, 1046 (1925).

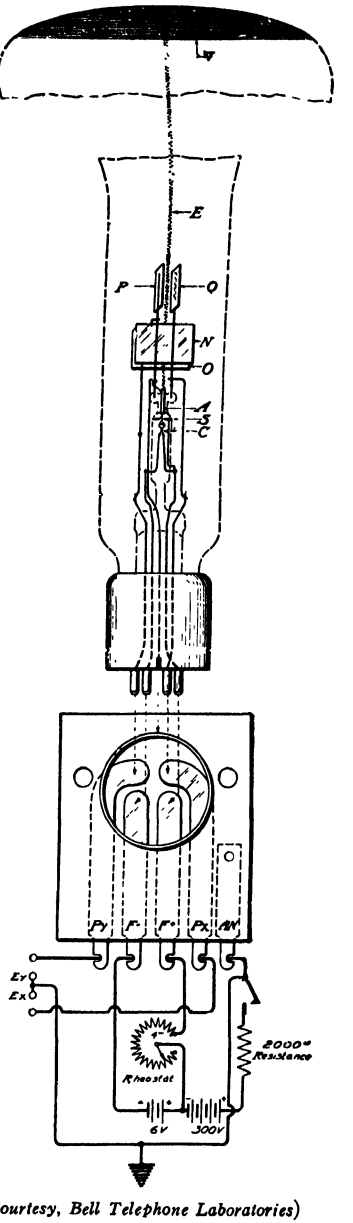
sible with the older type of Braun tube. By making use of a Wehnelt cathode in a pressure of argon of 5 to 10 bars, a fine spot is obtained on the fluorescent screen with a driving voltage of only 300 volts.

Two pairs of deflector plates at right angles to each other are mounted inside the tube and the fluorescent material consisting of a mixture of equal parts of calcium tungstate and zinc silicate is deposited on the inner wall of the large end of the pear-shaped bulb. See Fig. 66 and Fig. 67.

When the two pairs of deflector plates are connected to different a.c. circuits the fluorescent spot will in general trace a Lissajou figure on the screen and this figure can be photographed and analyzed.

Dufour Oscillograph

The Dufour tube is designed to operate with higher velocity cathode rays from a cold cathode, voltages up to 60 kv. being employed to accelerate the electrons. The electron stream is reduced to a fine pencil by passing through the anode which is a hollow



(*Courtesy, Bell Telephone Laboratories*)

FIG. 67.—SCHEMATIC DIAGRAM OF WESTERN ELECTRIC CATHODE RAY OSCILLOGRAPH.

cylinder with small apertures at each end. After passing through the anode, the electron stream is acted upon by the deflector plates or coils which are placed outside the tube. The beam then enters a camera chamber where it strikes the photographic plate, also in the vacuum.

By an ingenious device, the wave form may be recorded on a stationary plate. The method of accomplishing this is to cause the electron beam to sweep across the plate with a predetermined speed, while the oscillatory current is acting on a pair of deflector plates or coils. A wave trace is thus recorded just as though the photographic plate had been in motion at right angles to the motion caused by the deflector plates or coils. This sweeping motion is obtained by means of an electromagnet in which the current is increasing at a known rate. By such means, oscillograms have been made while the electron beam was sweeping across the plate with a speed of 4×10^8 cm. per second. See Fig. 68.

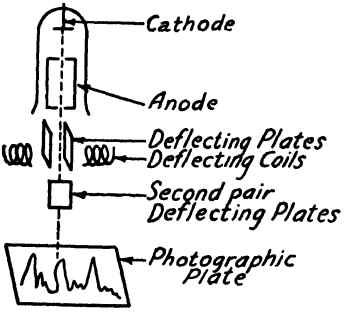


FIG. 68.—DIAGRAM OF DUFOUR OSCILLOGRAPH.

This is a much greater speed than could be attained with a moving plate, and the device is therefore particularly adapted for studying radio-frequency oscillations and transient phenomena.

The tube must of course be operated while connected to the vacuum pumps, and a constant pressure is maintained by providing a small leak which is just balanced by the pumps. A number of plates may be mounted in the camera chamber

at the same time and each successively rotated into position by means of a magnetic clutch or a ground joint.

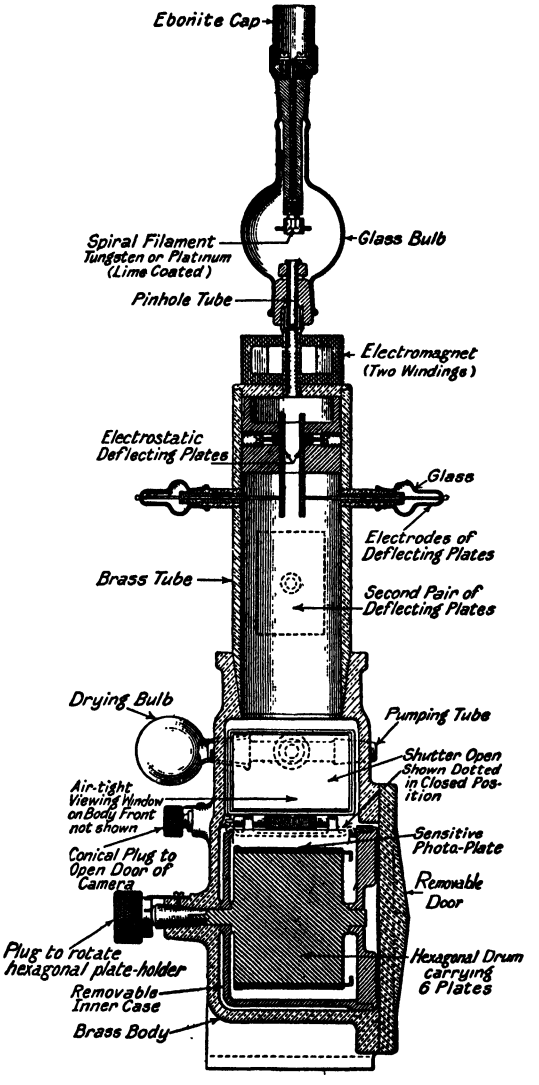


FIG. 69.—MODIFIED DUFOUR OSCILLOGRAPH.

A. B. Wood has designed a modified form of the Dufour oscillograph using a thermionic cathode in a high vacuum,

This tube is operated at 3000 volts and the deflecting plates are placed inside the tube since there is no appreciable conduction current between the plates in such a high vacuum. When the tube is employed for studying high-frequency oscillations or transient phenomena, the electron beam is made to traverse the photographic plate by means of a condenser and resistance connected in series to one pair of deflector plates. The time of the traverse can be varied as desired by changing the electrical constants of this circuit. See Fig. 69.

C.P.D.C. Methods of Voltage Measurement

With c.p.d.c., the problem of voltage measurements becomes much simpler, for there is here no question of wave form; at least it is taken for granted that the ripple is negligible. There are four general methods in use, viz., resistance, spark gap, electrostatic voltmeter, and spectrograph or spectrometer.

Resistance Methods

The fundamental and most precise method of measuring c.p.d.c. voltage is by the use of a high resistance. The method might be regarded as the use of an ordinary voltmeter with a high resistance multiplier, although usually, in practice, a milliammeter is used.

It has the disadvantage of high cost, for suitable resistances are very expensive, costing 30 dollars per megohm or more, and further, unless the resistance is extremely high, it cannot be left in the circuit while the X-ray tube is being used and so give a continuous indication of the voltage. A resistance of 10 or 20 megohms will draw at high voltage almost as much current as the tube itself and such an increased load on the generating plant is not desirable. Another factor militating against continuous use is the heat generated, which, unless provision is made for dissipating it, would cause the resistance to change in value. For general purposes, it seems

better to have an electrostatic voltmeter for continuous use as an indicating instrument, and to use the resistance to calibrate and check the electrostatic instrument.

The resistance must be wire wound, since none of the moulded resistances of graphite mixtures or carborundum have sufficient accuracy or constancy under load. One type consists of resistance wire about .0015 inch in diameter wound on porcelain cylinders and covered with a vitreous enamel which is fused on at a high temperature. The enamel is moisture proof, durable, and forms a mechanically strong casing for the windings. It can, however, cause trouble in various ways. Its insulation resistance may be low and such conductivity as it has will not follow Ohm's law so that the total resistance of the unit may vary slightly with the voltage applied. The baking process frequently causes shrinkage which breaks the wire, or the wires get oxidized from the heat and of course, with such fine wire, a surface coating of oxide does not have to be very thick to be an appreciable fraction of the whole diameter. Instances are known of enamelled resistor units that tested perfectly when delivered by the maker, but which, after a period of six months or a year show open circuit, presumably due to destruction of the wire by oxidation that started during the baking process.

Figure 70 shows some of these enamelled porcelain units fastened to a bakelite frame for convenient handling. The total resistance of the units on the frame is 1 megohm. Ten or twenty of these frames supported with proper insulation in a dust-proof box or a tank of transformer oil would make up a complete high resistance. It is undoubtedly better to have them submerged in the oil as it prevents corona, keeps moisture away and holds the temperature more nearly constant, but it has the disadvantage of adding weight and requiring a heavy oil-tight metal tank so that the whole outfit is not very portable. Furthermore, there is the general sloppiness of all oil-immersed apparatus, especially when it has to be withdrawn from the oil for repairs or testing purposes.

At one time it was possible to purchase units made with

enamelled wire wound on shellacked paper cylinders, but at the present time these are not on the market.

Regarding the choice of metal for the wire, any of the alloys with small temperature coefficients are suitable. Manganin, which is advocated so highly for standard resistance boxes is for this use probably not so good as constantan, for manganin requires greater protection from oxidation, while the high thermo-e.m.f. of constantan against copper is no disadvantage in a resistance of this kind. The most accurate method is to have the resistance made up in 1-megohm sections like that shown in Fig. 70 and to have taps or means

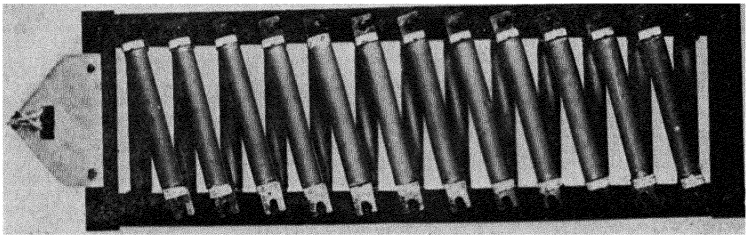


FIG. 70.—SECTION OF HIGH RESISTANCE.

for connecting to each section. The resistance of each section is then determined separately by a bridge made up from the standard megohm and two dial resistance boxes which are set almost at their maximum resistance, using at least 1000 volts across the bridge. The galvanometer used to indicate the balance should be of the high resistance, high current sensitivity type. The advantage of testing the whole apparatus in sections is manifest, for supposing there were twenty sections, each having been tested at 1000 volts, this is equivalent to 20 kv. across the whole, a value comparable at least to that at which it is to be used.

It is also important to make one reading at low voltage to search for breaks in the wire or open places in the circuit. A minute break in the wire will show an infinitely high resistance under low voltage, but will arc across and be almost

without effect on the resistance under high voltage. Units showing open circuit under low voltage should be removed.

Calibrating the Resistance

When a high resistance such as described above has been constructed, its value must be determined and of course, for such a high resistance as this, the ordinary Wheatstone bridge is not sufficient. The single units can be measured by an ordinary bridge, before they are built into the apparatus, but ordinarily, this is not satisfactory, both on account of the labor involved and because there is no certainty that the sum of these

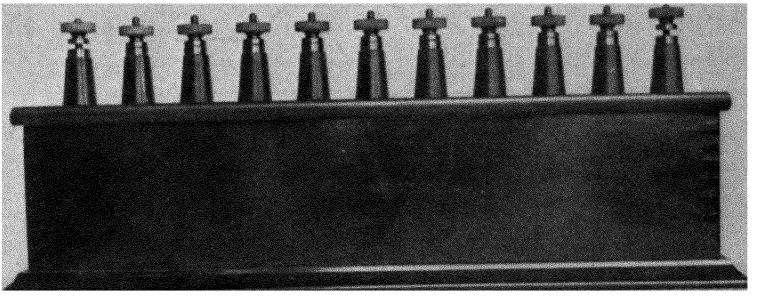


FIG. 71.—STANDARD MEGOHM.

values would represent the total resistance of the completed apparatus. Strain may be set up during the construction, or accidents happen to the units, so it is necessary to have a reliable method of determining the resistance as a whole, or at least in large sections. This is all the more desirable since the resistance should have its value checked periodically, for changes may occur, especially on account of corrosion or breakage of the wire.

It is necessary to have a standard megohm for this purpose. Such a one is shown in Fig. 71. Voltages up to 1000 volts can be safely placed across its terminals.

If two standard megohms are available the whole resistance may be measured at once, a bridge being made up as

in Fig. 72. Here X is the high resistance, M and M_1 the standard megohms and R an ordinary dial resistance box, which is adjusted until the bridge is balanced. Thus if a balance is obtained at $R = 50{,}000$ ohms, the value of X is 20 megohms. Voltages up to 1000 volts or so should be used across the bridge, and although the readings may show slight variations for different voltages, they will probably approach a limit as higher voltages are used. Radio B batteries are probably the most constant source of high voltage, but any of the substitutes mentioned in the section on ionization chambers may be used if they provide a source sufficiently con-

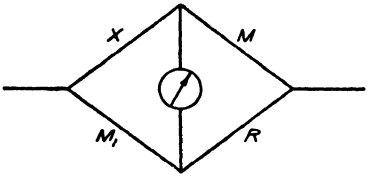


FIG. 72.—DIAGRAM OF BRIDGE CIRCUIT.

stant. Since the exact voltage is not important, the X-ray set itself may be used.

If a sensitive microammeter and a milliammeter are available, a comparison may be made of the current through the resistance and through the standard megohm when both are connected to the same voltage. This is hardly desirable as a method for regular use, but is very handy for emergencies or to use as a quick method of checking the value of the resistance after it has been subjected to an unusual strain. The microammeter should be a Weston model 322 or something similar with a full-scale range of 50 microamperes. The voltage should be about 1000 volts and care should be taken to connect the two meters on the ground side of their respective resistances and to see that they are placed at opposite ends of the table or at least 2 feet apart.

Determination of Voltage With a Spectrometer

When using a spectrometer to determine the voltage of c.p.d.c., the previously mentioned objections regarding the energy corrections do not apply, for in this case, all that is wanted is the short wave-length limit, and the spectrometer can determine that with great accuracy. This limit being determined, the voltage in kilovolts is at once obtained from the relation $V\lambda = 12.35$.*

The method is not to be recommended, save in those cases where a spectrometer happens to be already set up and in adjustment for work on other problems, as may be the case in some research institutions. Comparatively, a great deal of time is required in making a measurement and there is the further disadvantage of the method not being continuous reading, and, therefore, not showing voltage variations. In general, the more direct methods are preferable.

The ordinary spectrographs such as found on the market are not so well suited to precise voltage measurements as spectrometers. The picture is too small for accurate measurement and the short wave-length limit is not sharply defined like spectral lines so that comparators using high magnification cannot be employed with such advantage. Of course, large spectrographs have been built, and some of those existing in research institutions give as great accuracy as spectrometer measurements.

Electrostatic Voltmeters

There are several types of electrostatic voltmeters, but they all depend on either the repulsion of like charges, or the attraction of unlike. Those instruments depending on repulsion have weak operating torque. In those depending on the attraction, the torque can be increased by bringing the at-

* $Ve/300 = hc/\lambda$

$$V\lambda = \frac{300 \times 6.554 \times 10^{-27} \times 2.9986 \times 10^{10}}{10^{-8} \times 4.774 \times 10^{-10}} = 12{,}350,$$

where λ is in A.U. and V in volts.

tracted elements closer together, but at the risk, however, of the electric stress ionizing the air and ultimately causing a spark over.

These meters should be calibrated on c.p.d.c. by using a high resistance. Calibration by means of a spectrometer is very accurate but involves considerable labor, especially if the spectrometer is not already set up. Calibration by a spark gap is only a makeshift. Calibration by a.c. with a transformer of known ratio is not to be recommended for very high voltages.

The most common of the repulsion type electrostatic voltmeters is the torsion electrometer also known as the Coulomb electrometer or Coulomb torsion balance.

Figure 73 gives the principal features. It consists simply of two fixed balls that are connected with and consequently repel two movable ones which are attached to a suspended cross-arm. The case is of sheet metal and is connected with the ground.

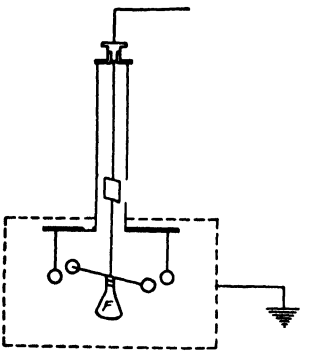


FIG. 73.—TORSION ELECTROMETER.

The readings are usually made by a mirror and scale, but with considerable advantages over the familiar type used in galvanometers. Here the mirror may be an inch or two in diameter, brilliant images may be had, and a large scale placed on the wall may be read from the opposite end of the room. Sometimes a telescope is used, but a lamp throwing a spot of light upon a scale is more convenient to read.

Meters of this type require some form of damping, and ordinarily it is not good practice simply to have attached to the moving parts a vane which dips in an oil dash pot. The oil creeps up over the balls, collects dust and becomes gummy, and if the meter happens to be so adjusted that the balls can touch each other when at rest, they will stick together on contact.

A better way of damping has been suggested by Pegram. A vessel containing oil is entirely closed and attached to the moving parts. The most convenient method seems to be that of fastening to the crossbar a corked Erlenmeyer flask partially full of motor oil as at *F* in the figure. Mobiloil A, or a mixture of A and B, has about the right viscosity to give good damping.

S. Ruben has constructed small repulsion type voltmeters patterned somewhat after the Braun electrometers but which are enclosed in a highly exhausted glass bulb to prevent corona effect.

The attracted disk type consists of two flat disks held apart by a spring or counterbalance. When pulled toward each other by electrostatic attraction, the motion is magnified by a pointer. The essential parts of one of these instruments are given in Fig. 74. In this instrument the disks are held apart

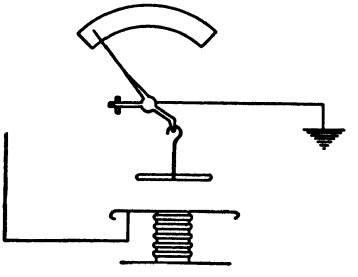


FIG. 74.—ATTRACTED DISK VOLTMETER.

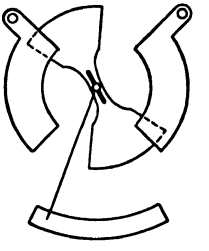


FIG. 75.—VANE TYPE VOLTMETER.

by a counterbalance weight whose distance from the fulcrum can be varied. When the instrument is first set up, it should be adjusted to bring the pointer to zero, but before this adjustment is made, care should be taken that the whole instrument is level. The original Kelvin instrument had a guard plate surrounding the upper disk to avoid the edge effect, but that is not necessary when the scale is to be calibrated against known voltages. Instruments of the type shown in the figure are catalogued by the General Electric Company.

Another instrument that depends on attraction is the vane type voltmeter. As will be seen from Fig. 75, this is some-

what similar to a quadrant electrometer. These are usually built to read up to 10 kv. and so would not be useful for X-ray work, but there is no reason why instruments could not be built with greater clearance and rounded edges so as to read to higher voltages. A modification of this type is similar to the repulsion meter first described, save that the fixed balls attract the movable pair instead of repelling them.

In all instruments involving attraction, the chance of arc-over becomes greater as the voltage is increased, but some of the difficulties can be solved by placing the working parts of the instrument in transformer oil. The attracted parts can then be brought much closer together without fear of arc-over, and as the forces vary as the square of the distance, the operating torque might be increased many times. A further advantage would be the damping effect of the oil, so that no other provision for damping would be required.

Despite, however, the obvious advantages of oil-immersed electrostatic voltmeters, they do not seem to have come into any extensive use. Some years ago, Siemens and Halske manufactured an oil-immersed voltmeter of the attracted disk type.

The Westinghouse Electric & Manufacturing Company catalogues an oil-immersed electrostatic voltmeter with certain novel properties. The large insulated terminal consists of concentric alternate insulating and conducting layers which form in effect a number of condensers in series. The range of the instrument can be changed by short-circuiting certain of these condensers. The moving element, which is connected in series with some of the condensers, consists of two hollow cylinders, whose connecting shaft turns on a jeweled bearing. The cylinders move between two curved plates, and these plates can be shaped so that the calibration curve is approximately a straight line over the upper portion of the range. The instrument has the disadvantages of being large and heavy and the list price is over a thousand dollars.

One of the difficulties of electrostatic voltmeter construction comes from the necessity of making precise readings from a distance. If an oil-immersed type were used, it would be

possible to design a meter such that the voltage caused increase in the oil pressure, and a line of bakelite tubing transmitting the oil to a pressure gauge on the control panel would permit readings to be made from close at hand.

Although there are not a few quite satisfactory electrostatic voltmeters in use in physics laboratories, these have been mostly made and calibrated by the users, and there is not on the market in this country a satisfactory electrostatic voltmeter for X-ray use. It is a comparatively simple matter for a laboratory mechanician to construct a voltmeter using a mirror and scale that will give considerable sensitivity and it is easy for the user to calibrate this with the aid of a high resistance. But such a meter occupies considerable space and is not portable. It may change its calibration simply on standing for a month or so and it would not retain its calibration on being taken down and packed for shipment.

What is needed is a small instrument, not exactly portable, but one that can be shipped and still retain the factory calibration, not occupying too much space, and finally, not having a prohibitive cost.

Cathode-Ray and Other Voltmeters

A sort of electrostatic voltmeter using cathode rays might be made, somewhat on the principle of the cathode ray oscillograph. In one type a stream of electrons at known velocity is deflected by the electrostatic force of the voltage to be measured. Another design has the cathode connected with the potential to be measured and the stream of electrons, after traversing a pair of slits, falls on a fluorescent screen and produces an image of the slits. A current of 1 microampere would be sufficient to produce a visible image. A magnetic field produced by a measured current in a pair of coils would deflect this image by an amount depending on the original voltage of the cathode rays.

A substitute for a high resistance would be any device that would permit a small amount of current to flow, provided

that this current was always proportioned to the voltage. For example, suppose a condenser connected alternately to the high voltage line and to a grounded milliammeter sixty times a minute. This would permit a small amount of current to escape through the meter. Various methods have been experimented with at the Institute of Cancer Research, among them a flowing jet of transformer oil. The method which seemed to give the best promise of success was a rotating disk. Micanite was used, although glass would be preferable. The disk was attached to the shaft of a synchronous motor, with a brush from the high-tension lead bearing against its surface. A collecting brush connected to ground through a milliammeter bore against the disk in another place. On the opposite side of the disk were grounded brushes so that the disk itself was really the dielectric of a condenser. As the disk rotated, a current of several milliamperes was picked up from the high-tension brush and carried over to the collecting brush.

Spark-gap

The spark-gap method of measuring voltage hardly merits classification under precision methods. It does happen to be a convenient way of determining the peak voltage of a wave form, but as has been insisted upon before, this elusive peak voltage is of small importance when determined. Much has been written about spark-gaps but the substance of what is known can be given in a few words. The best spark-gap is only a moderately accurate means of measuring the voltage. Better methods exist, but worse ones have been and are used. Sphere gaps are far more accurate than point gaps, and in a general way, the larger the spheres, the greater the accuracy.

Point gaps, or point and plane gaps, though once largely used must now be considered as relics of the past. The points get blunt and the readings depend too much on the condition of the air and surrounding objects to be of value. There are two reasons for their having been such favorites. First, they were cheap, and second, there was a psychological reason.

They gave big sparking distances and thus permitted manufacturers to rate their apparatus in terms of big numbers. Terms like "twenty-inch gap" are still used by medical men as a way of stating voltage capacity of X-ray machines, but the point gap itself is not much used.

The gaps now in use are mostly sphere gaps. The spheres should be of such diameter that the field between them is not distorted by other objects (such as the leads, line, etc.) in their vicinity. For voltages up to 100 kv., spheres of 12.5 cm. diameter are satisfactory. The separation of the spheres should never be greater than their radius.

While sphere gap methods of voltage measurement are not to be recommended where precision is desired, there are occasionally times when no other method is available. For those occasions where they must be used, the following precautions are appended.

A high resistance such as a carbon composition rod or water resistance should be placed in series with the gap. There are two reasons for this: first, that the discharge may not be so violent as to endanger other apparatus, and, second, without it, the values are not trustworthy, for small, high-frequency surges may start the spark at lower voltages than normal. The spheres must be kept clean and polished, but rough abrasives like coarse emery paper should not be used. If cleaned frequently there will be little need for anything but wiping with a soft cloth. The distance apart of the spheres should be accurately known. Those gaps which have the rod carrying the movable sphere graduated in centimeters or kilovolts, or geared to a movable pointer, should have these graduations checked by closing the spheres against a block whose thickness can be calipered with a micrometer.

In making the measurements, the controls should be set and the load adjusted to the amount desired, after which the spheres should be made to approach each other by a screw or other slow motion until a spark occurs. The distance should be read, the spheres separated and the operation repeated, the result being obtained from the mean of several readings.

If the controls provide fine adjustment, it is also possible to set the gap to a predetermined distance, and slowly raise the voltage until the spark occurs.

Below is given a table of sphere gap and voltages for 25 cm. and for 12.5 cm. spheres. These are for c.p.d.c. or if used with machines giving a wave form, correspond to peak voltages. Methods will be found in the literature for making

Kv.	25-cm. Spheres, Cm.	12.5-cm. Spheres, Cm.
25	0 8	0 8
50	1.6	1 6
75	2 5	2 6
100	3 5	3 6
125	4.5	4 8
150	5.6	
175	6 75	
200	7 95	
225	9 1	
250	10 2	

corrections for barometric pressure, etc., but the method is hardly accurate enough to warrant such refinements.

Under certain conditions, the sparking distance for the same voltage difference, when the two spheres are at equal and opposite voltages, will be different from what it is with all the voltage on one sphere and the other sphere is grounded. The explanation for this is probably found in the difference of the effects of corona in the two cases, but the whole difference is always small as long as the sparking distance is less than the radius of the spheres. Thus, in the above table, such differences may be neglected.

Routine Operation without Voltmeter

For general use in therapy, it is possible to calibrate the machine for definite settings of the control handles and to do without a voltmeter entirely. While for research and experi-

mental work it may be necessary to use many different voltages, in routine work, one, or at most two or three standard voltages will usually suffice.

For example, suppose a tube-rectifying deep therapy plant were adjusted at the factory, or after it was installed, to run at 200 kv. with a given load, say 16 ma., the setting of the controls once determined, would never have to be changed, and the operators would simply switch the voltage off and on, as required.

There are certain disadvantages in this method, the greatest being that the load must be kept constant. The difficulty here is that such machines usually supply two X-ray tubes. Thus in the above example, the 16 ma. load presupposed two tubes, each drawing 8 ma. There would occur times when only one tube was needed, and it would be necessary to run both simply to keep the load constant. The waste of power is small, however, compared with the other advantages gained.

A second difficulty is the fluctuation of the primary voltage. Of course, a primary voltmeter can be supplied and a special series of, say 1-volt steps, furnished on the auto-transformer, so that the primary voltage might always be adjusted to standard, but the problem is not so simple. Fluctuations of a volt or two may occur every few seconds and occasional fluctuations as large as 5 volts may be found if the elevators in the building are run from the same circuit. To hold the primary voltage constant would require either some automatic device or the continuous attention of the operator.

However, the primary voltage averaged over a twenty-minute exposure will usually come out constant from hour to hour or from day to day, and in large cities, where reasonable care is taken at the central station, fluctuations of the primary voltage may be negligible.

On the whole, it is quite possible to do without a voltmeter of any kind and still be reasonably certain of the voltage across the tube, if the machine has been properly calibrated and the calibration checked say once a year.

Current Measurements

Current measurements are somewhat less important than voltage measurements, since the yield of X-rays varies as the square of the voltage, and only directly as the current. Contrasted with the difficulty of voltage measurements, current measurements are comparatively easy, for the current is simply read on a milliammeter. No question of wave form enters because the milliammeter integrates or averages all current passing through it, whether it be continuous or pulsating. This point can readily be checked by oscillograph measurements.

X-ray milliameters are of the pivoted movable coil permanent magnet type, having open legible scales and thick pointers, since they usually must be read from a distance. Most of them have round pattern metal cases and are mounted in bearings so that they may be tilted slightly so as to face down toward the operator.

The use of the meter at ground potential, as in the case where it is placed between the two halves of the secondary presents no special problems, but when the meter is at high potential, certain difficulties arise due to the electrostatic forces.

One terminal of the meter should be connected to the case. It is true that many of these meters are too heavy because of the cast metal case, but the substitution of bakelite fronts is not an improvement. The use of insulating materials like bakelite in the construction of the case should be avoided, since trouble is likely to arise from a charge accumulating on them and the electrostatic forces affecting the pointer. The common glass front is the worst offender in this way.

Various remedies have been tried to prevent electrostatic forces on the glass from affecting the pointer, and while most meters are satisfactory with wave form machines, very few will indicate correctly on c.p.d.c.

In some instruments the case is made deep so as to give considerable clearance between the glass and the pointer. Others have the inside of the glass coated with metal foil, or aluminum paint, save for a moderate sized opening in the

center through which the pointer can be observed. With high voltage c.p.d.c., these precautions are not sufficient and it will frequently be seen that the pointer is sluggish in following changes in the current, and sometimes seems to stick in one place when the current has been considerably changed, or even entirely shut off. The remedy in this case is to take out the glass front and substitute a piece of fine wire gauze. A very fine mesh should be used so that it will keep out dust particles. It may happen that such gauze will reflect light from the polished surface of the wire and make reading of the pointer difficult. If the gauze is well smoked in a candle flame before being put in place, there will be no trouble from this source.

The ideal meter would have a case spun from light gauge sheet metal, with smooth rounded edges, as the cross-section in Fig. 76.



FIG. 76.—IMPROVED MILLIAMMETER CASE.

It would have a narrow opening through which to observe the pointer, and this opening would be covered with blackened fine mesh gauze, with a detachable glass front on the outside of the gauze. The moving coil and bearings would be enclosed in sheet metal shieldings so that the meter could be used without the glass front when necessary.

A device sometimes used to increase the accuracy of current measurements is to place a band of lead foil around the arm of the tube and a connection from this is carried around the milliammeter. The object of course is to prevent leakage currents over the outside of the tube from registering on the meter. At high voltages, however, to place any metal in contact with the arm of the tube, would increase the risk of puncturing.

A similar device has been suggested for use in oil tanks. The current to the meter passes up a wire insulated inside the brass sleeve that supports the end of the tube, and a wire from the sleeve is led around the meter. Tests have shown that this device is largely unnecessary.

Protection against Surges

Milliammeters must be protected against surges and overloads such as occur when accidents happen to the tube. Ordinarily, X-ray milliammeters are rugged enough to stand temporary overloads since the current output of the machine is more or less limited anyway. It is another matter, however, with the high-frequency surges that occur when the tube gases or punctures. Sparks may jump from the moving coil to other parts of the meter, or between the turns of the coil and short-circuit all or part of them.

If the moving coil is completely burnt out or short-circuited, that is easily detected because the meter is dead and will not respond. From one point of view, it is more serious to have just a few turns of the coil short-circuited, for then the meter responds, but simply reads too low. Considerable trouble could be caused by a meter that was indicating 8 ma. when the tube was passing 12 ma. The tube might be damaged by overloading, or an overdose given in a therapy treatment without suspicion falling on the true cause of the error.

Some manufacturers supply on their high voltage outfits, two milliammeters connected in series. The supposition is that an accident of this kind is unlikely to happen to both meters at the same time, or at least, that they will not both be damaged by the same amount. Accordingly, if the meters no longer read alike after a surge or a spark-over has occurred, they should both be checked.

Meters can be protected to some extent against high frequency surges, and some manufacturers incorporate such protection within the meter case. The protection consists in

shunting the meter with a condenser or needle-point spark-gap or both. Neon tubes have also been used for this purpose.

A further protection consists in placing between the condenser leads and in series with the moving coil, a small inductance, but such inductance should have only a single layer winding and be properly designed to keep its distributed capacity small, otherwise it will offer hardly any impedence to the high-frequency surge. See Fig. 77. A small point gap, set to a few thousandths of an inch with a feeler gauge may also be placed across the terminals of the milliammeter or the gap may be spaced by a thickness of cigarette paper. An additional safeguard to the meter is secured by using a fuse of 10 to 20 milliampere capacity. In operating experimental tubes with c.p.d.c., in cases where gassing may be expected, it is a good plan to place a resistance in series with the tube. The enamelled resistor units previously described are good for this work. The electrostatic voltmeter should be connected between the resistance and the tube, so that no allowance need be made for voltage drop in the resistance.

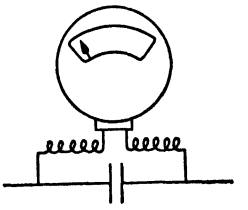


FIG. 77. — PROTECTIVE CONDENSER FOR MILLIAMMETER.

Meters should be checked regularly, and a special check should be made whenever a spark-over or tube breakdown has occurred. The best plan is to have a standard milliammeter that is used only for checking the other instruments, and is never placed in the circuit when the tube is running.

Such an instrument should be a portable meter of high precision, similar to the Weston Model 1. A dry cell, and an adjustable resistance of several hundred ohms are also required. For the resistance, one of the tubular sliding contact rheostats will do very well. Two long leads with spring clip terminals are very convenient, so that the current can be thus led to the meter to be checked, which is in its place in the overhead wiring, and thence down to the precision meter on the table. The two meters being connected in series, the rheo-

stat is adjusted and the meters compared at various current values.

In checking milliammeters one precaution must be observed. Two meters of the permanent magnet type should not be placed side by side on a table, for their magnetic fields may interfere with each other and cause errors in the reading. When two sensitive milliammeters are being checked, they should be at least 3 feet apart. This applies especially to the portable instruments enclosed in wood or bakelite cases. Switchboard meters and meters of the type used on X-ray aerials are usually shielded from external fields and may be placed close together.

Precision

In many instances exaggerated attention has been paid to the precision of current measurement while errors are made in the voltage measurement which would affect the yield of X-rays by large percentages.

Supposing, however, that with modern methods, the voltage can be accurately determined, what precautions are necessary so that the current readings shall attain high precision? For precise measurements, a meter should have large diameter so as to permit a large scale being attached. It is important that the meter should have more than one range, or more than one meter should be available, so that the meter is used with the pointer near the upper end of the scale. In choosing a meter, a scale range should be selected which is just greater than the value of the current habitually used. For example, certain tubes much used for deep therapy are commonly run at 8 ma. For use with one of these tubes, a convenient range for the meter would be 10 ma.

Shunting Meters

Whenever, for emergency use, it is desired to increase the range, it is simply necessary to shunt the meter with a few

feet of resistance wire. Thus, if the shunt had the same resistance as the meter, the range would be doubled; the indications of the pointer being multiplied by two to get the true current. One objection to this plan is that the internal resistance of these meters is ordinarily very low, and it is difficult to adjust accurately the resistance of the shunt. To avoid this difficulty, first increase the resistance of the meter by placing a coil of about 10 ohms in series with it, and then place the shunt across both meter and coil. In Fig. 78, R is the resistance in series with the meter and S is the shunt adjusted to equal the combined resistance of R and the meter.

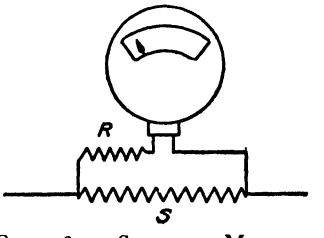


FIG. 78. — SHUNTED MILLIAMMETER.

Value of Power Measurement in Determining Output

There is a good reason for the growing importance of the need of accuracy in voltage and current measurements. In the past, the power measurement could not be depended upon to give an indication of the output of X-rays, and this output had to be measured in another way, usually by ionization methods. Ionization measurements attained popularity and importance principally because with the rotary switch rectifier machines in use, a measurement of the current and spark-gap voltage did not give a very close indication of the actual X-ray output. In fact, it was possible to set two machines at the same current and peak voltage, and have one give twice the yield of X-rays of the other. With the c.p.d.c. generating plants, however, the situation is different. Aside from certain differences in tube efficiency, which, as mentioned in another section, can by suitable precautions in design be reduced to 2% or less, with c.p.d.c. the same voltage and current always gives the same output of X-rays. There is no question of wave-form, no difference whether the control be by resistance or auto-transformer. A c.p.d.c. generating out-

fit in New York City will give the same amount of X-rays as a plant on San Francisco, which may be built by a different maker, so long as both are set to the same voltage and current.

The importance of this in therapy can hardly be overestimated. If all hospitals become equipped with c.p.d.c., dosage in therapy treatments will shortly become standardized and no physician will have any more need of making ionization readings on his X-ray plant than he would of standardizing his own serums or antitoxins. But before this state of affairs can come to pass, it must be emphasized that two things are necessary. The voltage must be actually c.p.d.c. and, second, the voltage and current must be accurately measured.

Thus, even with c.p.d.c. installations, the difficulty will not have been completely solved. The second part of the problem still remains, since there does not exist a really good voltmeter, at least one that can be made at a price relatively commensurate with that of the other parts of the equipment. With the rotary switch machines, in one sense, there was no voltage to measure, but with c.p.d.c., if only a good voltmeter were to be had, the fundamental problem of dosage measurement would be solved.

Of course, a wire-wound high resistance provides an accurate method of measuring voltage, but such resistance must have an enormously high value if it is to be left in the circuit continuously, and possibly, means for cooling it would have to be supplied. A value of 100 megohms would be about right as this would not take too much current away from the tube. Unfortunately, if of the usual construction, at present prices such a resistance would cost more than the X-ray machine itself. Experiments are being conducted with such materials as Taylor process fine wires, chemical compositions of high natural resistance as certain selenides and tellurides, with a view to finding a less costly method of construction, and, furthermore, efforts are being made to approach the problem from a different angle by doing away entirely with the high resistance and using some other method.

CHAPTER VI

Ionization Measurements

Because of their speed and comparative ease of operation, ionization measurements have become the most important direct method of determining the intensity of an X-ray beam. At present they are the most reliable of all methods in use, despite the fact that the phenomenon of ionization is a very complicated one and is not completely understood. It is necessary to have some idea of the process in order to understand the need for the various precautions required in precise ionization measurements and the following picture of the mechanism of the action is generally agreed to represent the facts.

When a beam of X-rays traverses matter, we observe three things. A certain fraction is transmitted, another part is scattered and a third portion is absorbed, being ultimately transformed into heat. It is the absorbed portion that is responsible for ionization.

Photo-electrons

The absorbed energy first manifests itself by causing the emission of electrons. They are called photo-electrons from analogy to the electrons emitted by matter under the influence of visible light, but are emitted with velocities some 10,000 times greater than those emitted by ordinary light. The exact velocities depend in each case on the hardness of the X-rays and have for an upper limit that of the cathode rays producing the X-rays in question.

The absorption of X-rays is thus a photo-electric phenomenon. Absorption, photo-electrons, and emission of char-

acteristic radiation are all parts of one process and one involves the other. When the high-speed photo-electrons traverse a gas they collide with the molecules and ionize them, each high-speed electron making many collisions until gradually its velocity is so reduced that it loses the power of ionizing. This is the fundamental process of ionization. Ionization by X-rays is an indirect process, through the medium of the photo-electrons. These are emitted first, and though small in number, have high speed, and passing through the gas, ionize it.

In the case of hard X-rays there is another effect that contributes to the ionization. According to the theory of the Compton effect, the scattering of a quantum is responsible for the recoil of a loosely bound electron, and these recoil electrons have speeds sufficient to cause ionization. It can be shown that the fraction of the energy going into the recoil electrons is very small for soft X-rays, but for very hard rays, e.g., those produced at 200 kv. and filtered through 2 mm. of copper, it is possible that more energy goes into the recoil electrons than the photo-electrons.

The excitation of the characteristic radiation of the gas would return some of the energy back to the form of X-rays, but this radiation is, in general, of long wave-length and is re-absorbed before travelling far.

Ionization Current—Saturation Curve

If two electrodes, e.g., metal plates, are maintained at a difference of potential, when the gas between them is ionized, a current will pass. Such ionization currents are very small, at best of the order of a microampere or so, and often so small that they can only be measured on delicate electrostatic instruments. The variation of the current with the potential difference between the electrodes is shown in Fig. 79. It will be seen that the current increases with the voltage as long as this is low, but ultimately reaches a maximum at which it remains constant and independent of the voltage. This maximum is called the saturation current, I.

The equation for the curve is derived in the text books by means of a differential equation which reduces, in the steady state, to the following rule. The number of ions produced per second by the X-rays equals those lost by recombination plus those diffusing off to the walls and those taken out by the electric field. The equation of the curve may be written:

$$I - i = c\, i^2/v^2 \text{ where } c \text{ and } I \text{ are constants.}$$

Saturation current is obtained when all the ions are taken out by the electric field as fast as they are formed. Whenever ionization current is used as a measure of X-radiation, it is always understood that saturation current is meant.

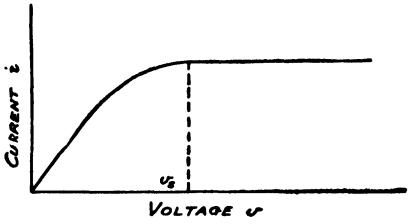


FIG. 79.—SATURATION CURVE.

Referring to the figure, it will be seen that v_s is the saturation voltage, i.e., that voltage sufficient to give saturation current. This is the least voltage that should be used across the ionization chamber.

It should be noted that v_s depends on several factors such as the distance apart of the electrodes and their shape in case they are not parallel plates. For example, if the electrodes are a round rod of small diameter and an enclosing hollow cylinder, a much higher voltage is required because the field intensity is not uniform.

Saturation Voltage

It should be noted also that v_s depends on the intensity of ionization. This is important, since it is a common error to suppose that the saturation voltage is determined by the de-

sign and dimensions of the chamber alone. A rule sometimes given is that for parallel plates, the voltage should be 100 volts for each centimeter of separation. It is obvious that such a rule can hold only as long as the intensity of the X-rays used in the chamber is not too great.

Whenever a new ionization chamber is first put into use, it is advisable, by trying various voltages across it, to obtain a few points on the curve and thus determine what voltage is necessary to give saturation current for the particular intensity of X-rays being used. It is customary to allow a liberal margin of extra voltage in regular use and the chamber may be then regarded as always giving saturation current under any small variation from the original conditions.

If the chamber is to be used for an unusually intense beam of X-rays, or other experimental conditions have changed, it is a simple matter to test for saturation current by adding extra voltage. If an increase in voltage does not change the ionization current, it may be assumed that saturation current has been secured.

Unrestricted Volume

Adopting the picture previously mentioned of the mechanism of ionization, we have numbers of these high-speed photo-electrons darting through the gas, ionizing the atoms they come in contact with. One of these high-speed electrons might easily produce a thousand ions before it has lost its high velocity. Thus for every one of these photo-electrons that should happen to strike the wall of the chamber before it had completed its course, there would be a loss in ionization current of a thousand or so ions. Accordingly, an ionization chamber that is to be free from errors, must have sufficient volume that all of these high-speed electrons are absorbed before they strike the walls.

The following table, computed from data mentioned in Chapter 1 is appended, giving the range in air electrons moving with speeds corresponding to various voltages.

V In Kilovolts	*R* Range in Centimeters
25	1 3
50	5 2
75	12
100	21
150	47
200	83
250	130

Actually the paths are crooked and irregular and so, as a practical guide for designing the clearance distances in ionization chambers, the distances given in the table are perhaps eight or ten times larger than necessary. Duane, experimenting with a chamber having parallel plates whose distance apart could be varied, found no increase in ionization for 160-kv. X-rays after the plates had been separated some 5 or 6 cm.

Coolidge has measured the range in air by a fluorescent method and obtained values considerably less than those in the above table.

Radiation from the Walls

A further possible cause of error is that of the X-rays themselves striking the walls, particularly if these happen to be metal. The radiation falling on the metal produces an emission both of high-speed electrons and characteristic X-rays, the effects of which are added to the ionization being measured.

The three requirements for an ionization chamber are accordingly

I. Saturation current necessary.
II. Volume large enough so all high-speed electrons are absorbed.
III. No X-rays hit the walls.

Ionization Chambers

An ionization chamber is simply an enclosure in which to determine the ionization in a definite volume. It must have two electrodes, but these may be part of the walls.

There are in general two types of ionization chamber:

1. Those made of thick metal in which the beam enters through a small opening or window in a protective diaphragm.

In this type, it is possible to arrange that no X-rays hit the walls and that sufficient volume of unionized air surrounds the beam of X-rays to insure absorption of the high-speed electrons. This type is suitable for use as a standard.

2. Those in which the whole chamber is made of thin material and is completely penetrated by the X-rays.

In this type the above provisions cannot be fulfilled. These chambers are usually made of the lighter elements, aluminum or carbon, to minimize the effect of the X-rays striking the walls. Since the volume is limited, there is no way to compensate for the loss of high-speed electrons, but all errors may be allowed for in one operation by calibrating the chamber against a standard.

For a given beam of X-rays, the ionization varies with different gases. Experiments show that the ionization varies approximately as the absorption but at present there are on this subject very little data entirely free from objections on some point.

Heavy vapors of high atomic number have high absorption and give large ionization currents. As a consequence, they are used in X-ray spectrometry where the very weak intensities necessitate the employment of every possible means of increasing the sensitivity. The radiation from the crystal being monochromatic, its absorption coefficient may be computed and workers using soft radiation (e.g., below 50 kv.) commonly employ a column of vapor long enough to give prac-

tically total absorption of the radiation they are using. Ethyl bromide vapor is probably the most used; others will be mentioned in the section on spectrometry.

For the high voltage used in X-ray therapy, only partial absorption is possible, at least with apparatus of ordinary dimensions. Gases and vapors of high atomic number are generally not used since they all exhibit characteristic absorption in some portion of the spectrum, and the absorption not being parallel to the absorption in the tissue of the body, the biological results would not vary with the ionization. An exception is Dauvillier's use of xenon, which is used on account of the high current it provides, but in that case the readings are of no value until calibrated against a chamber using air.

Air is almost universally used, for it is convenient, the chambers need not be sealed, and it has an average atomic number that is low and sufficiently close to that of tissue that the biological results are parallel to the ionization.

However, air is a mixture. It has been calculated that for certain wave-lengths, possibly as much as 10 per cent of the ionization current may be due to the argon and rare gases. If ionization measurements continue in their present importance, it is quite possible that as the mechanism of ionization is better understood, it will be found desirable to base the fundamental unit on the ionization of a pure gas such as oxygen.

Ionization Units

The unit of X-ray intensity suggested by Duane for biological purposes is that beam of X-rays that would produce an ionization current of one electrostatic current unit in 1 cc. of air.

It is understood here that all three requirements, saturation current, no radiation striking the walls, and sufficient volume to utilize all high-speed electrons are fulfilled. It is further understood that the radiation is comparatively pene-

trating and fairly homogeneous, i.e., the ordinary filtered radiation used in therapy.

The word intensity requires some qualification. It is obvious that true intensity in the physical sense is not meant. Intensity here means simply ability to cause ionization. Perhaps a better choice would be the words "ionization intensity."

The electrostatic current unit is 1/3000 microampere, so that a beam of unit intensity produces an ionization current of $.333 \times 10^{-9}$ amperes per cubic centimeter. The unit is commonly denoted by *e*. It should be noted that this is a unit of ionization intensity, and not of quantity. For example, to get the dosage, it is necessary to multiply the intensity by the time of exposure in seconds so that the dose is thus expressed in *e*-seconds.

Most European instruments for measuring ionization use electrometers or other electrostatic instruments to determine the ionization current and these are more readily calibrated in quantity units than in current units. Accordingly, they use a definition similar to the above save that for the words "electrostatic current unit," they substitute "electrostatic unit of quantity," which is 1/3000 microcoulomb. The unit of quantity of radiation defined in this way is commonly denoted by *R* and it will be observed that *R* is a unit of dosage and of course, 1*R* is equal to 1*e*-second. It has been pointed out by Duane that it is important in estimating and recording dosage to determine and state both the intensity and the time, since, two doses of different intensities, yet equal in amount as measured by the products *intensity* $\times$ *time*, are not always biologically equivalent. They are equivalent within a limited range of intensities but the limit depends on the biological material exposed and other factors. In general, the unit of intensity is the preferable fundamental unit.

It must be realized that the unit is a highly artificial one, something very different from the absolute units of electrical resistance and capacity. This of course does not detract from its usefulness. It is definite, something that can be measured

without too much difficulty, and runs parallel to many biological results.

This last is one of the important advantages ionization measurements have over other methods. Even if it were possible to make as easily and accurately, measurements of true intensity, these measurements would not be so useful for many purposes, especially X-ray therapy or other biological uses. What is wanted here is not a measure of true intensity or total energy in the beam, but rather of the amount that will be utilized in the tissue. Of two beams of X-rays of different wave-length, the one having the greater biological effect is not that which has the greater total energy, but that which will cause the greater amount of energy to be absorbed by the tissue. If total energy measurements only were available, to decide which beam was the more effective, it would be necessary to determine also the effective wave-length of each beam, and the coefficient of true absorption. All of this is done automatically in the ionization chamber, since the readings are proportional to the energy absorbed. The effective atomic number of air being approximately the same as that of living tissue, they have about the same mass absorption and scattering coefficients, and so, for the case of therapy, at least, measurements of air ionization give just the information about the radiation that is required.

Standard Ionization Chamber

The so-called standard ionization chamber described by Duane and others consists of an open ionization chamber, using air as the ionization medium. The X-ray beam passes between parallel metal plates, but is limited by a diaphragm so that no radiation strikes the walls or metal plates. Referring to Fig. 80, one of the plates, *S*, is connected with the battery or source of voltage, the other, *C*, to the galvanometer. This latter has the guard plates *A* and *B* at either end which are simply connected to the case which is grounded.

The metal case, save for the space covered by the plates, is lined with sheet bakelite, and it is desirable to have the outside covered with sheet lead to protect it from radiation that might possibly be scattered from walls and surrounding objects. The air is of course ionized all along the whole beam of X-rays, but the ions are taken out by the voltage only in that section of the beam between the plates. The field is nearly parallel, except near the extreme ends of the guard plates, and the volume of air from which the ions are actually swept out and measured is shown by the shaded area in the figure.

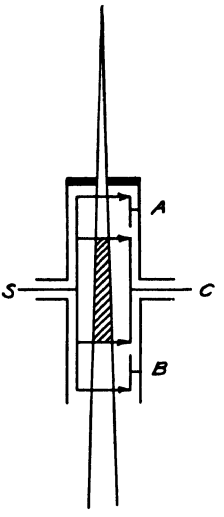


FIG. 80.—STANDARD IONIZATION CHAMBER.

This volume is of the form of a truncated prism, its exact shape depending on the distance of the X-ray tube from the diaphragm, but as will appear, it is unnecessary to determine the exact shape or volume, for it has nothing to do with the measurements.

The object of the ionization measurement is to determine the intensity at a point, and the point in this case is in the plane of the front face of the diaphragm. Now, on the assumption that the tube is sufficiently far away so that the beam does not spread within the chamber enough to make the rays strike the walls, and on the further assumption that the absorption due to the air is negligible over a length comparable with that of the chamber, then the effective volume of the chamber, i.e., the volume to be used to calculate the ionization per cubic centimeter, is determined by two things, the area of the diaphragm aperture and the length of the guarded plate, and is, in fact, equal to the product of these two numbers.

That this is the case may be readily seen from the following reasoning. The intensity of a sharply defined beam of radiation may be considered as the energy per unit length, and

a definite length of the beam may be taken at any point along it, the spreading out as it recedes from the source having no effect on the total energy content, always supposing of course, that the loss by absorption is negligible.

The aperture in the diaphragm should have its edges bevelled to an angle slightly greater than that of the entering beam, so that no radiation can touch the sides of the opening. The size of the aperture must be known and the accuracy with which this is measured is a factor in the accuracy of the whole measurement. Lead is soft, easily bent, and even if the size is correct when built, it could get out of shape through careless handling. It is best to have a gauge made of steel, which can be calipered with a micrometer. This is occasionally tried in the hole, and if light shows through edges, the lead can be peened up to a fit. Figure 81 gives a picture of two such gauges.

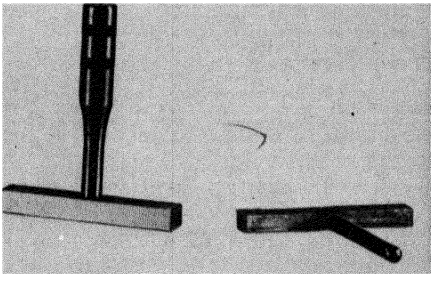


FIG. 81.—APERTURE GAUGE FOR STANDARD CHAMBER.

In a chamber used at the Institute of Cancer Research, the opening was 1 × 5 cm. and the guarded plate was 14.7 cm. long, giving a volume of 73.5 cm.[3]

The distance between plates was 10 cm. which was found by Duane's experiments to be sufficient. It is much less than the theoretical range of 200 kv. electrons, but these have very crooked paths and on the average do not travel far from the

Pressure Type Chamber

Instead of being open to the air, ionization chambers may easily be fitted with a thin aluminum window over the diaphragm aperture and be closed at the opposite end, permitting them to be filled with air at increased pressure. Chambers of this type have been described by Behnken and others.

The main reason for using air under pressure is to utilize the high-speed electrons that would otherwise, in the case of hard X-rays, require a very large volume of air to completely absorb them. The pressure chamber provides a means of utilizing them and still keeping the dimensions of the chamber within reasonable limits. The advantage of a small easily handled chamber, however, is somewhat offset by the added equipment incident to producing and maintaining the pressure.

A second advantage of pressure chambers is that the higher pressure gives larger ionization currents and hence greater sensitivity, although this could be obtained with the open chamber by increasing the length of the plates. This advantage also is offset by the fact that the thin aluminum window must be kept small because of the high pressure, and hence a beam of smaller cross-section must be used. Of course, large windows may be used if they are made thick enough, say ½ mm. aluminum, but this introduces other complications.

As the filters commonly used in therapy include a sheet of aluminum of this thickness, the window can be used to replace that part of the filter, although there might be minor objections to this method from considerations of scattering, etc.

One possibility of the pressure chamber that should not be overlooked is that it can be filled with other gases besides air. This is not so important at the present time, but may be of importance in the future, if it should ever be desirable to use some other gas than air, e.g., oxygen, for the standard. As has been pointed out in another section, the use of a pure gas, such as oxygen, would have certain advantages.

Details of Pressure Chamber

Pressure chambers are usually made circular in cross-section, being often constructed of a piece of tubing having flanged ends, with cover plates bolted on. European chambers commonly use an excentral rod electrode, but this is open to certain objections. Figure 82 shows one constructed at the

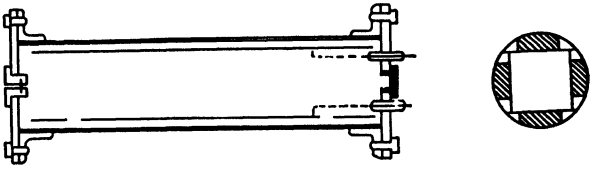


FIG. 82.—PRESSURE IONIZATION CHAMBER.

Institute of Cancer Research with electrodes in the form of parallel plates. Guard plates are used just as in the previously described chambers.

The lead-in insulators are machined from transparent bakelite, with the central wire threaded in place. The joints are made tight by shellac. For experimenting with very high pressures, automobile spark plugs may be used, a little shellac being flowed in around the porcelain to prevent slow leakage.

The details of the window are shown in Fig. 83. This is mounted in a steel plug, the actual size of the aperture being determined by a lead bushing. The hole in the lead bushing is slightly tapered, and all the other holes in the plug are bored larger, so as to give good clearance to the X-ray beam. For the window, sheet aluminum, .002 inch thick is very good, although mica and celluloid have been used. For low pressures the window is simply stuck on with shellac, but for high pressures it is clamped in place as in the figure.

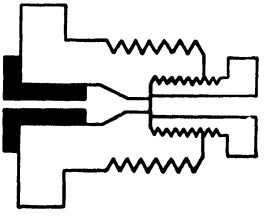


FIG. 83.—WINDOW FOR PRESSURE CHAMBER.

The pressures generally used vary between 6 and 10 atmospheres. The chamber just described was filled with air at 10 atmospheres pressure.

Use of Higher Pressures

While increased current and consequently greater sensitivity can be obtained by increasing pressures, there are certain limits in the use of increased pressure. Obviously, if the pressure were too high, an appreciable absorption would take place within the chamber, so that the intensity at the rear end of the plates would be less than at the front end. Thus the chamber could no longer be used as a standard, at least without applying some corrections.

It may be of interest to consider another possibility, i.e., of raising the pressure so high that almost complete absorption would take place. This has been done, even without pressure, in X-ray spectrometry, by using heavy vapors and working with comparatively soft radiation. To attempt it with air and hard radiation, however, is another matter. The high percentage absorption obtained in spectrometry with dense vapors is not possible for the case of hard radiation using air in the chamber. In the first instance, the absorption is nearly all true absorption, with very little scattering, while in the second case, the effect of scattering is larger than that of the true absorption.

Thus, by using the coefficient of total absorption, one might calculate that a chamber 12 feet long filled with air at a pressure of 1000 pounds per sq. in. would stop 95 per cent of the radiation corresponding to 100 kv. However, this 95 per cent would not be absorbed. Most of it would be scattered, and would strike the side walls. Accordingly, to actually absorb 95 per cent of the radiation, the chamber would have to be, not only 12 feet long, but also 12 feet in radius.

Potential for Ionization Chambers

Chambers of the standard type require from 500 to 800 volts to ensure complete saturation current. The source of potential may be dry cells, a small direct current generator, or the regular supply of alternating current stepped up by a transformer and rectified by some type of vacuum tube.

If dry cells are used, the most convenient are radio B batteries. The current used being negligible, a long life may be secured by protecting them from moisture. If they are to be kept in a box or drawer, it is well to pour in first a quarter inch of melted paraffin, and when this is cold, the batteries in units of 22½ or 45 volts may be arranged on the hard surface, and the terminals connected. When all is complete, another quarter inch of paraffin poured in will hold the units in place. When it is necessary to replace a unit, the old one may be pried out and the new one wedged back into the cavity. In some cases it is desirable to cover the units and connections completely with the melted paraffin, but this causes difficulty when a unit has to be replaced. A high resistance should be placed in series with the battery.

An installation built at the Institute of Cancer Research consisted of a chest of three drawers, each containing six 45-volt units arranged on paraffin. Each drawer also contained a small resistance unit of about 1/10 megohm, such as used for radio grid leaks, mounted in fuse clips. When not in use, the ground connection was broken and the resistances removed from the clips, thus opening the circuit in three places.

That these resistances are necessary is evidenced by the fact that before they were installed the battery was capable of giving a painful shock if accidentally shorted through the body.

Small motor-generator sets giving from 350 to 1000 volts are on the market, being used principally for supplying the plate voltage in amateur radio transmitting stations. These serve very well for the voltage supply for the chambers. They have been used with a condenser across the terminals, but ordinarily this does not appear to be necessary.

A small transformer and vacuum tube rectifier, if combined with a suitable filter circuit, provides a reliable and constant source of potential. Figure 84 gives the diagram of a circuit embodying an S-tube rectifier, which does not require a hot filament. The set can be compactly arranged in a small box, and when needed, simply plugged into a lamp socket. A

suitable inductance for the filter circuit consists of three audio transformers such as are used in radio sets, the secondary terminals only being connected. The condensers may be ordinary telephone condensers of 1 mf. capacity.

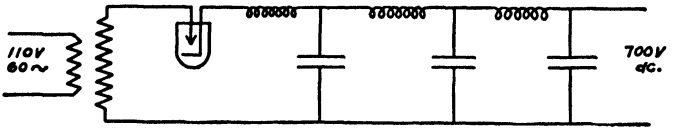


FIG. 84.—CIRCUIT FOR HIGH-POTENTIAL D.C. SOURCE.

Instead of an S-tube, a contact rectifier or thermionic rectifier may be used. For small chambers which do not require high voltage for saturation, any of the B-eliminators on the market for use in radio sets may be used.

Galvanometer Calibration

The very weak currents employed in air ionization chambers necessitate a galvanometer of high sensitivity. As a means of calibrating it, a standard cell and resistance are used. These may well be wired up in permanent form since they will be needed every time the galvanometer is used. Figure 85 gives

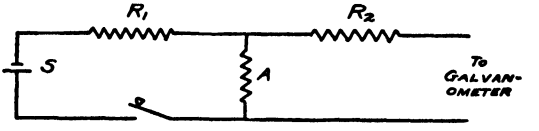


FIG. 85.—CIRCUIT FOR CALIBRATING GALVANOMETER.

a diagram of the connections. R_1 and R_2 should preferably be over 50,000 ohms.

Using a Weston standard cell, S, and a L. & N. galvanometer, type 2285, such a unit has been made with resistances as follows: $R_1 = 100{,}000\ \Omega$, $R_2 = 300{,}000\ \Omega$, $A = 99\ \Omega$. This unit then supplied 10 electrostatic units per second or 1/300 microampere.

When using a galvanometer to measure ionization currents, instead of an electrometer, an instrument of high sensitivity is

required. A sensitivity of at least 10,000 megohms is required, and more is desirable. Leeds & Northrup manufacture galvanometers with sensitivities upwards of 100,000 megohms. In actual use, the rated sensitivity may be increased by using a telescope and scale at a distance of 3 or 4 meters.

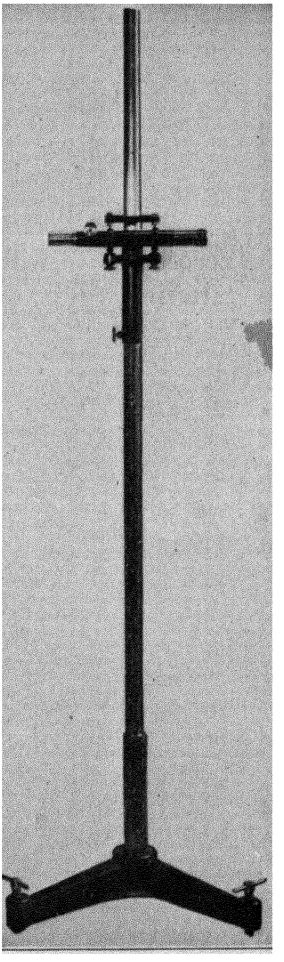


FIG. 86.—CATHETOMETER.

Measuring Distance

Since intensity varies as the square of the distance, accurate measurements of the distance must be made. Elaborate precautions taken with other parts of the system are nullified if the distance of the ionization chamber is not properly determined. Thus, at 40 cm., a distance commonly used in ionization measurements, an error of 2 cm. in the distance can amount to as much as 10 per cent in the result, and an error of 2 cm. can readily be made if a tape measure is held up to a point judged by the eye to be on the same level as the target of the tube. The main difficulty with distance measurements lies in the fact that the target of the X-ray tube is inaccessible; in fact, if the tube is in a lead holder or oil tank, it is not even visible. The most satisfactory way of making these measurements if the target can be seen, is with a simple form of cathetometer. The focal spot can be located on the face of the target by pin-hole photographs, if extreme accuracy is desired, and the distance of the ionization chamber determined to within less than a millimeter. See Fig. 86.

Correction for Leak

A point of practical importance in using an ionization chamber is that there usually is some leakage current. This may be due to current through the insulation, or may be ionization current caused by scattered radiation or other causes.

In using a standard chamber with a galvanometer, in order to correct for the leak, the galvanometer zero is determined after the voltage is on the plates and the X-ray tube running, by placing a lead shutter over the diaphragm opening. It is very important that the zero be obtained in this way, for if the zero be taken with the tube not running, not only leak due to scattering will be omitted, but also any electrostatic effect of the high voltage, which often has an influence on the delicate galvanometer.

If an electroscope or electrometer is used and the current determined by timing with a stop watch the passage of a spot of light across a scale, the intensity is represented by the reciprocal of the number of seconds. The correction for leak must be made by noting the time for passage of the light spot when the beam of X-rays is cut off by a lead shutter as before, determining the intensity of the leak by taking the reciprocal, and subtracting this from the intensity previously found.

Small Ionization Chambers

According to the classification previously mentioned, ionization chambers of the second type are those that are completely penetrated by the X-rays. They are sometimes called small chambers, since they can be made very small, although they need not be so. One reason for the need of this type is that in water phantoms, or wherever scattered rays coming from all angles must be measured, the standard chamber cannot be used, while chambers that are completely penetrated by the radiation have no diaphragms and can receive and measure all radiation falling on them. The smaller sizes are consequently useful for introducing into cavities in the human body.

Another use for this type of chamber is in the measurement of hard γ-rays from radium, for here no chamber requiring a diaphragm can be used, since these rays will penetrate any ordinary diaphragm.

These chambers are frequently of a portable type, especially those that employ a gold-leaf electroscope, or a string electrometer.

Since the requirements concerning X-rays striking the walls cannot be fulfilled, it is necessary that these be made of a material of low atomic number. Graphite has been used, organic substances painted with carbon inks, very thin aluminum and other materials.

It is also impossible to fulfill the requirements regarding unrestricted volume. On this account it is necessary to calibrate the chamber against a standard ionization chamber. Such a calibration consists in comparing the readings over a range of wave-lengths. It is desirable that the readings of the small chamber bear a constant proportionality to those of the standard over a large range of wave-lengths. The reason for this is that it is frequently impossible to determine the exact wave-length at which the small chamber is used and if the proportionality is constant, no error will result from an uncertainty in wave-length. As an example, the wave-length of a direct beam of X-rays may be known very accurately, but the small ionization chamber placed under a patient will receive scattered radiation of a different and more or less unknown wave-length. If the calibration curve varied rapidly with the wave-length, there would be difficulty in deciding what point on the curve to use.

A point to be noticed in the design of small chambers is that although they are specially designed to receive radiation from all angles, they are shielded from radiation from one direction, i.e., that in which the leads or cable is attached. The insulators at this point are usually set in a metal tube, but care must be taken to make the dimensions such that the solid angle subtended from the center of the chamber by the tube and cable is sufficiently small that the loss of radiation can be neglected.

Well designed chambers do not lose over 1 or 2 per cent through this shielding, especially if, when the chamber is in use, the cable is placed in the direction from which the least radiation is expected.

The original design of a very small chamber known as the *fingerhutkammer* is due largely to Friedrich. One of these is shown in section in Fig. 87. The essential features are the

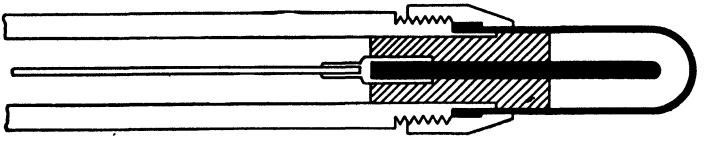


FIG. 87.—FINGERHUTKAMMER.

flexible metallic tube to shield the lead to the electrometer, and the inner electrode of graphite supported on amber insulation. The outer electrode is the thimble-shaped cap of horn or celluloid which is graphitized on the inside to render it conducting.

Duane has described a small chamber, about 2 × 2 × 8 cm. containing parallel aluminum plates enclosed in a casing of hard rubber and sealing wax. He mentions an experiment showing that of the two chambers shown in Fig. 88, satura-

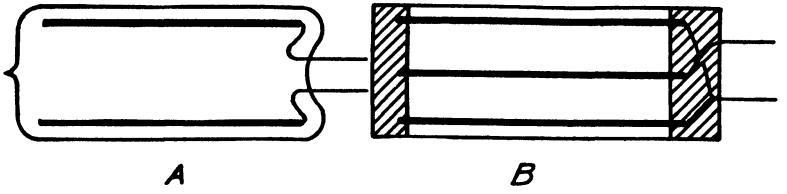


FIG. 88.—TWO TYPES OF SMALL IONIZATION CHAMBERS.

tion current is difficult to produce in *A*, but comparatively easy to produce in *B*.

In *A*, the metal plates did not cover the entire side of the glass container and left corners from which even a comparatively high voltage did not suffice to withdraw all the ions. In type *B*, the metal plates extended completely across the enclosed air, the edges actually touching the hard rubber or being embedded in the sealing wax. This chamber, while small

enough to be used with a water phanton etc., still gave sufficient current that it could be used with a galvanometer.

Ionization Measurement with a Water Phantom

Small ionization chambers such as have just been described are particularly adapted for use with a water phantom. The water phantom is usually a wooden box filled with water, which represents the tissues of the human body, and ionization measurements are made at various depths below the surface to determine the variation of intensity with depth. The intensity at a point beneath the surface will depend on the horizontal and vertical coordinates of the point, the hardness of the radiation, the distance of the X-ray tube from the surface, and the size of the portal. Since the X-rays are scattered, the measurements are not confined to the path of the direct beam. The size of the portal is determined by a lead diaphragm above the surface of the water.

Usually, in beginning a series of such measurements, the water phantom is removed, and the intensity of the direct beam is measured at a point which will be at the surface of the water when the phantom is in position. This intensity is called 100 per cent, and when the phantom is back in place, the intensity at this point will be increased by the scattering from the water and thus will then be something over 100 per cent.

A convenient way of recording the intensities at points beneath the surface is by a series of curves of iso-intensity. Thus Fig. 89 gives a typical curve for an intensity corresponding to 10 per cent. By drawing these curves for various percentages, say 15, 20, etc., the whole series is obtained. A new series must be made for different hardness of radiation, different size of portal, etc.

Miscellaneous Types

For some purposes, it is useful to have an ionization reading that is not used for purposes of computing dosage, but

simply as a check on the constancy of the tube and apparatus. For such purpose, an ionization chamber that can be placed in the filter holder just beneath the filters and can be left in during treatment, is desirable.

It must be thin and flat, and offer no appreciable absorption to the beam. Such a chamber using graphitized silk for plates

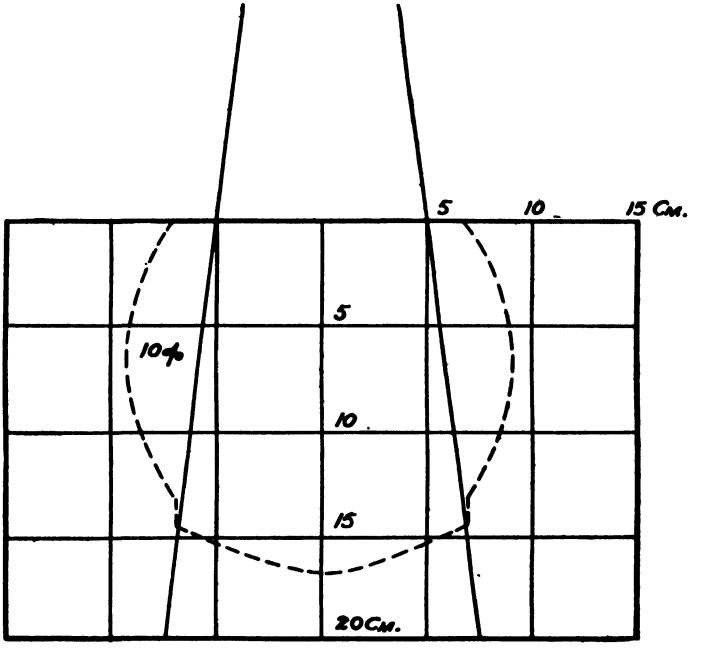


FIG. 89.—ISO-DOSAGE CURVE IN WATER PHANTOM.

has been described by Failla. Carbon paper has also been tried.

These chambers can be calibrated against a standard, but since other properties have been sacrificed for the sake of making them fit the filter holder, the calibration is more difficult. After all, their chief use is as a check. They are easy to use, and can be left in place continuously if desired, and their indications are valuable in case of accidents happening to the voltmeter, milliammeter, or other parts of the system. Like most of the other chambers, however, their indications are not particularly trustworthy on a rainy day.

A modification of the flat type of chamber sometimes seen, is one, where, in order to increase the effect, the electrodes consist of a large number of thin sheets of metal, through which the X-rays must pass. Brass and tinfoil have been used, the latter apparently giving the larger current. However, the readings of such chambers are unreliable for a number of reasons. While the metal sheets are thin, in the aggregate they exert a considerable filtering effect on the beam of radiation. Also, the large amount of ionization produced is probably chiefly due to the fluorescent radiation from the metal, and the chamber will show increased sensitivity for those wave-lengths that excite its characteristic radiation.

An ionization chamber designed by Kegerreis has an unusual method of shielding which permits the use of a single cable between the chamber and the galvanometer. The connections are shown in diagrammatic form in Fig. 90 at *A*.

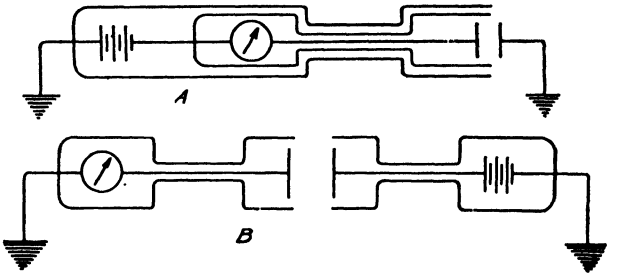


FIG. 90.—TWO TYPES OF SHIELDING.

For comparison, the usual method of shielding, such as used on the standard ionization chamber, is shown at *B*. In each case, the constricted portion represents the cable. In *B*, the leads are shielded separately. In *A*, the galvanometer and its shield are maintained at high voltage, being separated from the ground by the chamber at one end, and the battery at the other. A second grounded shield then surrounds the whole apparatus. The cable to the chamber thus consists of a wire with two concentric metal coverings the outer of which is grounded.

Xenon Chamber

An ionization chamber consisting of a small glass bulb containing xenon at about atmospheric pressure has been developed by Dauvillier and is manufactured and sold in France. It has not had any extensive use in this country. Its chief advantage is that large ionization currents are obtained, of the order of a microampere or so, and consequently, instead of the customary reflecting galvanometer, a pointer instrument may be used. Xenon, however, having selective absorption within the range of wave-lengths used in therapy, the same objections would apply as in the case of ethyl bromide and methyl iodide.

Amplification of Ionization Current

It is possible to amplify small currents such as produced in an ionization chamber or photoelectric cell by means of a radio tube acting as an amplifier. A simple circuit for such an amplifier is illustrated by Fig. 91 in which *R* is a resistance

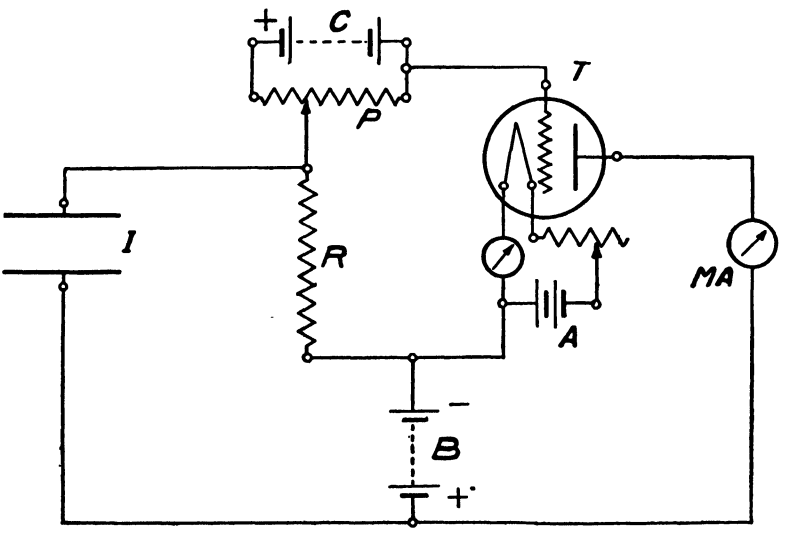


FIG. 91.—CIRCUIT FOR AMPLIFICATION OF IONIZATION CURRENTS.

of 100 megohms, *I* is the ionization chamber and *P* is a potentiometer for varying the potential of the grid of the amplifier

tube *T*. With no current in the ionization chamber, the grid potential is adjusted to a negative value with respect to the filament, such that the milliammeter in the plate circuit reads zero (or some small value). Now when an ionization current is produced in the chamber, the grid becomes less negative due to the voltage drop in the high resistance *R* and consequently an increased current flows through the milliammeter.

The apparatus must first be calibrated by applying known potentials on the grid and noting the corresponding plate currents, from which a calibration curve can be made. The amplifier tube should have a high amplification constant and must be of special construction to prevent leakage currents over the inside or outside of the tube. It is essential that the grid connections be well insulated and that the whole apparatus be completely shielded by a metal case.

An apparatus employing an amplifier tube is manufactured by the Siemens-Reiniger-Veifa Company and has been described by Siegmund Strauss.[1]

In this instrument the grid is allowed to charge up positively by the ionization current until the plate current reaches a predetermined value which operates a relay, discharges the grid, and the process is repeated automatically as many times as desired. The instrument is calibrated in *"R"* units and is used chiefly to measure dosage in X-ray therapy.

[1] Acta Radiologica IX, 55, 482 (1929).

CHAPTER VII

Total Energy Measurements

When a beam of X-rays strikes a block of solid matter so as to be almost completely absorbed in it, together with all secondary effects, the energy of the radiation is ultimately converted into heat. This principle can be used as a method of determining the total energy of the beam of X-rays. The radiation is allowed to strike on a block of matter and raise its temperature, which is measured with a sensitive thermometer. The amount of heat collected in a given time being known from the temperature rise, the total energy of the beam is determined, provided suitable measures have been taken to minimize or correct for losses.

The actual mechanism of the conversion of the X-rays into heat is somewhat as follows: The energy of the primary beam is divided among the transmitted, scattered, fluorescent and absorbed portions. The absorber is made sufficiently thick so that the transmitted fraction is reduced to 1 per cent or less.

The absorbed fraction has its energy converted into the kinetic energy of photo-electrons which is gradually converted into heat as the electrons move through the material and lose velocity. As there are still the fluorescent and scattered portions to be accounted for, it cannot be said that all the energy of the X-rays is completely transformed into heat, but both the fluorescent and scattered radiation, in passing through the material are partially reabsorbed and so a part of their energy is ultimately transformed into heat. Furthermore, the material for the absorber is chosen with a view to insuring that not only shall the fraction of fluorescent and scattered radiation be as small as possible but that a large percentage of both of

these fractions shall be reabsorbed before they can escape from the absorber.

Usually, the material for the absorber is chosen to be a metal of high atomic number, such as lead, and consequently, scattering of X-rays is reduced to a minimum. The loss of some photo-electrons cannot be easily avoided, but this loss is principally from the surface, for all electrons liberated in the interior are reabsorbed before they can escape. This would also be true, to a certain extent, for the fluorescent radiation. Some loss by fluorescent radiation can be prevented by always taking care that the X-ray beam used has not high enough frequency to excite the K radiation of the absorbing material.

Losses of both electrons and X-rays can be still further reduced by the employment of a cup-shaped absorber, something on the principle of the Faraday cylinder. If made sufficiently deep, any radiation scattered from the bottom would be largely caught by the sides and the amount escaping through the mouth of the cylinder would be comparatively small. Such an arrangement has not been extensively used, however, for possibly several reasons. It is difficult to construct; it requires more material and so its heat capacity is high, and it is difficult to shield against certain other energy losses.

The loss of energy in the form of heat is probably more serious than the loss of energy in the form of X-rays, but this can be partially prevented by surrounding the absorber with proper insulation. Wool batting and eiderdown have been used, and in some cases the absorber has been mounted in a vacuum bottle. Thus, while the heat losses cannot be entirely prevented, they can be kept small, and the residual losses can be allowed for by various compensatory methods in determining the total quantity of heat. For example, instead of calculating the quantity of heat from the temperature, mass, and specific heat of the lead absorber, it may be determined by burying a heating coil in the lead and finding the amount of electrical energy that must be supplied to this heating coil to bring the lead to the same temperature as the exposure to X-rays. Since the lead is brought to the same temperature in

each case, the heat losses would be the same and may be neglected.

Heat-measuring Apparatus

It is very important that water-cooled X-ray tubes be used in total energy measurements of this kind. There are two reasons for this. In the first place, the power input can be increased eight or ten times that possible with the uncooled tubes. The advantages of such a gain in sensitivity are obvious, especially in a case like this where the sensitivity is, at best, very small. A second reason for the use of water-cooled tubes is the fact that the target, running at low temperature, does not disturb the measuring apparatus nor permit heat to radiate into it as it would from a white hot target of the universal type. While measurements have been made in the past with uncooled tubes, the difficulties have been enormous. Any one who has worked with sensitive thermometers can easily appreciate the difficulty of carrying on precise temperature measurements in the vicinity of a piece of white hot metal radiating from 500 to 1000 watts.

Some tests on the disturbing influence of a hot target were made at the Institute for Cancer Research. As a substitute for the heated target, a glow coil unit from a radiation heater was used. This heater was rated at 660 watts which is less than the rating of the deep therapy X-ray tube.

This heater coil would affect a sensitive resistance thermometer through a considerable amount of shielding even when placed at distances greater than 40 cm., and the experiments left no doubt that for precise total energy measurements, the white hot target must be avoided.

The absorber must be made sufficiently thick to stop practically all the X-rays, but should not be made unnecessarily thick for that would increase its heat capacity and consequently lower the sensitivity of the whole apparatus. If the apparatus were to be used for a single wave-length, it would be a simple matter to calculate the optimum thickness, but

for general use, all that can be done is to make the absorber thick enough to stop, say 96 per cent of the shortest wave-length with which it is to be used.

The thermometer or temperature-measuring apparatus must be very sensitive as the temperature changes are usually very small, sometimes not more than a few thousandths of a degree. Various types have been used, thermocouples, resistance thermometers, and devices depending on the expansion of gases or liquids.

As will appear, despite the small amounts of heat dealt with, these measurements are not particularly difficult. On the contrary, they are comparatively simple, once the proper apparatus is assembled. How then are we to regard the conflicting results of certain earlier experimenters? The trouble probably lies, not in the energy measurement but in whatever measurements they were compared with.

A measurement of the total energy of a beam of X-rays is of no value by itself. Some other measurement must be made, or some experiment performed with the same beam, in order that we may say a beam of so much total energy gives so much of the other effect. Thus, a measurement of the energy of a definite quantity of X-rays implies that this definite quantity of X-rays has been determined by some other method. There are two methods commonly used.

The energy may be determined as a fraction of the power supplied to the tube, thus leading to a determination of the efficiency. The efficiency is a function of the voltage, and the measurements should be extended over a range of voltages. On the other hand, the energy of a beam of X-rays may be measured and this compared with an ionization measurement made with the same beam. This leads to a determination of the ratio of ionizing effect to energy, and the ratio being possibly a function of the wave-length, the measurements should be made with monochromatic rays, and extended over a range of wave-lengths.

Efficiency of X-ray Tube

A measurement of the total X-ray output of an X-ray tube has been made by Terrill.[1] The absorber was a coil of lead wire which at the same time acted as a resistance thermometer. Two coils were used, one being exposed to the X-rays, the other occupying the opposite arm of the thermometer bridge for compensation. A switch was provided making it possible to disconnect one of the coils from the thermometer bridge and pass a measured current through it, so that the amount of heat received from the X-rays could be determined by measuring the electrical energy that must be absorbed in the coil in order to give the same temperature rise. The coils are of the pancake type, 5 cm. in diameter, .28 cm. thick and have a 1-cm. hole in the center. They are wound with No. 26 single silk-covered lead wire, have a resistance of 36 ohms each and a weight of 32 gm. or 1.6 gm. per sq. cm. of area. A diagram of the bridge arrangement is shown in Fig. 92.

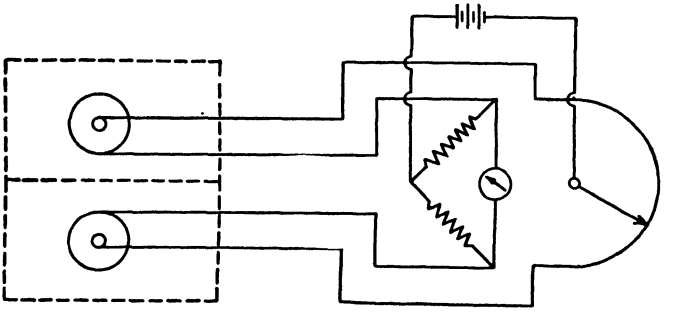


FIG. 92.—DIAGRAM OF APPARATUS FOR TOTAL ENERGY MEASUREMENT.

The coils are supported on wool batting in a lead-lined shield of heavy sheet brass. So long as both coils are affected alike, the actual temperature is immaterial. A series of metal containers, one within the other, each separated from the next by an air space, makes a very efficient shield, but in the present case was unnecessary as the single shield was found sufficient.

[1] Terrill, H. M., Phys. Rev., 28, 438 (1926).

The apparatus is shown in position beneath the tube in Fig. 93. The windows to admit the X-rays to the coils are made of two sheets of .002 cm. aluminum, separated by a 5 cm. air space. There is also in the path of the rays, another sheet of the same foil close to the tube, as well as a sheet of lens paper within the brass shield, which serves to prevent air currents. A fluoroscope is used to center the measuring coil under the X-ray tube and to adjust diaphragms to limit the beam of radiation.

Some time before readings are made the windows in front of the coils are closed by lead shutters, the X-ray tube switched on and temperature conditions allowed to come to equilibrium. The bridge being balanced, X-rays are allowed to fall on one of the coils by opening the shutter, and at definite time intervals the measuring current is switched on the bridge long enough to read the galvanometer, or rebalance the bridge by cutting in resistance with the slide wire. Using the measuring current only during the few seconds required to make the reading avoids unnecessary heating of the coils. To determine the energy collected, the coil is radiated for a period of five minutes, readings of the galvanometer or slide wire being made at half-minute intervals, after which the X-rays are shut off and the coil allowed to cool. It is then disconnected from the bridge by a mercury switch and the amount of current is found by trial that must be passed through it to give the same galvanometer deflections or the same slide wire readings in the same time intervals. When this amount of current is known, the energy, computed by the I^2R relation is assumed to be equal to the energy of the X-rays. The requirement of *same time interval* is very important, for it is by this that compensation for heat losses is effected. If the coil, in the two cases, is heated to the same temperature during the

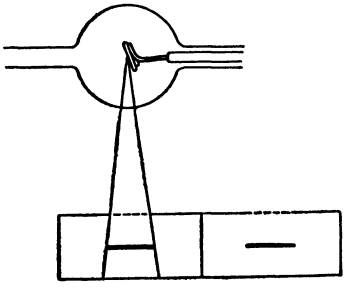


FIG. 93.—APPARATUS IN POSITION FOR TOTAL ENERGY MEASUREMENT.

same length of time, it is reasonable to assume that the losses are the same. It will be noted that the time interval used was five minutes. If the heating is continued too long, a point of equilibrium is finally reached at which the lead absorber loses heat as fast as the X-rays are supplying it. In the present apparatus, with the X-ray intensities ordinarily used, equilibrium was approached in something less than thirty minutes. It is very desirable that the measurements are not carried too close to the equilibrium point.

For measurements of the total energy as a fraction of the input, a water-cooled tungsten target tube which is excited by constant potential direct current, is used. The radiated coil is held at 27.3 cm. from the target and subtends .027 unit of solid angle, or 1/466 of the whole sphere.

The voltage is varied upward from 30 kv. in steps of 10 kv. The current is adjusted so as to keep the output approximately constant. While preliminary runs show that the energy collected is proportional to the current through the tube, it is advisable to make all readings at approximately constant output. The lead coil then receives the same amount of heat each time, and if there are errors due to heat losses, etc., these affect only the absolute value of the results. In these measurements, this amount of heat is 39×10^5 ergs in a five-minute period.

In the following table is listed for each voltage the fraction of the input radiated in unit solid angle. The third

Voltage, Kilovolts	Fraction of input in Unit Solid Angle	Column 2 $\times 2\pi$
30	39×10^{-6}	.00025
40	68×10^{-6}	.00043
50	96×10^{-6}	.00061
60	137×10^{-6}	.00086
70	179×10^{-6}	.00112
80	215×10^{-6}	.00135
90	260×10^{-6}	.00163
100	305×10^{-6}	.00192

column gives the product of these values and 2π, being the energy that would be radiated were the intensity uniform over the lighted hemisphere. This is an approximation to the total amount of X-ray energy actually radiated from the tube.

To investigate the general law followed by the values in column 2, they are plotted against the square of the voltage in Fig. 94. Up to 69 kv. they lie quite closely on a straight line, there being but a slight deviation from this at the extreme low voltage end.

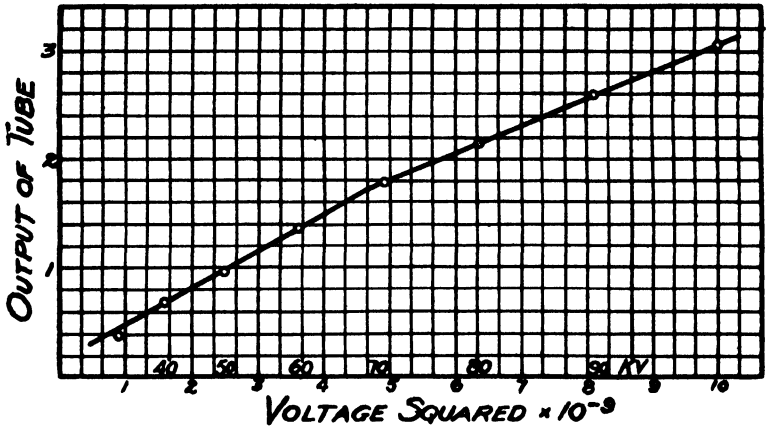


FIG. 94.—RELATION BETWEEN TOTAL ENERGY AND VOLTAGE.

No corrections are made for the absorption in the walls of the tube. To throw further light on this point, the readings are repeated with interposed filters of one to three sheets of half-millimeter aluminum, one of these sheets being roughly equivalent to the wall of the tube. It is found that the filters have little effect on the general shape of the curve, all the points being lowered proportionately.

A downward change of slope occurs between 69 and 70 kv., for which a possible explanation may be found in the filtering action of the target itself. The face of the target stands at an angle of 70° to the direction of the cathode and 20° to that of the measuring apparatus. Hence, in all cases, the X-rays pass through more than twice as much tungsten as the

cathode rays that produced them and this distance may be enormously increased by the presence of small pits and scratches in the face of the target. The sudden increase of the absorption above the *K* limit would then affect the radiation produced at voltages over 69.3 kv., and so account for the change of slope at this point.

These results are in agreement with the work of Ulrey[2] who found, by integrating curves obtained with a spectrometer, that the total X-ray emission of tungsten is proportional to the voltage squared, between the limits 20 and 50 kv. They are also in agreement with the results of Kegerreis,[3] who made determinations of the efficiency by a thermometric method over a range of voltages extending approximately from 100 to 200 kv. using a machine equipped with a rotary switch rectifier.

Energy of Ionization of Air

Comparison of the total energy with the ionization in air is a more difficult task. While it is a comparatively simple matter to make an ionization reading of an X-ray beam and then determine its total energy content by means of the apparatus described in the preceding section, such measurement is valueless unless there is determined at the same time the wave-length of the X-ray beam and the actual amount of energy utilized in producing the measured ionization.

The energy required for ionization depends on the energy absorbed by the air and it is consequently necessary to determine what fraction of the total energy is absorbed by the air in the ionization chamber. This is the difficult part of the procedure. The only available method is to calculate this fraction from the known absorption coefficient of air, and as this coefficient varies with the cube of the wave-length, unless the X-ray beam is strictly monochromatic, it will be exceedingly difficult to arrive at an accurate result. The energy absorbed in one second being determined, the number of pairs of ions

[2] Phys. Rev., 11, 401 (1918).

[3] Kegerreis, Phys. Rev., 29, 775 (1927).

liberated in one second is found from the ionization current and so the absorbed energy necessary to produce one ion pair is immediately known. The energy required to produce an ion pair can be expressed in ergs, but it is, in some ways, more convenient to express it in volts. That is, the energy in volts is the potential difference necessary to give an electron that much energy, and is found by dividing the energy in ergs by 1.59×10^{-12}.

The method just outlined has been used by several experimenters. The X-ray beam has been made as nearly monochromatic as possible by proper choice of the voltage across the tube, the material and thickness of the filter, and in some instances, selection of the metal used for the target of the X-ray tube in order to utilize the *K* characteristic radiation.

There would be a great advantage in using a strictly monochromatic beam of X-rays such as produced by a crystal spectrometer, but so far, no experiments have been recorded where this has been actually done. While the absorption coefficient could be determined to a high degree of precision and the fraction of the total energy absorbed readily calculated, the intensity of such a beam is so weak that it would be very difficult to determine its energy by a thermometric method. However, with improvements in the sensitivity of the measuring apparatus, and increases in the power of X-ray tubes, there are here possibilities for future development.

A modification of the method first described would consist in employing an X-ray beam of the roughly monochromatic radiation obtained by filtering, but instead of attempting to calculate the fraction of the energy absorbed in a small volume of air, to use an ionization chamber large enough and a medium dense enough to absorb approximately all the energy in the beam. If the energy were all absorbed, no computations would be necessary. One difficulty, however, confronting this procedure, is the increasing ratio of scattering to true absorption with decreasing wave-length. An ionization chamber filled with ethyl bromide vapor may be made long enough to almost completely absorb radiation of wave-length approximating the

K characteristic radiation of molybdenum, and such chambers have been often used on X-ray spectrometers. It is a different matter to design a chamber containing air that would be able to absorb completely the *K* characteristic radiation of tungsten. It is true that if a chamber were built say 12 feet long and filled with air at a pressure of 1000 lbs. per sq. in., practically no radiation of the above wave-length would reach the farther end. However, the greater proportion of this radiation would be scattered, and if the chamber were a tube of small diameter, this scattered radiation would strike the walls. Thus, to ensure that all the scattered radiation would be reabsorbed, it would be necessary to make the chamber 24 feet in diameter. Consequently, there seems little hope that this method will ever be of use.

Measurements of Ionization Energy

Determination of the energy required for ionization of air have been made by Grebe and his co-workers Boos and Kriegesmann, by Kircher and Schmitz, by Kulenkampff,[4] and others, but none of these measurements can be said to be very precise and they all depend on certain approximations.

Kulenkampff's apparatus consisted of a piece of sheet silver to absorb the radiation and attached to the silver, an iron-bismuth thermopile to measure the temperature rise. He took particular care to secure a series of nearly monochromatic beams of X-rays of different wave-lengths by using X-ray tubes having targets of various metals, in each case with the proper voltage and filter to isolate some line in the characteristic spectrum. Even with such precautions, the beam is not truly monochromatic and Kulenkampff determined with a spectrometer what percentage of general radiation passed through the filter in addition to the desired characteristic line, and also the energy distribution in this background of general radiation. The value of his results lies in the very elaborate calculation of the absorption coefficient for the complex mixture of wave-lengths used.

Kulenkampff finds that throughout the range of wave-

[4] Ann. Physik, 79, 97 (1926).

lengths in which he worked, 2 A to .56 A, the energy of ionization is independent of the wave-length and equal to 35 volts per ion pair. Of course, it is quite natural to wish to generalize immediately, and say that the energy of ionization is constant for all wave-lengths. Such a conclusion, however, is certainly not justified. It will be necessary to actually perform the measurements with the shorter wave-lengths before we can reach any conclusion regarding them, and incidentally, it may be remarked that the difficulties become greater with shorter wave-lengths.

It must be observed that all Kulenkampff's measurements were made at comparatively long wave-lengths. The hardest radiation he used is much softer than the radiation regularly employed in deep therapy. At the wave-lengths he used, the Compton effect is comparatively small while with 200 kv. filtered radiation, possibly as much as one-half the energy is absorbed in the form of recoil electrons. The efficiency of ionization through the emission of photo-electrons may well have a different value from the efficiency of ionization through recoil electrons. Accordingly, there is no reason to expect that a value for the energy of ionization found constant over a limited range will hold constant for those shorter wave-lengths at which no satisfactory measurements have yet been made.

Absorption Coefficients of Air

The following table of air absorption coefficients taken from Kulenkampff's article is given here as being of general interest.

Wave-length in A units	μ/ρ
.3	.073
.4	.173
.5	.348
.6	.597
.7	.960
.8	1.40
.9	2.00

It should be noted that these are coefficients of true absorption, and as such are proportional to the cube of the wave-length. Accordingly, this law might be used to extrapolate the table to shorter wave-lengths. Thus the value for .2 A would be .022.

It might be well to point out that even if the beam of X-rays were strictly monochromatic such as given by a crystal spectrometer, there might be still some difficulty in determining the proper value of the absorption coefficient to use as shorter wave-lengths are approached. As shown by Compton,[5] the total absorption coefficient may be written

$$\mu = \tau + \omega + \sigma,$$

where τ represents the fluorescent absorption; σ the energy lost as X-rays scattered from the original beam; and ω the momentum absorption, or the energy imparted to recoil electrons in the scattering process.

In calculating the value of the absorption coefficient to be used, we should expect to use the value $\tau + \omega$ since the recoil electrons undoubtedly contribute to the ionization.

While τ can be extrapolated by the λ^3 rule from observations at longer wave-lengths, there is much more uncertainty in the value of ω.

Estimates have been made for values of ω, but until something more accurate is available, it is hardly possible to hope to obtain accurate determinations of the energy of ionization at short wave-lengths.

Ionization by Cathode Rays

Experiments on the determination of critical potentials have shown that when electrons are accelerated through gases whose pressure is such that the mean free path is comparable with the distance between the electrodes, direct measurements may be made of the potential difference at which the electrons excite or ionize the gas molecules at impact. The results of

[5] Bull. Nat. Res. Council No. 20, p. 47 (1922).

several observers place the ionization potential of nitrogen at somewhere near 17 volts and that of oxygen at about a volt and a half less, so that a mean value for air would be slightly less than 17 volts. The much higher values obtained for ionization by means of X-rays would seem to indicate that such ionization is a rather inefficient process and that some energy is expended in other effects such as possibly heating the gas.

Since ionization by X-rays is an indirect process, accomplished through the medium of high-speed photoelectrons, it would be of great advantage to have direct measurements on the total number of ions formed by each high-speed electron and to determine how this number varies with the velocity of the electron. There have been several attempts to determine this, some of them comparatively old, but none entirely satisfactory. In general, the apparatus required is a vacuum chamber in which the electrons are accelerated and an ionization chamber, filled with gas or air in which the ionization is measured. The two are separated by a thin aluminum window through which the electrons readily pass. At first thought, a piece of apparatus like the Lenard ray tube would seem to offer increased advantages for an experiment of this kind, but the difficulties imposed by the thin window still remain. The cathode rays, after passing through the window, are no longer of uniform velocity, and further, there are produced in the passage of the cathode rays through the window, and also because of their striking the anode, some soft X-rays that ionize the air in the vicinity and cause error in the measurements.

Attempts to calculate theoretically the energy of ionization of X-rays or to determine the law of the variation of this energy with the wave-length, usually require as a starting point data on the ionization by cathode rays. Consequently, it is to be hoped that the future will bring more precise experiments on the ionization by cathode rays as these may serve to clear up some of the questions regarding the energy of ionization of X-rays.

Value of Total Energy Measurements

It has been shown that total energy measurements like all other measurements, become of value only when some application is made of them; i.e., when the measurement is applied to a beam of X-rays that has produced some other definite effect, or in other words, where they are compared with some other measurement or quantitative effect. Thus, total energy measurements have been used to determine the efficiency of the X-ray tube and to determine the energy of ionization of air; both problems in pure physics.

It remains to consider the desirability of these measurements to determine the intensity of X-ray beams for purposes of ordinary use, that is, therapy and radiography. Intensity has been estimated in the past from indirect effects such as ionization, blackening of photographic plates, fluorescence, color change and skin reactions. It can be logically asked at this point, if, with the improvements in the methods of determining absolute intensity by total energy measurements, these will ultimately come to supplant the relative intensity measurements hitherto employed.

Certainly the measurement of X-ray intensity is a problem of importance to all X-ray users, but it should be observed that the measurement of absolute intensity, such as would be made by total energy determinations, is not always valuable. In the principal uses of X-rays, therapy, and radiography, both medical and industrial, it is the absorbed energy that produces the effect, and therefore it is the absorbed energy that it is desirable to measure. For practical every-day use, a measurement of the *total* energy of the beam of X-rays is not so valuable as a measurement that will tell the amount of *useful* energy in that beam, i.e., some measurement that corrects for the fraction that is not absorbed. In radiography, certainly the simplest and best estimate of the strength of the beam is made by observing the effect on a photographic plate or film of the same thickness and quality as that with which the picture is ultimately to be taken.

In therapy, if a measuring apparatus is to be used, an air ionization chamber is probably the most convenient because the effective atomic number of air is approximately the same as that of tissue and consequently the fraction of the beam absorbed in the chamber bears a constant ratio to the fraction absorbed in the tissue over the range of wave-lengths commonly used.

It can be readily seen, for example, that if greater intensity of an X-ray beam is sought by increasing the voltage, the total amount of energy is increased, as has been shown, proportionately to the square of the voltage, but the useful effect may not have increased at any thing like this proportion.

The extra energy gained is largely in the form of highly penetrating radiation, and it passes through the tissue without suffering much absorption and consequently without producing much effect. It would pass through an ionization chamber in the same way and thus the ionization chamber readings remain proportional to the biological effect of the radiation. From the above reasoning, it will be seen that total energy measurements are unlikely to become a practical every-day method for the determination of the intensity of an X-ray beam. They are of utmost importance for deciding questions in pure physics but for general use in therapy, such methods as those giving a merely relative intensity as obtained by ionization measurements are much more valuable.

CHAPTER VIII

Wave-Length Measurements

X-rays has come to be considered as a branch of optics and the same nomenclature is used in this new branch. Reflection, refraction, dispersion, polarization, diffraction, fluorescence, and other optical phenomena have been observed and measured for X-radiation. Many of the laws of optics have been extended to include X-rays and where they do not apply new ones have been or are being formulated.

In X-rays, as in optics, most of the phenomena depend upon frequency or wave-length. Measurements are usually expressed in terms of wave-length, though frequency is the most fundamental property in all radiation phenomena.

Optical instruments used to measure frequency or wave-length are based upon the laws of dispersion by a prism or diffraction by a ruled grating but when such instruments were first applied to the study of X-rays they gave negative results because, as we now know, the methods used were not capable of detecting these effects for radiation of such high frequency. In recent years, however, both these methods have been applied to X-ray measurements.

Following a suggestion by Laue that the cleavage planes of a crystal should act as a diffraction grating for X-rays, since it was known that the spacing of these planes is smaller than anything that could be ruled by a machine, the experiment was carried out with the result that remarkably distinct diffraction effects were produced.

Soon after the discovery of diffraction of X-rays by crystals, the Bragg X-ray spectrometer was developed and for the early history and theory of X-ray spectroscopy, students should consult the book, "X-rays and Crystal Structure," by W. H. and

W. L. Bragg. This instrument in the hands of the Braggs and a host of others has revealed so much information concerning the nature of X-rays and the structure of matter that now it ranks in importance with the microscope and spectroscope as a scientific instrument.

The X-ray spectrometer is primarily an instrument for measuring angles, the angle between a crystal and a beam of X-rays. Besides the means for measuring angles, it comprises a pair of slits to define the beam of X-rays and an ionization chamber to locate and determine the relative intensity of the X-ray beam after diffraction by the crystal. The essential working parts of an X-ray spectrometer are illustrated in Fig. 95.

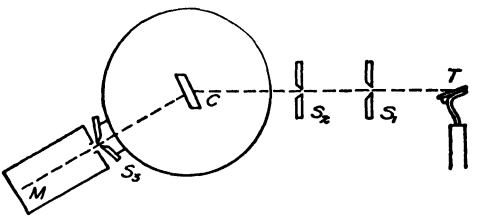


FIG. 95.—DIAGRAM OF SPECTROMETER.

The instrument consists of a divided circle or other means for accurate determination of angles, upon which is mounted the crystal *C*. An ionization chamber is mounted upon an arm rotating about the same center, and a means is provided for reading the angle of the chamber itself, or of a slit placed just in front of its aperture.

The path of the X-ray beam is indicated by the broken line. Starting from the target of the X-ray tube, it passes between the collimating slits S_1 and S_2 and strikes the crystal *C*.

For work at low voltages, the crystal is placed sideways to the beam, so that the X-rays strike one face of it, but for high voltages, e.g., above 70 kv., it is customary to place a thin slip of the crystal crosswise to the beam, so that the X-rays pass directly through it, as in the diagram.

The action is the same whether the beam is reflected from a face of the crystal, or from internal cleavage planes by

passing through it, and it will be convenient to use the term reflected beam in the latter case also. The equation known as Bragg's law giving the relation between the crystal angle θ and the wave-length λ is

$$\lambda = 2d \sin \theta,$$

where d is the distance between planes of atoms in the crystal, or, as it is called, the grating space.

Slits S_1 and S_2 are very narrow and define a narrow pencil of X-rays. The angle θ refers to the angle between the series of parallel atomic planes in the crystal and the narrow pencil of X-rays limited by the slits. The reflected beam proceeds at an angle 2θ and the opening of the ionization chamber must be placed along the line CM to receive it. Usually, the opening of the slit S_3 is made much wider than that of S_1 and S_2 and a very close adjustment of the angle in this case is not necessary, although it must always be set accurately enough so that the whole of the reflected beam can enter the ionization chamber. The X-ray spectrometer is then primarily an instrument for determining the crystal angle θ, and for setting the ionization chamber at the angle 2θ. As most research institutions are sufficiently well equipped with shop facilities to build their own instruments, and as the total number in use is comparatively small, designs have not become standardized.

An instrument designed by Terrill[1] has some advantages for certain lines of work that require precision combined with speed of operation and spectrometers of this type or modifications of this type are being used in various X-ray laboratories. The outstanding feature of this instrument is the use of large gear wheels driven by worm gears, to obtain angle settings accurately and rapidly without the necessity of reading verniers. A general view of one of these instruments is given in Fig. 96. There are two of the large gears, one actuating the chamber slit and the other the crystal. They revolve on tapered bearings, the upper gear on a steel spindle and the lower on a cone surrounding the bronze center.

[1] Jour. Opt. Soc. of Amer. and Rev. of Sci. Inst., 9, 189 (1924).

The chamber slit, while moved by the lower gear, is not attached directly to it. In order to avoid strains, it is sup-

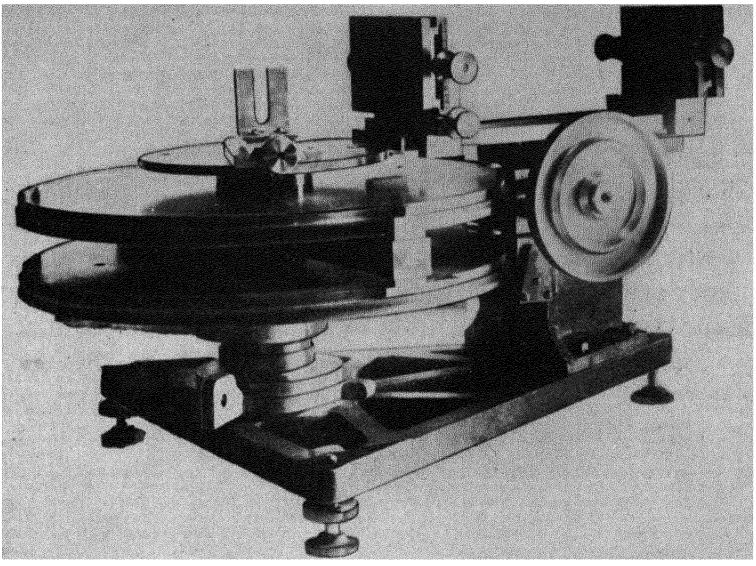


FIG. 96.—SPECTROMETER.

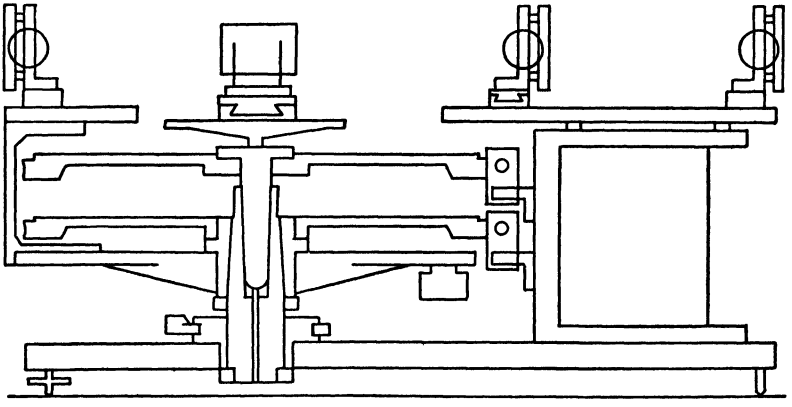


FIG. 96A.—SECTIONAL VIEW OF SPECTROMETER.

ported on an arm bolted to the gear close to the center and carrying a counterbalance weight on the further end. When a small ionization chamber is used, it is mounted directly on

this arm and additional weight added to the counterbalance. When a very large chamber is required, it is mounted on an extra center and it is lined up in proper position to receive the reflected beam by pushing it around by hand until an index on the chamber coincides with a line scribed on the frame of the chamber slit.

The gears have 720 teeth and are moved by turning the hand wheels attached to the worms. One revolution of the hand wheel moves the gear thirty minutes of arc and the rim of the hand wheel is cut with 30 divisions, representing single minutes, each division being subdivided into 5 parts so that readings can be made to twelve seconds.

The front slits are carried on the standard that supports the worm gears. A separate standard may be used when it is desired to have the slits very close to the crystal. Of the two front slits, the one nearest the crystal is mounted on a slide and can be moved with a micrometer screw at right angles to the beam of X-rays.

Ionization Chambers

Ionization chambers for spectrometer use are usually cylindrical in form and are often made 3 or 4 feet long. Such long chambers must be supported independently of the instrument, either by wheels rolling on a flat table top, or by a wire fastened to an overhead swivel. Short chambers, a foot or so in length, are much more convenient to use, as they can be attached directly to an arm of the spectrometer. However, the ionization currents obtained from them are smaller.

The chamber is usually filled with the vapor of ethyl bromide. Methyl iodide is sometimes used, but is much more expensive, and for general work no better. It would be reasonable to expect a larger amount of ionization by using a mixture of the two, but no such gain is found. A slight gain is possible by using a mixture of SO_2 and ethyl bromide. If SO_2 is used, the chamber must be entirely sealed, or means provided to replenish the supply as it leaks out. Methyl bromide, which boils at about 4° C., also requires a sealed chamber. If ethyl

bromide is used, the chamber is usually kept saturated with the vapor by having a small bottle of the liquid attached to a side tube.

An ordinary metal chamber with flanged ends bolted on will leak considerably, and the ethyl bromide bottle must be refilled every few days. A second bottle filled with P_2O_5 for a drying agent must be attached to the chamber and this also should be replaced regularly. Duane has had considerable success with all glass chambers that may be sealed, but these chambers are rather difficult to construct.

The arrangement of the electrodes is shown in Fig. 97 which gives a cross-section of the usual type. The dotted oval in the center is the outline of the window through which the beam of X-rays enters the chamber. At *A* is a metal rod supported on quartz or amber insulators and running the length of the chamber. It is placed slightly off center so that no X-rays will strike it. This rod acts as one electrode. The other electrode may be the walls of the chamber itself, supposing this to be metal, or a separate tube, close to, but separated from the walls.

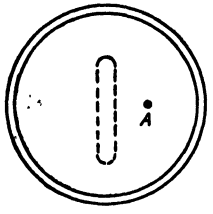


FIG. 97. — CROSS-SECTION OF IONIZATION CHAMBER.

In the first case, which is the simplest, the chamber itself being grounded, the rod is brought to a high potential, and as the current slowly leaks off to the walls, the reciprocal of the time required for a given drop in potential of the rod measures the ionization current.

In the second case, the chamber is also grounded, but the inner tube or sleeve is maintained at high potential. This tube is of smaller diameter than the chamber itself, so as to give about $\frac{1}{8}$ inch clearance all around, and may be supported on bakelite rings. The rod is connected to ground by means of a grounding key.

When a reading is to be taken, the grounding key is opened and the rod starts to acquire a charge. The rate of charging up measures the ionization current.

Electroscopes

If a gold leaf electroscope is to be used to measure the ionization current, it is usually mounted directly on the ionization chamber. The connection between the gold leaf and the central rod is then very short. A charging switch must be provided, to momentarily connect the rod to a source of potential of such magnitude as found by trial to be well above that required for saturation current, usually 150 or 200 volts. The image of the leaf being observed on a graduated scale, the time of fall for say 5 or 10 divisions, corresponding to a few volts, is determined and the reciprocal of this time measures the ionization current.

Gold leaf, between two layers of paper, can be cut with a razor blade on a sheet of glass. The gold leaf may be fastened to its plate with soap. The remainder of the plate should be highly polished so the gold leaf will not stick to it. In case much trouble is experienced by the gold leaf sticking, it sometimes helps to rub the plate with crumpled pieces of scrap gold leaf. Glasser has suggested a tip on the leaf for an index to facilitate observation. He uses a small piece of wire, sometimes a broken piece of lamp filament. However there are usually little irregular projections on the torn edge of the leaf, one of which will serve as an index.

There are two methods of observing the leaf, viz., throwing the image on a screen and direct vision with a microscope. In either case, the gold leaf must be strongly illuminated by a light from behind. If the microscope is used it should have a micrometer eyepiece and an objective with a rather long working distance, as the objective must not be brought so close that the leaf will be attracted to it and stick. The method of projecting the image of the leaf on a ground glass screen does very well for stationary electroscopes, but is rather inconvenient when the electroscope has to be mounted on the ionization chamber and move with it. For a projecting lens, one of the small magnifiers used for dissecting microscopes does very well.

Quadrant Electrometer

When a quadrant electrometer is used, it must be mounted on a solid support, and connected with the ionization chamber by a wire run through the center of a pipe or tubing to shield it. This line of tubing leads first to a point above the center of rotation of the spectrometer, and passing through a swiveled joint, proceeds to the electrometer case. A simple way to make this shielding is to use ½-inch iron pipe, filled with melted sulphur. A small diameter glass tube is placed in the center of the pipe to prevent the wire coming in direct contact with the sulphur, and the melted sulphur poured in around it. Elbows may be made in the same manner, from regular pipe fittings, using a small bent glass elbow in the center. Sulphur insulation is good for a year or so.

The potential is carried on a separate metal tube and the time required for the rod to charge up to some predetermined fraction of a volt is measured.

A grounding key is used to break the connection between the ground and the insulated system. This may be made up in a pipe fitting, a four-way tee or cross being convenient, as in Fig. 98. The insulated line *AA* is supported on amber plugs held in brass bushings.

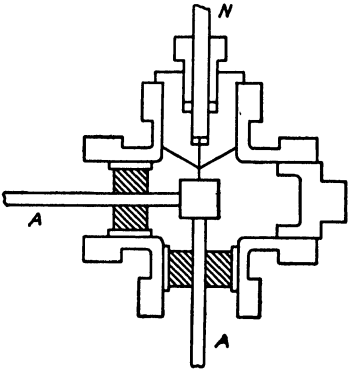


FIG. 98.—GROUNDING KEY.

The rod *N* has a needle at the lower end and the housing is brought very close to the point so that withdrawing the needle to break the connection does not greatly change the capacity. The fourth arm of the cross gives access to the working parts to adjust clearances, etc. It is closed by a plug.

The quadrant electrometer shown in Fig. 99 is provided with leads shielded by brass tubing, so that there is no break in the shielding where the wire enters the instrument. The

tight-fitting cover sets in a deep groove that can be sealed with oil. The needle consists of a mica vane cemented on a brass wire, and is painted with aquadag to render it conducting. Sputtered quartz suspensions may be used, or platinum-rhodium strip. If the strip is used, the ends are bent back sharply to form hooks, and when the jacket is removed with acid, the ends are left untouched.

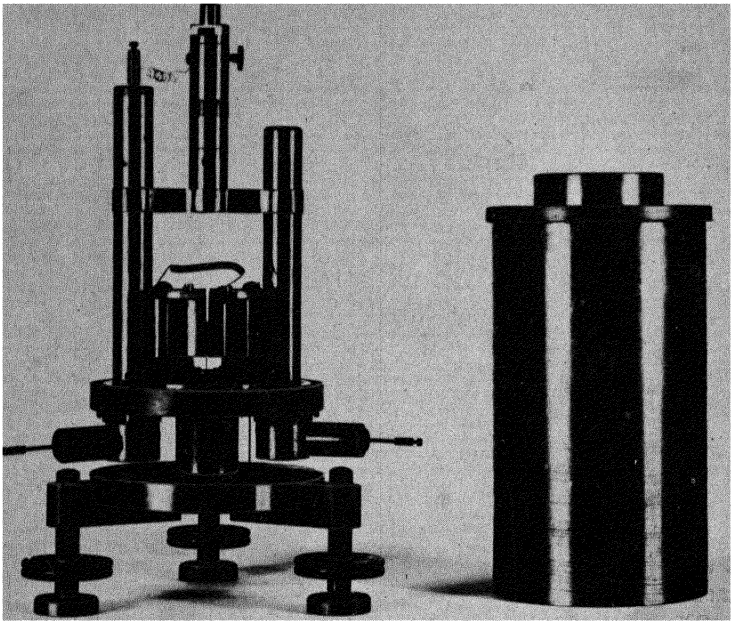


FIG. 99.—OIL-SEALED QUADRANT ELECTROMETER.

Sometimes electrometers are fitted with resistances of paper and india ink so that the ionization current is obtained by direct reading, but it is a much more common practice to observe the time for charging up or discharging a given amount. The time is taken with a stop watch, and an interval of say twenty seconds can be determined to within 1 per cent.

It must be observed that the X-ray intensities are proportional, not to the time intervals, but to their reciprocals, and it is these reciprocals that are plotted as ordinates in the usual

graph of an X-ray spectrum. A determination of the leak would also be found as a time interval, and its reciprocal is the correction to be subtracted.

Crystals

Not many crystals are suitable for X-ray use. For general work, either rock salt or calcite is generally used, especially the latter, since rock salt is difficult to obtain in pieces free from flaws and distortions. Supposing that the spectrometer is to be used for high voltage X-rays, the crystal will be placed transversely to the beam and the thickness of the crystal will depend on the class of work to be done. For very accurate work, such as determining the position of spectral lines, a thin slip of the crystal, not over 1½ mm. in thickness should be used. For work requiring less precision in the determination of the wave-lengths, such as measuring absorption coefficients and obtaining absorption curves of certain filters, a thicker crystal can be used. A thickness of 3 mm. is suitable for this work and by its use there is a decided gain in the amount of energy entering the ionization chamber, with consequent saving of time.

Increasing the thickness gives more power at the expense of sharpness of definition, but it is not practical to go much beyond 3 mm. for the spectral lines get badly blurred. Since the X-rays pass through the crystal there is some loss by absorption and it is to be expected that there exists a certain thickness beyond which the loss by absorption more than counterbalances the gain in X-rays diffracted. Such a thickness can be easily calculated, but as it happens, it comes out to be so thick that the overlapping of wave-lengths makes it impractical to use.

As shown by Hull, the optimum thickness in the sense just defined is equal to $1/\mu$ cm. For calcite, at the wave-length of the tungsten K lines, this formula gives a little over 1 cm., which is too thick for ordinary use.

By placing the second slit, S_2, on the crystal table so that

it is immediately behind the crystal, it is possible to use crystals thicker than would be otherwise possible.

Since fundamentally, all spectrometers are alike in principle, the methods to be given in the following paragraphs for setting up, adjusting and operating one of these spectrometers will apply equally well to almost any type of instrument.

The Crystal Mounting

To hold the crystal to the metal mounting, the simplest method is to use paraffin. The metal is warmed slightly until the paraffin will melt and run on it, and the crystal is laid in place and left until the paraffin cools.

The crystal table carries a sliding plate with a micrometer screw adjustment for moving the crystal directly over the center. Various methods have been used for adjusting one face of the crystal directly over the center of the instrument. For example, a surface gauge may be clamped to the upper circle and the point of the scriber observed with a microscope from above, and adjusted until it does not move when the circle is turned. A crystal, the face of which has been previously adjusted until it is perpendicular to the horizontal plane of the instrument, is brought up into contact with this point and will then have its face in the axis of rotation.

If the X-rays are to pass through the crystal, it should have its thickness calipered with a micrometer, and after the face is in contact as described above, the surface gauge is removed, and the crystal screwed along in its slide for a distance equal to one half its thickness. If the sides of the crystal are not parallel it may be necessary to use an approximate or average value for the thickness, but usually, this part of the adjustment is not critical, or at least need not be so carefully made as in the case where the X-rays are to be reflected from the face of the crystal.

To obtain the zero from which the angle θ is read, no method involving the faces of the crystal can be used, since these faces may not be exactly parallel to the atomic planes.

The usual method is to put the crystal at an approximate angle to reflect some prominent line in the characteristic spectrum of the target, and taking ionization readings, vary the angle by small amounts until a maximum is found. The grating space of the crystal being known and the wave-length of the line being obtained from tables, the value of θ can be calculated. For general use, the K_{α_1} line of tungsten makes a convenient reference point.

An alternate method is to set the crystal to the same line on both sides of the center. The difference of the two angular readings is then 2θ and the mean of the two readings gives the crystal zero. This method of course must be employed when a crystal of unknown grating space is used or if there is any uncertainty about the spectral lines of the target. Furthermore, it provides a check upon possible inaccuracies of the other method, and in research investigations requiring a high order of accuracy, readings are usually taken on both sides as a routine precaution.

If no characteristic lines are available, it is possible to use the short wave-length limit as a reference point, the mean of the readings on opposite sides giving the crystal zero as before.

Setting Up

In setting up a spectrometer, care should be taken that a substantial table or support is provided. If it is not sufficiently rigid, it is sometimes of help to weigh it down with pieces of scrap iron or cement building blocks. The instrument is placed so that the target of the X-ray tube is directly in front of the slits and is levelled up with its levelling screws. It is convenient to have the support for the X-ray tube so constructed that it can slide for an inch or two over its base, this motion to be regulated by a screw that can be turned from outside the lead box. The final adjusting of the position of the tube in front of the slits is done with this screw.

The crystal is temporarily removed from the instrument and in its place is put a narrow slit cut in a piece of $\frac{1}{8}$ inch

sheet brass which is mounted on a tapered pin just fitting a socket in the center of the crystal table.

It is necessary that the beam defined by the slits S_1 and S_2 cross accurately the center of rotation. This adjustment may be provided for by a screw moving the slit S_2 in its slide. The four slits are first lined up by eye, using an electric light in place of the X-ray tube if necessary, although, usually enough light will be reflected from the polished face of the target if the filament is lighted. A window in the further end of the ionization chamber is of assistance in bringing it into line.

The relative positions for the ionization chamber and its slit, the center slit and the front slits, are shown in Fig. 100.

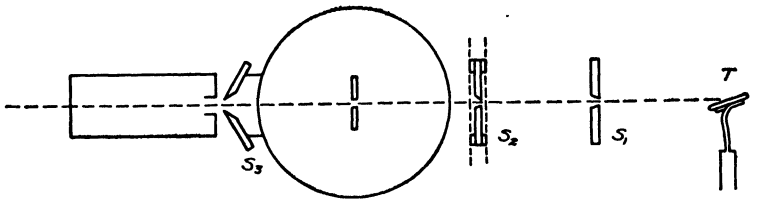


FIG. 100.—SPECTROMETER IN POSITION FOR ZERO POINT ADJUSTMENT.

The X-ray tube being now excited, slit S_3 is left wide open and the slide screw of S_2 is adjusted until maximum ionization readings are obtained. To make sure the tube is squarely in front of the slide, it may be moved in its slide until a position of maximum ionization reading is found, after which the position of S_2 will have to be checked. For highest accuracy, the crystal table with the center slit is rotated through 180° and S_2 again adjusted to position giving a maximum ionization reading. If this is different from the position last found, the final position is taken half way between the two. Once the slit S_2 is in its place, it is advisable to pour a few drops of melted paraffin or candle drippings over the head of the adjusting screw to seal it in position against careless handling or tampering.

When S_2 is in adjustment, S_3 is narrowed to about the same width and brought into line by the same methods, except of course, the motion of S_3 is accomplished by the angular rota-

tion of the lower circle, where again, if great accuracy is desired, readings are made with the center slit rotated through 180°. The mean of the two is recorded as the ionization chamber zero.

It is next necessary to get the crystal in the proper angle for reflection and to obtain the crystal zero. The center slit is removed and the crystal is replaced. Suppose it to be a calcite crystal. The slit S_3 is turned to an angle of 3° 57′ 06″ which is twice the value of θ for the K_{α_1} line of tungsten. The ionization chamber is brought to the same angle, the tube run at a potential of say 100 kv., and readings of the ionization made for various angular settings of the crystal until a maximum, or more accurately, a sharp peak, is obtained. When the crystal is set in such position that it is reflecting the maximum, it may be assumed that it is at the correct angle for the tungsten K_{α_1} line. The crystal zero is found by subtracting 1° 58′ 33″ from the reading at this point. As a check, it would of course be advisable to observe the same line on the opposite side. The slit S_3 is then widened, and the instrument is ready for use.

Suppose now that it is desired to obtain the complete spectrum of the radiation at some voltage and with some filter used in therapy. The tube being run at the desired voltage and with the filter in place just in front of slit S_1, readings are taken for various angular settings of the crystal. It must be remembered that whenever the crystal angle is changed, the ionization chamber and slit must be changed by an amount twice as great. When very small changes are made in the crystal angle, the ionization chamber need not be touched, provided account is kept of the changes, and as soon as these amount to say ten or fifteen minutes of arc, the chamber is moved up the whole amount at one setting.

X-ray Spectra

As an example of low voltage spectra, consider the curve in Fig. 101 obtained by Ulrey,[2] using a long ionization cham-

[2] Ulrey, Phys. Rev., 11, 401 (1918).

ber filled with ethyl bromide vapor so that approximately complete absorption was obtained in the chamber. These curves represent the spectral energy distribution of the X-rays from a tungsten target X-ray tube operated at various d.c. voltages. In obtaining the data for these curves the voltage was chosen so that only the continuous spectrum, free from characteristic lines, was reflected by the crystal in the wave-length range investigated.

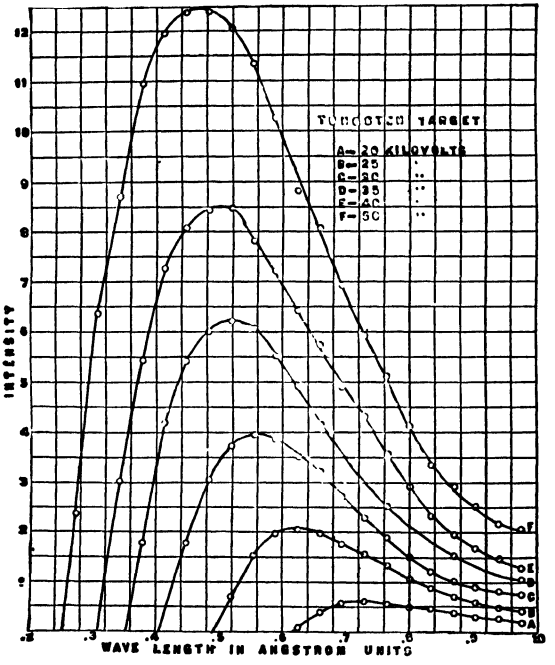


FIG. 101.—CONTINUOUS X-RAY SPECTRA OF A TUNGSTEN-TARGET TUBE.

In the continuous spectrum the threshold wave-length, on the short wave-length end, is determined by the voltage and, as Duane has shown, can be calculated from the quantum relation $\lambda_t = \frac{300\,hc}{Ve}$. Beyond the threshold wave-length, the intensity rises to a maximum and then gradually decreases, but the intensities in the long wave-length region are much

reduced by absorption in the path from the target to the ionization chamber, and therefore the curves in Fig. 101 do not represent the energy distribution of the radiation emitted by the target. Except for the absorption in the crystal they do however represent approximately the distribution at a short distance from the X-ray bulb, and therefore that which is available for any practical application.

Another example, taken from the same article, is shown in Fig. 102.

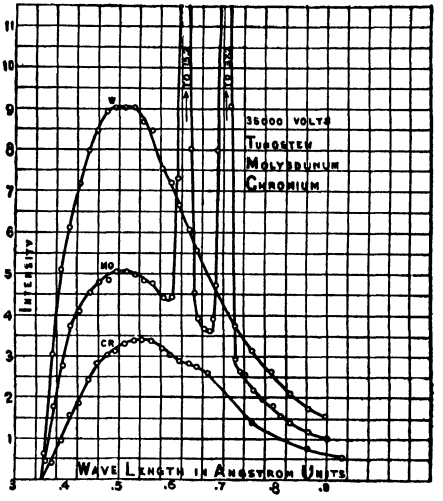


FIG. 102.—SPECTRA OF TUNGSTEN, MOLYBDENUM AND CHROMIUM.

High-voltage Spectra

Figure 103, taken from an article by Terrill and Pine,[3] gives an example of a tungsten spectrum excited by means of constant potential direct current at 200 kv. with a filter of 1 mm. of copper. It should be noted that since the rays pass through the crystal, this is equivalent to additional filtration. Due to the high voltage, the X-ray tube had to be run in a tank of oil. A small mica window was provided at the side of the tank for the rays to emerge; a thin-walled glass flask inverted

[3] Terrill and Pine, Jour. Cancer Research, 8, 68 (1924).

in the oil and filled with trapped air occupying the space between the X-ray tube and mica window.

When high voltage X-ray spectra are being obtained, it is very important that precautions are taken to shield the X-ray tube and also to prevent scattered radiation from entering the ionization chamber.

The tube should be completely enclosed in a lead box. The side opposite the spectrometer should not be left open, as is frequently done in low voltage work. If possible, the

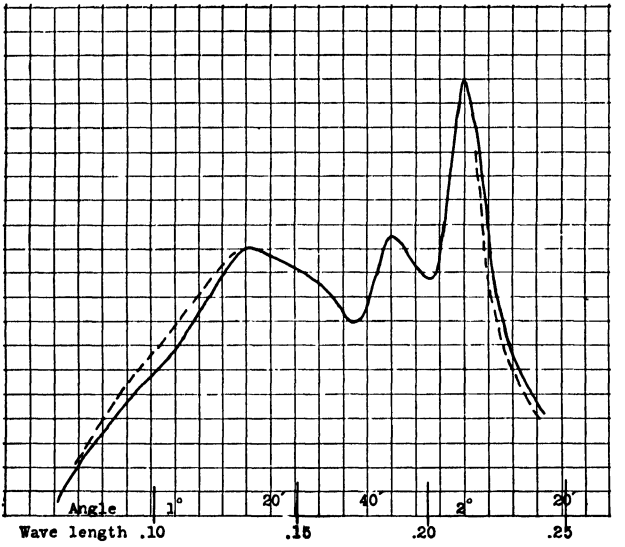


FIG. 103.—SPECTRUM OF TUNGSTEN TARGET AT 200 KV.

tube should be placed in another room, so that the tube and the spectrometer are on opposite sides of a brick or concrete wall, with only a small opening to permit a narrow beam of radiation to pass through.

If the tube is used in an oil tank, the top of the tank should be completely covered. The space near the high tension leads can be covered with lead glass, or heavy sheets of ordinary glass backed with lead rubber.

To prevent scattered radiation entering the ionization chamber, the chamber slit should be as close to the end of

the chamber as possible and the slit should not be opened very wide. Two plates of sheet lead, parallel to each other and ¼ inch apart may be attached to the slit so that the X-ray beam passes between them. These act as baffles, and radiation scattered from wide angles is thus prevented from entering the chamber. It is a good plan to cover the whole ionization chamber with sheet lead.

The test as to whether the shielding is efficient is made by the ionization chamber. With the spectrometer set up and adjusted, and the tube running, the crystal is turned to such an angle that the reflection would fall within the short wave-length quantum limit. Theoretically there should be no ionization reading at any angle within this limit, but in practice, with high voltages, a great deal will be found. This will, of course, become the correction for leak and this intensity must be subtracted from all spectral intensities. The value of the minimum wave-length depends on the voltage applied to the tube. The relation between this voltage V in kv. and the minimum wave-length is determined by the equation

$$V\lambda = 12.354.$$

Thus the spectrum in the figure, having been corrected for the leak, shows no X-rays of wave-length shorter than .062 A. On the long wave-length side, there is of course no such limit, but practically, the spectrum is limited by several factors. With a thick filter, there is very little energy getting through at the longer wave-lengths, and further, if the shape of the continuous spectrum is desired, it does not pay to go to wave-lengths much longer than twice the minimum, for the second order spectrum begins to appear and corrections are difficult to make.

When the positions of characteristic lines are being obtained, the case is different, and the higher orders are often valuable. Figure 104 gives a remarkable example of the spectrum carried out through the higher orders. It was taken with a molybdenum target water-cooled tube run at 30 kv. c.p.d.c., using a sheet of mica to reflect the rays. The spectral lines are the K_α and the K_β of molybdenum, and the K_β line is clearly visible

at the eighth order. It is interesting to note how a complex crystal like mica may enhance the lines in certain orders, or rather suppress the intensities in other orders. This is due to the fact that the diffracted rays from different atomic layers are out of phase in certain orders. In a normal spectrum, i.e., one produced by a monatomic crystal, the intensity varies approximately inversely as the square of the order.

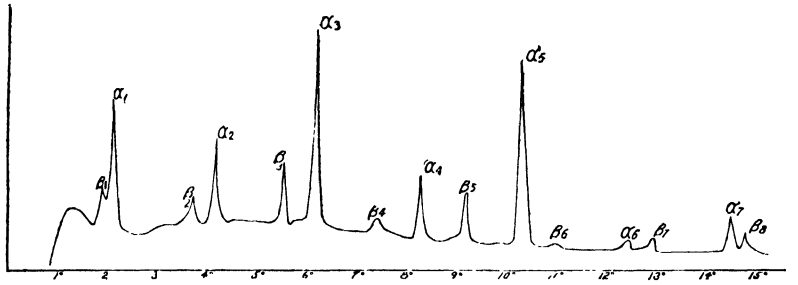


FIG. 104.—MOLYBDENUM SPECTRUM OBTAINED WITH A MICA CRYSTAL.

Absorption of X-rays

It is frequently required to determine the effect on the X-ray spectrum of certain filters or absorbing substances. In making such measurements, the filter is usually placed in front of the slit S_1. The spectrometer is set to some desired wave-length, and a series of readings made with the filter alternately in and out of the beam. The crystal is then turned to a new position, and readings again made, and so on, until the whole spectrum has been gone over. Care should be taken to limit the voltage on the tube in order to avoid second order reflection.

The methods of absorption are particularly valuable in obtaining strong beams of more or less monochromatic radiation. As suggested by Hull, a zirconia filter is used with a molybdenum tube to isolate the K_α doublet. For biological purposes, where a stronger beam of radiation is required, a molybdenum filter may be used, transmitting both the α and β lines. The spectrum is shown in Fig. 105.

The variation of the position of the absorption limit with

atomic number is shown in striking manner in Fig. 106, where filters of copper, tungsten, tantalum, ytterbium, and thulium

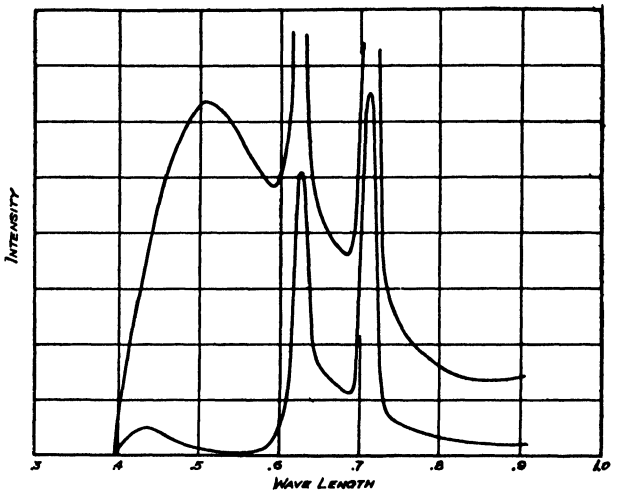


FIG. 105.—MOLYBDENUM SPECTRUM WITH MOLYBDENUM FILTER.

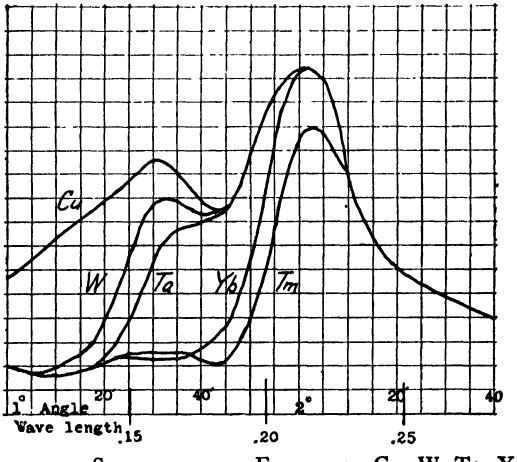


FIG. 106.—TUNGSTEN SPECTRUM WITH FILTERS OF CU, W, TA, YB, AND TM.

are used. The first three were in metallic form, while the ytterbium and thulium were in the form of oxide and glycollate respectively. The thicknesses were adjusted by trial to give the

same absorption on the long wave-length side of the limit as ½ mm. of copper.

The general laws governing the variation of absorption coefficients with wave-length and atomic number are very clearly set forth in an article by Richtmyer,[4] which should be consulted by all who are interested in this subject. The article gives also practical details of the method for making absorption measurements and values of the absorption coefficients for the more common metals.

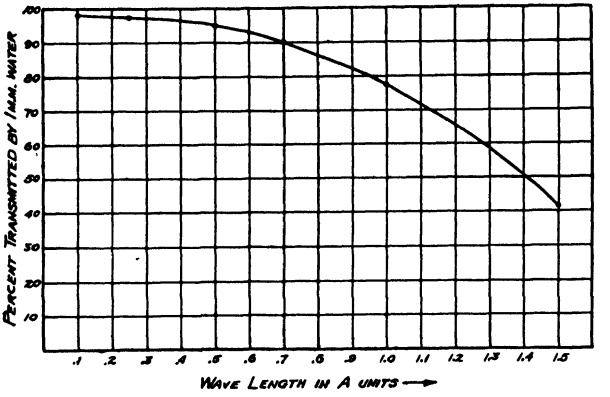


FIG. 107.—ABSORPTION IN 1 MILLIMETER OF WATER.

Following is a table of absorption coefficients of water partly taken from the above article.

Wave-length, A	Absorption Coefficient
.45	.42
.40	.35
.35	.30
.30	.26
.25	.23
.20	.20
.15	.18
.10	.17

[4] Richtmyer, Phys. Rev., 18, 13 (1921).

A convenient way of exhibiting graphically the absorption properties of a substance is by means of a curve showing the variation with wave-length of the per cent transmitted by one millimeter of the substance. This has been done for 1 mm. water in Fig. 107. The curve may also be taken to represent the absorption in the tissues of the human body, since tissue, being principally water, has about the same absorption coefficient.

CHAPTER IX

Biological Measurements

The general effect of X-rays on living material is a destructive one. X-rays kill tissue; this is the principle of X-ray therapy.

The stimulating effect that some experimenters have claimed to observe for extremely small doses of X-rays belongs in the category of debatable, or perhaps even doubtful phenomena. Even if its occurrence is actually substantiated, there is still the possibility of explanation on various other grounds, e.g., the assumption that the X-rays kill certain of the cells and leave others free to proliferate. In a somewhat different category is the effect of X-rays in producing evolutionary changes or mutations, but this effect need not be considered here. For the purpose of quantitative estimation of X-rays, the killing or destructive effect is the only one of importance.

For a discussion of the possibilities as to the actual mechanism of the destructive action of X-rays on living cells, reference may be made to the work of Holthusen.[1] It might be well, however, to point out that biological effects are probably produced in the same manner as ionization, by the liberation of high speed photo and recoil electrons.

On the next page is a table of the range of electrons in tissue. The values are calculated for a density corresponding to water, from data obtained from experiments on aluminum. It must be remembered that the paths of the electrons are quite crooked and they do not all move nearly as far from the point of origin as the following values would seem to indicate.

[1] Strahlentherapie, **25**, 157 (1927).

Electron Average Velocity, Kilovolts	Corresponding Voltage on X-ray Tube, Kilovolts	Range in Centimeters
200	275	.38
165	200	28
70	120	08

So far as the effect on tissue is concerned, all wave-lengths of X-rays seem to be alike, but this statement requires some qualifying remarks. In particular, it is necessary to specify how both the X-rays and the biological effects are to be measured. Furthermore, in some cases, wave-length is of considerable importance as regards the purely physical problem of getting the radiation into the tissue.

Biological measurements are complicated by the fact that a certain amount of time is required for the effect of X-rays to become apparent. A specimen may be given a killing dose of X-rays and yet its death may not actually occur until a week after the exposure. It will be understood, therefore, that in all biological measurements, the effect is determined, not at the conclusion of the raying, but at the end of the proper development period.

Biological Material

For the purposes of X-ray estimation, all biological material is not equally suitable. Although living insects, and small animals like mice have been used extensively by some experimenters, they are rather unsuitable. The average life span depends on many factors and is not easy to determine without a large number of specimens. A shortening of this life span produced by X-rays to the amount of say 20 per cent might be difficult to determine with any degree of precision. Also, X-rays might shorten the life of the specimen through indirect causes, e.g., weaken it and make it more susceptible

to disease. Results obtained in this way would not be reproducible.

It is much better to use a simpler material, such as, for example, tumor tissue, which has its viability tested by inoculation. Here a definite answer is obtained at the end of the development period, "take" or "no take."

Certain kinds of eggs are also good. At the end of the incubation period, there is a definite answer, hatch or not hatch. Fortunately, it happens that for the eggs that are most used in this way, the X-rays do not have the effect of slowing up the hatching time. If they did, the results would possibly contain, besides those killed and those hatched, a percentage having retarded development, and would be more or less indefinite, and the method less useful. Protozoa or bacteria would be free from some of the objections against the higher organisms, but in most cases, these are extremely resistant to radiation. Furthermore, their small size renders them particularly difficult to work with.

One factor in the choice of material is cheapness or availability. Since biological material is variable, it will be necessary to use a large number of specimens in order to obtain dependable mean or average values for the result. Accordingly, the smaller and more inexpensive the specimens, the larger number it will be possible to use for a given measurement.

The Survival Curve

In making a determination of the effect of radiation on any biological material, it will be supposed that the material has been selected and its suitability determined from preliminary experiments that also have given information as to the proper development period, etc.

The method of procedure will be somewhat as follows. A large number of specimens are placed in position under the X-ray tube and the exposure started. At intervals, say every five minutes or so, a definite number will be withdrawn, labeled,

and set aside. At the conclusion of the exposure, all the specimens will have been divided into groups, each group having had a different exposure. A control group is usually made up at the same time, the specimens receiving exactly similar treatment, save that the raying is omitted. All the groups are now set aside for the period of development, or processed according to the development requirements.

At the end of the development period, the results will be available. For each group corresponding to a time interval, the result is the fraction living or dead. If an ideal perfectly suitable material existed, experiments with it would show all groups below some definite exposure having 100 per cent alive

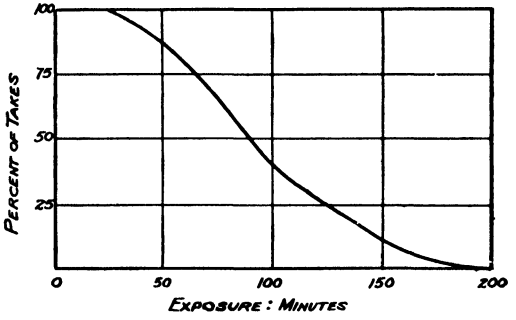


FIG. 108.—SURVIVAL CURVE, RAT CARCINOMA, FRC.

and all groups having greater exposure, 100 per cent dead. In practice, this does not happen, but with all classes of material, on account of natural variability and possibly other causes, there is a gradual decrease in the number living as the exposure proceeds.

If the fraction living is plotted as a function of the time of exposure, or what is the same thing, the total dose, the result will come out somewhat as in Fig. 108 which was taken from the work of Dr. F. C. Wood [2] on rat carcinoma, FRC.

This may be called a survival curve. Each different kind of material will give a curve of different shape, although all will have the general form shown in the figure. It would be desirable to give a mathematical expression as an equation

[2] Radiology, 5, 199 (1925).

for these curves, but there is no simple formula that can be used to express such an equation. Perhaps something might be done by considering them as integrals of skew frequency distributions, and a complicated expression arrived at, but so far, nothing of the kind has been attempted.

Condon and Terrill[3] have developed a statistical theory of the survival curve based on the quantum discreteness of the absorption process.

Optimum Percentage

When any new material is being studied, or any experiment performed where the emphasis is on the biological side, data for a complete survival curve should certainly be obtained. On the other hand, such a curve, being a two dimensional magnitude, is an inconvenient way of representing a quantity such as the strength of a beam of X-rays, that is essentially one dimensional. Consequently, when it is desired to use biological methods merely to make a determination of the intensity of a beam of X-rays, instead of the whole curve, one point on the curve is all that is necessary.

This is just what is ordinarily done, but unfortunately, in some experiments, the point selected is not the best one for the purpose. Many experimenters who have worked with biological material have arranged their results so as to show the length of exposure, or total dose in Roentgen units required to kill all their specimens. That is, they determine the amount of X-rays to kill 100 per cent, or in other words, without obtaining any data for the rest of the curve, they attempt to make a precise determination of the end point.

Now examination of survival curves for various kinds of biological material shows that in general, the end point, i.e., the amount of radiation to kill 100 per cent, is the most difficult point of the whole curve to determine precisely. Consider the curves in Fig. 109. If the curves were usually of the shape shown at *A*, the end point might be determined with-

[3] Condon and Terrill, Jour. Cancer Research, 9, 324 (1927).

out difficulty. However, curves usually met with are more nearly in the shape of *B*, and the end point is rather indefinite and can only be determined approximately. It will be seen that, for those experimenters who stated results in terms of radiation necessary to kill 100 per cent, their work would have had a much greater precision had they arranged their experiments to determine some other point on the curve.

As to what point should have been selected, the following analysis will provide an answer. Consider what point can be determined with the greatest precision, that is, at what part of the curve does the material show the highest sensitivity. Clearly when the specimens are dying at the most rapid rate, i.e., at that point at which the curve has the steepest slope. This point can be determined graphically from the curve, since

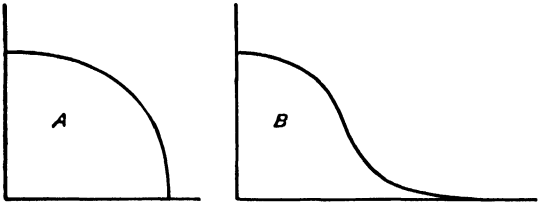


FIG. 109.—SURVIVAL CURVES.

no particular pains need be taken to secure the exact point of steepest slope, and any point in the neighborhood may be equally well selected.

Suppose in some particular case, it is found that the curve has the steepest slope in the neighborhood of 60 per cent surviving. Accordingly, the amount of radiation to kill exactly 40 per cent or leave 60 per cent alive is then taken as the best point to be determined for that particular material. In future measurements then, it will not be necessary to determine the whole curve, but only a small portion of it in the neighborhood of 60 per cent surviving. Two or three points close to this value being known, the value for exactly 60 per cent can be found by interpolation.

As the optimum percentage will vary for each different biological material, it might be well to adopt some arbitrary

value, say 50 per cent, which can be used for all classes of material. This value is near enough to the point of maximum slope to admit of comparatively precise determination in all cases that have come to the authors' attention.

Examples of Survival Curves

A good example of biological measurement is shown in Fig. 110, a survival curve obtained with the eggs of the fruit fly Drosophila. These have been the subject of considerable experimentation at the Institute of Cancer Research, where

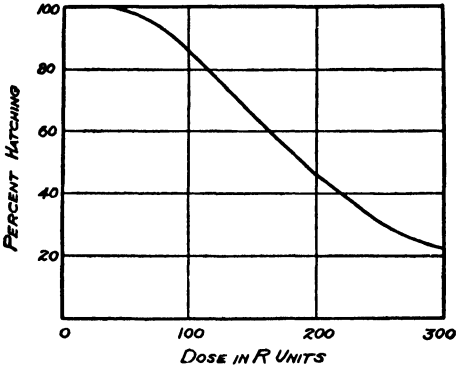


FIG. 110.—SURVIVAL CURVE, DROSOPHILA.

it has been found that a dose of 185 *R* units is required to kill 50 per cent of the eggs. This value is independent of the wave-length over a range of wave-lengths such as are commonly used in therapy, say from .7 A to .08 A, and is also independent of the intensity provided this exceeds a certain limiting value.

The importance of noting a lower limit for the intensity may well be emphasized. In all measurements with biological material, where the intensity is not specifically mentioned, it must be understood to be of such a value as commonly used in therapy. It is not, in general, true that the intensity may be varied indefinitely and the effect remain constant as long as the product of *intensity* $\times$ *time* is constant. The rule that

$$I \times t = const.$$

for a given effect, the so-called law of Bunsen and Roscoe, that first attained significance in application to the blackening of photographic printing paper, does not always apply in the case of biological material. With living tissue there is a possibility of growth, or repair processes going on, and it is conceivable that if the radiation were very weak, the organism might alter its resistance, or even be able to rebuild the tissue as fast as it was destroyed.

However, it is known from experimental results that the law does hold if the intensity of the radiation varies only over a limited range. In the case of Drosophila eggs, the limiting value of the intensity is found experimentally to be about .09 *e*, so that for radiation more intense than this, the law holds good. On the other hand, an intensity lower than this, of about .05 *e*, has been shown to give an irregular effect.

For other biological material, the limits have not been so clearly established. They will depend on the length of the development period, among other factors, since obviously the intensity must be such that the time of exposure will be less than this period. However the whole subject is one on which further study is needed.

The curve in Fig. 111 was obtained by Crowther for the protozoan Colpidium. It is remarkable for two things, the

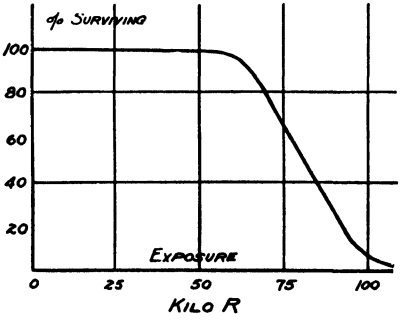


FIG. 111.—SURVIVAL CURVE, COLPIDIA.

resistance shown to radiation, requiring such enormous doses as 80,000 *R* units to kill 50 per cent, and also for the extremely

flat top, over 2/3 of the total dose being given before much effect is begun to be observed.

Considerable research has been done by Davey on the effect of X-rays on oatmeal bugs, *tribolium confusum*. As material for X-ray measurement, these beetles present a good illustration of the previously mentioned difficulties in dealing with higher organisms. Normally their death rate is such that over 96 per cent are alive at the end of 15 days while less than 1 per cent reach the extreme age of 150 days. A complete picture of the shortening of their life by X-rays requires a rather elaborate set of data. Since the beetles all die ultimately in any case, there is no question here of per cent killed. All that can be done is to observe the shortening of the life span.

For moderate exposures, those beetles affected at all were usually killed within 15 days. Some of the results are shown in the following table. The distance between X-ray target and specimen is 25 cm., voltage 50 kv. and the exposures are given in milliampere-minutes.

Exposure in Milliampere-minutes	Per cent Dead After 15 Days
200	10
250	40
300	60
500	100

For increasing exposures above 500 m.a.m., only a comparatively slight further shortening of the life span was observed, until 4000 m.a.m. was reached. Larger doses than this, however, killed more rapidly, and beetles rayed 15,000 m.a.m. were all dead at the end of the exposure.

Figure 112 gives an example of a survival curve obtained with mouse tumor tissue by Dr. F. C. Wood.[4] There are several strains of tumors available which are transplantable in mice and rats; the one in the figure being known as Mouse

[4] Wood, Am. Jour. Roentgenology, 12, 474 (1924).

Sarcoma 180. The method of procedure in obtaining data for one of these curves is as follows.

The tumor is cut from the animal, placed in a small rubber or celluloid container and exposed. After exposure it is cut into small pieces and these are grafted in a series of animals. If the tumor has not been destroyed by the radiation, it will, after the proper development period, begin to grow, and a large tumor will appear at the spot where the small piece was grafted. The length of time for the result to become apparent varies for the different types of tumors, from several weeks up to three months.

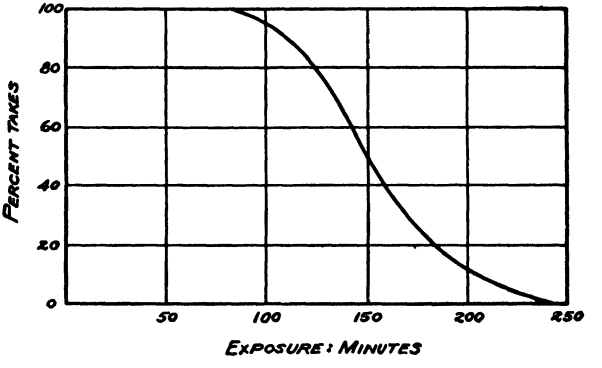


FIG. 112.—SURVIVAL CURVE, MOUSE SARCOMA 180.

In these experiments on tumors, the material was cut in such thin slices that the absorption was negligible. Even if larger masses are used, the effect of absorption may usually be neglected and the top and bottom layers assumed to have received the same dose. The problem, however, might become of importance when large tumors are rayed in vivo, or when experimental results are applied to deep therapy. The effect of absorption on the form of the survival curve has been studied by Terrill [5] and a method given for making corrections to this curve to allow for absorption.

The question of change in biological effect with wave-length belongs rather to the subject of special research, but

[5] Terrill, Jour. Cancer Res., 11, 293 (1927).

certain points may be considered here. This question has been very thoroughly investigated by Dr. F. C. Wood,[6] who has obtained data on different classes of material and succeeded in clearing up a subject that had hitherto been clouded by an enormous amount of misinformation.

If we define intensity of radiation as the ionization intensity measured by a standard air ionization chamber, the most precise experiments available indicate that two X-ray beams of equal intensity have the same biological effect, irrespective of the wave-length. This statement has been tested so far only for the wave-lengths commonly used in therapy.

The above result is as would be expected, since the mass absorption coefficients for air and living tissue are approximately the same, and hence the amounts of energy absorbed by the tissue and the ionization chamber maintain a constant ratio under change of wave-length.

Erythema Measurements

A method of biological measurement of radiation intensity differing considerably from those just described is one depending on the property of X-rays, when applied to the human body, of producing redness of the skin or erythema.

The erythema unit has been much used by medical men. Authorities differ in formulating exact definitions, but the following will give a general idea. The erythema dose is that amount of X-rays that will produce a distinct reddening of the human skin at the expiration of a proper development period, usually ten days after the exposure. Many writers state definitely what portion of the body is to be exposed, usually the thighs or belly.

Unfortunately, the erythema unit is very difficult to determine accurately. In the first place, the amount of reddening must be estimated for there is no practical method of quantitative measurement. Then also, there is a considerable difference in the resistance to radiation between various individuals;

[6] Wood, Jour. Roentgenology, 11, 474 (1924).

blonde and brunette skins, and children and adults especially showing large differences. Another factor of considerable importance is the area of skin to be radiated, or portal of entry, as it is called in deep therapy. With a large area, say 20 cm. square, the radiation falling directly on the skin is supplemented, especially at short wave-lengths, by a large amount of radiation scattered back from the interior tissue. In the case of a small portal, say 1 cm. square, very little of this scattered radiation is returned to the original area, and an X-ray beam of the same intensity as above would be some 30 per cent less effective. Consequently, in defining an erythema dose, it is necessary to make some statement about the area to be exposed. In the same connection, a beam of radiation of given intensity has greater effect on skin backed by large masses of tissue, such as the thigh, than it would on the forearm, since in the former case a greater amount of scattering is included.

Of course with a unit so much used as this, it is very desirable to have it compared with ionization measurements, and incidentally, to make the comparison at a number of wave-lengths, to determine if the value changes with the wave-length. At first sight, it would appear a simple matter to do this, but such has not proved to be the case. Around this point has arisen a greater amount of discussion and disagreement than perhaps any other debatable question in the whole X-ray field.

It has been stated in a previous section that, quantitatively, biological effects are independent of the wave-length of the X-rays, but it seems that an exception to this generalization must be made for the case of the erythema unit. In a comparison with an ionization chamber, Meyer and Glasser have found considerable variation with the wave-length in the number of *R* units equivalent to one erythema. This, however, is not unreasonable, as a little consideration will show, and is due, at least in part, to well known physical properties of X-rays.

The amount of radiation absorbed by the skin depends on several factors. The direct radiation falling on the skin is increased by a substantial amount, especially with large por-

tals, from dispersed radiation scattered back from the interior. The proportion due to scattering is largely increased at short wave-lengths, and hence the total dose on the skin is likewise increased. Another contributing factor is the fact that with the more penetrating radiation, the underlying tissue is also damaged to a greater degree, and this has an indirect effect on the skin, since it affects its nourishment, nerve connections, etc. Supposing it were possible to make a comparison of ionization and skin units by cutting off a small square of skin, exposing it while it was suspended on a thread in the open air, and then grafting it back in place for development, it is entirely probable that we might find considerably less influence due to the wave-length.

The erythema unit, on the whole, is unsatisfactory in many ways, and it might be desirable to abandon its use as a unit of X-ray measurement. Of course, the conception of skin reaction as a limit of dosage is indispensable in deep therapy, where dosage, portals and cross fire methods must be arranged so as to avoid irreparable damage to the skin, but this belongs rather to the field of medicine than of X-ray measurement.

For those who feel that erythema unit is so well established that they are compelled to think in terms of erythema units, possibly the best thing would be to adopt a new unit as a sort of artificial erythema; to be determined, however, not by skin reactions, but by the ionization chamber. For example, one might define arbitrarily the new unit as an amount of radiation equal to 500 *R* units.

This is something that can be definitely measured and is independent of the wave-length, while the value of 500 *R* units, selected as a round number, is an approximate average value of actual determinations of skin doses so that for most workers, this new unit would not be greatly at variance with any erythema unit they had been previously using.

There is perhaps further justification for the introduction of a new unit in the fact that the *R* unit is somewhat inconvenient on account of its small size, while the adoption of

a Kilo *R*, would result in a unit a little too large. At any rate the selection of a new unit as a multiple of the *R* unit would have the effect of permitting the statements of dosages in small, easily remembered numbers.

Summary

In considering all the various methods of X-ray measurement, it is easy to overestimate the importance of biological methods. It should be pointed out that although many medical men have a decided preference for biological methods of measurement, their reasons for such preference do not rest on very logical grounds.

While X-ray therapy is a biological process, it does not follow that for purposes of estimating X-ray dosage, a biological method is superior to any other. After all, what is wanted is an estimate of quantity of radiation, and the best method is the method that determines quantity with the greatest speed and precision.

A possible reason for the term biological measurement connoting superiority in the mind of medical practitioners is the fact that in the case of certain potent drugs, e.g., digitalin, the best method of determining strength is a biological assay. Another explanation of the predilection for biological methods is that physicians, as a class, are unfamiliar with such things as galvanometers and electroscopes, but are on very familiar ground when it comes to estimating the redness of a patch of skin.

Perhaps the best argument in favor of biological methods is that the results are proportional, not to the total amount of energy present in the beam of radiation, but to the amount absorbed by the measuring substance. In this feature, however, they have no advantage over the ionization chamber, and from their very nature have the serious disadvantages of lack of precision, of requiring a large number of determinations to allow for natural variability of the material, and of requiring

a certain amount of time for the development period before the results are available.

While it is desirable that the biological action of X-rays should be quantitatively studied as a matter of research, there is no reason at present why biological methods should supplant ionization methods for estimation of dosage in therapy.

CHAPTER X

RADIOGRAPHY

Roentgen discovered that X-rays affect a photographic plate and from the year of their discovery X-rays have been used to radiograph the bones and organs of the human body. The technique of radiography has been developed to such an extent that it is now a standard method of diagnosis used by physicians, surgeons, and dentists. More recently the field of usefulness has been extended by the application of radiography to other problems requiring a somewhat different technique.

In X-ray photography the image produced on the plate or film is only a shadow picture and is caused by variations of transparency of the object for X-rays. Since there is no known means for focusing X-rays, fine definition can be obtained only when the source of X-rays approximates a point source. Therefore the X-ray tube must have a small focal spot or the tube must be placed far away from the object to be radiographed.

Scattered Radiation

Any radiation reaching the X-ray film from sources other than the focal spot of the target causes fogging and blurring and should be eliminated as far as possible. The rays passing through the object produce considerable scattered radiation, especially if it is very thick, and the best way of preventing this from reaching the film is to use a Bucky grid, which effectively blocks out rays from all directions except that of the direct beam. Some improvement can be obtained by placing a thin filter between object and film since the scattered

radiation is somewhat less penetrating than the direct beam. Scattered radiation coming from objects back of the film can be easily prevented by placing a sheet of lead back of the film or if a cassette is used the back of this may be made of lead.

Photographic Effect of X-rays

The amount of blackening of the photographic film depends upon the amount of X-ray energy absorbed in the emulsion, within certain limits. In general, the energy tolerance in radiography is much greater than in therapy dosage. A deviation of 50 per cent from the optimum amount will still produce a usable photograph while a deviation of more than 10 per cent from the proper dosage can not be permitted in therapy.

The photographic effect depends upon the following factors:

1. The time of exposure.
2. The X-ray output of the tube.
3. The absorption in the object radiographed.
4. The absorption in the film.
5. Target-film distance.

With the exception of the exposure time and target-film distance all these factors vary with the voltage applied to the X-ray tube. It has been shown in a previous section that the X-ray output increases proportionally as the square of the voltage; the absorption in the object as well as in the film varies approximately as the cube of the effective wave-length or inversely as the cube of the voltage. The inverse square law applies to the target-film distance.

Optimum Voltage

For each object to be radiographed there is an optimum voltage. In the first place a sufficient voltage is necessary so

that an appreciable amount of X-rays will be transmitted through the object. On the other hand, as the voltage is increased the effective wave-length of the transmitted radiation decreases and therefore a smaller percentage will be absorbed in the film. Furthermore, the variations of density in the object and the nature of the information desired must be considered in determining the proper voltage to be used. The best results could be obtained in any case if it were practicable to use monochromatic radiation of the correct wave-length, but since an X-ray tube emits a heterogeneous beam, calculations must be based upon the average or effective wave-length of the beam.

The variation of absorption with wave-length is illustrated in Fig. 113, where the spectral distribution of the radiation

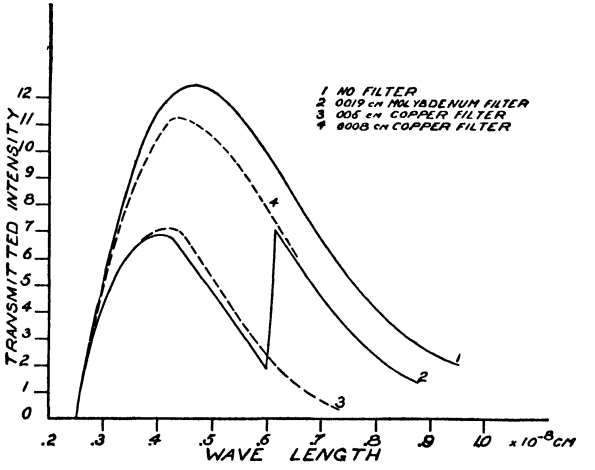


FIG. 113.—VARIATION OF ABSORPTION WITH WAVE-LENGTH.

transmitted by copper and molybdenum is plotted for the X-rays from a tungsten target tube operated at 50 kv. From the curves it can be seen that for a wave-length of .40 *A*, the absorption of a sheet of molybdenum of .0019 cm. thickness is equivalent to one of copper of .005 cm., while for a wave-length of .65 *A* it is equivalent to only .0008 cm. of copper.

In radiography of the human body there are certain limits to the intensity and time of exposure that may safely be used to avoid injury to the patient. Furthermore it is not always

possible to hold the body and organs immobile for a very long time. With inanimate objects, however, such limitations do not exist and exposure of several hours may be made if necessary.

Technique for Radiography of Metals

X-ray photography is used extensively for the examination of heavy metal castings for hidden defects such as flaws and gas pockets. By this means defective products can be rejected which might cause serious trouble if allowed to be used and subsequently fail in service. More important than this perhaps, is the information obtained as to the location and cause of the defects which can often be eliminated altogether by redesigning the moulds or changing the temperature conditions. This method of testing has the obvious advantage that no injury is caused to sound specimens.

The method is limited to castings of about three inches thickness, due to the voltage limitations of the X-ray tube and to aberration arising from X-rays scattered by the specimen.

In the examination of thick metals where it is essential to use extremely high voltage and long exposures it is especially important to exclude the scattered radiation as far as possible. The specimen should be exposed through an aperture which restricts the X-ray beam to an area not much larger than the cross-section of the specimen. A metal filter should be used to eliminate the soft X-rays which can serve no useful purpose.

It is also advisable to use some means of reducing the intensity of the X-rays reaching the film outside the boundary of the specimen. This can be accomplished effectively by placing the specimen in a box of powdered material which is made up to have about the same absorption for the X-ray beam as the specimen itself. If it is desired to see the outline of the specimen in the radiograph the powdered material is made to have a slightly different opacity than the object. The powder may be a mixture of two components, one of greater and the other of less opacity than the specimen, so that the desired absorp-

tion can be obtained by varying the proportions of the ingredients. Red lead, plaster of paris, flour and similar substances are suitable for this purpose.



FIG. 114.—VERTICAL AND HORIZONTAL FLAWS.

The size of a flaw or gas pocket which can be detected depends upon its location and orientation in the specimen. For example in a flat steel plate, a horizontal crack, as at *B* in Fig. 114 is comparatively difficult to detect, while a flaw or blow hole which extends in a vertical direction, as at *A* is compara-

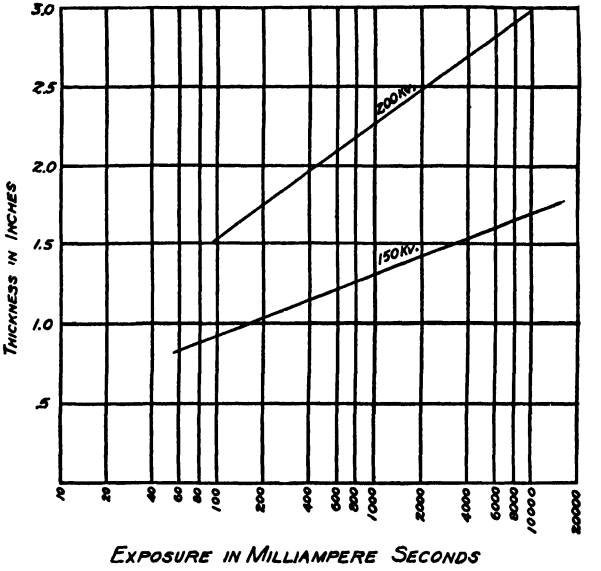


FIG. 115.—EXPOSURE CHART FOR STEEL.

tively easy. This limitation of the method should be recognized since a single clear photograph taken does not always guarantee a sound casting. As a check, other radiographs should be made with the rays passing through the object in different directions.

Some idea of the exposures necessary for different thicknesses of steel can be obtained from Fig. 115, which is plotted

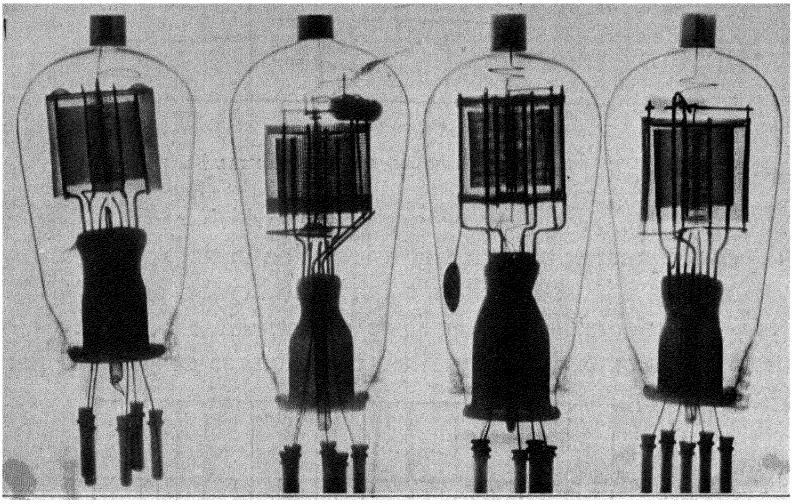


FIG. 116.—X-RAY PHOTOGRAPH OF RADIO TUBES.

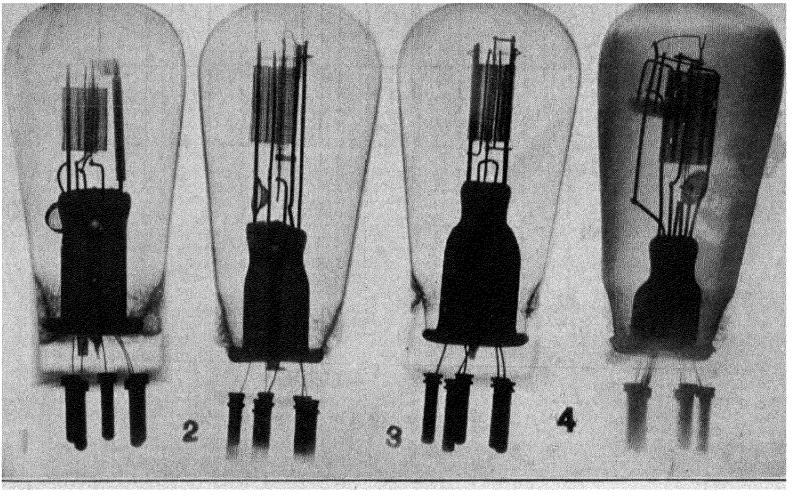


FIG. 117.—X-RAY PHOTOGRAPH OF RADIO TUBES.

from data obtained in the Siemens-Reiniger-Veifa laboratories. Exposures are given for steel up to 3 inches in thickness for two voltages, 150 kv. and 200 kv.

The value of radiographic examination is shown strikingly in Figures 116, 117 and 118, which are X-ray photographs of radio receiving tubes. They afford a valuable comparison of the methods of manufacture and give data on clearances, etc., which could not be otherwise obtained without destroying the tubes.

Figures 119 and 120 are radiographs of radio transmitting tubes. A voltage of 150 kv. is necessary to get a good radiograph of this type of tube which has a copper anode of .060

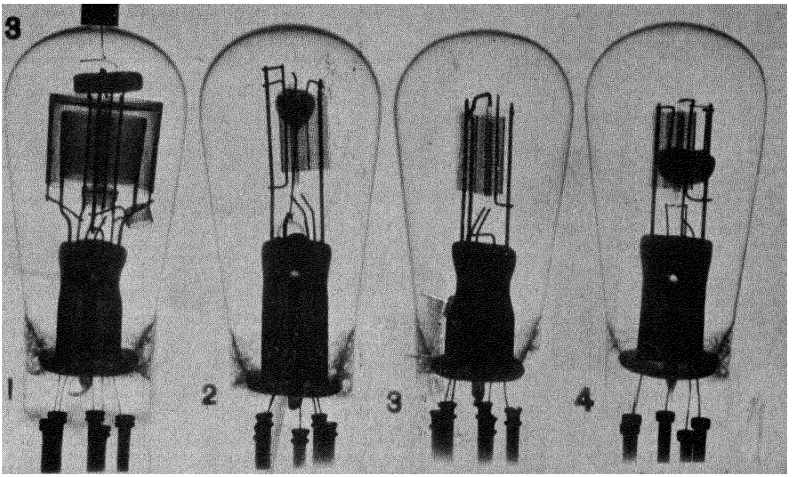


FIG. 118.—X-RAY PHOTOGRAPH OF RADIO TUBES.

inch thickness. These tubes are radiographed at the factory of the Westinghouse Lamp Company both before and after exhausting, as a routine inspection for the purpose of detecting faulty alignment of the elements and for detection of other defects which might affect the operation or life of the tube. The tube in the first radiograph is a perfect one, while the second shows defects which caused its rejection.

The following examples are given to show some of the possibilities of radiographs of electrical apparatus. In many cases such pictures will give information that leads to marked improvement in design. Figure 121 is a radiograph of a cartridge fuse and Fig. 122 is one of a carbon rheostat.

Intensifying Screens

When dealing with penetrating radiation the photographic effect can be increased by the use of intensifying screens placed in contact with the film. The usual type of screen for this purpose is made of a fluorescent material consisting largely of

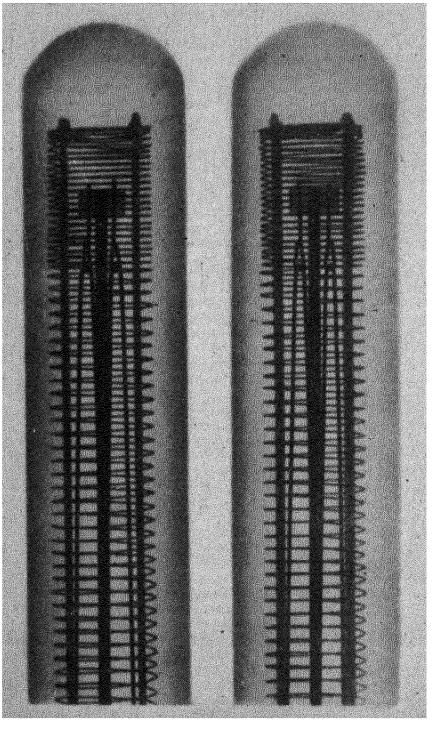


FIG. 119.—X-RAY PHOTOGRAPH OF WATER-COOLED RADIO TRANSMITTING TUBE, TWO POSITIONS

calcium tungstate which fluoresces with a blue colored light for which the photographic emulsion is most sensitive. Besides the fluorescence in the visible part of the spectrum, there is also produced in the screen some fluorescent or secondary X-rays as well as photo-electrons which add their effects to that of the X-rays absorbed in passing directly through the film. Con-

siderable increase in intensity is obtained by simply using a heavy metal sheet as intensifying screen. It is important that the screen should make good contact with the emulsion side of the film, otherwise a blurred image will result.

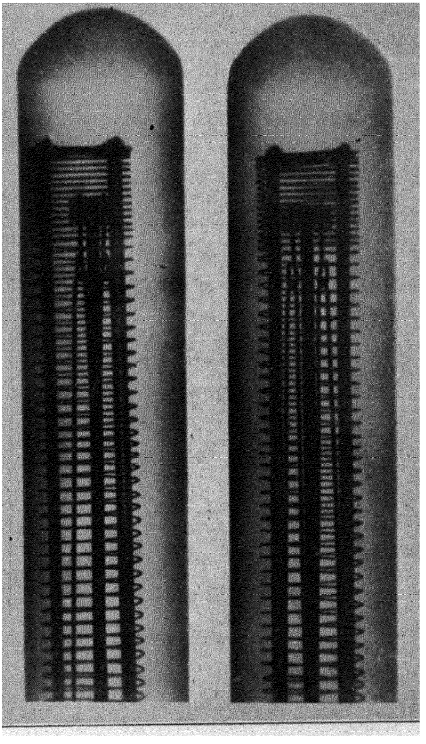


FIG. 120.—DEFECTIVE TRANSMITTING TUBE, TWO POSITIONS.

X-ray Films

Photographic films manufactured especially for X-ray photography have thick coatings of emulsion so as to obtain maximum absorption and the Eastman Kodak Co. produces a film coated on both sides. But the thickest practicable coatings utilize only a very small fraction of the X-rays available. Attempts have been made to produce a sensitive X-ray film by incorporating fluorescent and absorbing material in the emulsion itself but in general this has not proved satisfactory on

account of complications introduced in the development process. It does not appear, however, that the possibilities of producing a better X-ray film have been exhausted and it is in this direction that we may perhaps look for the present limitations in industrial radiography to be extended. One possible improvement may be found in the employment of desensitizing dyes. A photographic film may have pinakryptol-green and other soluble dyes added to the emulsion during manufacture so that it loses much of its sensitiveness to ordinary light while retaining its sensitivity to X-rays. Such a film might be loaded into its cassette and also developed in weak daylight, thus avoiding entirely the use of a dark-room.

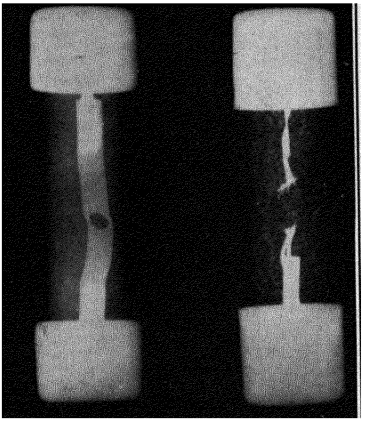


FIG. 121.—CARTRIDGE FUSES.

Photographic Method of Measuring X-ray Intensity

Attempts have been made to use the blackening of a photographic film as a means of measuring X-ray intensity. The method is convenient and gives qualitative results but cannot be recommended where precision is required. One difficulty is that the photographic blackening is not a linear function of the time of exposure and it is also too much influenced by variable factors in development. The method has the disadvantage inherent in most X-ray intensity measuring

methods, viz., that the sensitivity varies with the wave-length of the X-rays.

On account of the selective absorption of the silver and bromine in a photographic film there is an abnormal change in the blackening for wave-lengths in the neighborhood of .48 *A* and .917 *A*, the critical absorption wave-lengths for the *K* series of silver and bromine respectively. This fact must be consid-

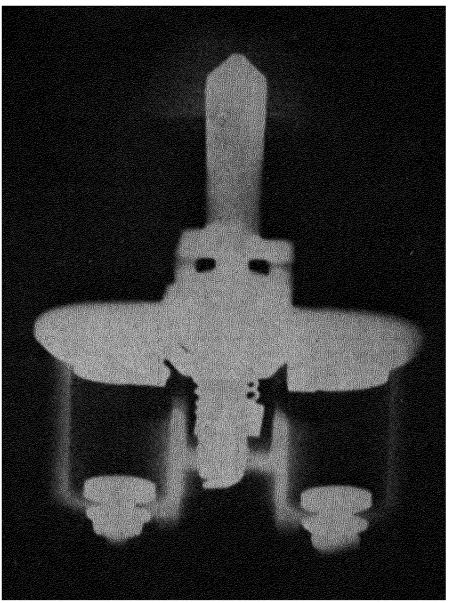


FIG. 122.—CARBON RHEOSTAT.

ered when comparing X-ray intensities by their photographic blackening and the method is therefore applicable only where the spectral distribution is the same in all cases. In particular, the intensity of spectral lines cannot be determined by their relative photographic effects over a very wide range of wave-lengths.

A method of evaluating the intensities of photographed X-ray spectra has been described by Mutscheller.[1] A standard

[1] Mutscheller, Radiology, May, 1929.

photographic scale is made by withdrawing, at uniform speed, a strip of film from beneath a lead shield into a beam of X-rays. On such a film, the blackening varies with the distance from the zero point. The blackening in any part of a spectrogram can then be matched with some point on the standard scale, the blackening of which can be read on a scale which measures the distance from the zero point. In a spectrogram, the method measures photographic blackening and not X-ray intensities for the reasons pointed out in the preceding paragraphs. The method can, however, be used to measure the X-ray intensities of the lines in a powdered crystal diffraction pattern since here the lines are all due to X-rays of the same wave-length. This is an important point, since a determination of the intensities of the lines is essential to the correct interpretation of the diffraction pattern.

Radiography with Pin-Hole Camera

Since X-rays cannot be focused by lenses, an object illuminated by X-rays cannot be photographed by means of an ordinary photographic camera. The principle of the pin-hole camera can, however, be used with X-rays in the same way as with ordinary light. For this purpose all that is required is a lead diaphragm with a small hole of from .1 mm. to .5 mm. diameter drilled through it.

The size and distribution of energy in the focal spot of an X-ray target can be determined by making radiographs by means of a pin-hole. In order to determine the size of a focal spot, the pin-hole should be placed midway between the target and film in which case the size of the photographic image will be the projection of the focal spot on the film, except for a correction due to the diameter of the pin-hole. In such an arrangement the diameter of the radiographic image is greater than the diameter of the focal spot projection on the film by an amount which is twice the diameter of the aperture. Thus if a focal spot of 2 mm. diameter is radiographed through an aperture of .5 mm. diameter under the above conditions, the image will have a diameter of 3 mm.

In investigations of the energy distribution in the focal spot, more detail can be obtained in the image by making the distance between aperture and film greater than that between aperture and target, in which case a magnified image is pro-

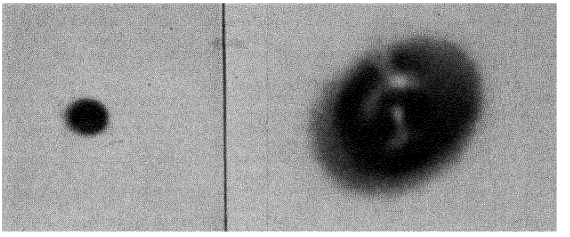


FIG. 123.—PIN-HOLE RADIOGRAPHS OF FOCAL SPOT, NATURAL SIZE AND MAGNIFIED 5 TIMES.

duced. The resolution in such a radiograph depends upon the angular width of the aperture with respect to a point on the target and upon the magnification. The magnification depends upon the relative distances of the film and target from the aperture. If the time of exposure is enough to cause intense blackening of the film, all details of the structure are lost and

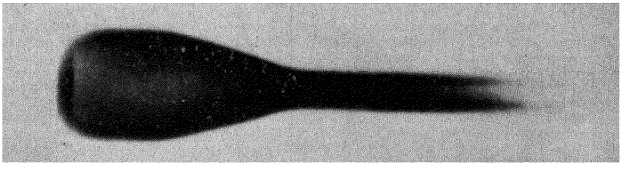


FIG. 124.—PIN-HOLE RADIOGRAPH OF BACK OF TARGET.

furthermore the size appears larger than it should, due to the scattering of the rays by the film and the spreading of the image by what is known in photography as halation.

Figure 123 gives a radiograph of a focal spot in natural size compared with a picture of the same spot taken with a magnification of 5× by using increased distance. In the larger picture, the irregularity of the energy distribution over the focal area is very apparent.

In Fig. 124, the back of a target is photographed by its own radiation. Of course, a much longer exposure is necessary in this case. It is worth while, however, to realize the amount of radiation that emanates from the back and stem.

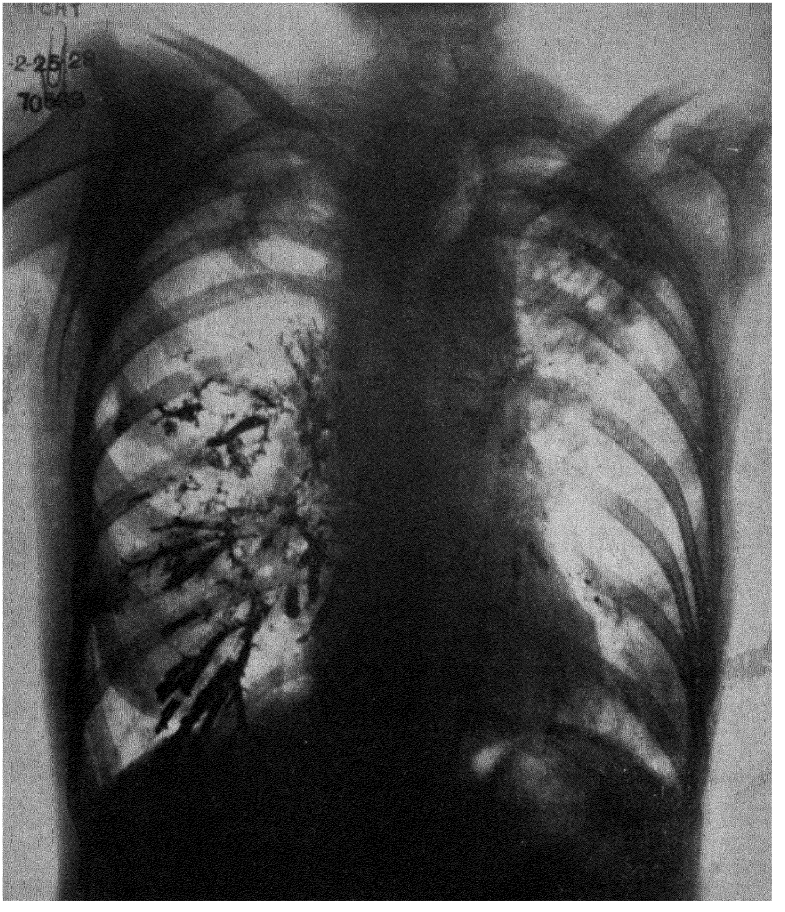


FIG. 125.—LIPIODOL INJECTION OF THE BRONCHI.

Use of Opaque Media

The applications of radiography in medicine have been considerably extended by artificially increasing the density of the

parts it is desired to portray. Perhaps the best known example is the use of a barium sulphate meal in taking radiographs of various portions of the alimentary tract. Following are three other examples of the use of opaque media.

The clinical roentgenograms were furnished by Dr. David R. Bowen, of the Pennsylvania Hospital, Philadelphia, and are



FIG. 126.—RADIOGRAPH OF THE GALL BLADDER.

from the services of Drs. Gibbon, Clerf, Bowen, Norris and Herman.

In Fig. 125, which is a lipiodol injection of the bronchi, the patient is shown to have chronic fibroid tuberculosis of the upper part of the left lung, with marked distortion of the trachea from scar tissue. There is also some involvement of the upper lobe of the right lung. Many of the smaller bronchi

are shown to be somewhat enlarged. The lipiodol is also shown as helping, to some extent, to bring out the outlines of the distorted trachea.

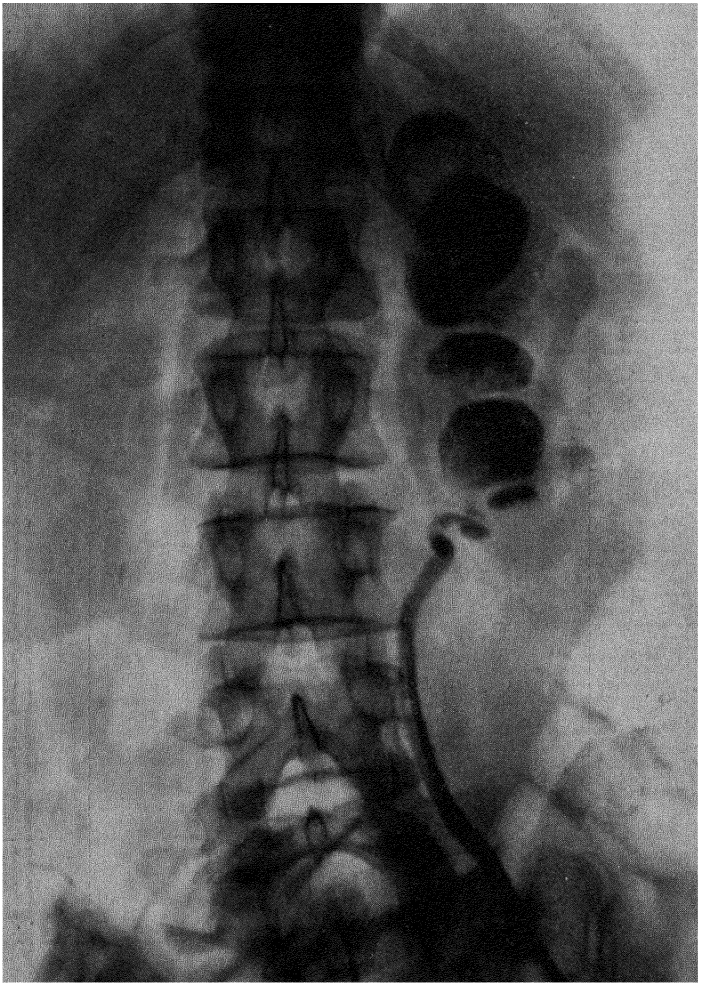


FIG. 127.—PYOCYSTIC KIDNEY.

Figure 126 shows a radiograph of the gall bladder taken after the method of Graham, with oral administration of sodium tetra-iodo-phenolphthalein. The gall bladder is shown

pendulous, somewhat lower and nearer the spine than usual. A large amount of unabsorbed dye is seen in the colon. The gall bladder shadow is overlapped by the shadow of the spinal muscles and calcification of the costal cartilages is seen above and to the right.

Figure 127 is taken of a pyocystic kidney. Sodium iodide solution has been injected by means of a ureteral catheter. Four large cystic cavities and several smaller ones are to be seen. The ureter is shown much dilated about the ureteral catheter which could not be inserted above the level of the third lumbar vertebra, because of irregularity of the ureter just above this point. The shadow surrounding the catheter is the sodium iodide solution which thus visualizes the caliber of the ureter and the pathological cystic formation within the kidney.

CHAPTER XI

X-RAY ANALYSIS

There are two general methods of X-ray analysis of matter. One method consists of the study of the nature of the X-rays emitted by different elements while the other method deals with the action of matter upon X-rays. The emission of X-rays is an atomic phenomenon and furnishes information concerning the structure and properties of atoms. On the other hand, the action of matter upon X-rays in such phenomena as absorption, reflection, diffraction and scattering depends also upon the arrangement of the atoms and molecules in matter.

Emission Spectra

The complete X-ray spectrum of an element consists of general radiation which has the same frequency distribution for all elements, and characteristic radiation of definite frequencies for each element. The characteristic spectra of the elements have been classified in groups or series of lines, designated by the letters *K, L, M* and *N,* in the order of increasing wave-length. According to the generally accepted theory of the structure of the atom, the *K*-series, of highest frequency, has its origin in the displacement of electrons from the orbit nearest the nucleus of the atom, while the other series are generated by displacement of electrons from orbits further removed from the nucleus.

Only the elements of high atomic number possess a sufficient number of electron orbits to give rise to all four of the series. For the elements of atomic number up to 24, chromium, the lines of *K*-series only, have been identified

while for all elements of higher atomic number, lines have been measured also in the *L*-series. The *M*-series has been identified for elements of atomic number above 66 and the *N*-series for those above 83.

In general the *K*-series is most useful in X-ray analysis work but for the elements of high atomic weight it is more convenient to make use of the *L*-series, since the latter can be excited at lower voltages.

Moseley discovered a simple relation between atomic number and frequency of the lines of a series in the X-ray spectra. If frequency or wave-length of homologous lines are plotted against atomic number the points all lie on a smooth curve while if the square root of the frequency is used the resulting graph is practically a straight line.

The *K* series in general consists of four lines designated by the letters α_1, α_2, β, and γ. The *L*-series is more complex, and over twenty lines have been assigned to this series. However, for X-ray analysis it is sufficient to consider only the stronger lines, say about twelve lines in all. The simplicity of the X-ray spectra of the elements as contrasted with their complex optical spectra makes identification much easier and more certain by this method.

Either the ionization or photographic method may be used to obtain the emission spectrum of a substance but the latter method has the advantage that it can easily be made automatic, an important consideration in cases where many hours may be required to obtain a well defined spectrum.

The substance to be analyzed must be made the source of X-rays by using it as the target in an X-ray tube or by using it as a secondary radiator in which case it is placed in the path of an X-ray beam from a powerful X-ray tube. It is obvious that very long exposures are necessary when the substance is employed as a secondary radiator but some substances, on account of their volatility, cannot be used as targets under the conditions of temperature and pressure in an X-ray tube.

Substances which are stable in a vacuum can be applied to the target in various ways depending upon the physical state

in which the material is available. If many substances are to be examined it is most satisfactory to use an X-ray tube with a removable target and to operate the tube while connected to the vacuum pumps. A convenient tube for this purpose is shown in Fig. 128.

The anode is made of pure copper and is cooled by allowing water to circulate through the hollow anode by means of inlet and outlet brass tubes brazed into the cup which is brazed on the end of the anode.

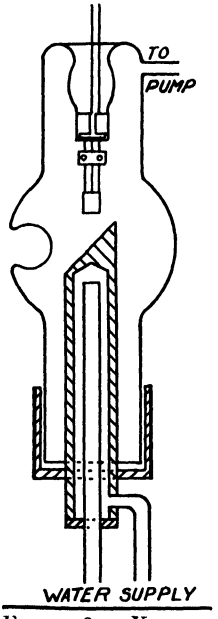


FIG. 128. — X-RAY TUBE FOR EMISSION SPECTRA.

The face of the target is roughened by scoring with a sharp-edged tool and the substance, in powdered form, is rubbed or ground into the face. After inserting the anode into the tube a hard wax is melted in the space between the glass neck and the metal cup, thus making a vacuum-tight seal. The bulb is made of pyrex glass and has a thin window blown in the wall as indicated in the figure. The thin window is important, especially when dealing with spectra of long wave-lengths.

For recording the spectrum photographically some device which will rotate the calcite crystal with uniform angular motion is necessary. A clock mechanism may be used or the crystal may be given an oscillatory motion by allowing an arm at right angles to the axis of the crystal table to slide on a heart-shaped cam revolving at constant r.p.m. See Fig. 129.

The photographic film is held in a circular film holder whose center of curvature lies in the axis of the crystal table. The film holder forms the removable curved wall of a metal box (not shown in the figure) which is necessary to reduce scattered radiation.

The spectra shown in Figs. 130 and 131 were obtained with such an apparatus. Figure 130 is a spectrum of an ore containing hafnium that came from Westchester County, New

York. Figure 131 shows the spectrum given by metallic hafnium.

The same technique should be followed in regard to the photographic films used in this apparatus as in the case of those used in the diffraction apparatus discussed in another section.

The most reliable method of determining the wave-lengths of the lines on a film is to calibrate a film with lines whose wave-

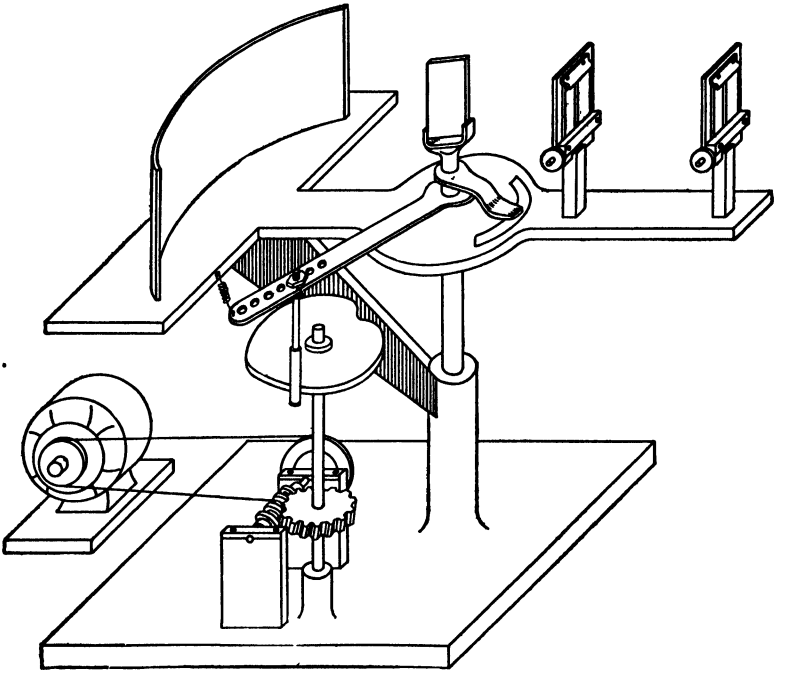


FIG. 129.—ROTATING CRYSTAL SPECTOGRAPH.

lengths are known. This can be done by using a molybdenum target X-ray tube and photographing both the first and second order lines of the *K*-series as well as the absorption edges of silver and bromine in the film. A graph can then be made using these wave-lengths as standards and plotting wave-length against distance on the film from the position of the unreflected beam. Certain known lines will always appear on a film together with the spectrum of the specimen to be analyzed and these can be used to detect any constant error which may occur

due to a displaced film. In most cases the absorption edge of silver or bromine will appear on the film as well as the *K*-series lines of the copper target. In addition to these, the *L*-series

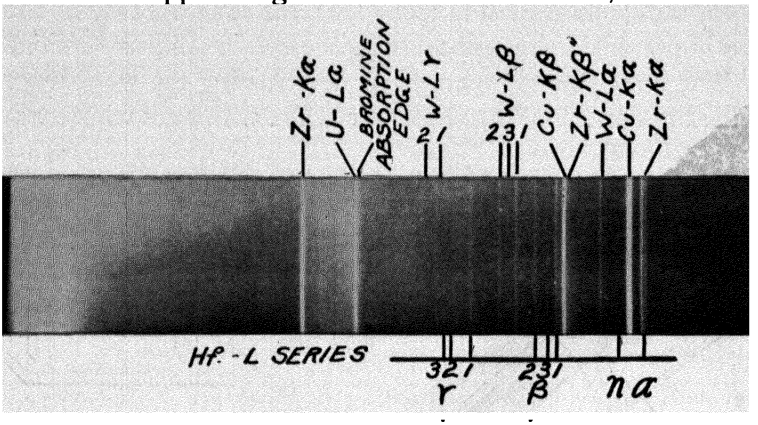


FIG. 130.—SPECTRUM OF HAFNIUM ORE.

lines of tungsten will nearly always show on the film if a tungsten filament is used for the cathode. The tungsten lines are caused by evaporation of the metal or oxide on to the target

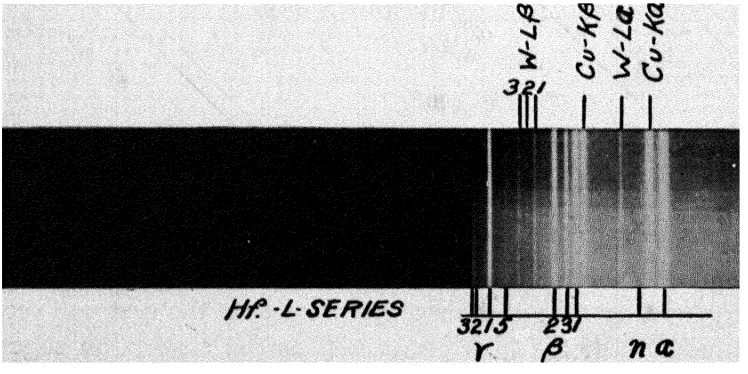


FIG. 131.—SPECTRUM OF METALLIC HAFNIUM.

during an exposure. If one is searching for lines in the region occupied by the tungsten lines, as for example when analyzing a specimen for rhenium, it is advisable to use tantalum or molybdenum filaments in the cathode instead of tungsten.

Sensitivity

The amount of an element which can be identified by its emission spectrum depends upon its concentration on the target, its atomic number, volatility, the nature of the other constituents in the specimen, etc., so that it is necessary to specify the conditions in order to speak of a sensitivity in terms of percentage of the element present in a specimen. Under the most favorable conditions it is possible to identify less than 1/10th of 1 per cent of an element in a specimen, while under other conditions several per cent may be undetectable.

The importance of qualitative X-ray analysis by the emission spectrum method has been emphasized in recent years by the discovery of the elements of atomic numbers 43, 61, 72 and 75 by this means. It is to be expected that the same method will eventually identify the two missing elements of atomic numbers 85 and 87.

Determination of Crystal Structure

That the symmetry exhibited by crystals is evidence of regularity of internal structure was commonly believed long before direct proof was available in the form of X-ray analysis. The employment of X-rays did more than this, however, for at one stroke it broadened immensely the field of application of the science of crystallography. While large crystals, as perfect objects, are of comparatively rare, and of what may be considered accidental occurrence in nature, X-rays have demonstrated that crystalline structure is almost universal. Indeed, subjected to the searching analysis of X-rays, it is difficult to find any solid substance that is perfectly amorphous.

The enormous importance of the study of crystal structure is just beginning to be realized. Nearly all the physical properties of solids, such as density, strength, rigidity, hardness, ductility, magnetic and electrical properties, etc., are directly referable to the ultimate structure.

As a preliminary to the study of crystal structure, the following important properties of crystals deserve mention. A

crystal is bounded by plane faces, symmetrically arranged, but such shapes as cubes, octahedra, etc., refer to crystals ideally perfect. In actual crystals the relative size of the faces, or their distances from the center, may be displaced; but the faces always remain parallel to their true position, so that the angles between them remain always the same. Thus a substance crystallizing in the cubic system may be found in the form of a rectangular prism, but the angles between the faces are all right angles. This law of constancy of angles is one of the fundamental laws of crystallography.

The positions of the various faces are specified by referring them to a set of axes. For these axes of reference, any three edges formed by the intersection of three faces might be chosen, but in practice, certain lines are seleted which are related to the symmetry of the crystal; in general, axes of symmetry.

The axes being chosen, the position of any face is specified by its intercepts on these axes. The intercepts of any face being selected as parameters, e.g., a, b, c, the intercept of any other face, after suitable reduction, may be expressed by the ratios $\frac{a}{h}, \frac{b}{k}, \frac{c}{l}$. A relation that exists between faces of a crystal is that these quantities h, k, l, will always be whole numbers. This law of rational intercepts is the second fundamental law of crystallography. The above-mentioned parameters being taken as a unit of measure, the reciprocals of the intercepts of a face (or any other plane) are called the indices (Miller indices) of that plane, and are expressed by being written in parenthesis. Thus in the cubic system, a face of a cube, being a plane perpendicular to the axis, would have the intercepts 1, ∞, ∞, and the indices (100). In like manner, a face of an octahedron, having intercepts 1, 1, 1, would have indices (111) and the face of a dodecahedron would be written (110).

As a useful convention which permits generalizing certain rules, the 2nd order reflection from the (100) planes is sometimes called reflection from the (200) plane, the third order called the (300) etc.

Crystal Classes and Space Lattices

Classified according to external symmetry, there are 32 classes of crystals divided among the six coordinate systems, triclinic, monoclinic, hexagonal, orthorhombic, tetragonal and cubic.

The atoms and molecules of the crystal are arranged in certain groups, and this group formation repeats itself indefinitely, like the pattern of wall paper. The space within the crystal may be divided into small cells or units, as for example, cubes, each containing one unit of pattern or grouping of

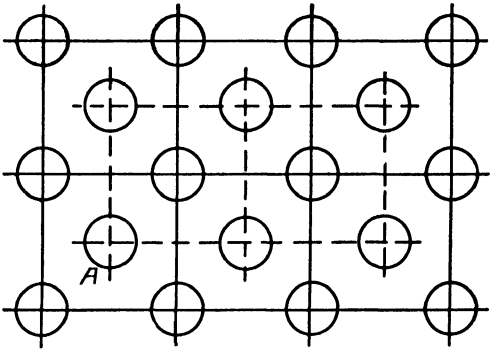


FIG. 132.—PROJECTION OF BODY-CENTERED CUBIC LATTICE.

atoms, such that an atom or group of atoms is associated with certain points of the cell.

The division of space into cells or lattices was first proposed about the middle of the 19th century, the formal proof of the existence of fourteen types of translation groups or lattices, being credited to Bravais.

The most familiar of the fourteen are the three cubic lattices, simple, body-centered and face-centered. Besides these, there are two body-centered lattices, tetragonal and rhombic; two end-face-centered, rhombic and monoclinic, and one face-centered, rhombic. The remaining ones are six simple lattices, rhombohedral, tetragonal, hexagonal, rhombic, monoclinic and triclinic.

The 14 lattices combined with the 32 symmetry groups result in some 230 classes of crystals.

The fundamental property of the space lattice is that every point is identically situated in relation to every other point. For example, in the body centered cubic, the same point serves equally well for a center or a corner, depending on how the lattice is set up. Thus, in Fig. 132, which is a plane projection of the body centered cubic lattice, the point *A* is a center or corner, according as the dotted or full line lattice is chosen.

Principles of the Powder Diffraction Method

Consider a crystal of rock salt, NaCl, mounted on a spectrometer, with the (100) face in position for reflection. Suppose that the radiation be the $K\alpha$ line of molybdenum, isolated with a Zr filter. The reflections, as obtained with an ionization chamber, would appear as in *A*, Fig. 133, carried out to the third order.

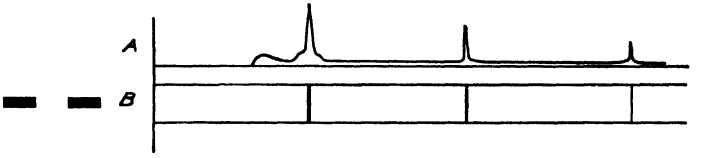


FIG. 133.—COMPARISON OF SPECTRAL LINES FROM SPECTROMETER AND SPECTROGRAPH.

If a photographic film be substituted for the ionization chamber, and the crystal is slowly rotated before it, a picture will be obtained in which the various orders of the spectral line will appear as a series of lines on the film as in *B*.

Now in the powder diffraction method as described by Hull,[1] instead of a single face of the crystal being used, such as the (100) face, the crystal is crushed and the narrow beam of monochromatic X-rays passed through the disordered mass of small crystals. There will be a certain number of small crystals whose (100) planes are at the proper angle to reflect the particular wave-length employed, a number of others whose (111)

[1] Hull, Phys. Rev. 10, 665 (1917).

planes are in position for reflection, and so on for every possible plane that belongs to the crystal system represented. As the angle increases, this results in hopeless confusion since the number of possible planes is infinite, but at smaller angles, say

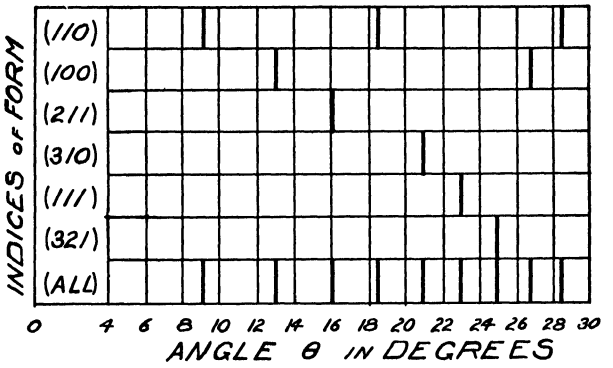


FIG. 134.—SCHEMATIC DIAGRAM SHOWING RELATIVE POSITIONS OF LINES DIFFRACTED BY VARIOUS CRYSTAL PLANES.

for the first twenty or thirty lines, the individual ones can be picked out and identified.

The first nine lines of tungsten, and the indices of the planes from which these lines are reflected are shown in Fig. 134. In the top row are the first three orders of the (110) plane, next two orders of the (100) plane and then the first orders of the next four planes.

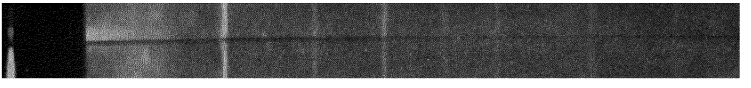


FIG. 135.—DIFFRACTION PATTERN OF TUNGSTEN.

At the bottom all these lines are shown together, just as they would appear on the film. For comparison, an actual film of tungsten is shown in Fig. 135. A comparison of the patterns for the simpler types of lattice is shown in Fig. 136. These are drawn to a scale which gives the spacings directly in A units.

Intensity of Reflection

While the position of the lines depends only on the arrangement of the atoms within the crystal, ie., on the type of lattice, etc., the intensities depend not only on the arrangement but also on the kind of atoms, i.e., atomic number. Thus the problem of predicting the intensities from known structure is very difficult and there is at present no satisfactory general expression for the law governing the intensity.

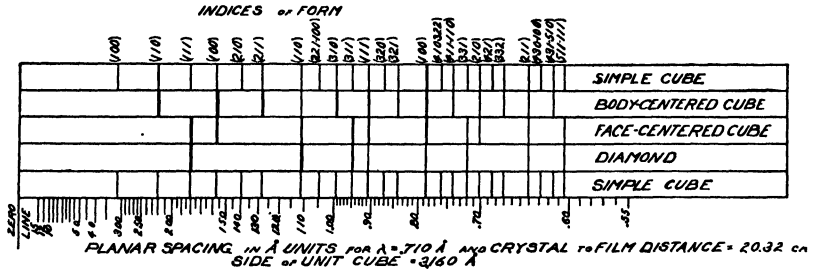


FIG. 136.—THEORETICAL PATTERNS OF THE SIMPLER LATTICES.

For a crystal composed of only one kind of atoms, as in the case for pure metals, the intensities of the lines depends principally upon the number of atoms per unit area in the different planes, the number of planes in the family of each type, and the angle of reflection. For example, in a face centered structure such as aluminum or copper, the relative intensities are as in the following table:

Indices of Form	Relative Number of Atoms per Unit Area	Number of Planes in Family	Observed Relative Intensity
(111)	$4/\sqrt{3}$	8	10
(100)	2	6	6
(110)	$2/\sqrt{2}$	12	5

In the case of compounds, a rule sometimes given, although of limited application, is that the amplitude is proportional to the number of electrons in the reflecting planes, the intensity

being proportional to the square of the amplitude. Bragg gives as illustration of this rule, a series of metallic carbonates. In the reflection from the (111) face of Fe CO_3, the first order is extinguished, since the alternate Fe and CO_3 planes contain approximately the same number of electrons, while in Ca CO_3 the first order is present but weak since the alternate planes do not exactly balance. In Ca CO_3 we have for the ratio of the first and second order, the following:

$$\frac{(30 - 18)^2}{.2\,(30 + 18)^2} = \frac{12^2}{.2 \times 48^2} = \frac{1}{3.2}$$

In counting electrons of calcium, the two valence electrons are omitted. The factor .2 is the normal diminution for second order. The above rule, however, when applied to alkaline halides, holds for 3 members of the series, and then breaks down.

In a general way, the positions of the lines are relied upon to give the size and shape of the unit cell, while the intensities are of aid in determining the arrangement of atoms within the cell.

For a given substance, as in the case of the powder diffraction method, the change of intensity with order and angle depends on the following factors, which are partly empirical:

1. Lorentz factor. Normal diminution of intensity.
2. Polarization factor.
3. Structure factor. Number and position of intermeshed lattices; e.g., in body centered cube, no reflection when sum of indices is odd.
4. Frequency factor. Number of planes cooperating to produce the line; e.g., in cube there are six (100) planes and twelve (110) planes.
5. Temperature factor. (Debye factor) Intensity decreases with higher temperatures.

For use in X-ray spectrometry, with monochromatic radiation, a quantity which may be called the coefficient of reflection has been defined by Compton [2] as $E\frac{\omega}{I_0}$, where I_0 is the electrometer deflection when the direct beam enters the ionization chamber for one second, and E the deflection for the reflected beam when the crystal is rotated with an angular velocity of ω degrees per second.

Bragg has given a similar definition based on the radian as the unit of angle. A table of values of the coefficient of reflection per degree taken from an article by Davis and Terrill [3] follows.

θ	R for Rock Salt	R for Calcite
3°	.047	.005
7°	.022	.005

It will be seen that in the case of rock salt, the coefficient varies with the angle, while for calcite it is approximately constant. Observations, however, show that it varies considerably with the polish or state of perfection of the crystal face.

The fact that the coefficient for rock salt is so much larger than for calcite is accounted for as follows. Monochromatic radiation is secured by reflecting the X-rays from one crystal, and a second crystal of the same substance is used to determine the coefficient. Not only is there reflection of radiation of wave-length corresponding to $\lambda = 2d \sin \theta$, but some energy of neighboring wave-lengths is also reflected. The crystal is rocked through a small angle on each side of the position corresponding to θ. The intensity can be plotted against the angle, and a curve obtained which rises to a maximum at θ, and then falls off again. The coefficient of reflection is the area under this curve, the unit of measurement being a rectangle whose height is the intensity of the direct beam and whose length is

[2] Compton, Phys. Rev., July, 1917.

[3] Davis and Terrill, Phil. Mag., 45, 463 (1923).

one degree on the scale of the diagram. Rock salt gives a low wide curve with large area but small intensity at maximum, while the curve for calcite is high and narrow, the total area being smaller, but the intensity at maximum being greater. It would appear, that to completely specify the reflectivity of a crystal would require the determination of two constants, one of which will relate to the degree of perfection of the surface (height of curve) and the other to the intrinsic reflecting power of the substance (area of the curve).

Apparatus for Crystal Analysis

Two types of apparatus are in common use for crystal analysis by the X-ray diffraction method, the one employing a pin-hole source of X-rays after the method of Laue, and the other using a line source obtained by the means of narrow slits. Both methods employ substantially monochromatic X-rays secured by filtering the beam with a screen which is relatively transparent for the characteristic $K\alpha$ line for the element composing the target of the X-ray tube. For most purposes targets of molybdenum or copper are suitable.

A diffraction apparatus manufactured by the General Electric Company is capable of obtaining as many as twelve patterns simultaneously, an important consideration when it is necessary to make exposures of 10 to 20 hours or more in many cases. An X-ray tube with a water-cooled molybdenum target is inclosed in a grounded metal housing which also contains the high voltage and filament heating transformers.

Each pattern is recorded on a strip of photographic film held in a cassette constructed so that the film is located on the arc of a circle with the specimen at its center. A zirconium filter is also mounted in each cassette, and intensifying screens may be added if required. A diagram of the slit system and cassette is shown in Fig. 137. The slit nearest the specimen is made wide enough so that the X-ray beam does not graze its edges and its purpose is to prevent radiation scattered and diffracted at the other slits from reaching the film.

The apparatus was designed for the use of powdered crystals although specimens in the form of wires, or sheets may be used. Powdered specimens may be packed in thin glass tubes or made into thin sheets after mixing with a non-crystalline binder such as collodion. A sheet may be pressed to the proper thickness between polished aluminum plates from which it can be readily detached when dry. To avoid trouble due to curling

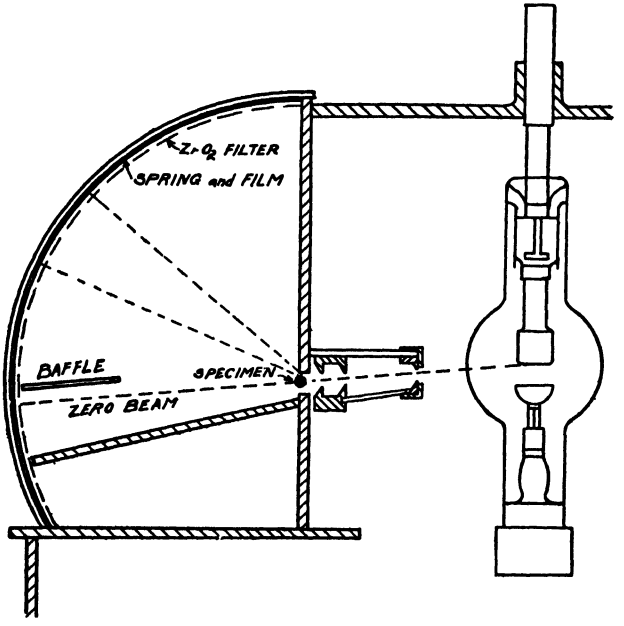


FIG. 137.—DIAGRAM OF THE GENERAL ELECTRIC CO. POWDER DIFFRACTION APPARATUS.

and to secure uniform distribution it is best to cement several thin sheets together.

Hull has pointed out that the optimum thickness of a specimen is, $t = 1/\mu$, where t is the thickness in centimeters and μ is the absorption coefficient for the radiation used. In some cases, however, it is difficult to mount specimens as thin as required and it is advisable to dilute the powder by mixing it with some light amorphous powder. In such cases the effective thickness can be determined by weighing, but the absorption

coefficient may not be known for the substance. A practical method of determining the proper thickness of a specimen is to select a sheet of aluminum of the proper thickness and then make an ordinary radiograph through the aluminum and specimen placed side by side. The thickness of the specimen can be found by trial such that the blackening of the photographic film matches in the two cases. Of course the radiograph should be made with the same filtered radiation as is used in obtaining the diffraction pattern.

The proper thickness of the specimen having been determined it is mounted in position together with a standard powder in such a way that half of the film will record the pattern of the unknown specimen along by the side of that of the standard on the other half. This will avoid uncertainities arising from shrinking of the film or displacement of the zero line.

Eastman duplitized films are suitable for this kind of work either with or without intensifying screens although if screens are used they must be kept clean and free from scratches which might give rise to lines on the film. Extreme care should be exercised in developing the films to avoid scratching and fogging, and the temperature of the developing and fixing baths should not exceed 70° F. as higher temperatures soften the emulsion and may cause shrinking or distortion and also fogging sufficient to obscure faint lines.

The crystal structure is determined by measurement of the positions of the lines on the film either with respect to the lines of the standard pattern or with respect to the unreflected beam, and the spacings of the respective planes are calculated from the equation $d = \frac{\lambda}{2 \sin \theta}$. The simpler structures like the three cubic types can usually be identified at a glance. The calculation of the spacings of the various planes, however, requires accurate measurements. A scale is supplied with the General Electric Co. apparatus which gives the spacings in A units directly. Such a scale is shown with the patterns of Fig. 136 and it will be observed that the smaller spacings can be measured with greater precision than the larger ones.

Having determined the spacings of the planes responsible for the various lines, some experience and ingenuity is required to analyze the crystal structure of the more complex types. The solution consists in trying to fit the calculated spacings, with no omissions or additions, to one type of lattice after another until one is found that has the same relative spacings as the specimen. A graphical method for several crystal systems has been devised by Hull and Davey,[4] by means of which considerable time can be saved for the types to which their graphs are applicable.

In the interpretation of diffraction patterns, the problem is sometimes confused by the appearance on the film of lines from sources other than the specimen. To avoid this confusion it is advisable, where doubt exists, to make an exposure with no specimen in position. On the other hand, certain important lines may be absent from a pattern which in other respects fits a known structure. This happens when there is a certain preferred orientation of the crystals in the specimen such as when the particles are needle-shaped or in the shape of flakes. For example, the absence of a strong line in a diffraction pattern of graphite was found to be due to the fact that the particles in the form of tiny flakes had arranged themselves with their flat sides parallel to the paper on which the specimen was mounted. When the graphite was further crushed and mixed the line appeared in the diffraction pattern.

Density

It is obvious that the volume of a unit cell can be calculated from the planar spacings given by the X-ray diffraction pattern, after the form of the cell is once determined. The density can then be calculated from the relation

$$\rho = \frac{\text{mass}}{\text{volume}} = \frac{NM}{V},$$

[4] A. W. Hull and W. P. Davey, Phys. Rev., 17, 549 (1921).

where V is the volume of the unit cell, M is the weight of a molecule of the substance, and N is the number of molecules per unit cell. M must be expressed in grams by multiplying the molecular weight by the chemical unit of mass, 1.663×10^{-24} grams, which is one-sixteenth the mass of the oxygen atom. It should be noted that such calculations give the density of the crystal grains and may therefore give results quite at variance with values of density obtained from measurements of mass and volume of a bulk of the substance, where voids and foreign matter are included in the measurements.

The usual laboratory method is therefore the correct method of determining the true average density of a bulk of matter, while the X-ray method is valuable in showing the theoretical maximum attainable value. For example, ordinary methods show that the density of a metal like tungsten or nickel increases as the diameter of a wire is decreased by drawing through a die, while the X-ray method gives the same density for the small as for the large diameter wire, or even for the metal in the form of a powder.

Compounds and Solid Solutions

X-ray diffraction patterns yield information that, in some cases, can be obtained by no other means. For example, when there is doubt as to whether several constituents of a substance are combined chemically, are in solid solution, or are a physical mixture, a comparison of the X-ray diffraction patterns of the substance with that of the separate constituents often solves the problem.

While it is not impossible for two elements which crystallize in the same form to be chemically combined in the same form, yet the probability of such occurrence is not great. For example, nickel and aluminum which are both face centered cubes form the chemical compound NiAl which is a body centered cube. Copper, which is also face centered combines with aluminum to form CuAl and $CuAl_2$ which have been reported to be hexagonal and tetragonal respectively.

It has been shown that the X-ray diffraction pattern of uranium is completely changed by allowing the metal powder to stand in an atmosphere of pure hydrogen, thus indicating that a compound of uranium and hydrogen was formed rather than that the hydrogen was simply absorbed by the powder, as was at first presumed.

When two metals of the same crystal form are combined under favorable temperature conditions they may form a solid solution in all proportions as indicated by the diffraction pattern remaining always of the same form but the lattice spacings changing in magnitude from that of the one component to that of the other as the percentage of the second component is varied from 0 to 100 per cent. As an example may be mentioned the case when tungsten and molybdenum powders in varying proportions are mixed and sintered. Both these metals are body centered cubes, the side of the elementary cube being 3.155 A. units for tungsten and 3.143 A. units for molybdenum.

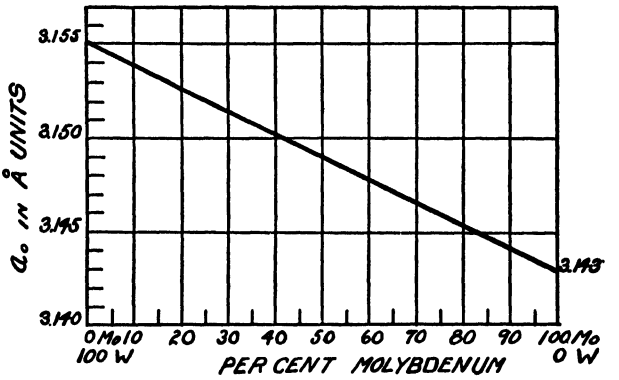


FIG. 138.—VARIATION IN PLANAR SPACING FOR MOLYBDENUM-TUNGSTEN ALLOYS.

The graph in Fig. 138 shows that the two metals form a continuous series of solid solutions in which the side of the elementary cube changes from that of tungsten to that of molybdenum as the percentage of molybdenum is increased from 0 to 100 per cent.

In general, when a solid solution of two elements of different crystal structure is formed, the structure of the alloy

is the same as that of the solvent, the atoms of the solute simply displacing atoms of the solvent. In such cases the diffraction patterns indicate a change in dimensions of the unit cell but no change in form. McKeehan has investigated the crystal structure of iron-nickel alloys and found that from 100 to 75 per cent iron the structure is of the body-centered type like iron while from 70 to 0 per cent iron the structure is face-centered like nickel. In the region of 75 to 70 per cent iron both body-centered and face-centered crystals are found.

Attempts have been made to use the X-ray diffraction pattern method for quantitative analysis of small amounts of a known element or compound in the presence of large amounts of other matter. The method, however, is not adapted for this kind of work and except in the simplest cases where the number of elements is very small the great number of lines makes even the identity of minor constituents doubtful. As pointed out in a previous section, the X-ray emission spectrum offers a much more reliable method of quantitative analysis.

Pin-hole Apparatus

While the pin-hole diffraction method has a variety of uses, it is particularly valuable in cases where only a few diffraction patterns are to be obtained and it is desired to avoid the time and expense of installing a special diffraction apparatus. The apparatus for the pin-hole method is so simple that a good mechanician can turn out the parts in an hour or so.

The X-ray tube may be enclosed in a lead-covered wooden box or similar shield. If only one photograph is to be taken at a time, it is simplest to fix the pin-hole system in a horizontal position, and incline the X-ray tube slightly.

A pin-hole mounting which can be attached to the wall of the X-ray tube shield is shown in Fig. 139. The system consists of two pin-holes in lead plugs which are mounted in the ends of a brass cylinder. The cylinder is made from a piece of $\frac{5}{8}$-inch round brass stock 3 inches long. A $\frac{1}{4}$-inch hole is drilled through the cylinder and the ends are counter bored to

provide shoulders for the lead plugs. The two lead plugs which define the pencil of X-rays are bored with a No. 55 drill and slightly tapered as shown in somewhat exaggerated form in the figure. A third plug bored with a larger hole, say with a No. 46 drill, is placed just beyond the second pin-hole and serves to prevent scattered rays from the second pin-hole reaching the film. This third diaphragm is essential, since without it a diffraction pattern of lead might be superimposed on the pattern of the specimen. To avoid the possibility of confusion arising from extraneous lines appearing on the film it is advisable to first make an exposure without any specimen in position.

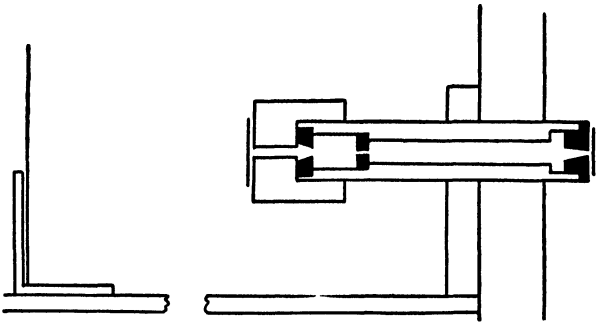


FIG. 139.—APPARATUS FOR PIN-HOLE DIFFRACTION PATTERNS.

The bakelite cap or spacer, which is shown in the figure, is not essential for ordinary work, but was used in an experiment which required a potential of 7500 volts to be applied to the specimen. The specimen may be in the form of a thin sheet in the case of metals or if in powder form may be attached to a stiff paper with collodion binder. An alternative method is to hold the specimen in a cell which can be made by drilling a hole with a No. 25 drill in a piece of celluloid about a millimeter thick and then covering the faces with thin sheets of collodion, gold beater's skin, or any non-crystalline substance. Such a cell can be used for liquids as well as powders.

A suitable film to use with this type of apparatus is the Eastman extra fast No. 2 dental film which is supplied in a

light proof paper wrapper so it may be exposed and handled in day-light in the original wrapper until ready for developing. The film may be conveniently placed at a distance of 10 cm. from the specimen.

The information which can be obtained from a pin-hole diffraction pattern is more complete than that obtained from

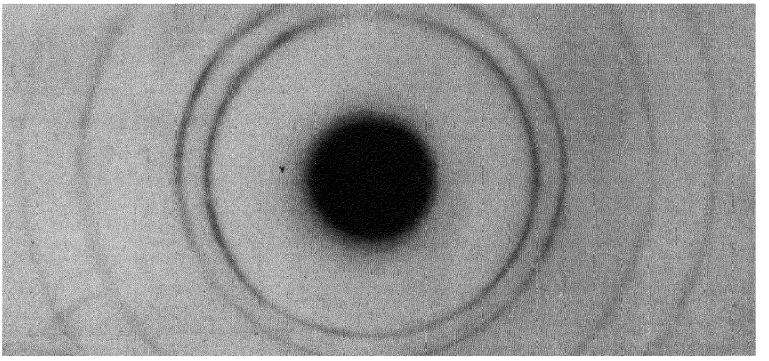


FIG. 140.

a pattern made with a slit system although, in general, longer exposures are necessary and calculations of planar spacings are not quite so simple. The method is particularly adapted to

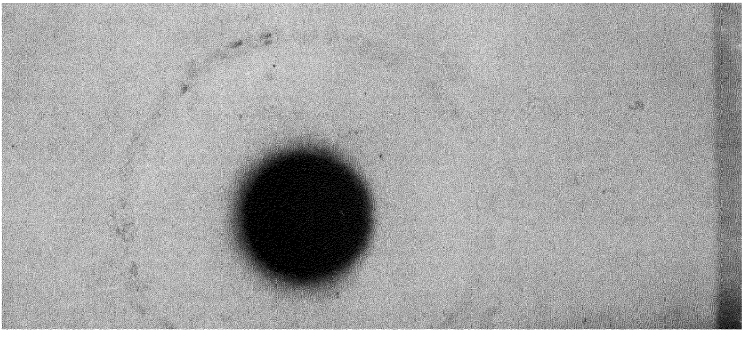


FIG. 141.

the study of crystal orientation in solids and the changes which occur in metals when rolled, drawn or annealed.

Some interesting illustrations of the application of this

method of analysis are given in Clark's "Applied X-rays," which show the effects of stretching such substances as rubber and gelatin and the effects of annealing and mechanical working of metals.

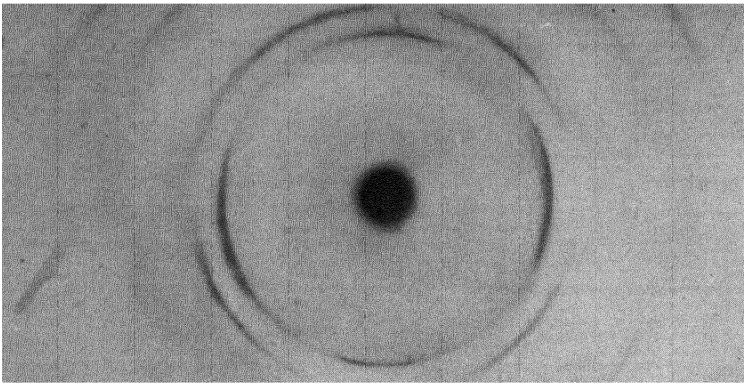


FIG. 142.

The influence of grain size on the nature of the pin-hole diffraction pattern is illustrated in the aluminum patterns in Figs. 140 and 141. Figures 142 and 143 show the effect of rolling and drawing, respectively.

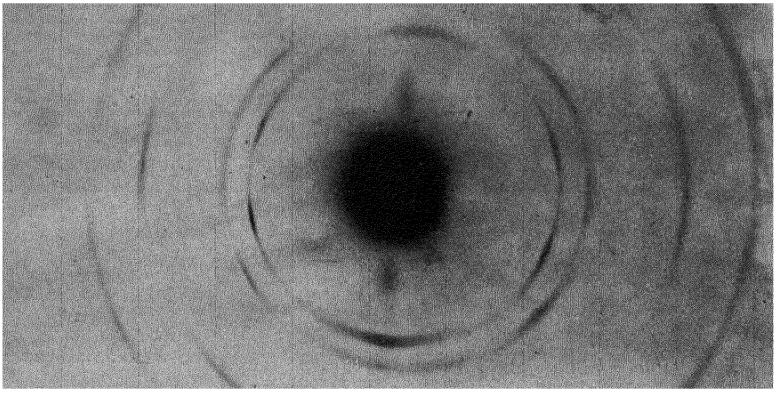


FIG. 143.

The methods of analysis dicussed in this chapter are still in the state of development and new applications are being found each year.

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