PRACTICAL APPLICATIONS
OF
X-RAYS

G. W. C. KAYE

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A B

FIG. 45.—Showing great advance in technique in 25 years. (A) Radiograph of hand taken in 1896 by Campbell Swinton; exposure 20 mins. (B) Ditto, taken in 1921 by Knox; exposure $\frac{1}{100}$ sec.

[*See page* 73.

FIG. 56.—Radiograph of defective oxy-acetylene weld in $\frac{1}{2}$-inch steel plate.

[*See page* 91.
[*Frontispiece.*

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OF

X-RAYS

BY

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PREFACE.

This book is based largely on a course of Cantor Lectures delivered before the Royal Society of Arts in 1921. The manuscripts of other lectures given at the Royal Institution and the Royal Society of Medicine have also been drawn upon.

The book is concerned primarily with the practical applications of the X-rays, and although other aspects have not been neglected, notably that of measurement, the reader is referred to the author's "X-Rays" (Longmans) for a more extended theoretical treatment of the fundamentals of the subject. W. H. and W. L. Bragg's masterly work on "X-Rays and Crystal Structure" (Bell) is unapproached in its account of X-ray spectroscopy.

The writer wishes to thank his wife for her ever-effective assistance. He is also indebted to various friends who have kindly permitted the reproduction of radiographs.

G. W. C. K.

July, 1922.

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CHAPTER I.

INTRODUCTORY.

The Nature of X-Rays.—The study of the X-rays now occupies a prominent position in physics and medicine and has led to such momentous results in a variety of directions that one is apt to forget that it was only in 1895 that the rays were discovered by Prof. Röntgen, and that it was only just prior to the war that a long controversy as to their nature was stilled.

The problem had attracted many minds, for the ability of the rays to pass through opaque bodies was wholly unprecedented. The explanation of the anomaly was obviously bound up with the nature of the rays, but despite shrewd guesses, the secret was withheld from us for nearly twenty years.

We now know that the X-rays are another manifestation of radiant energy, of which light and heat are familiar examples. Indeed, the X-rays resemble light rays in almost every particular, the chief difference being that the X-rays have wave lengths which are much shorter. In other words, the X-rays are situated away beyond the violet end of the visible spectrum, and may be regarded, in a sense, as a very "treble" form of ultra-violet light. It was this very minuteness of wave length—a distance of the same order as the sizes of atoms—that defeated all our earlier attempts to direct and sort out the rays. All our highest quality polished surfaces are inconceivably rough for such a purpose, and it was not until Nature herself was found to have provided an instrument of the requisite surpassing delicacy—in the shape of crystals which can function as diffraction gratings—that we began to analyse and sort out X-ray beams with much the same ease as in the case of visible light.

There are further parallelisms between X-rays and light rays. For example, we know that the spectrum of a hot body consists under suitable conditions of white light (which is a mixture of all wave lengths) superposed on which are certain spectrum lines whose wave lengths are characteristic of the radiating material, e.g. the D line of sodium, the H and K lines of calcium. In just the same way an element when caused to emit X-rays not only gives out general radiation (which yields a continuous spectrum of wave lengths) but under suitable conditions impresses its own characteristic lines on the general spectrum. The characteristic X-ray spectra are found to be much less complicated than light spectra, and are more readily sorted out into groups or series of associated lines. These several series, each of which includes a number of lines, are designated—J, K, L, M—and are broadly differentiated by a progressive increase in the average wave length of each group as we pass from one to another, series J having the shortest wave length.

Fig. 1 shows the known range of electromagnetic waves. We see that just about a single octave of light waves is visible to the eye. Their spectroscopic examination has been conducted mainly with the diffraction grating, the distance between the rulings of

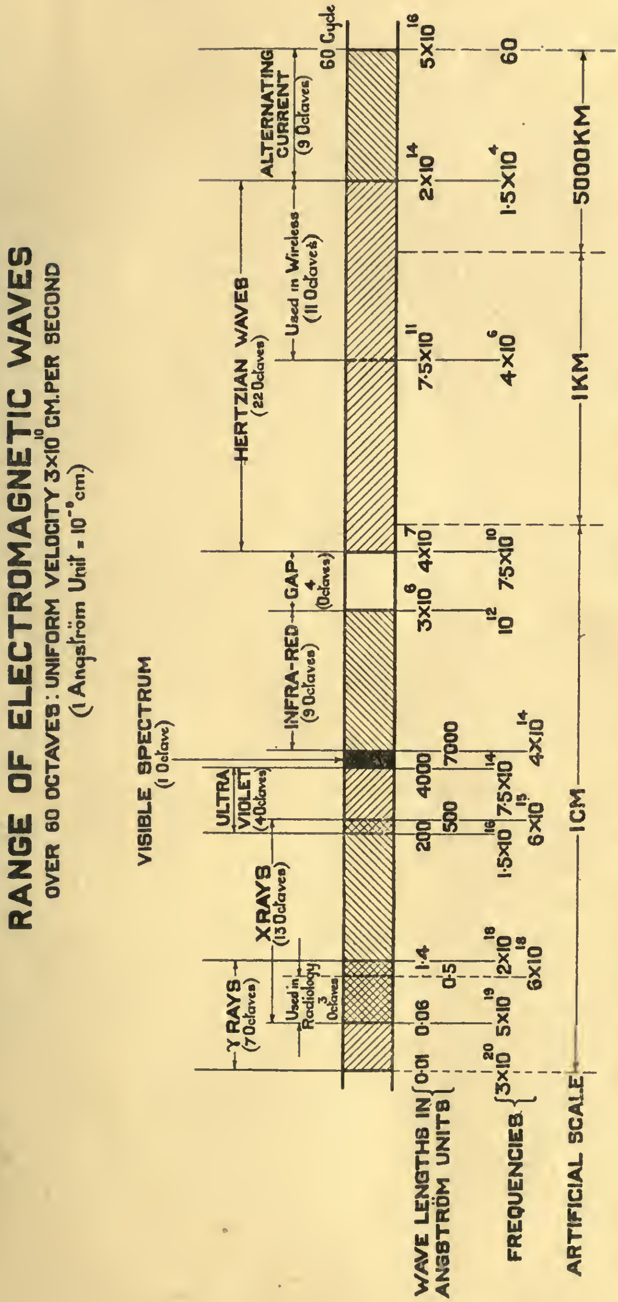


FIG. 1.—Showing position of X-rays in the 80 octaves of known electromagnetic waves.

which is comparable with the wave lengths to be measured. With the help of special gratings and vacuum spectrometers, Schumann, Lyman, and Millikan have extended the measurements some four octaves onwards into the ultra-violet. Until recently, a gap of about four octaves followed before we came to the longest waved X-ray, but in 1921 it was discovered that the continuity is complete and that the X-rays follow on and, indeed, overlap the ultra-violet end of the spectrum.

The study of this missing group of octaves had invited attention for some time. The grating method

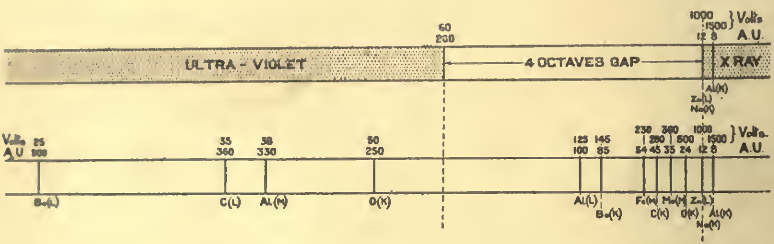


FIG. 2.—Some X-ray spectrum lines in the former gap between the ultra-violet and X-ray regions.

proved unavailing for the purpose, the wave lengths being too small for our artificially ruled gratings and too big for crystal gratings. Further, at either end of the gap the vacuum spectrometer had proved necessary owing to the extremely absorbable nature of the rays. The problem was finally attacked with success both in this country and America by a number of workers (Millikan, Richardson, Hughes, and Kurth) using indirect photoelectric methods, and they have traced X-ray spectrum lines of various elements right across the gap and into the already explored ultra-violet. Fig. 2 shows the positions of a few of these new lines.

Following is a short table of some of the wave lengths, in Angström units, i.e. 10^{-8} cm.

Visible light	7200 to 4000
Ultra-violet light . . .	4000 ,, 200
X-rays	500 ,, 0·06
γ rays	1·4 ,, 0·01

It thus appears that we can now claim a knowledge of the existence of over thirteen octaves of X-rays or, including radium γ rays, nearly sixteen octaves. The radiologist has turned about three octaves of X-rays to account.

X-Rays and Electrons.—Experiment has shown the most intimate relationship between X-rays and the electron—either is the manifestation of the other. Whenever an electron has its speed altered, an electromagnetic wave is produced. If the alteration of speed of the electron is very great, the frequency of the wave is very high, and we get a high-frequency or "hard" X-ray. If the change of speed is less, the frequency is less and we get a "softer" or less penetrating ray. With much slower electrons, light rays may be similarly produced. Always, however, we find that the frequency of the wave is proportional to the energy given up by the electron. There will be a proportion of encounters where the whole of the energy is transferred, and in these cases the frequency will reach an upper limit. Below this limit we find a variety of energy-contents depending on the experience of the electron involved.

The reverse effect is equally true. If X-rays or light rays strike a substance they may give up all their energy to moving electrons, or they may give up only a part, the rest being transferred to a series of groups of rays, all characteristic of the atom of the material. The energy balance-sheet can be fully written down, and the several items are all definite and specific. The relation is not quite so simple as the general case, but the exchange and partition of energy are equally precise.

The process we have just described is of universal application in Nature. There is, for example, little doubt that the X-rays play a prominent part in atmospheric electricity. The earth is not an electrically neutral body, but its surface may be considered to be covered with a layer of negative electricity, and this gives rise to an electrical field in the atmosphere. The rate of alteration of potential is found to decrease with the altitude: the potential gradient being about 150 volts per metre on the ground, and only about 2 volts per metre at a height of 9 kilometres—as we know by balloon tests. In other words, the atmospheric conductivity steadily increases, the higher we go, and the rapidity of the increase suggests very large values at greater heights.

Some of this conductivity, we know, is due to radioactive emanations from the soil, but we are led to infer from the increase of conductivity with height that the majority is due to some agent external to our globe. Modern opinion favours the view that the effect is produced by very high speed electrons ejected from the sun, and probably moving nearly as fast as light itself. Some of these strike the atoms of the outer atmosphere, very penetrating X-rays are generated, and thus the whole depth of the atmosphere may be permeated by these electrons through the intermediary of the more penetrating X-rays. It follows that the earth's negative charge which is being continually dissipated by the action of the potential gradient in the atmosphere is as steadily replenished by a current of electrons passing downwards. It may be added that the conductivity of the air diminishes at night and during a solar eclipse.

One is tempted also to believe that in view of the temperature and gigantic electrical disturbances in the sun—as Hale's work has shown and Eddington's speculations would indicate—there may be an emission of X-rays from the sun itself. The sun may in fact be looked upon as a huge X-ray bulb which is responsible directly or indirectly for the part X-rays play in atmospheric electricity and for the existence of the conducting or "Heaviside" layer in the upper atmosphere which is the main transmitting medium in wireless or radio-telegraphy.

One other source of X-rays in Nature may be referred to—the γ radiation of the radioactive elements. It will suffice to say that while some of the γ rays can be exactly imitated, others are much more penetrating than any X-ray we have been able to generate artificially.

X-Rays and Atomic Structure.—The work on X-ray spectra has thrown great light on the structure of the atom, and, in passing, it is interesting to note that present-day theory regards all atoms, of whatever kind, as built of two kinds of "bricks" and two only: (*a*) negatively charged electrons, and (*b*) hydrogen "nuclei," each over 1800 times as heavy as an electron and carrying a charge equal to that on the electron, but positive in sign. Rutherford's nucleus theory of the atom, now universally accepted, regards an atom as built up of a minute positive nucleus (to which practically the whole mass of the atom is attributed) surrounded by a cluster of electrons grouped in rings.

The total number of electrons in these rings is equal to the atomic number (N), the atomic number being the ordinal number representing the position of the element in question when the elements are grouped in the order of the periodic classification, hydrogen being 1 and uranium 92.[1] The nucleus of the atom is regarded as built up of hydrogen nuclei cemented together by electrons, the former being in excess to just such an extent that the nucleus as a whole contains N positive charges. This serves to counterbalance the N negative charges of the electron rings, the result being an uncharged atom. For example, platinum has an atomic number of 78. Its atomic weight, determined chemically, is 195. Thus if platinum is a simple element,[2] the platinum atom has a nucleus composed of 195 hydrogen nuclei and 117 electrons, the difference (78) serving to counterbalance the 78 electrons in the rings. The various elements differ only one from another in that they have different nuclear charges, the nucleus determining the mass and the radio-active properties, while the number and grouping of the cluster of electrons in the rings control the chemical and spectroscopic properties. For example, the K radiation is supposed to arise from the displacement of an electron in the innermost ring, the L radiation from the next ring and so on. The existence of the J radiation is problematical,

[1] See Appendix III. [2] See "Isotopes," Aston (Arnold).

but if it is a real thing it would seem to be emitted by a ring system on the border of or within the nucleus itself.

It was Moseley's work on characteristic X-ray spectra that led him to a recognition of the fundamental importance of the atomic number. He was able to show that the wave lengths (λ) of corresponding lines in the spectra of different elements are very simply related to the several atomic numbers (N), the relation being that λ is inversely proportional to N^2. This is often referred to as Moseley's law.

The Generation of X-Rays.—Although the electron is ubiquitous, it escaped detection until Crookes conducted his famous experiments in discharge tubes at low pressures, and so reduced the number of molecules present, that instead of the electron being absorbed and suppressed within a mm. or so, as it would be at atmospheric pressure, it can now travel great distances without encountering more than say 100 or so atoms, the majority of which it passes clean through without being deviated in any way. The high speed it has received from the potential in the discharge tube gives it, so to speak, an innings.

The electron is indeed the "cathode ray," and it was by the use of a Crookes' tube that Röntgen first discovered the X-rays in November, 1895.

The present-day method is essentially unaltered. The electrons (or cathode rays) are given enormous speeds of the order of 50,000 miles a second, by means of a high-tension discharge, and are directed on a heavy block of metal called the anticathode or target. By the use of a focussing device the electrons are concentrated on a small central area of the target, which area is the source or "focus" whence the X-rays set out. As a producer of X-rays the arrangement is extremely inefficient, although we take steps to increase the chances of an effective collision by choosing a target of high atomic weight or number.

Almost all the energy of the electrons is degraded into heat, and for this reason it is essential that the target shall be of a very refractory metal. The great heat developed is removed by water cooling, radiator fins, or the like. Tungsten (with a melting-point of over 3000° C.) is, nowadays, most frequently employed for a target, though platinum and other metals find use for certain purposes.

All that we need consider for the moment is that the X-rays radiate uniformly in all directions from the focus, travelling in straight lines just as light rays radiate from a lamp. The X-ray bulb is, indeed, an X-ray lamp, in which the voltage applied to the bulb corresponds to the temperature of a luminous lamp. If we raise the temperature of the latter, we increase the intensity and at the same time shorten the average wave length ; so with the X-ray bulb, if we raise the voltage we shorten the average wave length. In practice the voltages employed range up to 200,000 or even more. The quantity of radiation is controlled by the current through the tube, and a milliampere is a convenient size of unit for the purpose.

The Detection of X-Rays.—Although X-rays are not in the visible spectrum, they can be detected photographically or by their power of exciting fluorescence in screens made of salts, such as barium platinocyanide or cadmium tungstate. Another method makes use of the ionising ability of the rays and measures the temporary conductivity so produced in a gas. Certain chemical reactions are also induced by the rays, and can be made to serve as the basis of a method of detection and measurement.

X-rays can penetrate all substances to a greater or less degree, and in general, the shorter the wave length the higher is the penetrating power. Chemical combination or temperature is without effect on the absorbing power of an atom. The penetrability of a material by a given beam of rays is governed by the number and mass of the atoms it encounters, that is, by the atomic weight and thickness. We have already mentioned that the rays travel in straight lines, and thus it will be seen that an X-ray photograph or radiograph is essentially nothing but a shadowgraph. Here it may be remarked that the relative depths of objects are not indicated in a radiograph. To overcome this difficulty a pair of radiographs are taken from slightly different angles. By viewing these in the stereoscope or by a variety of other methods it is possible to calculate the exact position of a body below the surface. X-ray stereoscopy is bound up with the name of the late Sir James Mackenzie Davidson.

Radiography was the first and still remains the most important application of the rays, and as Röntgen himself perceived, a new weapon was put into the hands of the medical man, which was destined to find enormous application. The late war brought this home in unexampled fashion, and no man can over-estimate the services which radiology rendered in the great world tragedy. While human endeavour reached its maximum in almost every phase of life, a word may be spared in recognition of the way British radiologists and British X-ray manufacturers flung themselves into the gigantic task of expansion.

Mention may here be made of the necessity of protecting the X-ray operator from the rays. As many of the early workers discovered to their cost, indiscriminate exposure results in dermatitis, which may be followed by dangerous cancerous growths. A further danger is impoverishment of the blood corpuscles. Nowadays every precaution is taken, and such casualties rarely occur. Heavy lead screening in some form limits the beam of rays and protects the worker. The question of the protection of X-ray operators has recently received close attention in this country at the hands of a representative committee. Their recommendations will be found in Appendix I.

CHAPTER II.

THE X-RAY BULB.

There are two main types of X-ray bulbs or lamps in use, (*a*) the hot-cathode tube, (*b*) the gas tube. The Coolidge tube, invented by Dr. Coolidge in America, is the chief representative of the first class, in which the electrons are produced from a cathode consisting of a spiral of tungsten wire, raised to a white heat by an electric current. The vacuum in the tube is very high, and no discharge can pass if the cathode is not heated. The Coolidge tube has the valuable property of precise and reproducible control with a great range, advantages which cannot be claimed for the gas tube. In the gas tube the cathode is not heated: it usually takes the form of a shallow aluminium bowl. Very complete exhaustion is not attempted in the gas tube; a trace of residual gas is deliberately left, and this serves as a constant source of electrons through shock ionisation by indirect action of the voltage applied to the tube in operation.

With either type of tube the metal of the target or anticathode is all important. For the purposes of the radiologist it is essential that the target shall have (*a*) a high atomic number or weight and great coherency, (*b*) a high melting-point and low vapour pressure, (*c*) a high thermal conductivity, and a high specific heat. Few metals at present commercially available can compete with tungsten in the light of these requirements.

If we compare the characteristic curves of the two types of X-ray tubes by plotting current against voltage, we find differences which are fundamental (Fig. 3). Under the conditions in which a gas tube operates, the current increases steadily with the voltage, while in the case of the Coolidge tube the current is independent of the voltage. In the latter case the current is limited only by the number of electrons emitted, which number increases or decreases with the temperature of the cathode filament. Thus we can alter either voltage or current independently of each other, and this fact gives the hot-cathode tube a great advantage over the gas tube, in which independent control of voltage and current is impossible.

The hot-cathode tube thus utilises its "saturation" current, and for that reason is much less affected by changes in the wave form of the exciting potential than is a gas tube. On the other hand, the absence of saturation in a gas tube leads to a more effective use of very high voltages, and it is found that, at any rate, at low gas pressures a gas tube gives about twice the X-ray output of a Coolidge tube for the same milliamperage and voltage (Fig. 4, Dauvillier). But the gas tube is far from being the equal of the Coolidge tube as regards control and reliability, though experience counts for a good deal.

It may be added that both types of tube give heterogeneous X-rays, and there is little to choose between them on this score.

The Gas Tube.—The gas tube depends for its action on the presence of a few ions in the residual gas in the tube. These ions or electrified atoms have their velocities increased by the electric field; positive ions being drawn to the cathode and negative to the anode. The positive ions bombarding the cathode release electrons in abundance which, being attracted to the anode, ionise freely by shock or collision those atoms encountered en route, generating more positive ions and more electrons. The electrons which hit the target generate X-rays and the cycle of operations continues so long as the voltage is applied. Bound up

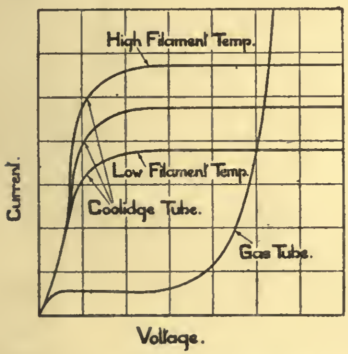


FIG. 3.—Characteristic curves for gas and Coolidge tubes.

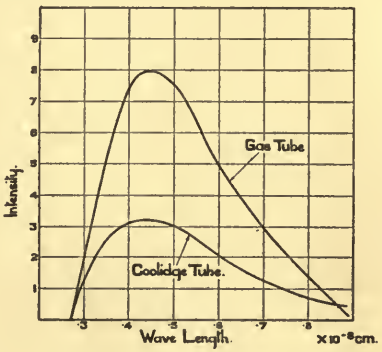


FIG. 4.—X-ray output from Coolidge tube and gas tube. 46,000 volts. 1 milliamp.

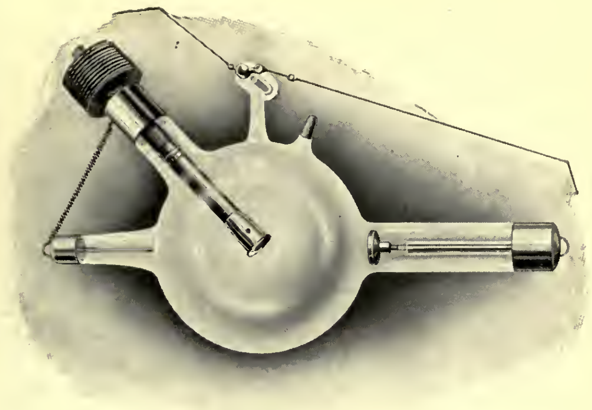
with the large increase in the ions is the experimental fact that the starting or break-down voltage of a gas tube is a good deal higher than the running voltage.

The positive ions or positive atoms on which Sir J. J. Thomson and more recently Dr. F. W. Aston, have done such brilliant work, thus play a fundamental and essential part in the ionics of a gas tube. They are also responsible for one or two other effects, the elucidation of which has been very puzzling. One of the great difficulties in exact work with the gas tube is the continual tendency of the gas pressure to change. One would first look to the electrodes which, depending on the conditions, may either emit or absorb gas and do so control very materially the well-known "crankiness" of a gas tube. But it is found that, provided the current is not too heavy to overheat the electrodes, there is a continual and steady disappearance of gas, more especially at high voltages. Various devices are employed to re-lower the vacuum by admitting automatically or at will fresh gas to replace that which has so mysteriously disappeared. Otherwise the vacuum becomes so high as to render the tube unusable. To cut a long story short, we now know that some of the positively charged atoms of gas by reason of their high velocity actually crash into the glass walls of the tube and are mechanically trapped there, an effect which is enhanced by the presence of volatilised metal. Incidentally this also accounts for the positive electrification on the greater part of the walls. It may be added that the positive rays are responsible for the pitting of the cathode and the glass stem round it, and without a doubt they have produced many punctures in that region.

The variation in gas pressure is also very liable to produce spasmodic displacement of the focal spot, an effect prejudicial to definition in radiography.

Examples of present-day gas tubes are shown in Fig. 5.

The gas tube received a good deal of attention in Germany during the war. In the so-called "boiling tube" of Müller, first made in Germany and now also constructed in this country (Fig. 6), the gas tube is



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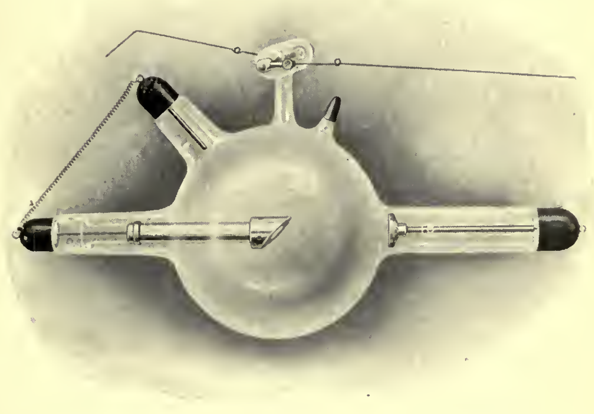

B

FIG. 5.—Gas X-ray tubes (Andrews) with automatic gas regulators.

A. Anticathode with external cooling radiator fins.

B. Massive anticathode.

[*To face page* 16.

employed to generate very penetrating X-rays primarily for use in deep therapy. The gas pressure in the tube is very low and tending to get lower as the discharge passes. To prevent emission of gas from the (platinum) anticathode, it is kept at a constant temperature by boiling water, and water-cooling is also adopted for the cathode. The focus is very broad as the tube is not designed for radiographic purposes. There is a supplementary bent wire anode, which during the final stages of exhaustion helps to remove the last traces of gas. The tube is operated at about 200,000 volts and with small currents, 2-3 milliamperes, a condition which assists the hardening tendency. Puffs of gas are introduced by an osmosis tube heated by a small flame ignited and operated through a relay by an automatic regulator which is controlled by a milliammeter in series with the X-ray tube. In action the water quietly boils and the tube may be run for hours at a time at a constant milliamperage.

It is claimed that there is a greater proportion of homogeneous "end" radiation in the filtered X-rays from a gas tube than there is from a Coolidge tube under the same conditions. Whether that is so or not, it must not be forgotten that an increase of potential tends to render a beam more homogeneous. Further, the spark-gap readings on a gas tube are liable to indicate voltages higher than those which are effectively operating the tube.

The Coolidge Tube.—In 1913, Dr. W. D. Coolidge, following up his outstanding work on the metallurgy of tungsten, introduced his now well-known X-ray bulb (Fig. 7), which forms one of the milestones in the history of the subject. The electrons are furnished by a hot spiral of tungsten, which is mounted within a focussing tube or bowl of molybdenum (Fig. 8). The gas pressure is some 20 times lower than that of an average gas tube, special care being taken to free the electrodes and bulb as far as possible from gas. Such a vacuum is often referred to as a Coolidge vacuum. The pre-heating of the electrodes is found greatly to facilitate exhaustion. The electrodes can afterwards be left about in the air for some days before being incorporated into the tube. The repair or reconstruction of Coolidge tubes does not on this score present the same difficulties as in the original manufacture.

The residual gas plays little or no part and positive rays do not operate appreciably in the functioning of the tube. Unless the cathode is heated it is impossible to send a discharge through the tube. The focal spot does not wander or vary in size as it does in a gas tube.

In prolonged use of a Coolidge tube a small amount of gas is usually liberated, as is indicated by a small drop of the milliamperes through the tube, which can be corrected by raising the filament temperature ; such gas is promptly reabsorbed when the discharge is stopped.

In the radiator type of tube, the tungsten target is embedded in a massive block of copper which is kept cool by external radiator fins (Fig. 9). This type of tube can, within limits, act as its own rectifier, so that it can be operated direct from a transformer. A recent development is a small portable type of radiator tube with walls of lead glass ¼-in. thick, a small window of soda glass allowing a pencil of rays to emerge

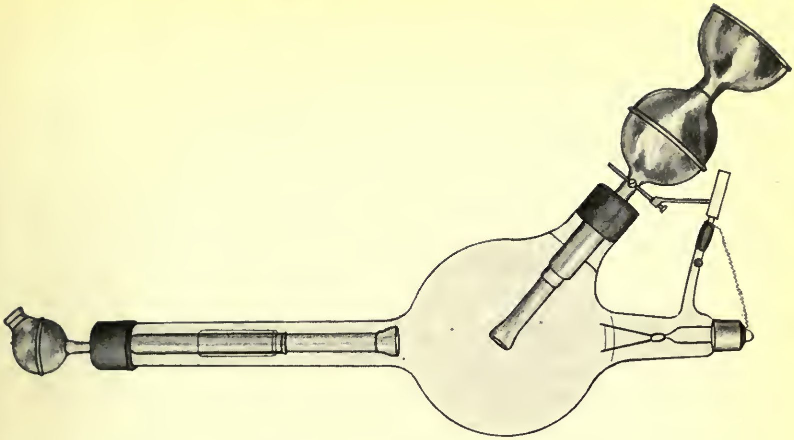

FIG. 6.—Boiling tube by Müller.

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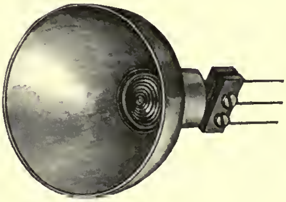

FIG. 7.—Cathode of Coolidge tube, showing tungsten spiral and molybdenum focussing bowl.

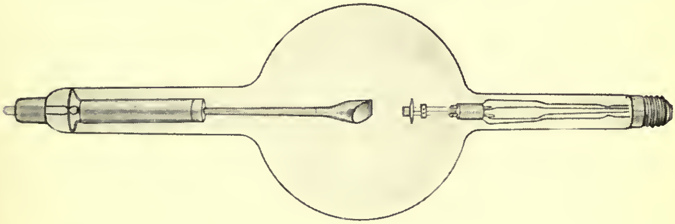

FIG. 8.—" Universal " type of Coolidge tube, showing cathode and 45° tungsten target.

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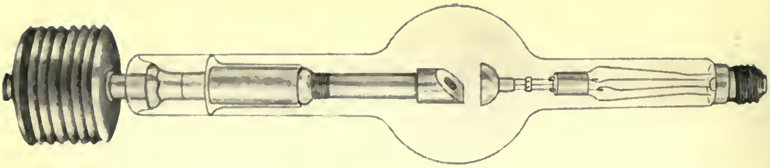

FIG. 9.—Radiator type of Coolidge tube, with 45° tungsten target embedded in copper anticathode cooled by external radiating fins.

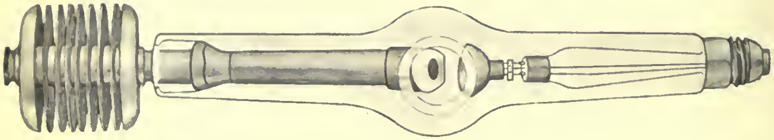

FIG. 10.—Portable type of radiator Coolidge tube, with thick lead-glass walls and soda-glass window.

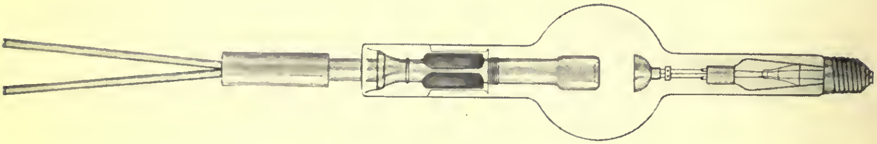

FIG. 11.—Coolidge tube, showing "right-angled" tungsten target embedded in water-cooled copper anticathode.

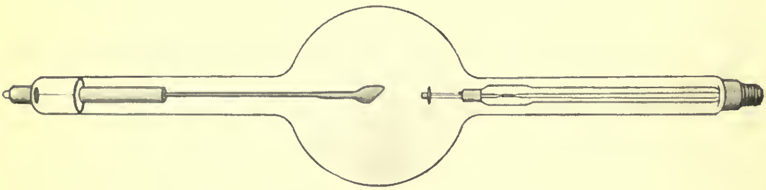

FIG. 12.—Deep therapy Coolidge tube.

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(Fig. 10). The lead glass (which contains 55 per cent. of lead) serves to protect the operator from radiation.

Fig. 11 shows a water-cooled Coolidge tube with its target mounted at right angles to the cathode ray stream. Such tubes are useful in X-ray spectrometry. Fig. 12 illustrates a Coolidge tube designed to work at 200,000 volts, mainly for deep therapy treatment. The tube is approximately 3 feet long.

The General Electric Co. of America has adopted the methods of mass production of the various forms of Coolidge tube, and is now turning out over 100 tubes a day. The bulbs and glass parts are blown in moulds at the glass factory, and the operation of assembly is carried out by girls with the aid of glass-blowing machines. An incidental advantage is the resulting uniformity of size of the glass bulbs.

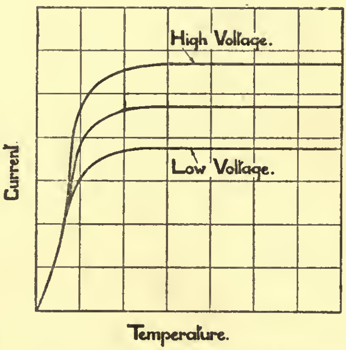

FIG. 13.—Restricting effect of "space-charge" on current through a Coolidge tube.

It may be added that Coolidge has also constructed water-cooled bulbs which absorbed nearly 20 kw. or about 27 h.p. Coolidge and others have also used silica bulbs.

There is one feature of the Coolidge tube to which reference should be made. As already remarked, in consequence of the low pressure "shock" ionisation of the residual gas is negligible or practically so, and it is left to the electrons to do all the carrying of the current. Thus the space between the electrodes is filled with carriers of one sign, with the result that at high current densities, there is an appreciable obstructing effect due to electrostatic repulsion between the electrons crossing over and those following. This "space-charge" sets an upper limit to the current through a Coolidge tube at high filament temperatures (Fig. 13). The restricting effect of the space-charge can be lessened by raising the voltage, or by introducing positive ions in some fashion, e.g. by a trace of gas. In the case of very heavy momentary discharges, tungsten vapour is pro-

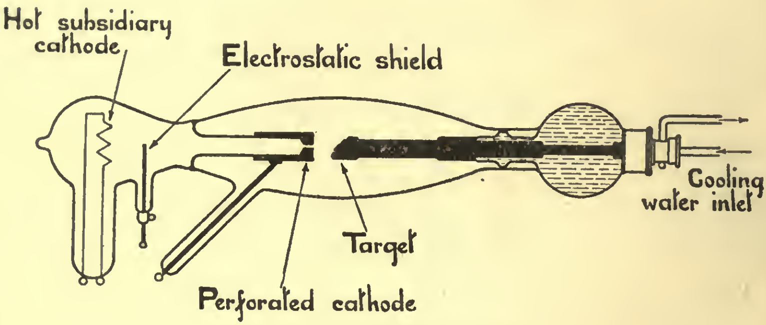

FIG. 14.—Lilienfeld tube.

duced at the focal spot, and this also serves greatly to diminish the tube resistance.

The Lilienfeld Tube.—The Lilienfeld tube introduced in 1913, and since extensively modified, may be said to act as a combination of hot-cathode tube and gas tube, and incidentally is claimed to possess the advantages of both. In an annexe to the main discharge tube, a hot cathode is separately excited by a moderate potential (Fig. 14). The electrons pass through a hole in the main cathode and are there subjected to a much higher potential difference before they strike the water-cooled anticathode. Lilienfeld lays stress on the importance of using a coil discharge as yielding high momentary current densities. At high voltages (above 120 kv. and up to 170 kv.), the rays after filtering through 3 mm. of aluminium are stated to be homogeneous.

Metal X-Ray Tubes.—From time to time various experimenters have worked with metal bulbs. Sir Oliver Lodge designed such a bulb in 1897, and since then Coolidge (Fig. 15), Siegbahn,[1] Müller, and others have made use of them. It is possible that future commercial

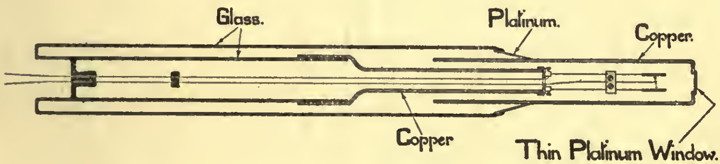

FIG. 15.—Metal X-ray tube by Coolidge, in which the thin platinum window serves also as target.

developments will be on such lines. A good deal of the work on X-ray spectrometry has been carried out with metal X-ray bulbs. Fig. 16 shows a water-cooled tube with a right-angled target, designed by Shearer. One of the chief difficulties with metal tubes is to obtain metal which is vacuum proof. Steel and brass are apt to be porous or contain various kinds of objectionable slag inclusions. Westgren and Phragmen[2] tried Skefko ball-bearing steel and found it to be wholly satisfactory.

[1] *Jahrbuch d. Radioakt. und Elekt.*, 18, 1921.
[2] *Journ. Iron and Steel Institute*, 1922.

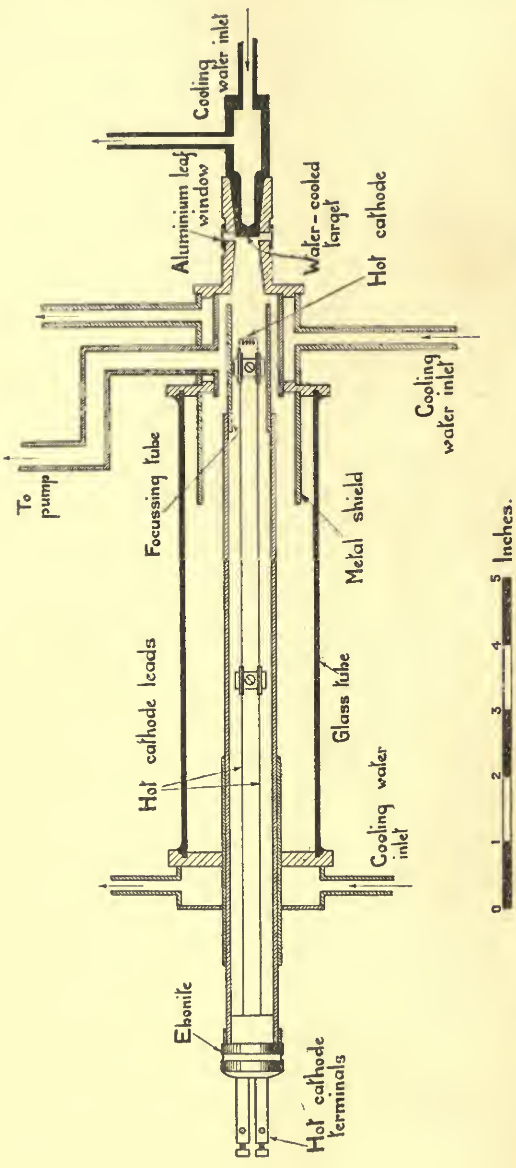

FIG. 16.—Metal X-ray tube by Shearer. Coolidge cathode; aluminium leaf windows; water-cooled target mounted normally to cathode rays; water-cooled sealing-wax joints. A metal tube shield protects the glass tube from the disintegrating action of positive rays.

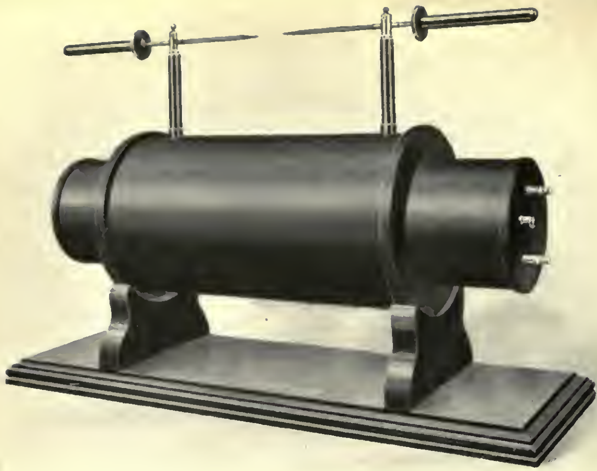

FIG. 17.—Induction coil.

FIG. 18.—Oil-immersed transformer, with rotary converter and mechanical rectifier.

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CHAPTER III.

THE HIGH-POTENTIAL GENERATOR.

THE voltages which obtain in practice for exciting X-ray bulbs are, roughly speaking, of the order of up to 100,000 volts for radiography and superficial therapy; and up to 200,000 volts or so for deep therapy and radio-metallography.

The high-potential generator is almost always a step-up transformer. Less commonly, especially in this country, influence or static machines are employed, though they would have many advantages if they could be sufficiently improved to withstand atmospheric humidity.

Induction Coils and Transformers.—It is customary in radiology to speak of "induction coils" and "transformers," though both are varieties of step-up, static, high-tension transformers. By an induction coil is meant an open-cored transformer (Fig. 17) which depends for its action on the interruptions of the primary current by an independent break or interrupter. By a transformer is implied a closed-core transformer, fed with alternating current (almost always single phase), either straight from the main or (in the case of a D.C. supply) from the alternating side of a rotary converter. Such a transformer may be either oil-immersed or have "dry" insulation. The present-day tendency of X-ray manufacturers is to utilise the experience obtained with power transformers and employ oil as the insulating medium in transformers for X-ray purposes (Fig. 18).

As shown in Fig. 20 the coil ordinarily yields a "peaky" potential wave as compared with the approximately sinusoidal wave form of the transformer. For X-ray purposes the high-tension current must be unidirectional and with both coil and transformer some sort of valve or mechanical rectifier is employed, either to cut out or invert the half of the high-potential wave which would tend to pass in the wrong direction through the X-ray bulb. In the case of a coil and rotary interrupter the mechanical rectifier is a commutator mounted on a disc or cross arm on an extension of the spindle of the interrupter (Fig. 19). In the case of a transformer, a similar commutator is mounted, either on the shaft of a synchronous motor (if A.C. supply is used), or on an extension of the shaft of the rotary converter (Fig. 18), as the case may be. If a valve is used instead, there are several types available, but preference is leaning towards the hot-cathode type, such as the Kenetron. As already remarked, Coolidge tubes of the radiator type are self-rectifying.

Fig. 20 shows a variety of potential wave forms :—

(*a*) Constant potential.

(*b*) Coil-discharge.

(*c*) Coil-discharge rectified (that is, with the inverse current removed).

(*d*) Transformer-discharge of single phase.

(*e*) Coil-discharge rectified.

(*f*) Transformer-discharge of single phase, rectified selectively (the peaks alone picked off by a rotating commutator).

(*g*) Transformer-discharge three-phase.

(*h*) Transformer-discharge three-phase rectified (giving a rough approximation to a constant potential).

In trying to weigh up the relative advantages of coils

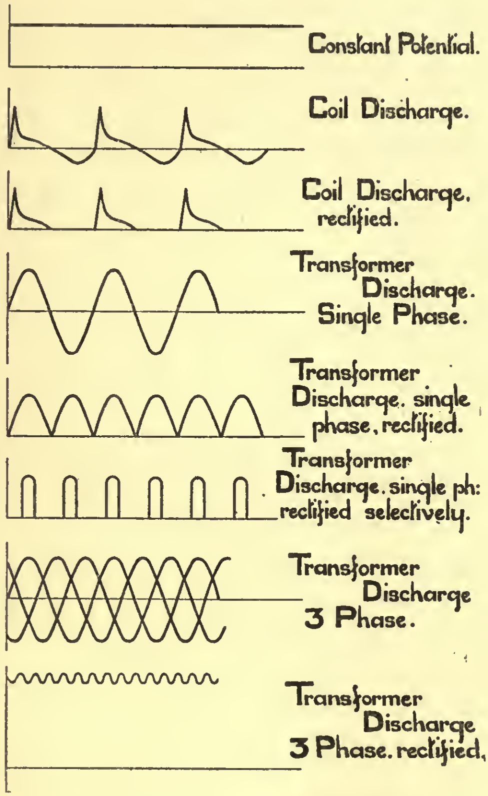

FIG. 20.—Potential wave-forms.

and transformers we have to remember that the initial cost of a transformer outfit is approximately twice that of an induction coil outfit of corresponding power. A transformer outfit is rather more bulky, and any repairs are also usually more expensive. On the other hand, the efficiency of a transformer is roughly twice that of a coil (including a break and rectifier). Further, owing to the occasional vagaries of all interrupters, control is more precise and measurements are more definite with the transformer and, if A.C. is available and we dispense with the mechanical rectifier, there are no moving parts. Transformers produce greater heating effect on the target of the X-ray bulb, but this objection is met by arranging the rotating commutator so that it picks off only the regions round the crests of the loops, and thereby eliminates the less efficient lower voltages. In this respect a mechanical rectifier has advantages over a valve.

In the case of X-ray tubes the targets of which are cooled by streams of water, the use of a coil or transformer which permits one pole to be earthed is a convenience.

The induction coil is an empirically designed instrument, the present-day type of which is not fundamentally very different from the early models of Spottiswoode, although in detail it differs very considerably. The exact measurement of the performance of coils is difficult and, as a consequence, coil makers have been led to adopt certain arbitrary standards of design, which are based chiefly on practical experience. Some of the features which arise in the design are conflicting, and it is in the methods of reconciling necessarily antagonistic factors that the skill of the coil designer finds chief scope.

The subject of induction coil design for X-ray purposes is a large one and only certain broad conclusions can be touched upon here. A transformation ratio of from 50 to 200, and an efficiency of 0·3 to 0·6 are usual figures. Some form of sectional winding is adopted for the secondary coil, allowing about 4000 volts for every 1000 turns, and arranging that the outside diameter does not exceed $2\frac{1}{2}$ times the bore. The resistance and, more especially, the self-induction of the secondary must be kept down. The primary should be capable of being connected directly to the 200 volt mains. The capacity of the condenser should be no greater than will prevent undue arcing in the interrupter. The interrupter should run at as high a speed as is expedient and be of adequate design and robust construction.

About 15 lb. of iron core should be allowed for every kilovolt-ampere input. The core may well have a length in the neighbourhood of up to 10 times the diameter. The primary windings should extend over almost the whole length of the core; the secondary windings over not more than the middle three-quarters, though care must be taken that this (the length of the secondary) is at least 4/3 times the maximum spark length.

The induction coil is essentially a shock apparatus, and the shock-excitation method of interruption may result in the presence of many superposed harmonics in the oscillation waves. These harmonics, which have high frequencies (several thousands a second) are reflected in the secondary circuit where, from a practical point of view, they evince themselves in the reluctance with which they pass through an X-ray bulb. The resulting tendency to spark across the surface of the tube can only be met by lowering the gas pressure, by immersing the tube in oil, by lengthening the arms or, of course, by suppressing the high-frequency waves before they reach the tube.

This is done in the so-called "symmetrical coil" which has been developed in Germany, similar apparatus being now also made in this country. In this apparatus two separate coils mounted vertically side by side, have their secondaries connected in series and also their primaries (Fig. 21). In the two connecting leads

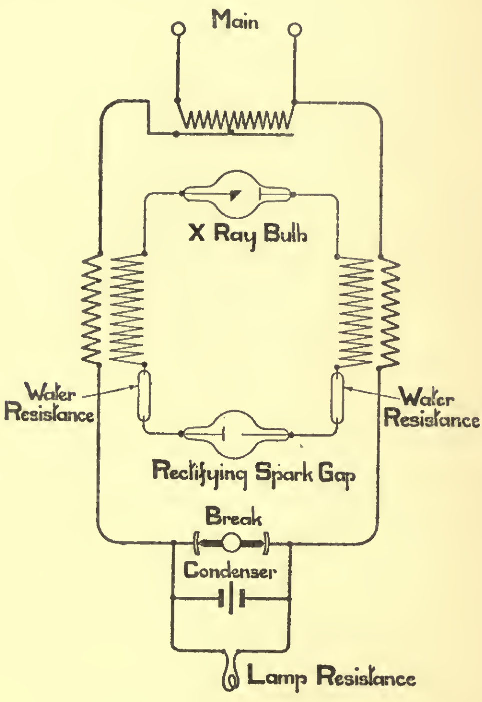

FIG. 21.—Symmetrical coil.

between the secondaries are inserted a gas X-ray bulb in the one and an enclosed rectifying spark-gap in the other. On each side of the spark-gap and in series with it is a high resistance (water). The self-induction of the secondary circuit is low, but the resistance is very high and serves to damp out the high-frequency oscillations.

FIG. 22.—Oil-immersed double coil.

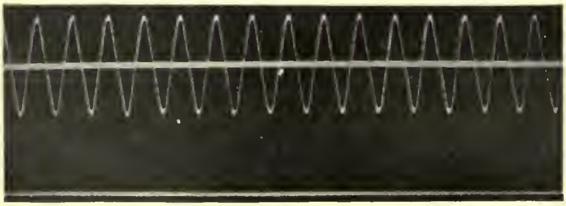

FIG. 28.—Upper curve, oscillograph showing 2000 cycle primary voltage ; lower line, rectified voltage at terminals of X-ray tube (Hull).

[*See page* 37.

[*To face page* 29.

The spark-gap helps to enhance the break-down potential of the gas bulb. High voltage (200,000) and low current (2 to 3 m.a.) are aimed at. An annular air space between primary and secondary assists natural cooling. A mercury break is used. Fig. 22 shows a twin coil which is designed to work in oil.

Interrupters.—Much of the progress that has been made with the performance of coils has resulted from the proper selection of interrupter. The hammer break, the accompaniment of most of the earlier coils, is now rarely fitted. The majority of present-day interrupters are of the motor-driven type which employ mercury in a dielectric either of coal gas or a liquid such as paraffin oil. A large proportion of mercury interrupters are of the turbine variety in which a jet of mercury is pumped against a series of rapidly revolving vanes. A common frequency is fifty. As already remarked a rotating high-tension rectifier is nowadays usually mounted on the shaft of the interrupter (Fig. 19).

The electrolytic or Wehnelt interrupter still finds favour with some workers. In the usual form it consists of two electrodes immersed in dilute sulphuric acid. The cathode is a large lead plate, the anode consisting of one or more platinum points, the exposed amount of which may be controlled by an adjustable porcelain sleeve. The frequency of interruption is high.

There is still scope for much work on the design of interrupters, which may fairly be said to be the most untrustworthy feature of a present-day coil outfit. A large amount of energy is apt to be wasted in the interrupter, especially with heavy currents. Too often the interrupter is insufficiently robust and massive.

Effect of Potential Wave-Form.—So long as radiologists confined their measurements on the X-ray bulb to the milliammeter and the alternative spark-gap, little progress was made in the subject of the best form of exciting potential wave. It was realised that the milliammeter was often misleading if used alone, but insight into the problem only came with the use of the X-ray spectrometer and the oscillograph.

The oscillograph (preferably of the cathode-ray type) should be arranged to give simultaneous graphs of both potential and current wave-forms in the X-ray tube. The current wave-form can also be rendered visible by the rotating oscilloscope. The spectrometer analyses the X-ray output and shows the distribution of intensity among the various wave lengths.

Work such as this has shown the truth of what might have been anticipated on a priori grounds, i.e. the importance in pulsating discharges of keeping the conditions so that the potential and current waves are in phase. In other words, for efficient output of X-rays as much of the current as possible should be sent through the tube with the maximum potential actuating it.

As J. J. Thomson showed long ago, the output of X-rays depends on the square of the voltage, and therefore the ideal state of things would appear to be to rush the potential as quickly as possible to the maximum and keep it there for as long as any current is passing. Voltages lower than the maximum are obviously less efficient. Further, the longer the time during which the maximum voltage is maintained the greater the proportion of short wave radiation generated.

In practice much depends on the type of X-ray bulb used—whether gas or hot-cathode, and it will be instructive to compare the behaviour of three main types of exciting potentials : (*a*) constant potential ; (*b*) sinusoidal transformer-discharge ; (*c*) sharp-peaked pulsating coil-discharge, all running at the same maximum voltage and the same milliamperage.

First take the case of the Coolidge tube. Owing to the existence of the saturation current, the shape and limits of the current curve are greatly dependent on the characteristics of the potential wave. With constant potential, the current remains constant at its saturation value (Fig. 23.) In the case of the transformer loop the current rises gradually to its saturation value and dies away again as the potential loop terminates. In the case of the coil and interrupter, the current again rises to its saturation value, but as a whole the current curve is prone to lag behind the potential curve. The defect, which is largely due to arcing within the interrupter, increases as the current through the tube is increased. This is the explanation of the well-known fact that, as the current is raised, the output of X-rays increases only slowly and by no means proportionately. A partial

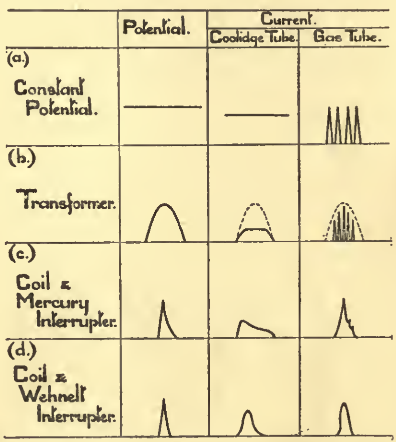

Fig. 23.—Typical potential and current wave-forms.

cure is to raise the speed of interruption, as in the Wehnelt break.

We are led to anticipate the results of the spectrometer curves. Remembering that the area of each curve is a measure of the total output of radiation (of all wave lengths), we see from Fig. 24 (derived from Dauvillier) that the constant potential is much the most

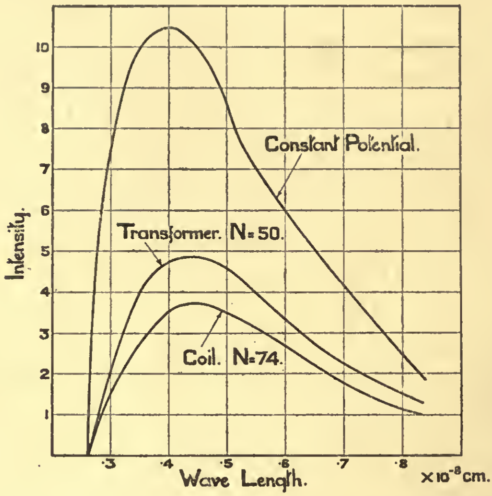

FIG. 24.—X-ray output of Coolidge tube (tungsten target) excited by various means. 46,000 volts; 1 milliamp.; unfiltered.

efficient, then the transformer, and lastly the coil. Furthermore, the crest of the curve is of slightly shorter wave length in the case of the constant potential. It may be added that the superiority of the constant potential becomes somewhat less marked as the potential rises.

In Fig. 25 is an analogous curve (due to Hull in America) representing the X-ray output from a Coolidge tube operated by 70,000 volts D.C. and 2 milliamperes. If alternating current is used, with the same peak voltage and milliamperage, the X-ray output suffers; it is represented in the figure by the smaller curve. If now the A.C. is increased from 2 milliamperes to 3, a curve

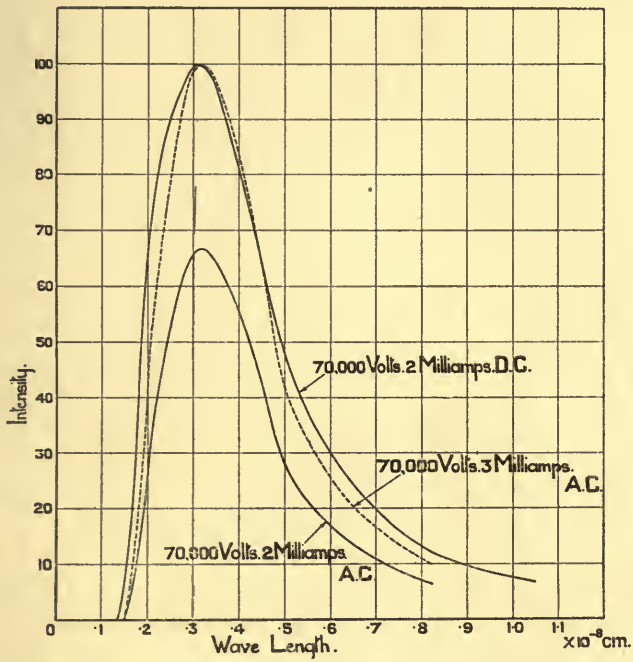

FIG. 25.—Intensity distribution of X-ray spectrum of tungsten. 70,000 volts A.C. and D.C.

is obtained which closely approximates to that obtained with direct current at 2 milliamperes, showing that the output suffers in the ratio of about 2 to 3 when alternating current is employed. This proportion refers to unfiltered rays: the figure would be modified somewhat if a filter were used.

If we now consider the case of the gas tube, the current curves (Fig. 23) prove, in most circumstances, to be quite different from those for the Coolidge tube. The current curve now exhibits no saturation value, but consists instead of a succession of peaks, no matter whether the exciting potential is constant or varying. The constant potential produces, so to speak, all the effects of an intermittent one. In the case of the transformer, the middle portion of the potential loop produces a number of current peaks whose heights

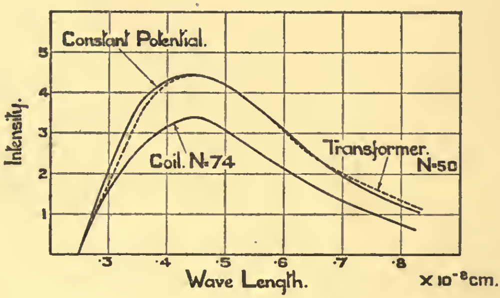

FIG. 26.—X-ray outputs of gas tube (tungsten target) excited by various means. 48,000 volts; 1 milliamp.; unfiltered.

wax and wane with the potential. The coil produces one or more current peaks corresponding to each potential peak. We are led to infer that the spectral curves for different excitants will not differ appreciably, and this proves to be the case (Fig. 26; Dauvillier). Further, the maxima of the several spectral curves all agree in wave length. We realise then that the shape and limits of the spectral curve are determined mainly by the tube rather than by the excitant.

In the case of both gas and hot-cathode tubes there is a variety of factors which may modify the various curves and graphs appreciably in detail, without affecting the main outlines.

To sum up, we may conclude that for maximum efficiency in the case of a Coolidge tube we should raise the potential on the tube as high as is expedient or possible and keep it there. Thus the ideal excitant would appear to be constant potential or, failing that, a transformer of high-frequency.

While this is also true of the gas tube, the fact is much less pronounced, for the "shock tactics" of a coil, which appear to be largely wasted on a Coolidge tube, are doubtless well adapted to a gas tube owing to its characteristic way of breaking down under potential stress.

The interval between the discharges of a coil-driven bulb is not without its advantage in helping to keep down the temperature rise of the target. But with a mercury break under ordinary conditions, this interval amounts to about 90 per cent. of the time between successive impulses, and is needlessly long. In the case of a single phase transformer, the corresponding figure is of the order of 60 per cent.

We can raise the efficiency of the coil or transformer by increasing the frequency substantially, and so crowding in more impulses per second, though the increased heating of the target may have to be met. If, further, in the case of a coil, we raise the voltage on the primary and increase the capacity of the condenser, we can produce a series of flat-topped peaks with little or none of the "tail" in evidence. We are thus approximating more and more to the transformer (selectively rectified), and, in the limit, the ideal steady potential. During

these changes the readings of the milliameter will approach more & more the effective values from these changes, the readings of the milliammeter will approach more and more the effective values from an X-ray point of view.

Constant Potential.—The value of constant potential has been referred to. It is not only an efficient means of generating X-rays, but it permits precise measurement. As already remarked, the superiority of constant over varying potential is somewhat less marked as the voltage is increased, except when the characteristic radiations begin to be generated when the constant potential increases its relative effectiveness. Moreover, constant potential is preferable in its precision for therapeutic purposes. For radiography it generates sufficient diversity of wave lengths to give good contrast and detail.

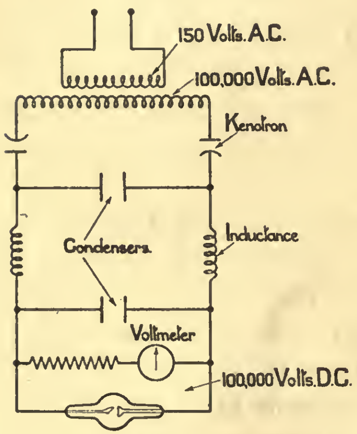

FIG. 27.—Method of obtaining steady high voltage from alternating current (Hull).

Those workers who have used influence machines in America and elsewhere speak highly of the results. There is a future for a static machine of engineering design and large output, which will defy the varying and generous humidity of this country.

The only other means of obtaining steady potential is by use of the transformer, together with the kenetron or hot-cathode valve. These latter can now be obtained to rectify 100,000 volts. By the use of 3-phase current and 6 kenetrons, a voltage fluctuating only 15 per cent. (Fig. 20) can be obtained. There are a variety of ways of combining kenetrons with condensers and inductances, so that the variation in the resulting potential is trifling. For example, Hull,[1] of the G.E.C. Laboratory at Schenectady, has so transformed and rectified 150 volts A.C. (∽ = 2000) to 92,000 (Fig. 27), with a fluctuation of about 1 per cent.; or 50,000 volts with a fluctuation of only 0·1 per cent. (Fig. 28).

Homogeneous X-Rays.—An ideal of the radiologist has always been a means of producing homogeneous X-rays, so that, among other things, a precision dose can be the better formulated in therapy. It was at one time believed that the heterogeneity of X-ray beams was due to the pulsating potentials employed. But as has already been evidenced, constant potential is but little better in this respect. However, while all X-ray beams are heterogeneous, they tend to become less so as the voltage is raised and the rays are filtered by the right choice of substance of a suitable thickness. In Fig. 29 (Hull), two of the curves show spectrographically the effect of filtering X-rays from tungsten through 3 mm. of aluminium, the exciting voltage being 40,000. We see at a glance the effect of the aluminium is to increase the proportion of short waves at the expense of the longer waves. There is, however, no very marked gain in homogeneity. The third curve is interesting in showing that 30,000 volts unfiltered gives a curve of the same maximum height as 40,000 volts filtered. The shapes of the two curves are, however, very different

[1] *Amer. Journal Röntgenology*, 1915.

and there is much more soft radiation in the case of the unfiltered 30,000 volt curve.

But the nearest approach to homogeneity can be reached by operating the X-ray bulb at a voltage somewhat above one of the critical values necessary to generate one of the characteristic radiations of the anticathode, and then filtering by a screen either of the same element as the anticathode or, preferably, by an element of slightly smaller atomic number. The

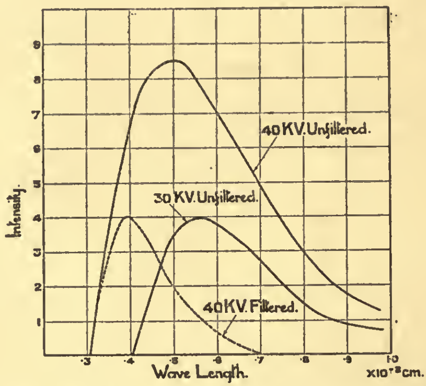

FIG. 29.—X-ray output of Coolidge tube. 40,000 volts (unfiltered and 3 mm. Al. filter) and 30,000 volts (unfiltered).

general radiation is by this means largely removed, and as we have already remarked, the characteristic radiations are generated above the critical voltage more copiously than the general radiation. The value of selective filtering was first evident from the writer's absorption experiments in 1908.[1] For example, Fig. 30 shows how platinum radiation can be rendered much more homogeneous by filtering through platinum than through aluminium.

[1] *Phil. Trans.*

It should here be added that the exciting voltage

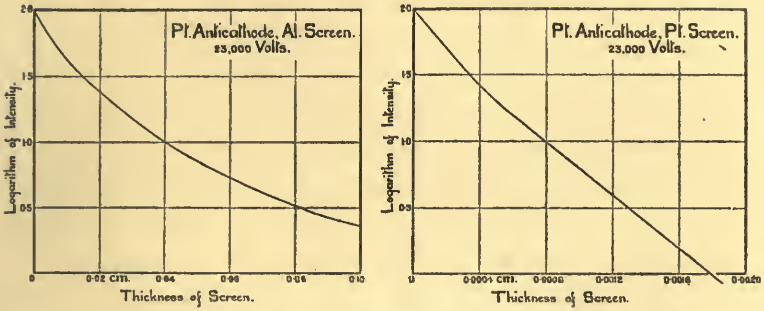

FIG. 30.—Showing increase of homogeneity of platinum radiation by filtering through platinum instead of aluminium.

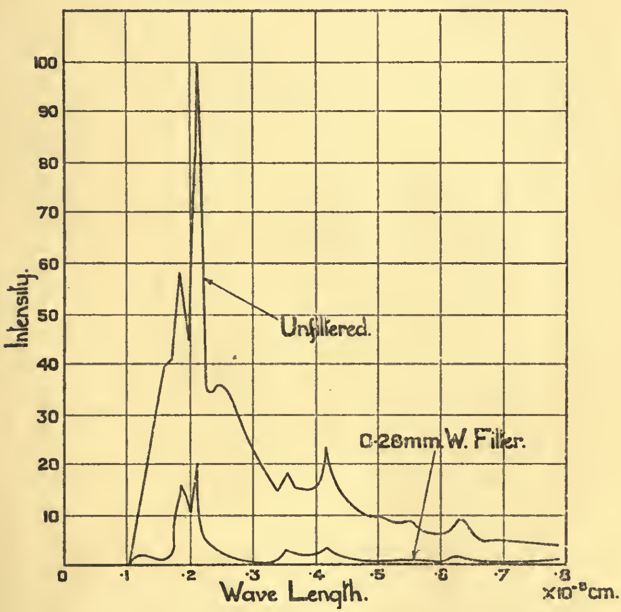

FIG. 31.—Intensity distribution of X-ray spectrum of tungsten at 110,000 volts (*a*) unfiltered, and (*b*) filtered by tungsten (Hull).

should not be too high, or short-wave general radiation will begin to make its appearance, and will not be removed by filtration. There is, in fact, an optimum voltage. For example, while the critical voltage for

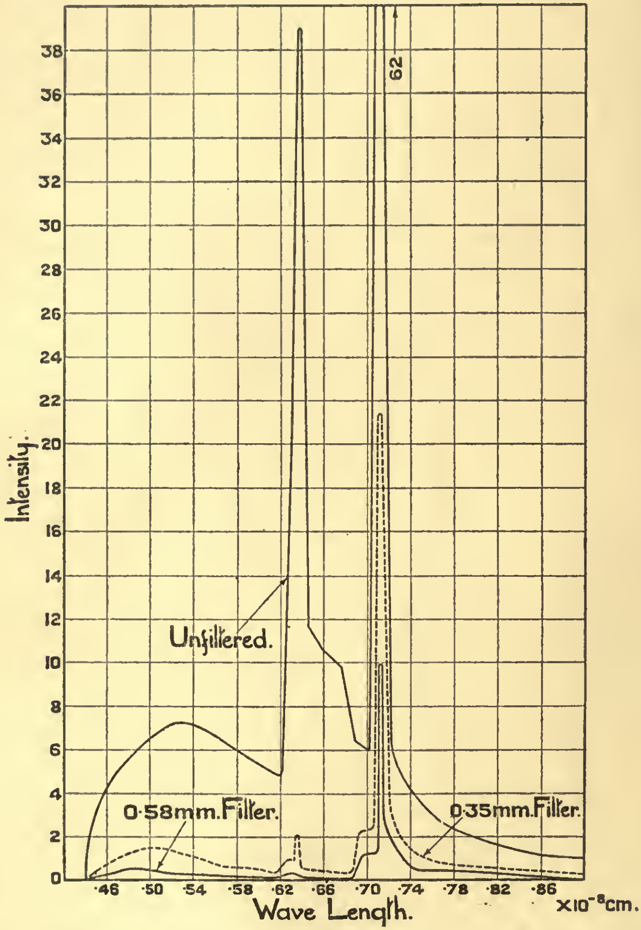

FIG. 32.—Effect of filtering on molybdenum X-ray spectrum. 28,000 volts. Filter of $ZrSiO_4$ (Hull).

the K radiation of tungsten (At. No. = 74) is about 70,000 volts, the optimum voltage is about 100,000 volts. A filter of tungsten or tantalum (At. No. = 73), 0·15 mm. thick, removes most of the general radiation, but leaves both the β and α components of the K radiation. An equally thick filter of ytterbium (At. No. = 70) would leave only the α component, with an intensity at least 30 times that of the remaining general radiation. Fig. 31 (Hull) illustrates spectrographically the case of a tungsten filter.

Similarly, for molybdenum (At. No. = 42) the optimum voltage is about 30,000, and the best filter zirconium (At. No. = 40) (Fig. 32). Tungsten would be a good filter for platinum radiation (At. No. = 78).

It may be noted that the various filters need not be in the form of metallic sheets; salts of a metal will serve equally well so long as the equivalent thickness is employed.

The above method gives us the nearest approach to homogeneity which is available at present. At the National Physical Laboratory there is a battery of X-ray tubes each with a different anticathode so that a variety of homogeneous rays can be obtained. Unfortunately, such beams are of feeble intensity for radiological purposes.

CHAPTER IV.

THE MEASUREMENT OF X-RAYS.

The problem of X-ray measurement is complicated somewhat by the existence of two types of radiation: (1) a continuous spectrum of general X-rays with a range of wave lengths; (2) the various series (—J, K, L, M—) of "characteristic" or "monochromatic" rays which are wholly characteristic of the metal of the anticathode.

The proportions of these two classes depend on the conditions of discharge, and on the material of the target. The characteristic radiations only appear when the exciting cathode rays are sufficiently fast. As already stated there is a critical voltage for each metal, which is required in order to excite each of the series of characteristic rays, and the proportion of these rays increases rapidly as the voltage is raised above this critical limit.

For simplicity let us take the case of platinum; mount a target of that metal in an X-ray bulb, and subject it to a potential which is gradually increased, keeping the current through the tube constant. For the sake of the argument, let us presume that platinum can be caused to generate all the known characteristic series, and, further, let us suppose that our experimental arrangements are such that we are in a position to detect them all. As the voltage (V) applied to the tube grows, the amount of "white" or general radiation steadily increases (according to a V^2 law), and the proportion of hard radiation also increases. But every so long, at a number of critical voltages, a new series of lines flashes simultaneously into existence, and the output and homogeneity of the beam are both temporarily enhanced. The approximate values of these critical voltages and corresponding wave lengths (in A.U.) (see p. 57) are as follows:—

PLATINUM.

Series.	Exciting Voltage.	Corresponding Wave Length.
M	2,500	5·2
L	13,000	0·96
K	75,000	0·17
J (?)	{180,000 and upwards}	{0·07 and less}

The J series is, as yet, undiscovered, and the data has been computed by the aid of Moseley's law, from the probable experimental values for other elements.

Fig. 33 displays, purely diagrammatically, the emission curve for platinum excited by 200,000 volts. This shows the distribution of the X-rays among the various wave lengths present. For simplicity only two lines are indicated in each of the groups of characteristic rays, which are superposed at various points on the smooth curve of output of general X-rays. The shaded area represents the X-rays which at present are turned to practical account. It is evident that the K and J radiations are the only ones of interest to the radiologist, the L and M radiations being almost, if not completely, arrested by the walls of the X-ray bulb. The K radiation is excited to greatest advantage by about 100,000 volts (6-inch spark between points). The existence of the

J radiation is problematical; there is some evidence that it consists of a large number of isolated lines excited by voltages in the region of from 200,000 (14-inch spark between points) up to perhaps 1,000,000. If so, we might hope to find evidence of its generation in the new deep-therapy tubes, and it would lend colour to the claim for the enhanced homogeneity at these high voltages. As far as output and homogeneity are concerned, there would appear to be advantages in running a platinum target tube at about either 100,000 or 200,000 volts.

If we now take the case of tungsten, then, as Moseley's law provides, the voltages are all correspondingly less than for platinum in the ratio of the squares of the atomic numbers :—

TUNGSTEN.

Series.	Exciting Voltage.	Corresponding Wave Length in A.U.
M	2,000	6
L	11,000	1·1
K	70,000	0·18
J (?)	160,000 and upwards	0·08 and less

The output from an X-ray bulb must be specified with respect to (1) wave length, quality, or hardness, and (2) intensity, i.e. quantity of rays per unit area.

Methods of Measuring Quality or Hardness.—The various methods of determining quality depend on measuring either (*a*) the wave length, absorption coefficient, or other property of the beam of X-rays emitted by an X-ray tube, or (*b*) the exciting voltage applied to the tube by means of the spark-gap, electrostatic voltmeter, or other means.

1. *Wave Length.*—As already remarked the hardness, or penetrating power, of an X-ray is precisely defined by its wave length—the shorter the wave length, the harder the ray. The most precise means of measuring the quality of X-rays is by the Crystal Spectrometer. It may be added that the precision of X-ray spectrometry measurements now approaches that of high-grade optical spectrometry work. Measurements taken by this means show that the wave lengths of the X-rays, in common use, lie mainly between about 10^{-7} and 10^{-9} cm.

It has been shown by Laue, the Braggs, Moseley, and others, that measurements of the diffraction of X-rays by crystals can be made to yield the wave lengths of X-rays as well as the dimensions of the space lattice of the crystal concerned.

This arises from the fact that in any crystal the atoms are regularly disposed in a network of intercrossing groups of planes, each of the planes in a group being parallel to and equidistant from its like neighbouring planes. There is thus a space lattice or unit of pattern of which the shape and dimensions are characteristic of the crystal. The lattice constant of a crystal is the distance separating the main atomic planes parallel to some specified crystal face. Provided the right conditions are fulfilled these atomic planes can act as "reflectors" of X-rays, the result being somewhat analogous to the resolution of light by a diffraction grating.

Measurements of wave length by the X-ray spectrometer are referred to later. As will be seen presently, measurements of the voltage exciting the X-ray bulb can also be utilised to the same end.

In view of their importance in X-ray measurement, we give below a table of X-ray wave lengths for the main characteristic lines of most of the elements. Preceding this, is a table of lattice constants for several crystals on which extended measurements have been made.

LATTICE CONSTANTS OF CRYSTALS.

Crystal.	Lattice Constant.	Observer.
	$\times 10^{-8}$ cm.	
Rock salt, NaCl . . .	2·8140	W. L. Bragg, *Roy. Soc. Proc.*, 1913.
Calcite (cleavage face), $CaCO_3$	3·0290	Siegbahn, *Phil. Mag.*, 1919.
Potassium ferrocyanide, $K_4Fe(CN)_6 . 3H_2O$ . . .	8·408	"
Gypsum, $CaSO_4 . 2H_2O$.	7·621	"

Characteristic X-Ray Wave Lengths.—Up to now, about 16 lines have been found to be associated with the characteristic X-ray spectrum of each element. Three series of lines are known at present—the K, L, and M, of which the K has the highest frequency. A J and N series have also been claimed to exist, but the evidence needs confirmation. The K series contains at least 4 lines, α_2, α_1, β and γ of which the γ line has the highest frequency. The L series contains probably three groups of lines, each group similar to the K series.

The values of the wave lengths of the principal lines are given below in Angström units. It should be noted that all the values rest on W. L. Bragg's estimate of the lattice constant of rock salt (see above).

K SERIES.

At. No.	Element.	α_2.	α_1.	β_1.	β_2.	Observer.
		× 10⁻⁸ cm.	× 10⁻⁸ cm.	× 10⁻⁸ cm.	× 10⁻⁸ cm.	
11	Na	—	11·95	—	—	Siegbahn & Stenström, *P.Z.*, July, '16.
12	Mg	—	9·92	9·48	—	,,
13	Al	—	8·36	7·99	—	,,
14	Si	—	7·13	6·76	—	,,
15	P	—	6·17	5·81	—	,,
16	S	—	5·36	5·02	—	,,
17	Cl	—	4·7187	4·39	—	Siegbahn, *P.M.*, June, '19.
19	K	—	3·7339	3·4474	—	,,
20	Ca	—	3·3519	3·0879	—	,,
21	Sc	—	3·0253	2·7745	—	,,
22	Ti	2·746	2·742	2·509	2·492	Siegbahn & Stenström, *P.Z.*, July, '16.
23	V	2·502	2·498	2·281	—	,,
24	Cr	—	2·2852	2·0814	—	Siegbahn, *P.M.*, June, '19.
25	Mn	2·093	2·093	1·902	1·892	Siegbahn & Stenström, *P.Z.*, Feb., '16.
26	Fe	—	1·9324	1·7540	—	Siegbahn, *P.M.*, June, '19.
27	Co	—	1·7852	1·6176	—	Siegbahn, *P.M.*, June, '19.
28	Ni	—	1·6547	—	—	,,
29	Cu	—	1·5374	1·3895	—	,,
30	Zn	1·437	1·433	1·294	1·281	Siegbahn & Stenström, *P.Z.*, Feb., '16.
32	Ge	1·261	1·257	1·131	1·121	,,
39	Y	—	0·833	—	—	Moseley (corrected), *P.M.*, April, '14.
40	Zr	—	0·790	—	—	,,
41	Nb	—	0·746	—	—	,,
42	Mo	—	0·717	—	—	,,
44	Ru	—	0·635	—	—	,,
45	Rh	0·6164	0·6121	0·5453	0·5342	Duane & Hu, *P.R.*, 1919.
46	Pd	0·589	0·583	0·516	—	Bragg.
47	Ag	0·562	0·557	0·495	—	,,
48	Cd	—	0·537	0·475	—	Siegbahn, *D.P.G.V.*, 1916.
49	In	—	0·506	0·454	—	,,
50	Sn	—	0·486	0·432	—	,,
51	Sb	—	0·469	0·416	—	,,
52	Te	—	0·456	0·404	—	,,
53	I	—	0·437	0·388	—	,,
56	Ba	—	0·388	0·344	—	,,
74	W	0·2135	0·2089	0·1844	0·1794	Siegbahn, *P.M.*, Nov., 1919.
92	U	—	0·15	0·10	—	,,

L SERIES.

At. No.	Element.	α_2.	α_1.	β_1.	β_2.	γ_1.	Observer.
		$\times 10^{-8}$ cm.	$\times 10^{-8}$ cm.	$\times 10^{-8}$ cm.	$\times 10^{-8}$ cm.	$\times 10^{-8}$ cm.	
30	Zn	—	12·35	—	—	—	Friman, *P.M.*, Nov., '16.
33	As	—	9·701	9·449	—	—	,,
35	Br	—	8·391	8·141	—	—	,,
37	Rb	—	7·335	7·091	—	—	,,
38	Sr	—	6·879	6·639	—	—	,,
39	Y	—	6·464	6·227	—	—	,,
40	Zr	—	6·083	5·851	—	5·386	,,
41	Nb	5·731	5·724	5·493	5·317	—	,,
42	Mo	5·410	5·403	5·175	—	—	,,
44	Ru	4·853	4·845	4·630	—	—	,,
45	Rh	—	4·596	4·372	—	—	,,
46	Pd	4·374	4·363	4·142	3·903	3·720	,,
47	Ag	4·156	4·146	3·929	3·698	3·515	,,
48	Cd	3·959	3·949	3·733	3·514	3·331	,,
49	In	3·774	3·766	3·550	3·335	3·160	,,
50	Sn	3·604	3·594	3·381	3·172	2·999	,,
51	Sb	3·443	3·434	3·222	3·021	2·849	,,
52	Te	3·299	3·290	3·074	2·881	2·712	,,
53	I	3·155	3·146	2·934	2·750	2·583	,,
55	Cs	2·899	2·891	2·684	2·514	2·350	,,
56	Ba	2·786	2·776	2·569	2·407	2·245	,,
57	La	2·674	2·665	2·461	2·307	2·146	,,
58	Ce	2·573	2·563	2·359	2·212	2·052	,,
59	Pr	2·472	2·462	2·259	2·120	1·958	,,
60	Nd	2·379	2·369	2·167	2·036	1·875	,,
62	Sa	2·210	2·200	2·000	1·884	1·725	,,
63	Eu	2·131	2·121	1·918	1·810	1·662	,,
64	Gd	2·054	2·043	1·844	1·744	1·597	,,
65	Tb	1·983	1·973	1·775	1·682	1·531	,,
66	Dy	1·916	1·907	1·709	1·622	1·470	,,
67	Ho	1·854	1·843	1·646	1·568	1·415	,,
68	Er	1·794	1·783	1·586	1·514	1·367	,,
70	Yb	1·681	1·670	1·474	1·414	1·267	,,
71	Lu	1·629	1·619	1·421	1·368	1·224	,,
72	Ce	—	1·562	—	1·319	—	Dauvillier, *C.R.*, May, 1922.
73	Ta	1·528	1·518	1·323	1·280	1·135	Siegbahn & Friman, *P.M.*, July, '16.
74	W	1·4845	1·4735	1·2792	1·2419	1·0955	Siegbahn, *P.M.*, Nov., '19.
76	Os	1·398	1·388	1·194	1·167	1·021	Siegbahn & Friman, *P.M.*, July, '16.
77	Ir	1·360	1·350	1·154	1·133	0·989	,,
78	Pt	1·323	1·313	1·120	1·101	0·958	,,
79	Au	1·283	1·271	1·080	1·065	0·922	,,
80	Hg	1·251	1·240	1·049	1·042	0·896	,,
81	Tl	1·215	1·205	1·012	1·006	0·864	,,
82	Pb	1·186	1·175	0·983	0·983	0·842	,,
83	Bi	1·153	1·144	0·950	0·954	0·810	,,
84	Po	—	1·109	0·920	—	—	,,
88	Ra	—	1·010	—	—	—	,,
90	Th	0·969	0·957	0·766	0·797	0·654	,,
92	U	0·922	0·911	0·720	0·756	0·615	,,

M SERIES.

At. No.	Element.	α.	β.	γ.	δ.	Observer.
		$\times 10^{-8}$ cm.	$\times 10^{-8}$ cm.	$\times 10^{-8}$ cm.	$\times 10^{-8}$ cm.	
79	Au	5·838	5·623	{5·348 5·284	5·146 5·102}	Siegbahn, *D.P.G.V.*, 1916.
81	Tl	5·479	5·256	—	4·826	,,
82	Pb	5·303	5·095	4·91 ?	4·695	,,
83	Bi	5·117	4·903	{4·726 4·561	4·532 4·456}	,,
90	Th	4·139	3·941	{3·812 3·678	— —}	,,
92	U	3·905	3·715	3·480	{3·363 3·324}	,,

C.R., Compt. Rend.; D.P.G.V., Verh. der Deutsch. Phys. Gesell.; P.M., Phil. Mag.; P.R., Phys. Rev.; P.Z., Phys. Zeits.

2. *Absorption Coefficients.*—A very usual method of determining the quality of X-rays is to measure their absorption in a standard material, such as aluminium. Aluminium is commonly chosen because it is readily procurable in convenient form, and does not normally complicate matters by superposing a dominating characteristic radiation.

Now it is found that if all the rays, both entering and leaving a plate of material, are homogeneous (that is, wholly of the same quality), then the rays are absorbed exponentially by the plate, i.e. if 1, 2, 3, . . . similar sheets are successively introduced, each additional sheet absorbs the same fraction of what it receives. It follows that if there is no "scattering" of the X-rays, and if μx is the fraction of the intensity which is absorbed when the rays pass normally through a very thin screen of thickness x (cm.), then for a plate of thickness d (cms.),

$$I = I_0 . e^{-\mu d},$$

in which I_0 is the intensity of the beam when it enters, and I that of the beam when it leaves the screen. e (= 2·72) is the base of the hyperbolic system of logarithms. μ is termed the linear absorption coefficient. In other words, the definition implies that for a particular quality of rays and a particular material μ is the ratio of the distance-rate of change of intensity at a point to the intensity at that point.

It follows that $\mu = \frac{2 \cdot 3}{d} (\log I_0 - \log I)$;

the logarithms are to base 10. If in a set of observations with homogeneous rays, log I is plotted as ordinate against d, the graph is a straight line, and μ is 2·3 times the slope of the line.

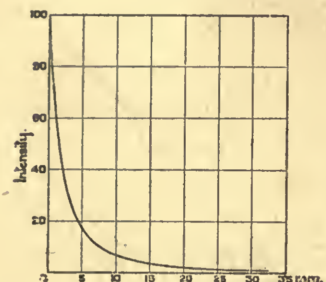

FIG. 34.—Absorption curve of X-rays in aluminium. Transformer 75,000 volts, Coolidge tube.

With ordinary heterogeneous rays, μ is greater for thin screens than for thick, and so we can only deal with an average μ, which, however, varies more and more slowly as the screen becomes thicker (Fig. 34).

The logarithmic curve of absorption for heterogeneous rays, such as are given out by an ordinary X-ray bulb, is not a straight line, but a curve which is steeper for thin screens than for thick (Fig. 35).

In the case of the characteristic radiations, an element exhibits a maximum transparency for X-rays closely approximating to its own characteristic radiations. For slightly harder rays than these, the absorption rapidly increases, the rays characteristic of the screen are produced and superposed on the transmitted rays to an extent which diminishes as the incident rays are increasingly hardened. For incident rays softer than the critical type, no characteristic rays are produced. Thus, as the incident rays are gradually hardened, the transmitted rays reach a maximum intensity when the incident rays are of a quality approximating to each of the characteristic rays in turn.

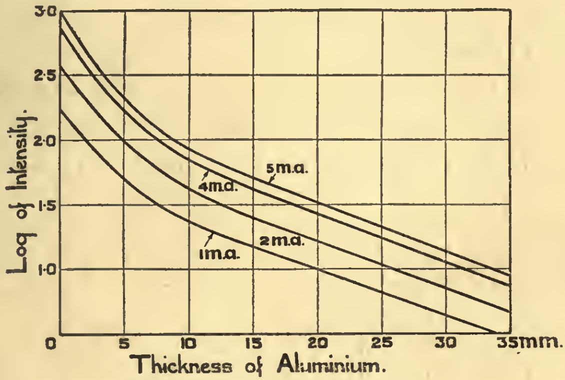

FIG. 35.—Log-absorption curves of X-rays in aluminium. Transformer 75,000 volts, Coolidge tube.

A large value of μ corresponds to easily absorbed rays, and a small one to very penetrating rays. μ also varies with the nature of the absorbing screen, so that it is necessary to specify the material used.

Someworkers prefer to think in terms of thethickness, D, which reduces the intensity to half value. D is connected with μ by the expression $D = 0{\cdot}69/\mu$. A notion of the order of values of μ may be got from the fact that for an X-ray beam of average hardness, μ lies between 4 and 8 $^{-1}$ cm.; for hard rays between 2 and 4 $^{-1}$ cm.

A more generally useful constant is obtained by dividing the absorption coefficient (μ) by the density (ρ) of the absorbing screen. This quantity, μ/ρ—usually called the mass-absorption co-efficient—gives a measure of the absorption per unit mass of the screen for a normally incident pencil of rays of unit cross section.

If, as was at one time supposed, the absorbing powers of different materials were truly proportional to their densities, then for the same rays μ/ρ would be a constant, no matter what the substance used as screen. In point of fact, dense substances are a good deal more absorptive, mass for mass, than light, and μ/ρ increases rapidly with the atomic weight of the screen. The increase is more noticeable with hard rays than with soft.

Wave Length, λ.	μ/ρ in Al.
$0 \cdot 1 \times 10^{-8}$ cm.	0·04
0·2 ,,	0·21
0·3 ,,	0·57
0·4 ,,	1·20
0·5 ,,	2·10
0·6 ,,	3·3
0·7 ,,	4·8
0·8 ,,	6·6
0·9 ,,	8·9
1·0 ,,	12·2
1·1 ,,	16·5
1·2 ,,	22
1·3 ,,	28
1·4 ,,	35
1·5 ,,	43
1·6 ,,	51
1·7 ,,	61
1·8 ,,	72
1·9 ,,	83
2·0 ,,	95
2·1 ,,	108
2·2 ,,	120

The table on page 52 gives a series of values connecting wave lengths and absorption coefficients in aluminium, derived from the results of Rutherford, Bragg, Moseley, and Barkla. A scrutiny of these results shows that if μ is the absorption coefficient and λ is the wave length, then, when the effect of scattering has been allowed for

$$\mu = k\lambda^n$$

where k is a constant, and n lies between 5/2 and 3.

3. *The Speed of the Exciting Cathode Rays.*—As already remarked a knowledge of the exciting voltage on an X-ray tube affords a measure of the quality of the rays emitted. If the exciting voltage is uniform and a magnetic field be applied to the cathode rays in the X-ray bulb, the pencil of rays is deflected as a whole to an extent dependent on the magnetic field and the speed of the cathode rays. If the exciting voltage is pulsating, and a similar experiment be tried, a magnetic spectrum of cathode rays is formed, the least deflected band of rays corresponding to the highest speed rays which owe their velocity (v) to the maximum voltage (V) applied (Fig. 36).

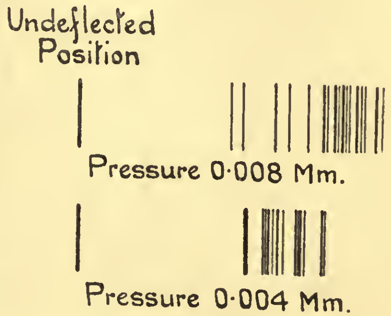

FIG. 36.—Examples of cathode ray deflections.

We have

$$\frac{1}{2} m v^2 = Ve$$

where e and m are respectively the electronic charge and mass. Substituting the accepted value of e/m

$$V = 2{\cdot}8\, v^2 \,.\, 10^{-16}$$

where V is in volts and v is in cms. per sec.

It is thus possible, by measuring v by means of the magnetic deflection in a known field, to arrive at the value of V.

In practice this is not a very convenient method of measuring maximum voltage, and the following method is of greater practical value :—

4. *The "Quantum Limit" to the X-ray Spectrum.*—Within the last few years it has been clearly established experimentally by Duane and others that there is a definite boundary to every spectrum of general X-rays on its short-wave side. The position of this boundary (or quantum limit, as it is called) is not affected by the nature of the element emitting the X-rays, but is solely dependent on the maximum voltage applied to the tube. The relationship is given by the well-known quantum equation of Planck, which is ever recurring in physics :—

$$Ve = h\nu$$

where V is the maximum applied voltage,
ν is the frequency of the shortest wave,
e is the electronic charge,
and h is Planck's universal constant.

Substituting the accepted values of the constants, we have—

$$\text{maximum voltage} = \frac{12{,}400}{\text{shortest wave length in A.U.}}$$

This very simple relation provides us with a scale of quality which, if not perfect, is more exact than any which the radiologist has been in the habit of using. If we glance at typical spectral curves of X-ray emission (Fig. 37), we see that they are not symmetrical—the centre of gravity of the curve is well towards the quantum limit—the shortest waves are the dominating ones, and still more so if the rays are subjected to normal type filtering. The mean effective wave length of a spectrum of rays is seen to approximate to the wave length of the peak of the curve, i.e. the wave length of maximum intensity. Now there is some evidence that this wave length of the peak (λ_m) is proportional to the limiting or

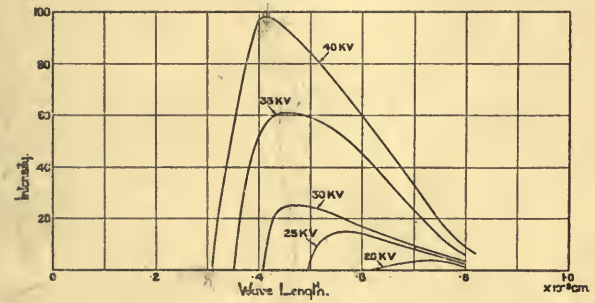

FIG. 37.—Intensity distribution of X-ray spectrum of tungsten at various voltages and const. milliamps showing positions of quantum limit (Hull).

quantum wave length (λ_o); in many cases λ_m is approximately 4/3 times λ_o. But in practice it is much easier to measure λ_o than λ_m, and this fact gives an added importance to the measurement of the quantum limit, and enables us so to identify very fairly the quality of a mixed bundle of X-rays. No doubt something depends on the wave form of the exciting potential, but the effect of this is probably less important as the voltage is raised. The precision of the method would be enhanced if steps were taken to standardise apparatus and technique, so that all work could be done by the use of, say, three or four spectra whose distinctive features, including energy distribution, could be determined and specified.

The quantum relation affords the radiologist a method of measuring wave lengths. The voltage can be obtained as described below by use of a reliable type of electrostatic voltmeter, or, failing that, by measuring the alternative spark-gap. An alternative and better plan is to measure the quantum limit directly by means of a portable direct-reading spectrograph, of the type designed in Germany by Seemann and others (Fig.

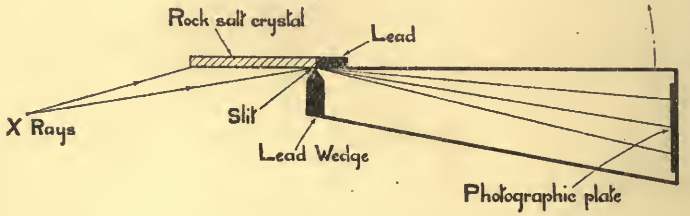

FIG. 38.—Seemann spectrometer.

38). Incidentally, these direct-reading spectrographs may be utilised as very convenient and accurate high-tension voltmeters, which afford a measure of the true maximum voltage effectively operating a tube. The table on page 57 will be found useful in this connection.

Fig. 39 shows a number of photographs of X-ray spectra, due to Müller. In the case of the first seven spectra, which all refer to platinum, we notice the steady shift in position of the quantum limit (marked by a small dot)—the gradual shortening of its wave length as the exciting voltage increases. The last three spectra are for copper, lead, and platinum. We see that if the same exciting voltage is applied to each the position of the quantum limit does not depend on the metal used.

Kilovolts (peak).	Shortest Wave Length in A.U. (10^{-8} cm.).	Highest Frequency.
10	1·240	$2·42 \times 10^{18}$
20	0·620	4·84 ,,
30	0·413	7·26 ,,
40	0·310	9·68 ,,
50	0·248	12·1 ,,
60	0·207	14·5 ,,
70	0·177	16·9 ,,
80	0·155	19·4 ,,
90	0·138	21·8 ,,
100	0·124	24·2 ,,
110	0·113	26·6 ,,
120	0·103	29·0 ,,
130	0·095	31·4 ,,
140	0·089	33·9 ,,
150	0·083	36·3 ,,
160	0·078	38·7 ,,
170	0·073	41·1 ,,
180	0·069	43·6 ,,
190	0·065	46·0 ,,
200	0·062	48·4 ,,
210	0·059	50·8 ,,
220	0·056	53·2 ,,
230	0·054	55·7 ,,
240	0·052	58·1 ,,
250	0·050	60·5 ,,
260	0·048	62·9 ,,
270	0·046	65·3 ,,
280	0·044	67·7 ,,
290	0·043	70·2 ,,
300	0·041	72·6 ,,

5. *The Maximum Spark-gap.*—The maximum voltage applied to a tube is most commonly measured

by means of the alternative spark-gap between points or spheres. Some experience is necessary especially in the case of a gas X-ray tube, where the method tends to give too high values especially with pulsating potentials. It should also be remembered that in the case of a self-rectifying tube (such as the Coolidge radiator) excited by A.C., the spark-gap will indicate the higher voltage of the suppressed half-wave and not the lower effective voltage of the useful half-wave. To measure the true effective voltage, a valve in series with the tube is necessary in such cases.

The work of Peek and others has shown that a spark-gap between spherical electrodes of equal size is preferable to that between points. The spark between points is now generally discredited for high voltages on account of its inconsistent dependency on atmospheric humidity and frequency of discharge. By reason of its time-lag, its readings may be largely in error in the case of high-frequency steep impulses.

On the other hand, frequency and wave shape have no appreciable effect in the case of the sphere-gap, and the effects of variation in the atmospheric conditions are well known, and can be readily corrected for.

The size of the spheres is important. A good rule is not to use a gap bigger than the diameter of either of the balls, though some latitude may be permitted in this direction. The main point is to avoid the breakdown discharge being preceded by brush-discharge or corona, otherwise a pulsating discharge will, in general, give gap readings which are too high. With the above precaution, a sphere-gap is capable of measuring (peak) voltages from say, 10,000 volts to 500,000 with an accuracy of about 2 per cent. A useful type of sphere-gap is shown in Fig. 40.

Table A on next page is based on Dr. A. Russell's formula, and incorporates the latest results of the American Institute of Electrical Engineers (1918) when both spheres are insulated. It includes also for convenience a column of figures for a needle-point gap (No. 00 new sewing needles) which furnish a rough notion of the voltages for an instrument which is still much used. The A.I.E.E. recommend that for voltages above 70,000 (and preferably above 40,000) a sphere-gap should always be employed.

The gap should not be exposed to any extraneous ionising influence, such as an arc or an adjacent spark, nor should the gap be enclosed. The first spark is the one for which the reading should be taken. The use of a water resistance in series with the gap will prevent arcing and assist in suppressing surges.

In Table A the values refer to 760 mm. pressure, 25° C., and 80 per cent. humidity. Where any gap is being used outside its recommended limits, the figures are shown in brackets. The blank spaces indicate that the gap is no longer suitable. The gaps are given to three significant figures for interpolation purposes.

In the case of sphere-gaps a correction is applicable for the density of the air. Table B gives the relative air density under different conditions. The figures are relative to air at 25° C. and 760 mm. pressure.

TABLE A.

Kilo Volts (peak).	Diameter of Spheres.						
	Needle Points.		2·5 Cms.	5 Cms.	10 Cms.	25 Cms.	50 Cms.
	Cms. Gap.	Inches Gap.	Cms. Gap.	Cms. Gap.	Cms. Gap.	Cms. Gap.	Cms. Gap.
5	(0·42)	(0·17)	(0·13)	(0·15)	(0·15)	(0·16)	(0·17)
10	(0·85)	(0·33)	0·27	0·29	0·30	0·32	0·33
15	1·30	0·51	0·42	0·44	0·46	0·48	0·50
20	1·75	0·69	0·58	0·60	0·62	0·64	0·67
25	2·20	0·87	0·76	0·77	0·78	0·81	0·84
30	2·69	1·06	0·95	0·94	0·95	0·98	1·01
35	3·20	1·26	1·17	1·12	1·12	1·15	1·18
40	3·81	1·50	1·41	1·30	1·29	1·32	1·35
45	4·49	1·77	1·68	1·50	1·47	1·49	1·52
50	5·20	2·05	2·00	1·71	1·65	1·66	1·69
60	6·81	2·68	2·82	2·17	2·02	2·01	2·04
70	8·81	3·47	(4·05)	2·68	2·42	2·37	2·39
80	(11·1)	(4·36)	—	3·26	2·84	2·74	2·75
90	(13·3)	(5·23)	—	3·94	3·28	3·11	3·10
100	(15·5)	(6·10)	—	4·77	3·75	3·49	3·46
110	(17·7)	(6·96)	—	5·79	4·25	3·88	3·83
120	(19·8)	(7·81)	—	(7·07)	4·78	4·28	4·20
130	(22·0)	(8·65)	—	(8·75)	5·35	4·69	4·57
140	(24·1)	(9·48)	—	—	5·97	5·10	4·94
150	(26·1)	(10·3)	—	—	6·64	5·52	5·32
160	(28·1)	(11·1)	—	—	7·37	5·95	5·70
170	(30·1)	(11·9)	—	—	8·16	6·39	6·09
180	(32·0)	(12·6)	—	—	9·03	6·84	6·48
190	(33·9)	(13·3)	—	—	10·0	7·30	6·88
200	(35·7)	(14·0)	—	—	11·1	7·76	7·28
210	(37·6)	(14·8)	—	—	(12·3)	8·24	7·68
220	(39·5)	(15·5)	—	—	(13·7)	8·73	8·09
230	(41·4)	(16·3)	—	—	(15·3)	9·24	8·50
240	(43·3)	(17·0)	—	—	(17·2)	9·76	8·92
250	(45·2)	(17·8)	—	—	—	10·3	9·34
260	(47·1)	(18·5)	—	—	—	10·9	9·76
270	(49·0)	(19·3)	—	—	—	11·5	10·2
280	(50·9)	(20·0)	—	—	—	12·1	10·6
290	(52·8)	(20·8)	—	—	—	12·7	11·0
300	(54·7)	(21·6)	—	—	—	13·3	11·5

TABLE B.

Temp.	Press. 720 mm.	Press. 740 mm.	Press. 760 mm.	Press. 780 mm.
0° C.	1·04	1·06	1·09	1·12
10	1·00	1·02	1·05	1·08
20	0·96	0·99	1·02	1·04
30	0·93	0·96	0·98	1·01

Within the limits of the above table the correction factor for a sphere-gap agrees substantially with the relative air density. Thus, for a given length of spark-gap, the tabulated kilovoltage in Table A must be multiplied by the appropriate correction factor in Table B. Alternatively, to calculate the gap which will just be sparked over by some specified voltage, the voltage must first be divided by the appropriate correction factor before Table A is used. It will be seen that under normal conditions, the correction is small or negligible. The correction for humidity is usually less than 1 per cent. and may ordinarily be disregarded.

As will have been remarked the spark-gap between points is substantially longer than between spheres for the same break-down voltage. The point and plane gap is longer still, e.g. about 50 per cent. longer than the point and point gap at 50,000 volts, about 25 per cent. longer at 75,000 volts; 15 per cent. longer at 100,000 volts, and 10 per cent. longer at 125,000 volts. The plane should be the negative electrode.

6. *Kilovoltmeters.*—The sphere gap is most conveniently employed as a standard of reference for calibrating kilovoltmeters which can be used for continuously indicating the exciting voltage. These are

often mounted on the switchboard of an outfit and are operated by means of an additional coil of a few turns wound on the primary. Their indications vary with the load, and the calibration should take account of this. Alternatively an electrostatic voltmeter may be employed. It must be borne in mind that such instruments measure root-mean-square voltages and not peak values. One type of instrument is shown diagrammatically in Fig. 41.

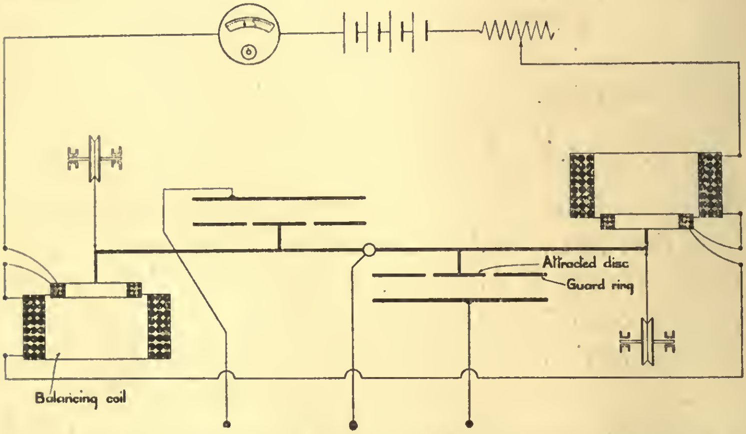

FIG. 41.—Diagram of absolute electrostatic voltmeter for high voltages up to 250 K.V. (Matthaei).

7. *Penetrometers: (a) Benoist Penetrometer.*—Among medical men, Benoist's penetrometer is often employed as a measurer of hardness. It consists of a thin silver disc 0·11 mm. thick, surrounded by twelve numbered aluminium sectors varying from 1 to 12 mms. in thickness. The X-rays are sent through the instrument, and the observations consist merely in matching on a fluorescent screen or photographic plate the image cast by the silver disc against the images of the

aluminium plates; the thickness of the matching sector increases with the hardness of the rays. The instrument indicates the average hardness of a beam of rays. A notion of the discharge potential across a tube may be got from the very rough relation that the voltage is from 5000 to 10,000 times the Benoist reading of the X-rays. The Benoist penetrometer is not so suited for the measurement of very penetrating rays, as of softer rays.

The Wappler Company of America have recently brought out a modification of the Benoist instrument in which the image of an aluminium wedge is matched against that of a copper strip. Aluminium is relatively more opaque than copper to very penetrating rays, while copper is relatively more opaque than aluminium to softer rays. The instrument is graduated to read mean wave lengths.

(*b*) *Bauer Qualimeter.*—This is a type of unipolar-electrostatic voltmeter, which serves to give a notion of the potential difference between the electrodes of a tube.

The hardness numbers of the various penetrometers are all much the same as Benoist's. Penetrometers are gradually dropping out of use.

Methods of Measuring Intensity.—The intensity of the X-rays at a particular point is defined as the energy of the rays falling on one square centimeter of a receiving surface passing through the point and placed at right angles to the surface. The question is thus on all fours with that of illumination by visible light, and the need of a unit of "candle power" in X-ray work is becoming pressing.

Factors Controlling X-Ray Output.—Fig. 42 shows the effect of current variation on the general X-ray output of a tube. There are two curves, one for 0·45 milliampere and the other for 1·15, the voltage being the same in each case. The range of wave lengths obtained from the bulb is not affected by the milliamperage employed, but the area of the 1·15 curve is considerably greater than that of the 0·45. There is

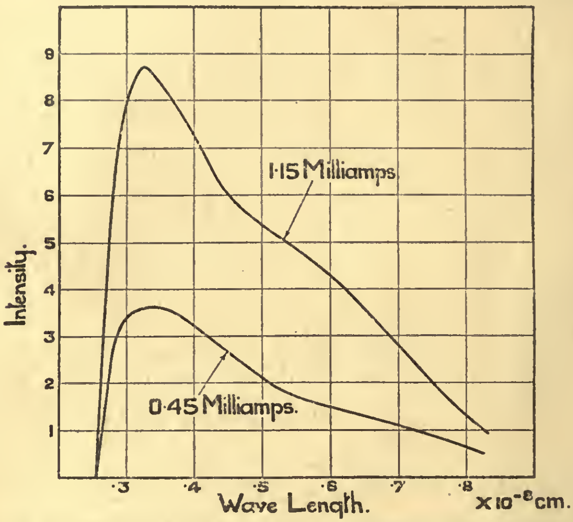

FIG. 42.—X-ray output of Coolidge tube (tungsten target). 48,000 volts; constant potential, 0·45 and 1·15 milliamps. (Dauvillier).

a very close relation between the milliamperage and the area of the curve; in fact, they prove on measurement to be proportional.

Fig. 37 shows the effect of variation of voltage on output of general X-rays, the milliamperage being kept constant. If we measure the areas of the several curves we find they increase roughly in proportion to the square of the voltage.

In Fig. 43 we have similar curves for higher voltages. The feature here is that, at about 70,000 volts, the curves are beginning to develop peaklets, which at still higher voltages almost dominate the curves. The peaklets are the spectrum lines of characteristic radiations; when they are present the output of X-rays

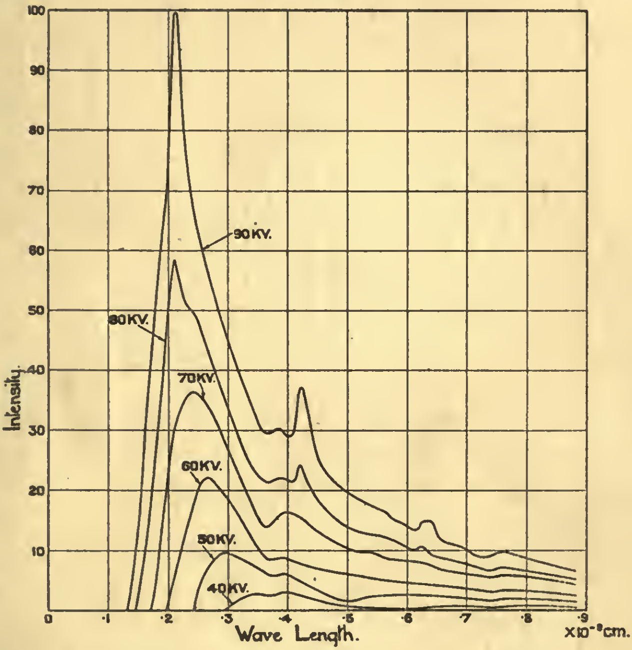

FIG. 43.—X-ray spectrum of tungsten at various voltages and const. milliamps; no filter. NaCl crystal (Hull).

increases more rapidly than by a square-of-voltage law.

Fig. 44 (Ulrey) shows output curves for various targets—platinum, tungsten, molybdenum, and nickel, in every case with 35,000 volts and 1 milliampere. If we measure the areas of these curves we find they are

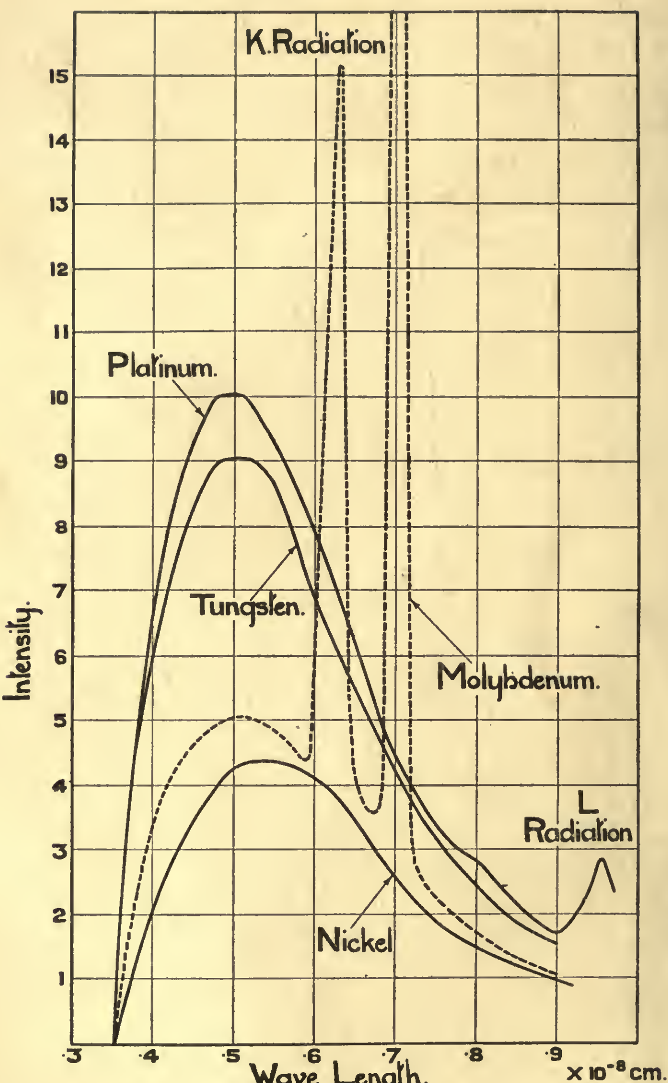

FIG. 44.—Intensity distribution of X-ray spectra of various metals; 35,000 volts, 1 milliamp.

roughly proportional to the atomic numbers of the elements.

From Figs. 37, 42, 44 we see that the total energy (E) emitted by an X-ray bulb may be written—

$$E = kNiV^2$$

where V is the voltage on the tube,
i is the current through the tube,
N is the atomic number of the target,
k is a constant.

The value of k will depend on whether a gas or a hot-cathode tube is employed, and also on the type of exciting potential. The above expression refers only to the general or "white" X radiation. If the voltage is such as to excite the characteristic radiations, the voltage comes in as a higher-powered term than V^2, and the efficiency increases.

Measurements of the value of k have been made and result in showing, unfortunately, that the efficiency of an X-ray bulb is deplorably small, of the order of 1 part in 1000. The chances that a cathode ray will ultimately come into suitable conflict with some atom and so generate an X-ray are slight. We raise those chances by increasing either the exciting voltage or the mass of the atom of the target.

The X-ray emission is virtually distributed over a sphere, or, more practically, over a hemisphere since the target blocks out most of one-half of the sphere of radiation.

Thus the intensity (comprising all wave lengths) falling on a square centimetre at distance d from the anticathode may be written—

$$\frac{kNiV^2}{d^2}.$$

If the length of exposure is t secs. the expression becomes—

$$\frac{kNiV^2t}{d^2}.$$

It is apparent that we can base on this relation a system of X-ray intensities and doses, provided we can measure i and V and be certain to what extent each is effective in generating rays which are of practical utility.

In practice we almost always filter out the long waves and we shall need then to know the new value of k, so as to correct for the proportion of i which is not usefully employed.

The measurement of all the terms in the above expression, except perhaps i and V, offers no difficulty. i can be measured by a milliammeter of suitable design which even with rapidly pulsating currents appears to indicate the arithmetic mean of the current, as has been verified by the use of the voltameter and oscillograph.

The measurement of V has already been referred to above. If the exciting potential is constant, it can be measured by a resistance type of voltmeter in series with a high resistance. If the potential is fluctuating, recourse will usually be had to the sphere spark-gap.

In addition to the above method, the radiologist has employed a variety of means of measuring the intensity of X-rays at some selected point in the beam. To this end one or other of the properties of the rays has been utilised—heating, ionising, photographic, fluorescing, or chemical.

The heating effects are minute, and the method is only fitted for the research laboratory.

1. *Ionisation Methods.*—When X-rays pass through

a gas they impart to it a temporary electrical conductivity, the extent of which depends on the number of ions formed, and thus on the amount of energy absorbed in the gas. An ionisation method of evaluating X-rays thus resolves itself into the measurement of a minute electric current. No galvanometer is sensitive enough for the purpose and an electroscope or electrometer is commonly employed, the delicacy and convenience being such that the method has found almost universal acceptance among research workers.

But in practical radiology the method is only beginning to find favour, more especially in deep therapy. The ionto-quantimeter of Szilard was one of the first instruments to be designed on this basis. In its most recent development a part of the quantimeter is sometimes actually introduced into the affected organ, and the rays measured are those which are actually received at the point concerned.

The ionisation method is unapproached in sensitiveness by any other method; it does not depend dominantly upon any selective process, and it is reasonable to anticipate that some unit of dosage thus developed (and connected perhaps with the accepted radium standard), will ultimately receive recognition as a standard.

2. *Photographic and Fluorescence Methods.*—Photographic plates record only about 1 per cent. of the energy of the X-rays passing through them, but, nevertheless, a method of measuring intensity by this means has been developed and finds favour with some workers.

As is the case with most types of intensity meters, the short-waved rays are recorded disadvantageously compared with the soft rays. Furthermore, a photographic film betrays marked selective absorption for rays approximating in wave length to the characteristic wave length of the two chief atoms in the emulsion—silver and bromine (p. 85). The photographic effect may be quite misleading in consequence.

Nevertheless to the worker with limited resources the photographic method of measuring intensities outside the critical regions offers advantages because of its simplicity. Some form of opacity meter for obtaining a measure of the density of the image is the chief requirement. The opacity meter measures the extent to which a standard beam of light is cut down by the photographic film whose density is required. If I_o is the intensity of the testing light which is incident on the developed film, and I_t that of the transmitted light, then, if μx is the fraction of the energy which is absorbed by a very small thickness, x, of the film,

$$I_t = I_o e^{-\mu d},$$

where d is the thickness of the film. The film is assumed to be equally dense throughout its thickness.

For films of uniform thickness, d is constant, so that μ is proportional to log (I_o/I_t). μ is called the absorption co-efficient; (I_o/I_t) is known as the opacity, and equals the number of times the incident light is cut down. Log (I_o/I_t) is termed the opacity-logarithm. The transparency is the reciprocal of the opacity. Now, by definition, μ is proportional to the density of the image, i.e. to the amount of silver per unit area of film. Thus the ratio of two opacity-logarithms gives the ratio of the film densities, and, therefore, the ratio of the photographic energies in the two cases. The opacity meter is graduated to read directly in opacity-logarithms.

In fluorescence methods the luminosity is matched against some standard fluorescence excited by a steady source of radiation, such as radium. The drawback to such methods is that the fluorescing salt becomes "tired" under the action of the rays. The sensitivity of a screen may also vary considerably from point to point, so that it is difficult to make a fair comparison. Barium platinocyanide and cadmium tungstate are the materials commonly used to sensitise a fluorescent screen.

3. *Chemical and other Methods.*—In the therapeutic use of X-rays, various chemical reactions brought about by the rays have been suggested, and employed, from time to time, as aids to "dosage;" for example, the discolouring of various alkaline salts (Holzknecht, 1902); the darkening of photographic paper (Kienböck); and the change of colour of pastilles of compressed barium platinocyanide (Sabouraud-Noiré and Bordier). X-rays resemble light in their property of lowering the electrical resistance of selenium; this property, if the pronounced fatiguing of the selenium could be overcome, would, doubtless, furnish the basis of a very convenient method of measurement, though Fürstenau, in his intensimeter (Fig. 82), claims to have got over this difficulty. It must be admitted that most of these methods provide little more than the roughest notion of the intensity of a beam of ordinary heterogeneous X-rays.

Of all the various intensity measurers, the pastille finds most favour with medical men in this country. The barium-platinocyanide discs are some 5 mms. in diameter, and their colour, initially a bright green, changes, when exposed to the rays, to a deep orange. The pastille is placed at a specified distance from the anticathode of the bulb, and the colour is matched against one of a number of standard tints. The method is easy in practice, and is fairly reliable as a guide, but the colour matching cannot be satisfactorily carried out without a tintometer, for example, of the Lovibond type. Levy has shown that the change of colour is due to a change from the crystalline to the amorphous condition. If the pastille is put aside, the reverse change slowly takes place, especially in the presence of light, so that the pastille should not be exposed to full daylight during the X-ray treatment. Users of pastilles may be advised in their own interests to have them tested at the National Physical Laboratory.

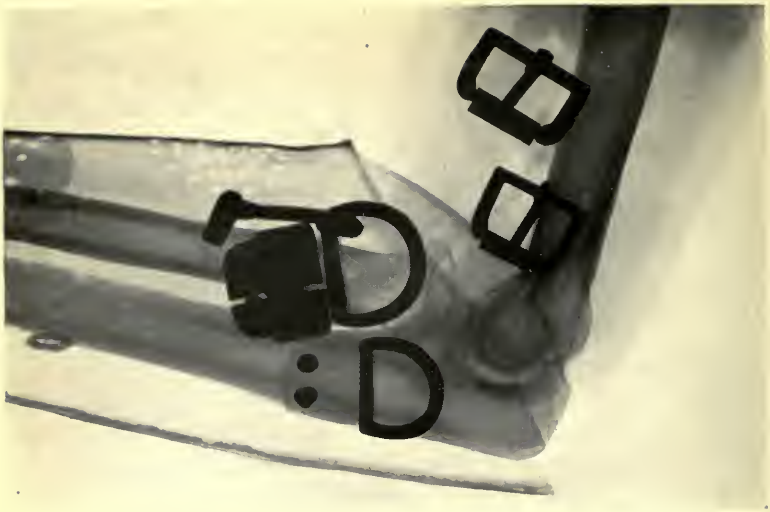

FIG. 46.—Radiograph of soldier's arm taken through artificial arm of aluminium alloy. The ventilation holes in the artificial arm and the buckles of the securing straps can be seen. The straps themselves are too transparent to show up (Luboshez).

FIG. 47.—Radiograph of a foot taken through the boot (Thorne-Baker and Levy).

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CHAPTER V.

MEDICAL APPLICATIONS OF X-RAYS.

ONLY a brief account of the medical applications of X-rays can properly be included within the scope of this volume. Readers are referred to Knox's "Radiography and Radiotherapeutics" (Black).

Radiography.—X-rays have become one of the handmaidens of medicine, a fact which is bound up with the great improvements of recent years in X-ray equipment and technique which have given the diagnostic methods of physicians and surgeons a facility and exactitude never dreamt of at one time. An atlas of every part of the body is being compiled in most X-ray laboratories. Exposures have been enormously shortened, and snapshots of the head, the chest or any part of the body can now be taken. Some idea of the advance in technique and apparatus may be gathered from Fig. 45 (see Frontispiece).

In surgery of the bone, not only fractures, but the intimate lamellar structure of the bone can be examined. Gouty and rheumatic joints clearly reveal themselves. We have learned that tumours and cysts in bones are not specially rare and that nearly all sprains are accompanied by slight fractures of the bone. When a bone is badly splintered, the dead bone splinters can be sorted out from the living. Good examples of modern technique are shown in Figs. 46 and 47.

Tumours in any part of the body, even the head, can be detected and their position determined. The diagnosis of diseases of all parts of the alimentary canal is routine—stricture of the œsophagus, stomachic disorders, diseases of the appendix and colon, etc., can all be demonstrated by the X-rays with the assistance of special food containing matter (bismuth or barium salts) opaque to the rays.

Stones in the kidney and (more recently) the gall bladder, diseases of the liver and pelvic organs, incipient tuberculosis in the lungs and joints can be diagnosed with certainty and without pain or danger.

Dental radiography has become an important subject. By suitably disposing a photographic film radiographs of individual teeth can be obtained, revealing in perfect fashion the condition of both the tooth and surrounding bone.

As to the well-known uses of X-rays in detecting foreign bodies, almost any hospital can furnish extraordinary illustrations. In one hospital alone in the course of a few weeks various patients were X-rayed who among them had swallowed nails, coins, hairpins, a small padlock, a toy pig, whistles, a watch, a put-and-take top, keys, rings, false teeth, etc. The rays have been employed by the police for the detection of jewelry which had been stolen and swallowed. They are also used by the Kimberley diamond mines for the detection of diamonds swallowed by the native diamond miners. The rays have also been employed in a similar fashion for tracing ornaments stolen by a band of Hindu dacoits in India.

During the war, many thousands of radiologists helped to build up the triumphs which X-rays achieved. The X-ray became as indispensable as the dressing or the splint, and it was an essential adjunct in prescribing and directing as well as avoiding operations. The detection of bullets and shell fragments in any part of the body was commonplace, and the X-rays were also used to guide the surgeon during his actual efforts to remove foreign bodies. Cleverly designed X-ray motor-lorries permitted early examination in the field. In the case of eye wounds, X-ray stereoscopy attains its fullest delicacy, and the location of small foreign bodies can be carried out to a small fraction of an inch. Another war development of radiology was its employment by the orthopædic surgeon in his efforts to restore damaged limbs. Many hundreds of thousands of radiographs were taken at the various hospitals during the war.

In another direction, the venous and arterial systems of the human body can, by the aid of suitable injections be radiographed and displayed to the student.

H. Béclère has done excellent work in the production of X-ray finger prints. For the purpose, the finger tip is rubbed with red lead, and the resulting radiograph is peculiar to the patient, not only in the design of the finger print, but also in the shape of the bone (Fig. 48).

The future will doubtless see an enormous extension of the use of X-rays in medicine. Equipment is becoming simplified and technique is becoming systematised. The general practitioner in days to come will probably use an X-ray camera as freely as we use a Kodak now in everyday photography.

Radiography not unnaturally has been turned to account by the veterinary surgeon. Race horses are not infrequently X-rayed for rheumatic and other troubles. Even the elephant has been radiographed (Fig. 49).

Radiotherapy.—The X-rays possess valuable properties in the treatment of malignant disease. The living cells have the power of resisting or responding to X-rays while malignant cells disappear with suitable "dosage." The method has, for example, been largely and successfully employed for lupus and rodent ulcers. Inflamed glands shrink in size and various morbid conditions of the blood clear up. Much attention is being paid to the treatment of cancer, and although it cannot be claimed that in X-rays we have a cure, the results are sometimes unexpectedly encouraging though often disappointing.

In many skin diseases, the X-rays have proved to be of notable service. For example, they are now the accepted and certain means of curing ringworm and sycosis. They are very successful in eczema and psoriasis and similar skin eruptions, and in the hands of some workers have proved of value in cases of exophthalmic goitre. The "dose" is all important, for the sweat glands and hair follicles are also affected, and, with excessive exposure, may even be destroyed, the result being baldness.

The corpuscles of the blood are prejudicially affected by X-rays, resulting in a form of aplastic anæmia. Curiously enough, the rays seem to have little or no action on bacteria or their spores, and in this respect stand out in marked contrast to ultra-violet light.

Deep-seated organs are now successfully treated

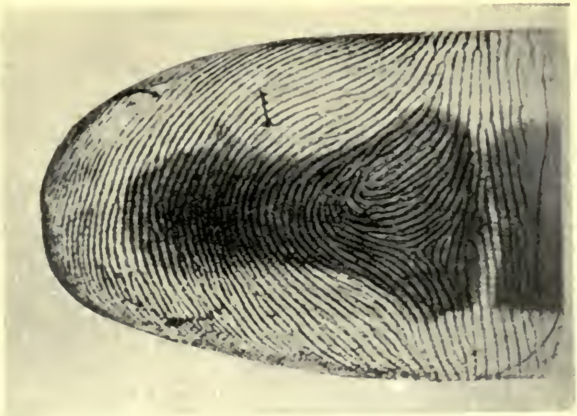

FIG. 48.—Radiograph of finger, showing finger print and bone (H. Béclère).

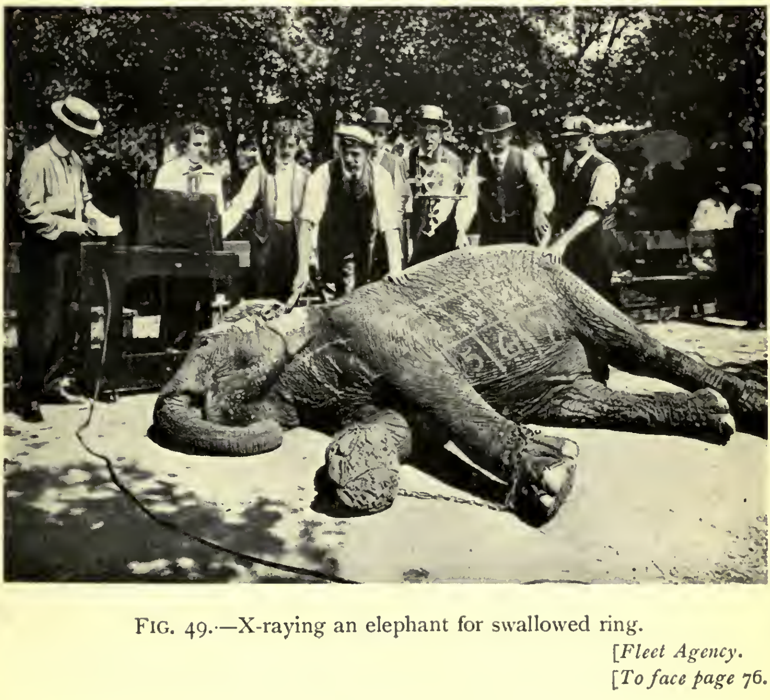

FIG. 49.—X-raying an elephant for swallowed ring.

[*Fleet Agency*.

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by X-rays. In deep radiotherapy German cancer technique is tending in the direction of administering massive doses of short-waved homogeneous X-rays. The soft rays are removed by using metal filters (Al, Cu or Zn), with a coating on the side nearest the skin of wood or leather, so that no characteristic radiation may play on the skin. Over-dosage of the skin is avoided by employing multiple parts of entry, each of the various beams being properly directed at the deep affected tissue. The choice of metal for the filter modifies considerably the composition of the beam. In the case of very penetrating radiations metals of high atomic weight such as lead are relatively very absorbent, while metals of medium atomic weight such as copper and zinc are relatively very transparent. In this connection see also p. 63.

One of the hindrances to precise radiotherapy at the present time is the difficulty of measuring the dose of radiation absorbed by the particular region concerned, especially if it be at a depth in the body. On physical grounds, at any rate, it would seem that it is only those rays which are absorbed that can produce physiological changes, and only such rays should be included when speaking of a dose. It may be, of course, that selective action is present, and that only a restricted range of wave lengths is appropriate for the conversion of energy in the correct spot. With this reservation it would seem that the degree of reaction should be a function of the absorbed and converted energy. The problem is complicated by the lack of homogeneity of the primary beam.

Among the tragedies of the war few were more pathetic than the ghastly disfigurements caused by shell wounds of the face and head. Fortunately, it was often possible, by the wonderful grafting operations of the surgeon, to restore at least a semblance of the patient's former appearance. Lips were renewed, new noses built up, eyelids replaced, cavities in the palate filled in by flaps taken from the skin or scalp. The scar-tissues and flaps were kept pliant and adaptable by "spraying" with X-rays, which also served to depilate hair and to stimulate the healing process in both flaps and bone.

CHAPTER VI.

INDUSTRIAL APPLICATIONS OF X-RAYS.

The Examination of Materials.—In well-nigh every branch of industry the testing of materials has come to be of importance. With increasing knowledge and the stress of competition, a variety of testing methods have been evolved to ascertain quality and uniformity as determined by the several physical, chemical, and visual characteristics. Such tests are commonly conducted on samples which are selected to be as representative as possible. From the nature of things, the value of the results is limited, and the engineer in particular is ever on the look-out for opportunities for greater insight into the materials he employs.

The employment of X-rays in the examination of materials, lies at present in two main directions :—

1. X-ray spectrometry or the study of crystal structure.
2. Radiography or X-ray shadow photography.

Both methods enjoy the advantage of not in any way injuring the structure or resolving the components of a material.

X-Ray Spectrometry.—Space forbids more than a reference to the great potentialities of the results of X-ray spectrometric analysis as applied to crystal structure. It is a matter of great satisfaction to Englishmen to know how much the subject owes to Sir William Bragg and his son, whose published work on the subject is of the highest fascination and importance. The literature is already large and is rapidly growing. The reader is referred to Braggs' book "X-Rays and Crystal Structure."

Several methods have been employed. As mentioned above Laue, at Munich, in 1912, sent a heterogeneous beam of X-rays through a thin crystal and photographically showed that a diffraction pattern was produced. The Braggs followed with the X-ray spectrometer which is based on the fact that a crystal can reflect a beam of X-rays when and only when the angle of incidence is exactly adjusted to suit the space lattice (p. 45) of the crystal and the wave length of the rays. In other words, if we imagine a narrow pencil of homogeneous X-rays to fall upon a crystal there will be no reflection of the rays except when the crystal is placed in certain sharply defined positions. The relation is given by the formula

$$n \lambda = 2d \sin \theta$$

where n is the "order" of the reflection, λ the wave length, d the lattice constant, and θ the glancing angle of the incident beam. The X-ray spectrometer is concerned with measuring θ by recording the reflected beam by photographic, ionisation or fluorescent means (Figs. 50 and 51). By this means the Braggs proceeded to disclose the atomic architecture of a large number of crystals, and the lines of the emission spectra of many elements (see Fig. 39).

The practical possibilities were greatly enlarged when Debye and Scherrer [1] at Zürich, and Hull,[2] at the G.E.C.

[1] *Phys. Zeit.*, 1916. [2] *Phys. Rev.*, 1917.

Research Laboratory, Schenectady, showed that large crystals were not essential, but that the method could be applied to an aggregate of finely powdered crystalline material, provided the orientation were sufficiently random. For the powdering does not obliterate the

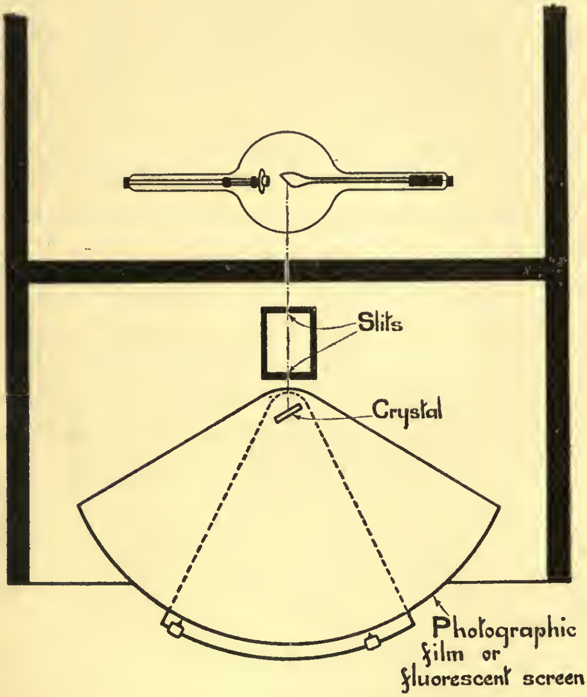


FIG. 50.—X-ray spectrometer.

crystal structure ; it merely replaces the one crystal by a myriad of others, each capable of reflecting the X-rays if only it were rightly oriented. There will be a small proportion of the minute crystals correctly placed for reflection and so we can get the effect we are looking for, despite the fact that the great majority of the crystals will not be assisting and merely serve to lengthen the exposure. The Debye and Scherrer result was a big step forward, for it enables the crystalline structure of a body to be examined even when the individual crystals are microscopic or ultra-microscopic in size. In practice the powdered crystals are either mounted on a cardboard backing or contained in a thin-walled glass capillary tube which is mounted on the X-ray spectrometer in place of the crystals (Fig. 50). Homogeneous X-rays are used (see p. 38).

We now know that almost every solid substance betrays crystalline structure. Scarcely any solid is amorphous, and it would seem that the various physical properties—elasticity, hardness, melting-points, etc., are all manifestations of the various atomic forces which reveal themselves in the crystalline form. The very formation of solids may be merely an outward and visible sign of crystallisation, and a definition of a "solid" may be so derived which is, at any rate, as adequate as others which have been framed. Not only the growth, but the decay, the change points, etc., can all be followed and watched without harming a body in any way.

We have thus a new tool of research, which, although at present rather delicate and tentative in application, would seem to offer unusual possibilities. The metallurgist, to whom crystalline formation means so much, need no longer have to content himself with inferring from their external forms what the internal structure of the crystals in his metals and alloys may be. He may also find that the method will throw light on the fundamental nature of the effect of heat-treatment,

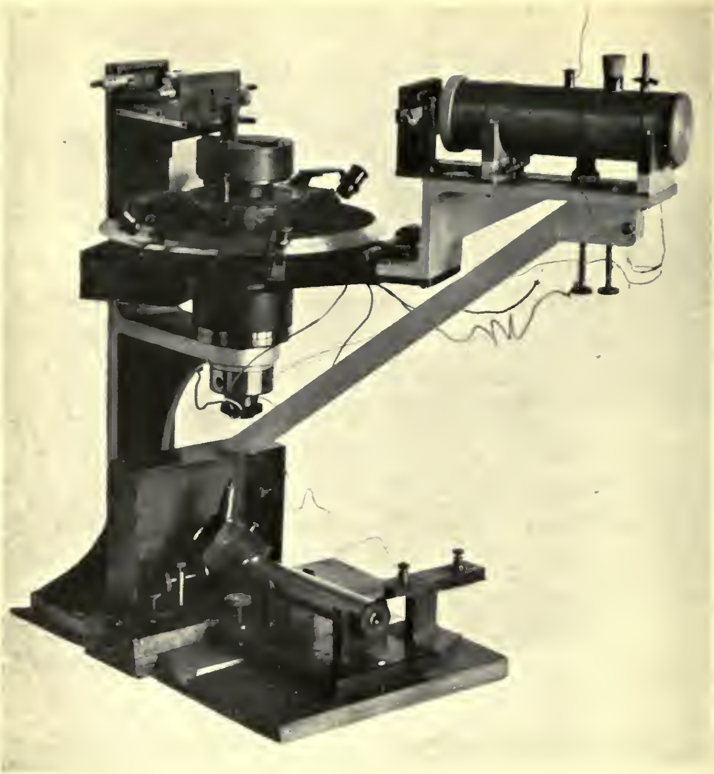


FIG. 51.—X-ray spectrometer at the National Physical Laboratory.
[*See page* 80.

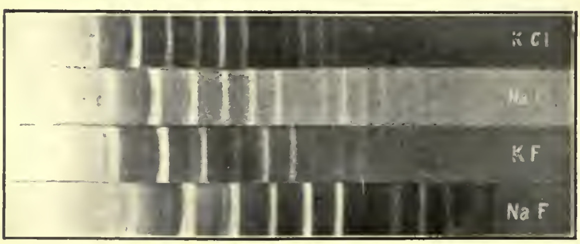


FIG. 52.—X-ray spectra of metallic salts (Hull).

[*To face page* 83.

tempering, rolling, and ageing on crystalline metals and alloys.

It has been shown that amorphous carbon really consists of minute graphite crystals ; colloidal gold and silver are made up of minute, yet perfect crystals so small that they contain only a few score atoms. Starch, pure fats, the cellulose in plants are all crystalline. Even the particles "sputtered" from a cathode in a discharge tube are possible of examination, and are found to be crystalline. The so-called liquid crystals have also been the subject of study.

Westgren and Phragmen[1] have examined iron and steel by this method at temperatures up to about 1500° C. and so determined for the first time the crystal shape and elementary volume of cementite (Fe_3C). They also showed that the well-known transformation of iron at 900° C. is reversed at 1400° C.

Hull[2] describes an interesting example of the application of X-ray spectroscopy to the analysis of mixed salts. A mixture containing sodium, potassium, chlorine, and fluorine might equally well be made up of crystals of NaCl and KF or crystals of NaF and KCl : the chemist would find it difficult to be sure. But each of these crystals has its characteristic space lattice and constant and this is clearly signified in the grouping and relative intensities of the lines in the X-ray spectra, so that it proves impossible to confuse the two arrangements when this test is applied (Fig. 52).

The presence of impurities in materials can be indicated much as in optical spectrometry, but with greater simplicity and certainty.

[1] *Journ. Iron and Steel Inst.*, 1922. [2] *Phys. Rev.*, 1917.

These are but a few of many examples. There is a great opportunity for the metallurgist, the chemist, and the physicist to get together on this work. At present, the main difficulties are those of technique. Monochromatic X-rays have at present to be used, and as these can be obtained only of feeble intensity, protracted exposures have hitherto been necessary, though these can now be greatly shortened by the use of more sensitive plates.

A useful type of X-ray tube for this work is shown in Fig. 16. An iron target excited by 50,000 volts is suitable for work on iron or steel. A copper target excited by 30,000 volts is convenient in many cases with substances of moderate density. The design of the tube in question allows the test material to be brought very near to the target. The beam of X-rays utilised is at right angles to the target, so that the focus functions as a narrow slit of emitting rays.

X-Ray Absorption Spectra.—Before leaving this branch of the subject, brief reference should be made to the subject of X-ray absorption spectra. Let us suppose that passing through a sheet of metal is a beam of X-rays of which we gradually shorten the wave length. The beam is transmitted with increasing ease until the wave length coincides with a characteristic wave length of the metal. At this point the absorption of the sheet suddenly and greatly increases. If we continue to shorten the wave length of the incident beam, the beam is once more transmitted with increasing ease but does not recover its former facility until the wave length has been very much shortened.

Let us now throw a spectrum of X-rays on a photographic plate. Instead of a uniformly dark image we find that there is a sharp discontinuity at a certain wave length characteristic of the silver in the emulsion. Shorter wave lengths than this are more strongly absorbed by the silver than the longer waves, and so we get an "absorption edge" with a pronounced darkening on the short-wave side. The existence of the edge at this particular wave length is an infallible indication of the presence of silver.

If in the path of the X-rays before they reach the photographic plate a filter of another metal is placed, its presence will be indicated by another "absorption edge" at a position in the spectrum characteristic of the new metal. If the atomic number of the filter is adjacent to that of silver we shall get a dark band, one edge being the absorption edge of silver, the other the absorption edge of the metal of the filter (Fig. 53).

The method which is associated with the name of de Broglie will undoubtedly find practical application ere long.

Industrial Radiography.—As was anticipated by Röntgen and others, when the art of radiography had sufficiently advanced in medicine, it extended its scope to industry. As already remarked, the method of X-ray inspection has the advantage of not injuring a body in any way. Furthermore, it provides in many cases the only means independent of human judgment of detecting concealed defects in a material, or of scrutinising in a structure the accuracy of assembly of component parts which are hidden from view.

The development of industrial radiology has been bound up with that of the Coolidge tube, and both during and since the War the X-rays have been applied to a variety of branches of industry. As already explained, the method depends on receiving the shadow of the object on a fluorescent screen or photographic plate. It should be made clear at the outset that a radiograph shows only the gross structure of a material, and gives no information as to the crystalline or microscopic structure from point to point.

The usual arrangement in X-ray radiographic examination is to place the object on a table above a well-earthed tube-box, thickly lined with lead (or its equivalent) and of dimensions adequate to prevent sparking to the walls. By the use of lead diaphragms the beam of rays is reduced to the minimum necessary for the work in hand. The fluorescent screen or photographic plate is placed immediately above the object. If much screening is to be done, arrangements should be made for the image to be viewed by reflection in a mirror. In the interests of the operator the protection and ventilation should be beyond reproach. The room should be spacious, preferably on the ground floor, well lighted but capable of being darkened. The operator should be guarded against accidental contact with high potential leads.

Protection.—As regards protection no risks whatever need or should be taken. The subject has already been referred to (p. 12) and the necessary precautions which are fully adequate are dealt with in Appendix I. It may be mentioned that in the case of X-rays generated by an exciting (peak) voltage of about 180,000, 3 mm. of lead reduces the intensity to less than 1/10,000, and 1 cm. of lead to less than 1/1,000,000.

Incidentally sheet lead is commercially described and sold by its weight per superficial foot, "2 lb. lead" referring to sheet lead weighing 2 lb. per square foot. In this connection the following table may be useful :—

Weight.	Thickness.
2 lb. lead	0·8 mm.
3 " "	1·25 "
4 " "	1·7 "
5 " "	2·15 "
6 " "	2·6 "
7 " "	3·05 "
8 " "	3·5 "
9 " "	3·95 "
10 " "	4·3 "
11 " "	4·75 "
12 " "	5·2 "

As regards the use of commercially obtainable lead glass and lead rubber, both are found to vary a good deal in protective value. The thickness of lead glass which is equivalent to 1 mm. of lead may vary for different samples between 5 mm. and 10 mm. : the corresponding commercial limits for lead rubber are 2 mm. and 4 mm. An N.P.L. certificate should always be asked for in buying protective material and equipment.

While the general technique is much the same as in medicine, mention should be made of one of the chief experimental precautions in the X-ray photography of metals. There are two things that may happen to a beam of X-rays when passing through a material. Part of it may be absorbed, which means that it is wholly transformed into characteristic radiations of the material, the process always being accompanied by the liberation of electrons. The rest of the beam is scattered or dispersed, which, in effect, is equivalent to stating that while the rays are unaltered in quality a considerable proportion of them have their direction altered. Scattering, which finds a close parallel in the dispersion of light by a fog, shows up more pronouncedly with light atoms than with heavy. Further, just as in absorption,

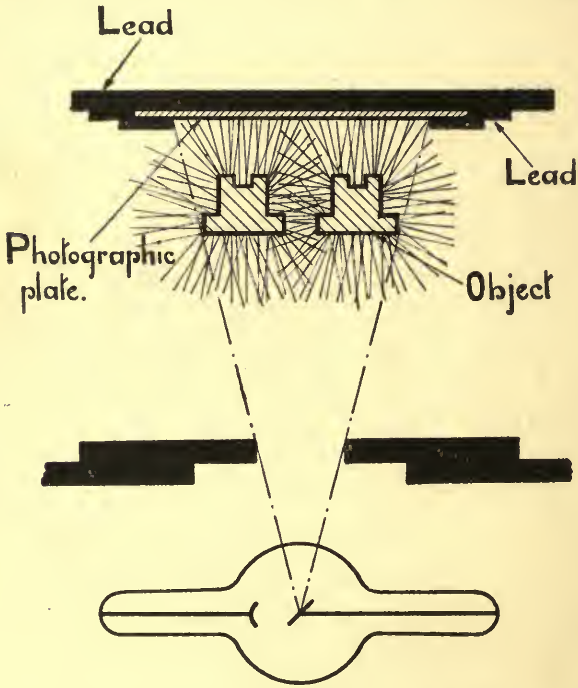


FIG. 54.—Showing protective measures against scattered radiation.

the extent of the effect naturally depends on the closeness of packing of the atoms or the density.

Even in medical radiography the experienced worker is well aware of the effect of scattered radiation. Such scattered radiation, if allowed to reach the photographic plate, tends to fog the main image. The various surfaces of the bodies encountered all offend and even the air contributes its quotum of scattered rays.

The effect is especially marked in radio-metallography in which intensities are great and exposures long. Worthless results will be obtained in the absence of suitable precautions. These consist in enveloping the photographic plate, back and front, with sheet lead (preferably with an inner lining of aluminium), a hole being left no bigger than necessary for the reception of the direct image of the object (Fig. 54). If the object is continuous and flat, there is no difficulty, for it can be brought into close contact with the plate. If, however, the body is irregular in contour, it may conveniently be cemented with paraffin wax to the bottom of a cardboard or aluminium tray, and mercury, fine lead powder, shot or the like poured round it. Wax filling is also necessary, both to fill up any pockets or cavities and to prevent the mercury or lead from straying into the path of the projected image.

Generous exposures and short development will tend to diminish the effects of scattered radiation on the photographic plate.

Considerable gain may result from the use of the Bucky grid between the object and the plate. This consists of a rectangular metal grid, the faces being spherical in contour and the dividing cell-walls of the grid everywhere radial. The grid, while allowing direct X-rays from the focus to pass, kills the majority of the scattered radiation. The grid is kept in slight motion to prevent it being registered on the photograph.

Naturally the orientation of the object with reference to the beam of X-rays may make or mar a radiograph.

Distortion may be reduced by avoiding undue obliquity of the rays, and to this end it is wise to keep the distance between the object and bulb as great as is expedient, and place the plate as near the object as possible. For good definition the rays should be stopped down as much as the work will allow.

X-Rays and Materials.—The present practicable depths which can be penetrated in various materials are :—

4 to 5 mm. of lead.
12 mm. of tin.
5 cm. of brass.
7·5 cm. of steel (carbon) or iron.
10 to 15 cm. of aluminium and its alloys.
30 ,, 40 cm. of wood.

These figures refer to photographic work with about 150,000 (peak) volts on the tube. They are much less for screen examination, for example, no more than about 1 cm. of steel can be screened and then only with difficulty. The visual acuity of different observers of course varies widely.

The limiting factor in radiometallography is the exposure which hitherto has been very protracted with the greater thicknesses increasing approximately as it does with the square of the thickness. However, with the latest type of X-ray plate, the exposures are greatly reduced, and 1 inch of steel, for example, now requires an exposure of about a minute, using a voltage of about 150,000 and a few milliamperes through the tube. Fig. 55 shows a radiograph taken through 2½ inches of steel.

Within the above limits we can, with considerable delicacy, hunt out anything which is so disposed as to cast a measurable variation in the shadow, provided the body is not too complicated in shape to render the shadow too confusing to interpret. The method is sensitive, for example, tool marks and fine mould marks often show up in a radiograph though ordinarily a variation in effective thickness of 1 or 2 per cent. is all that one can expect to detect. The opacity is merely a measure of the number and weight of the atoms encountered, and so different qualities of a metal possessing different densities display different intensities in a radiograph, e.g. a wrought rivet in a casting of the same metal shows a darker image. For the same reason, equal thicknesses of carbon, nickel, and tungsten steels differ markedly in transparency, a property which has been turned to account. For example, a 20 per cent. tungsten steel is nearly twice as opaque as mild steel.

Hidden cracks in a metal, which are a bugbear to metallurgists, can often be detected, though if they are very fine or tortuous (hair cracks) the method is rarely suitable. Such cracks are sometimes the sequel to "pipes" or blowholes in the ingot, and it is easier to detect them in the ingot than after working. Blowholes or other casting faults are shown up in cast iron or steel. The former is rarely stressed unduly and for that reason X-ray examination is not so important as with cast steel.

In the case of alloys, granularity or the uneven distribution of any component results in a "patchy" or streaky radiograph. X-ray examination will often diagnose defective soldering or brazing, the substitution of one metal by another, hidden stopping or pinning (p. 95), and so on. The method has also found application in detecting hidden corrosion (as in gas cylinders, in ferro-concrete, and the armouring of cables), in scrutinising steel turbine discs for segregations, the homogeneity of carborundum wheels, and so on.

X-Rays and Welds.—Electric and oxy-acetylene welding has come into great prominence during and since the war. Unfortunately an indifferent welder can turn out what appears, on the surface, to be an excellent weld, while inside little or no bonding has taken place. There appears to be no adequate mechanical test for a weld, and in any event any such test, whether mechanical or microscopical, destroys the weld, good or bad. The X-rays promise to be of great use in this connection. If the component parts are not actually fused together, a narrow dividing line comes out on the plate (Fig. 56) (see Frontispiece). Blisters and blowholes show up as light spots (Fig. 57). X-ray photography of welds up to 1 inch thick is now quick, easy, and certain; with modern equipment, lengths up to 2 feet can be taken at once, the exposure being of the order of a minute. In favourable circumstances, the amount of detail revealed is extraordinary, and the process compares favourably with that of photomicrography which is only very local in its test, and, as already remarked, involves the destruction of the weld. The X-ray method has been applied to the welding of various aeroplane parts, metal propellers, etc. The method has proved to be a somewhat severe critic of present-day welds as commonly carried out, but it may be added experience is valuable in diagnosing the indicated imperfections. Furthermore, the rays do not indicate the severe heat treatment—often deleterious—which the

FIG. 57.—Radiograph of defective electric weld in steel plate, showing blisters and blow-holes.

[*See page* 91.

FIG. 58.—Radiograph of a German armour-piercing explosive bullet. The two separate explosive compounds in the bullet may be noted (Pullin).

[*See page* 93.

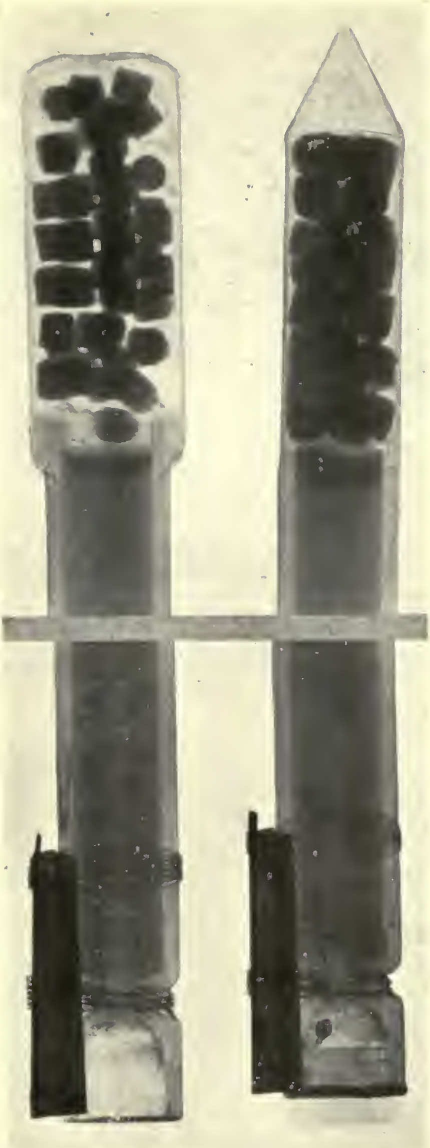


FIG. 59.—Radiograph of army signal rockets showing stars. The rockets are badly filled (Pullin).

[*See page* 93.

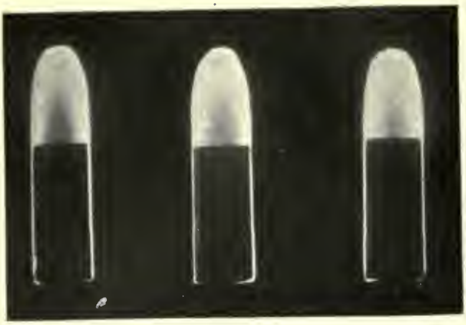


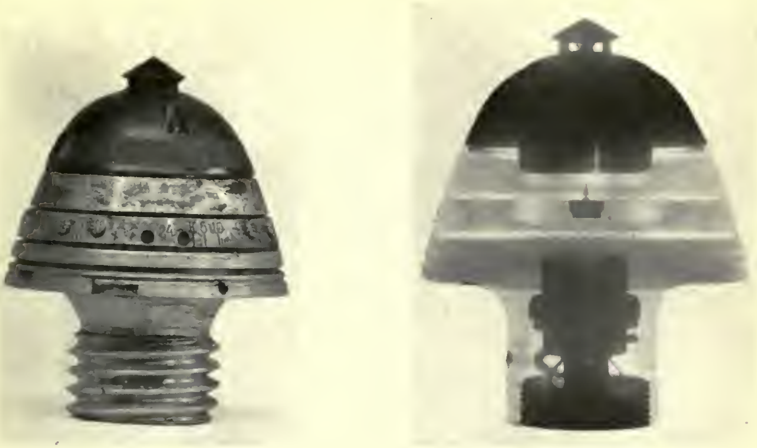
Fig. 60.—Radiograph of Austrian armour-piercing explosive bullets with detonators. The hard steel armour-piercing core may be distinguished from the lead base (Pullin).

A

B

Fig. 61.—(A) Ordinary photograph of rifle grenade. (B) Radiograph showing interior detail and presence and position of creep-spring (Pullin).

[*See page* 93.



A B

FIG. 62.—(A) Ordinary photograph ot a Russian fuse. (B) Radiograph showing internal details (Pullin).

A B

FIG. 63.—(A) Ordinary photograph of hand grenade. (B) Radiograph showing detonator and also flaws in the metal (Pullin).

[*See page* 93.

FIG. 64.—Radiograph of an automatic pistol, showing cartridges in chamber (Pullin).

FIG. 65.—Radiograph of an alarm clock taken through the case (Thorne-Baker and Levy).

adjacent metal has experienced during the welding. This is the chief objection to welding and is the reason why welding in aircraft has been largely replaced by riveting.

X-Rays and Explosives.—The X-rays have proved of service for testing the continuity of the gunpowder core in the safety fuse used for blasting and mining operations. Naturally enough the rays found a great opening during the war in the manufacture of explosives and related devices. In some instances, e.g. the correct filling of liquid-gas grenades, the examination of opaque cordite for air bubbles, the interior detail and accuracy of assembly of detonators, Stokes' igniters and vent-sealing tubes, no other method of inspection was possible. The X-rays also proved of value in examining enemy ammunition of unknown design, where, for reasons of safety, it was desirable to ascertain the internal construction before opening up. Other applications to pyrotechnic stores included the examination of the packing of army signal rockets (Fig. 59), the internal detail of armour-piercing bullets (Figs. 58 and 60), of rifle grenades (Fig. 61), of fuses (Fig. 62), of hand grenades (Fig. 63). Fig. 64 is a radiograph of an automatic pistol showing cartridges in the chamber. Most of this work was carried out by Pullin and his colleagues at the Research Department at the Royal Arsenal, Woolwich. As showing the amount of hidden detail that can be brought out Fig. 65—a radiograph of an alarm clock—is instructive. In the original the hair-spring can be easily seen.

X-Rays and Timber.—In the case of timber, the different varieties absorb X-rays to different extents.

Peculiarities in the structure and path of the fibres (such as the contortions which produce "figure") are easily discerned. The denser heart wood is differentiated from the sap wood, the summer and spring growths (Fig. 66) of the annual rings are readily identified, and defects such as knots, resin pockets, or grub holes (Fig. 67) show up with astonishing clearness. Wood is very transparent to X-rays and quite soft rays are necessary for this work, an alternative spark-gap of from 1 to 2 inches between points being suitable. Screen examination is possible in most cases.

Other possibilities may be foreseen of the practical applications of X-rays to the examination of timber generally. It may even prove expedient to radiograph valuable growing trees to search for defects. Further, X-rays are capable of revealing "figure" arising from contortions of the fibre—a feature of high commercial importance.

The presence of severe internal shakes, filled with mineral deposits (like the phosphates in teak) or of foreign bodies, is clearly revealed by the rays. Accidents to both saw-mill plant and workmen have frequently been caused by stones, old axes, nails, staples, etc., which, left in a fork of a tree or driven into the butt, have been subsequently overgrown with sound wood. Sabotage in the shape of steel spikes being driven into lumber, so as to ruin the band saws, was not unknown in Western America during the war.

Careful examination by the X-rays of hardwood destined for aeroplane propellers, etc., might serve to detect incipient cracks indicative of internal residual stresses produced by improper methods of kiln drying.

Fig. 66.—Radiograph of perfect specimen of silver (sitka) spruce aeroplane spar, showing annual rings. Also aluminium washer and steel wiring plate (Knox and Kaye).

Fig. 67.—Radiograph of aeroplane spruce, the lighter areas showing hidden grub holes. The dark patch near the centre proved on splitting the wood to be the remains of a grub (Knox and Kaye).

[*To face page* 94.

FIG. 68.—Radiograph of aluminium piston of aeroplane engine, showing crack.

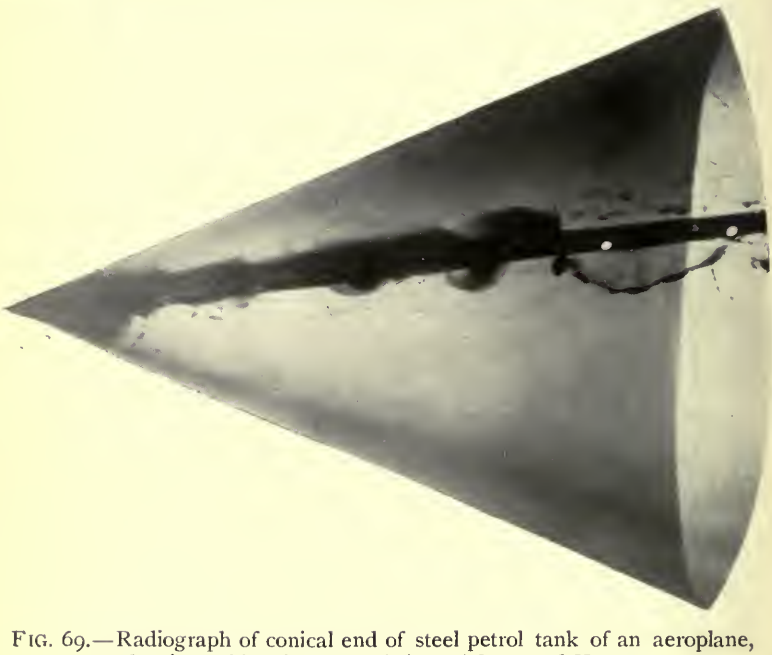


FIG. 69.—Radiograph of conical end of steel petrol tank of an aeroplane, showing soldered seam and rivets (Knox and Kaye).

[*To face page* 95.

Such stresses may lead to subsequent warping or even actual tearing of the glue joints.

X-Rays and Aircraft.—The utilisation of X-rays to examine the parts of aircraft was introduced by Knox and Kaye[1] on behalf of the Air Ministry during the war. During recent years the use of aluminium alloys has largely increased in the construction of internal combustion engines both for aircraft and general use. In the case of aircraft weight is reduced to a minimum and no imperfections can be tolerated. Quite small flaws can be detected by the X-rays in aluminium pistons (Fig. 68), cylinder heads, and crank cases. Steel parts are less amenable to the method, but are fortunately more reliable as a rule than aluminium. Fig. 69 shows the conical end of a steel petrol tank with soldered seam. Incidentally the rivets proved to have no heads on the inside of the tank. Other aircraft features which have received attention are the non-screwing home of tie-rods, the non-bottoming of struts in their sockets (Fig. 70), the quality of parachute harness rings, the fitting of the "olive" in the rubber (P.R.) hose unions for petrol pipes, etc. An interesting case was provided in the war by the axles of the undercarriages of a batch of aeroplanes. Collars are fitted on each end of the axle to prevent lateral movement, the collars being pinned through holes in the axle. In the case of the axles in question these holes were drilled in the wrong place, and to correct the mistake the holes were plugged up and cleaned off so that they could not be detected by ordinary examination. When an aeroplane lands considerable strain devolves upon the axle, and it was

[1] *Trans. Far. Soc.*, 15, 1919.

owing to one of the axles snapping at a plug hole that the faking was first discovered. The accident led to the close examination of the remaining axles in stock, with the result that a large number were found to have been treated in the same manner, though visual examination failed to detect them.

At a time when the submarine was seriously endangering the country's supplies of high-grade timber, from Canada and the States, designs for building up aeroplane parts from smaller timber were developed, using either laminated or hollow "box" structures. The workmanship required has to be of the finest, and much of it is hidden of necessity. Further, the solid or laminated strut or spar is often completely wrapped with fabric, and ordinary visual inspection of the final part is apt to be as ineffective as with hollow struts or spars of the "box" type which are usually covered with ply-wood or veneer. But the inspector has in the X-rays an ally which unerringly reveals hidden faults such as knots, large resin pockets, defective glueing, and poor workmanship (Fig. 71). The method is also useful for watching the behaviour of the various hidden members, splices, and joints of a composite wooden structure, while it is being subjected to test.

In hollow spars the internal strengthening blocks are sometimes badly shaped and fitted (Fig. 72): they may be split (Figs. 72 and 73) or out of position or even omitted altogether. A type of hollow aileron spar largely used in the war consisted of two halves glued together longitudinally after the sides had been spindled out (Fig. 74). It was important that the two outer webs should be of the same thickness; but in reducing the

FIG. 70.—Radiograph of an aeroplane wood wing-skid which did not bottom properly into its aluminium socket, a packing piece (B) having been inserted. Thickness of Al about $\frac{1}{8}$ inch (Knox and Kaye).

FIG. 71.—Radiograph of aeroplane hollow spar, showing concealed and prohibited joint in ply-wood sides (Knox and Kaye).

[*To face page* 96.

FIG. 72.—Radiograph (side and front views) of hollow aeroplane wooden spar, showing badly shaped end block split by screws. This was quite concealed from view (Knox and Kaye).

[*See page* 96.

FIG. 73.—Radiograph of hollow main-wing aeroplane spar of wood. The internal strengthening block is split and shows poor workmanship (Knox and Kaye).

FIG. 74.—Radiograph of hollow wooden longeron of aeroplane, showing the registering of the internal stiffening blocks (Knox and Kaye).

FIG. 75.—Radiograph (front and side view) of laminated wooden aeroplane spar, showing in centre lamina forbidden knots and grub hole which were quite concealed from view (Knox and Kaye).

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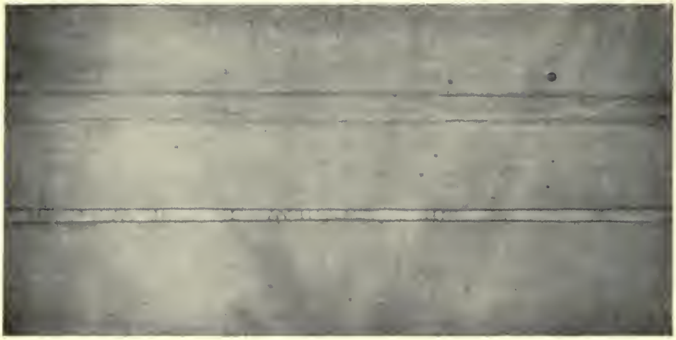

FIG 76.—Radiograph of ply-wood, showing concealed overlap and gap in inner plies (Knox and Kaye).

FIG. 77.—Radiograph showing nature of hidden splice in aeroplane spar (Knox and Kaye).

[*To face page* 97.

glued-up spar to correct finished dimensions, it was found that workmen were apt to plane away more wood from one side than from the other, occasionally reducing the strength to a critical degree. The X-rays form an immediate check on this. In laminated spars defects in the middle layers were similarly detected (Fig. 75). Incidentally the presence of the glue between the layers is plainly shown, and the rays will reveal either excess or deficiency of glue between glued surfaces.

Similarly in the case of three-ply boards we can detect the use of knotty or split wood or uneven distribution of cement in the hidden layers. Or again, as in Fig. 76, where an overlap and a gap occur in multi-ply intended for use in engine bulkheads and engine bearers, the defects in each case lying deep in the body of the ply-wood where they could not be seen by any external examination. Another example is the case of a split longeron which had a shaving glued over a crack. After sand-papering the defect was admirably concealed, but was easily revealed by the X-rays.

The usefulness of the method when it is applicable to the rapid routine inspection of large quantities of stores is obvious. Selective inspection, i.e. the inspection of only a selected percentage of the articles, may leave no alternative but the discarding of the whole of a batch, whereas with 100 per cent. inspection the defective articles may be sorted out from the serviceable. An example of this occurred in the war when doubt arose as to whether an essential accessory had been included as part of a large consignment of instruments each securely packed in its own packing case. To unscrew and open up each case and remove the packing material would have been a long and expensive business, but the X-rays provided a simple and satisfactory alternative. Again, a large consignment of aeroplane spars had been in store for some time before they were brought into use. These spars contained splices which were completely hidden by layers of glued-on tape, and it was not known whether these splices were of an earlier obsolete type or were of a later and much better type. It was impracticable to remove the covering type to test the matter visually, but the X-rays were able to demonstrate the fact that the splice was of the obsolete type and the spars were not permitted to be used (Fig. 77).

Radiography may also serve as a test of workmanship in almost any branch of carpentry or joinery, e.g. see Fig. 78.

X-Rays and Rubber.—X-rays are also being turned to account by the tyre manufacturer in his efforts to improve the union between the rubber and the Egyptian cotton fabric or cord (Fig. 79). By previously impregnating the canvas threads with a lead salt, the Dunlop Research Laboratory has been able to test whether the stretch of the threads in the several processes of manufacture of a tyre is within the limits of stretch tolerated by the yarn.

In the manufacture of golf balls, fine rubber tape is wound on a spherical core either of soft rubber or liquid. If care is not taken the core is distorted, becoming either roughly ellipsoidal or even dumb-bell shaped. The resulting ball is defective from the point of view of accurate flight, but such balls can be readily sorted out by the help of the X-rays (Fig. 80). The balls are allowed to roll slowly between the tube and

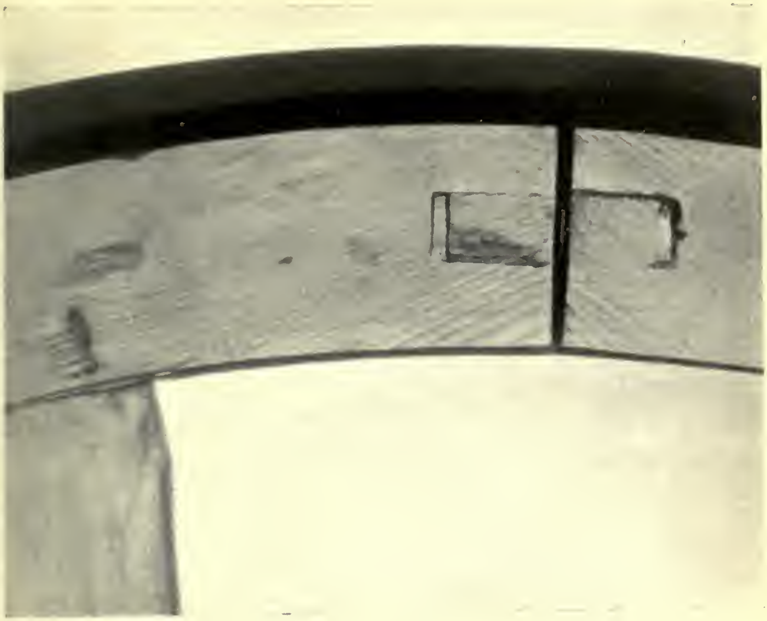

FIG. 78.—Radiograph of felloe of limber wheel, showing joint filled with lead paint (Pullin).

FIG. 79.—Radiograph of aeroplane tyre, showing corded structure under rubber (Knox and Kaye).

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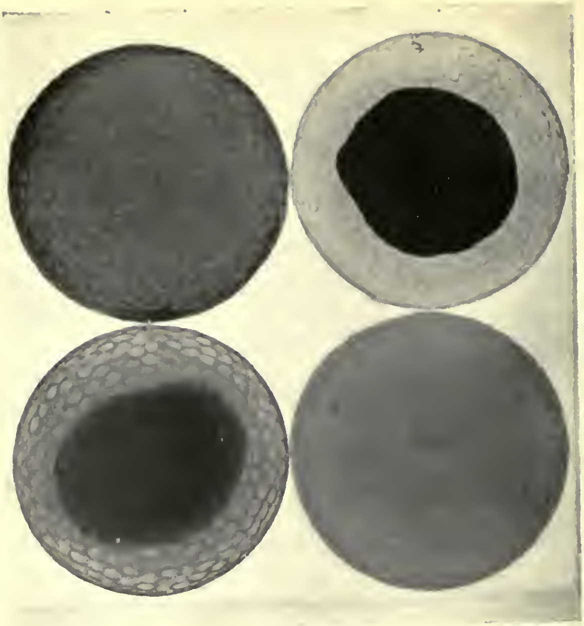

FIG. 80.—Radiograph of golf balls, showing denser and unsymmetrical cores; also "floaters."

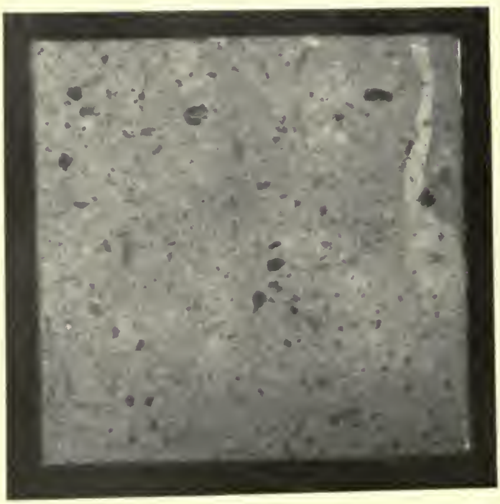

FIG. 81.—Radiograph of fire-clay pot, showing iron and other foreign particles (Owen).

[*To face page* 99.

the fluorescent screen and examined as they pass. The method is now in extensive use, no other being readily available. The Post Office has long used the rays for testing the amount of mineral matter in guttapercha.

X-Rays and Glass.—The manufacture of optical glass became a key industry during the war, as hitherto we had relied wholly on Germany for our supplies. One of the greatest troubles which was encountered was the destructive action of the molten glass on the fire-clay pot, in which the components were fused. It was found that the effect was caused by the presence of iron and other impurities in the clay. Recourse was had to the X-rays, and it was found that on examining the pots before they were fired, those containing prejudicial foreign matter could readily be sorted out (Fig. 81). In this way much expense can be saved. The "melt" of optical glass can also be examined for inclusions before working.

X-Rays and Electrical Engineering.—One of the chief causes of break-down of electrical machinery is defective insulation, and the makers of electrical insulators—ebonite, built-up mica, fibre, pressboard, fuller-board, etc.—find the method of service for detecting the presence of metallic particles, either from the steel rollers used in the preparation of the material, or more commonly in the case of those insulating materials built up of paper, from the paper itself. Where high dielectric strength is essential, the X-rays can be used to test for the complete absence of metal particles or undesirable salts. If female labour is employed the inclusion of pins and hairpins in the finished material is not unknown.

Another common cause of break-down is the presence of air pockets, which also can be detected. The path of a puncture through insulation can sometimes be traced by the rays.

X-ray photographs are useful for displaying the arrangement of concealed wiring, for example, when embedded in the interior of insulating panels or in radio apparatus. Fig. 82 shows the construction of a Furstenau selenium cell which it was not desirable to open up, and Fig. 83 the heating element in a coffee pot. In much the same way, during the war, the X-rays were useful in scrutinising the wiring within the leather of aeroplane pilots' electrically heated clothing (Fig. 84).

The testing of the exact centering of an insulated article with respect to the insulation can also be carried out, for example, the insulated plates used in switch gear. Fig. 85 shows some high-tension lead used in the war for the wireless apparatus of a seaplane. Owing to defective centering of the wire in its rubber insulation, sparking through occurred, resulting in a fire and partial destruction of the seaplane. The accident led to long lengths of the wire being inspected by the X-rays.

A similar field of work which the X-rays have found, is the examination of the interior of moulded articles, for example, the distributors of magnetos. During construction the insulation is moulded round the metal work, and subsequently machined. If, during the machining, blowholes are met with, the entire distributor formerly had to be rejected, though the difficulty can now be met in other ways.

Slate panels employed in switchboards and terminal

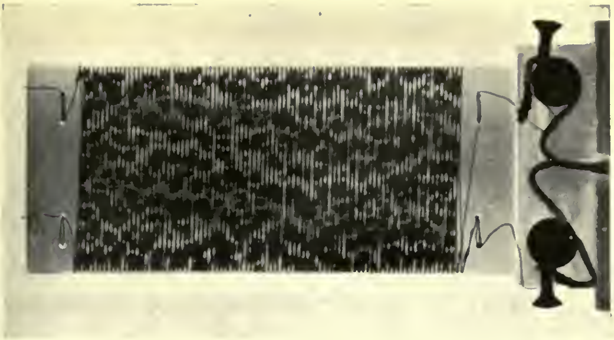

FIG. 82 —Radiograph of Fürstenau selenium cell, taken through case, showing selenium deposited on grid and making electrical contact between two adjacently wound wires (Knox).

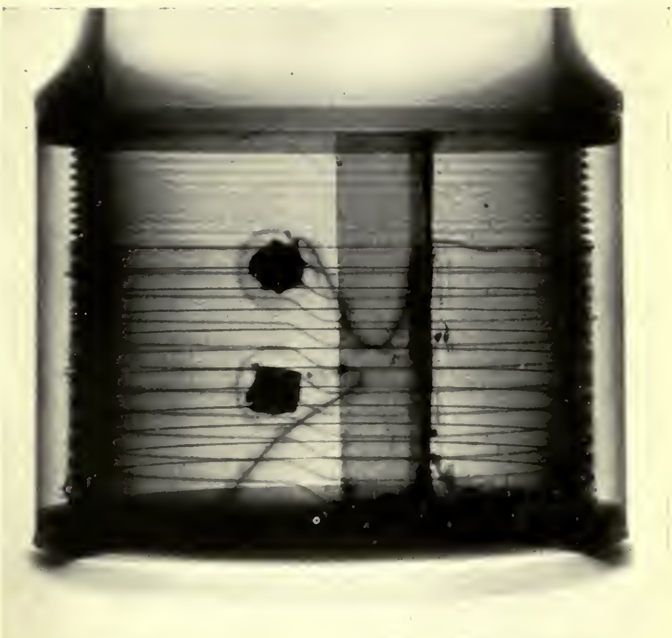

FIG. 83.—Radiograph of electrically heated porcelain coffee pot, showing concealed heating element.

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FIG. 84.—Radiograph of aeroplane pilot's electrically heated leather jacket, showing break in heating element. These jackets are indispensable to pilots flying at very high altitudes.

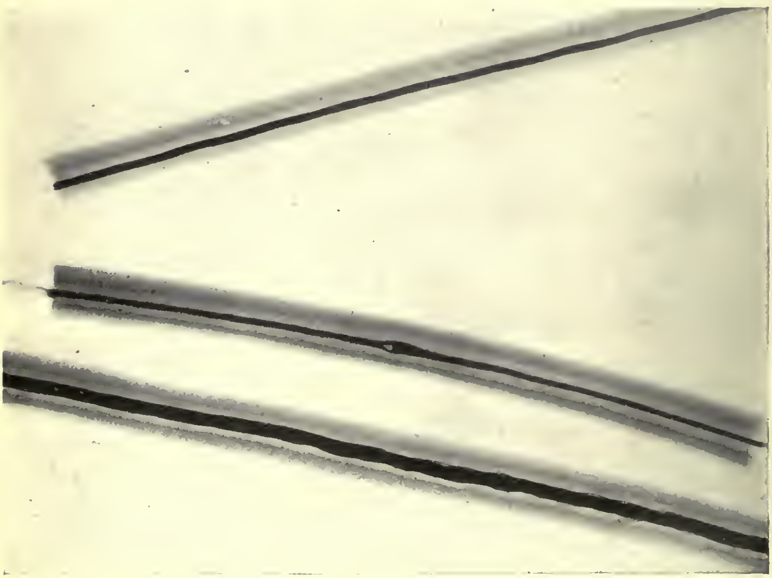


FIG. 85.—Radiograph of high-tension rubber-insulated cable, showing unsymmetrical and kinked wire (Knox and Kaye).

[*See page* 100.

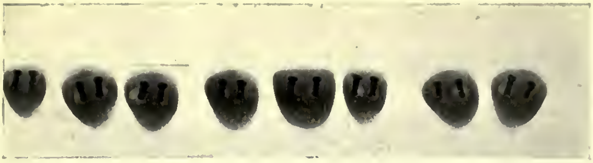


FIG. 86.—Radiograph of artificial teeth, showing gas bubbles present as a defect (Owen).

FIG. 87.—Radiograph of hand of mummy, showing scarab ring on hand of a Princess of the 2nd Dynasty, *c.* 4500 B.C. (Knox).

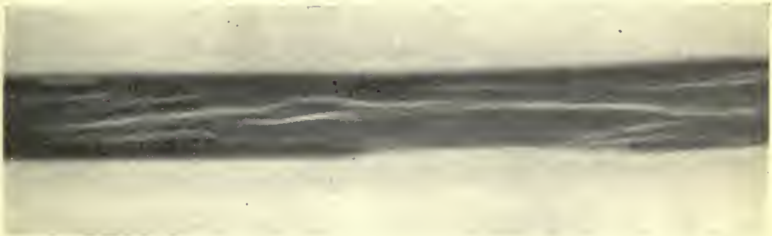


FIG. 88.—Radiograph of artificial graphite, showing internal cracks.

[*See page* 101.

FIG. 89.—Radiograph of a block of carbon from the electrode of an electric arc furnace, showing mineral impurities (Pullin).

FIG. 90.—Radiographs of shells (Rodman).

[*To face page* 101.

blocks sometimes break-down due to the presence of hidden metallic veins. These can readily be detected radiographically. The rays can also be used for scrutinising the workmanship in the condenser type of bush and terminal which are being increasingly used for extra high voltage work.

Miscellaneous Applications.—Among the miscellaneous uses of the X-rays we may mention the examination of oysters for pearls; the differentiation of lead-glass jewels from the more transparent genuine gems; the scrutiny of artificial teeth (Fig. 86); the detection of drugs and other contraband by the customs officials; the workmanship in the construction of hair brushes and tooth brushes; the sorting of fresh from stale eggs; the excellence of the mixing of the ingredients of powders; the direction of heavy elements in minerals, of weevils in grain, of mineral adulterants in certain powdered drugs (e.g. asafœtida), of moths in cigar tobacco, and the measurement of the internal diameters of metal or glass tubes.

The X-rays have also been employed as a preliminary means of disclosing or confirming the contents of mummies. Fig. 87 shows an example. The help of the rays has also been sought by the manufacturer of graphite brushes (Fig. 88) and carbon electrodes (Fig. 89) to reveal hidden cracks and flaws and mineral matter. Also by the manufacturer of chocolates, to detect small particles of metal or grit. Such articles can be carried on a slowly moving belt past the screen.

The X-ray examination of leather is a routine process in some boot factories. During the war the Bureau of Standards, Washington, used the X-rays in a study of the clinching of the nails used in repairing the soles of boots for the American Army. The method has been taken a little further by enterprising shoe stores which have installed screen outfits, so that the potential customer can see his " footigraph " and satisfy himself visually whether or not the shoe he is trying on is a good fit. The apparatus is of especial value with children in preventing malformation of the feet.

The application of the cinematograph principle to X-ray photography offers wide possibilities.

We can only refer to the more academic applications of the X-rays by the conchologist to examine the interior of shells (Fig. 90) and fossils, without in any way spoiling a rare specimen. These have valuable educational possibilities and, incidentally, are often of rare beauty.

The use of the X-rays for revealing the interior of plant life is comparatively recent. Considerable differences exist in the mineral content and density, and hence the transparency of the different parts of a plant —root, stem, leaf, flower, fruit, seed, etc.—and thus it happens that even the most delicate structures of plants can be laid bare without tearing the plant to pieces in order to study it (Fig. 91). Microscopic detail, is, of course, not revealed. Long-waved X-rays are required for such work.

X-Rays and Old Masters.—The first artistic oil painting of which there is any record was executed in the year 1399, by Hubert van Eyck, a Dutchman. From then up to the early Italian and Flemish schools, painters had possibly only eight or nine pigments, mostly mineral in origin. To-day there are over 200 in use, most of them vegetable or coal-tar in origin.

As is well known, the imitating of valuable pictures has always enjoyed a great vogue, and there are thousands of spurious paintings in existence—copies of both late and modern masters—which have been passed as genuine and sold for outstanding amounts. For example, so far as is known, Rembrandt painted some 700 pictures, yet Maximilian Toch estimates there are fully 4000 to 5000 in existence, all of which are regarded as genuine and have commanded great prices. Again, it would have been absolutely impossible for any human being to have painted all the Rubens that there are in existence. The remark is probably true of every great painter.

There are various scientific methods of determining the originality and age of paintings. Photomicrography is of great help; for example, in the case of a panel of a picture 300 years old, the protoplasm in the cells of the wood has entirely dried out, a feature unlike that of a modern panel. Chemical analysis of tiny detached fragments often throws light on the subject; for instance, zinc white (zinc oxide) was not known 300 years ago, and the Flemish painters used flake white (white lead). Again, bitumen, at first transparent, gradually becomes opaque and insoluble with the passage of time.

But not only pictures, but all works of art, are imitated in the same way. Furniture, pottery, bronzes, old weapons and brass work are so completely simulated that experts are frequently baffled. Sheraton furniture is a familiar example. We know that Sheraton had a little shop, and did most of his work himself, with only occasional help from a few expert artisans. The amount of Sheraton furniture in existence would, however, indicate that Sheraton had a factory of several acres employing a thousand men who were lifelong supporters of mass production.

It would appear that the X-rays may usefully be called in, in certain cases, as a supplementary method of scrutiny for the expert. A start has been made with pictures, as we shall proceed to show.

In any picture we have to consider three media: (1) the surface which is painted on—usually canvas or wood, though paper, porcelain or other materials may be used; (2) the priming or sizing—nowadays almost always white lead, though formerly carbonate of lime and glue were employed; (3) the actual pigments.

Both wood and canvas are very transparent to the X-rays, though different kinds of canvas vary a good deal. The white lead primer is much more opaque than carbonate of lime, and the former, moreover, penetrates much farther into the interstices of the canvas. This in itself is sufficient to show a marked difference under the X-rays between modern and older pictures.

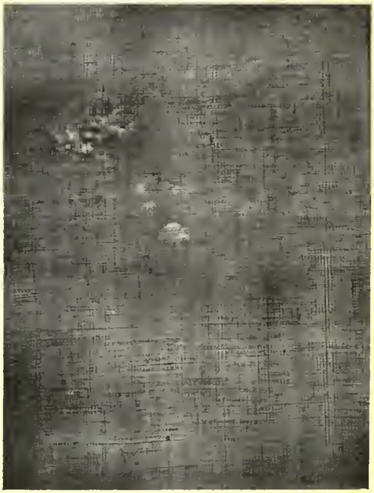
As to pigments, they vary greatly in X-ray opacity, from the opaque salts of lead, zinc, and mercury to the transparent aniline derivatives and bitumen. Both modern and ancient whites are usually opaque, most of the blacks (new or old) are transparent, and modern reds are more transparent than the old reds. In general, as already remarked, most of the earliest pigments are mineral in origin and opaque, while most of the modern pigments are coal-tar in origin and transparent.

In a modern picture the sizing is very commonly more opaque than the pigments and X-ray examination is, for that reason, usually inconclusive. Fig. 92 shows

FIG. 91.—Radiograph of carnations, ferns, etc. (Knox).

[*See page* 102.

A



B

FIG. 92.—(A) Ordinary photograph of a modern painting. (B) Radiograph showing nothing but canvas and a trace of the whites (Cnéron).

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FIG. 93.—(A) Ordinary photograph of Engelbrechtsen's "Crucifixion." (B) Radiograph showing priest in right foreground. (C) Ordinary photograph taken during restoration. (D) Picture after restoration (Heilbron).

[*To face page* 105.

a radiograph of a modern painting in which little can be seen but the canvas and a trace of the white pigment. But, fortunately, in the pictures of the old masters, the reverse conditions hold, and thus it is that with a little experience, and if the relative opacity of the various pigments is such as to yield good contrast, the X-rays can be employed most usefully as a means of identifying a modern fake, or detecting alterations to an old picture. It is a practical certainty that, however skilfully the process has been carried out, the several materials used—whether canvas, priming, or pigment—will differ from those in the original painting and will, in consequence, be differentiated in the radiograph.

Notable work on this subject has been carried out by Dr. Heilbron, of Amsterdam, and, more recently, by Dr. Chéron, of Paris. Among the sixteenth century paintings examined by the former, was the "Crucifixion," by Cornelis Engelbrechtsen, containing in the right foreground the portrait of a woman which it was suspected was that of a former "donatrice," who (after a fashion not unknown in those days) had thus sought to perpetuate her association with the picture. A radiograph of the painting showed many "restorations," especially on the right half, and beneath the portrait of the donatrice was revealed the picture of a priest in surplice and stole, the head being smaller than that of the over-painted lady. The evidence was so clear that the picture was sent to be restored at the Rijks Museum in Amsterdam, the result being to bring to light once more the priest who had been hidden for 400 years (Fig. 93).

Among the other paintings examined by Heilbron was a panel of the "Madonna," by Geertgen van St. Jans (*c.* 1500), which had always excited comment because of the apparently stiff and unnatural position of the arms. The radiograph showed that the presence of the Child in the arms of the Madonna fully explained their attitude. St. Jans is known to have painted his children disproportionately small, and the presumption is that this defect was the cause of some former owner having the Child painted out (Fig. 94).

Other examples of Heilbron's work include a panel by De Meester van Allmaar, where the portrait of a lady (again supposed to be the donatrice) is found to be painted over the original figures (Fig. 95). There is some chance that the panel will be restored to its original state. A radiograph of a panel by van Dyk, representing a waterfall, a knight with a horse, dogs, etc., shows that the artist originally painted a much bigger waterfall, the current of water appearing to pass through the animals. We are led to infer that the painting is an original and not a copy, for only in the case of the original can we trace such alterations in the ideas of the artist.

Dr. Chéron X-rayed a Flemish panel attributed to van Ostade and showing a party of country dancers and revellers. The radiograph revealed only a farmyard scene containing peacocks, ducks, and chickens. The supposed van Ostade is almost certainly modern, since practically all its colours are transparent to the rays. The farmyard picture is apparently old, since the sizing is not opaque (Fig. 96).

Another picture of the French school of the fifteenth century which was examined by Chéron was that of the

A B

FIG. 94.—(A) Ordinary photograph of St. Jans "Madonna," showing stiff position of the arms. (B) Radiograph revealing the Child in the Madonna's arms (Heilbron).

A B

FIG. 95.—(A) Ordinary photograph, and (B) radiograph of a panel by De Meester van Allmaar, showing hidden faces, etc. (Heilbron).

[*To face page* 106.

B

FIG. 96.—(A) Ordinary photograph of a reputed van Ostade. (B) Radiograph showing underlying farmyard picture (Chéron).

[*See page* 106.

Royal Infant at Prayer hanging in the Louvre. The black background was found to mask a badly deteriorated original background—confirming documentary evidence to that effect in the possession of the custodians.

We may here recall the recent pronouncement of Prof. Marten, director of the Art Museum at the Hague, that several of the best-known Rembrandt pictures are spurious, in particular "The Mill," the "Burgomaster Pancras and His Wife" in Buckingham Palace, the "Christ at Emmaus" in the Louvre, and the "Good Samaritan" in the Wallace Collection. To this Mr. Francis H. Clarke was able to reply that, on the contrary, X-ray examination had revealed the painter's signature on the canvas beneath the pigment in the case of these pictures, and that there was no doubt that this was Rembrandt's secret method of discriminating between his own work and that of the copyists in his famous school at Amsterdam.

The X-rays may find another field in the examination of palimpsests and ancient manuscripts which, hitherto regarded as carrying only their face value, may bear, under the trivial inscriptions of mediæval times, older matter of priceless worth. Again, it is well known that before millboard came into general use for book covers (about the middle of the sixteenth century), binders were accustomed to make them up from such loose pages as came to hand. Many discoveries of rare and valuable MSS. have been made when the bindings of old volumes have happened to fall to pieces. The X-rays may have a useful field here. It may even be that the Shakespeare folios will some day be discovered in this way.

As regards antique furniture and the like, it is not improbable that X-ray examination of constructional or other detail, which cannot otherwise be viewed except by destroying the article, would suffice to reveal in a fake, craftmanship out of tune with the reputed period.

Future Developments of Industrial Radiology.—Our ideal should be to make the taking of an X-ray photograph as easy and noiseless as that of light. The present limitations of radiometallography are largely those prescribed by equipment and technique. Considerable improvements will have to come if the subject is to extend its scope and become an attractive commercial proposition in heavy engineering. The routine photographic examination of large castings, even if thin, is often costly and inconvenient. Much can be saved by also utilising ordinary methods of inspection and utilising the X-rays as a "court of appeal."

The extension of radiometallography to thicknesses of about 6 inches of steel is desirable, but means will have to be found so that exposures are not intolerably long. There appear to be two means to this end: (*a*) by using much heavier X-ray outputs, at much higher voltages, or (*b*) by using much more sensitive screens, plates, or other detectors.

We have already considered the probable developments of the high-potential generator, and, as we should anticipate, all experience agrees in demanding higher and higher voltages for work with metals. The ordinary Coolidge tube will, however, take no more than about 150,000 volts, preferably less. This can be increased to 200,000 by lengthening the arms of the tube or completely immersing it in oil. The life of glass X-ray tubes excited by voltages in the region of 200,000 and more is, however, short, and the X-ray bulb is at present the chief obstacle to work at higher voltages.

If there is a demand, the electrical engineer will doubtless be to the fore with transformers capable of supplying half a million or more volts. Such transformers have already been made for other purposes, but their bulk, weight, and cost are formidable. For example, a single phase transformer giving a peak voltage of one million occupies a floor space of 13 feet × 8 feet, is 15 feet high, has terminals 28 feet high, weighs 20 tons, costs about £10,000 and requires to be specially housed. With such voltages both transformer and tube will doubtless be contained in a common oil tank, thus reducing the dangers arising from such large voltages and the considerable losses by brush discharge.

One point may be touched upon, and that is that very high voltage transformers can only be made at present of a power needlessly large for X-ray purposes.

It should, however, be noted that increased voltages such as are likely within the next few years will not of themselves greatly enlarge the scope of radiometallography. For considering the hardest rays from a bulb we know that—

$$\text{the wave length} \propto 1/\text{voltage.}$$

$$\text{Now the absorption coefficient} \propto (\text{wave length})^3$$

$$\propto 1/(\text{voltage})^3$$

$$\text{i.e. the penetrable thickness} \propto (\text{voltage})^3.$$

In other words if we wish to double the present maximum thickness penetrable (which we may take as 3 inches in the case of steel, for an exciting voltage of 200,000), we shall have to increase the voltage eight fold, i.e. to over 1,500,000 volts. Clearly not a promising outlook when considered alone. We may, however, recollect that the output of X-rays would at the same time be increased about 64 fold, so that this factor would tend to lessen the burden of increased voltage.

Another point that may be made is the decreasing contrast that obtains in a photographic plate with increasing voltage, though fortunately intensifying screens function more efficiently with hard rays than soft, at any rate within the present limits of experiment.

If we resort to heavier discharges, more elaborate cooling arrangements will be required and probably glass tubes will not stand up to the work. We may have to turn to metal tubes radically different in design, capable, for example, of absorbing 50 h.p. or more. Furthermore, we shall have to improve the deplorable efficiency of the whole outfit. How low the efficiency is may be gathered from the following. We may take it that the efficiency of the high-tension generator is of the order of 50 per cent., that of the X-ray bulb $\frac{1}{1000}$. We may assume that half the rays emitted by the bulb are utilised, that half these useful rays are arrested by the object, and that 1 per cent. of the remainder is recorded by the photographic plate or screen (rather more, say 5 per cent., if an intensifying screen is used). Thus the over-all efficiency of an X-ray equipment is of the order of 1 in 800,000.

It may be mentioned that some of the γ-rays of radium are far more penetrating than the hardest X-rays we can produce at present (being equivalent to X-rays excited by about 2,000,000 volts), but, unfortunately, the intensity is so weak (not more than a few per cent.

of that from a good bulb) that exposures for radiometallographic purposes are intolerably protracted.

As regards fluorescent screens and photographic plates, great improvements are called for. The questions of luminosity, granularity, and contrast call for study in connection with screens. There is little to choose between screens of barium platinocyanide and the now more common cadmium tungstate. As already remarked no screen at present available is sensitive enough for thicknesses exceeding $\frac{1}{2}$ inch of mild steel and only then with difficulty. Photography must be resorted to in such cases, and the time taken over the process may then become prohibitive, at any rate for routine "mass inspection."

A photographic plate only registers about 1 per cent. of the X-rays passing through it. Progress has mainly consisted in thickening the emulsion, loading it either with more silver or with heavier metals, and reducing the size of grain. Exposures may be shortened either by backing up the emulsion with a sheet of a heavy metal, such as lead, or more effectively (5 or 10 times) by the use of an intensifying screen, containing a very fine-grained fluorescing salt, such as calcium tungstate. All X-ray plates are much more sensitive to visible rays than to X-rays, but such intensifying screens, which are more efficacious with "hard" rays than "soft," are apt to impair the detail in certain classes of work, owing to "grain." It is important to have the closest contact between the screen and the emulsion. This is secured in the "Impex" plate in which the fluorescing salt is contained in a super-imposed gelatine film which is dissolved off before the plate is developed. Such plates reduce the exposure 20 to 30 times with hard rays, but the figure is much lower for long-waved rays. There are, moreover, added difficulties of development.

A real advance in X-ray photography has proved to be the duplitized film, i.e. a film coated with emulsion on both sides of the celluloid. A "pile" of several of these sandwiched with thin intensifying screens, gives a very sensitive detector. A film has the further advantage over a plate in that it can often be inserted and suitably mounted on a mandrel within an article to be radiographed from without, for example a howitzer tube or a tyre.

The ionisation method of detecting the X-rays offers great promise, for it can be made more sensitive than any photographic method at present available. An explorer built on these lines and "relayed" by one or more radio-valves of suitable design would have many advantages.

To sum up, the subject of industrial radiology is young and, although progress has been rapid, we must in all fairness be careful not to claim too much for it. From such experience as we have had it does appear, however, that the method is settling down to be a valuable laboratory tool, supplementing those which are already available for testing materials.

Finally, the mere existence of the method is not without its moral effect on the personnel, as regards standard of workmanship, and the disguising or faking of mistakes. A workman is not unnaturally aware that in certain types of construction it is possible for defects to be hidden from view. There is the tendency, which is known to exist in some natures, to try to conceal a mistake due to a slip, especially when from a lack of knowledge of design, the importance of the mistake might be underrated. Nowhere are the consequences likely to be more disastrous than in the case of aircraft; and despite the fact that British aeroplanes were unapproached in quality and output during the war, the existence of large notices in the various aircraft factories bearing the reminder that "A concealed mistake may cost a brave man his life" showed that the lesson had been brought home to the authorities.

APPENDIX NO. I.

REPORTS OF THE X-RAY AND RADIUM PROTECTION COMMITTEE.

Chairman:

Sir Humphry Rolleston, K.C.B.

Members:

Sir Archibald Reid, K.B.E., C.M.G. (St. Thomas's Hospital).
Dr. Robert Knox (King's College Hospital).
Dr. G. Harrison Orton (St. Mary's Hospital).
Dr. S. Gilbert Scott (London Hospital).
Dr. J. C. Mottram (Pathologist to the Radium Institute).
Dr. G. W. C. Kaye, O.B.E., M.A. (National Physical Laboratory).
Mr. Cuthbert Andrews.

Honorary Secretaries:

Dr. Stanley Melville (St. George's Hospital).
Prof. S. Russ (Middlesex Hospital).

MEMORANDUM NO. I.

Introduction.

The danger of over-exposure to X-rays and radium can be avoided by the provision of efficient protection and suitable working conditions.

The known effects on the operator to be guarded against are :—

1. Visible injuries to the superficial tissues, which may result in permanent damage.

2. Derangements of internal organs and changes in the blood. These are especially important, as their earlier manifestation is often unrecognised.

General Recommendations.

It is the duty of those in charge of X-ray and radium departments to ensure efficient protection and suitable working conditions for the personnel.

The following precautions are recommended :—

1. Not more than seven working hours a day.

2. Sundays and two half-days off duty each week, to be spent as much as possible out of doors.

3. An annual holiday of one month or two separate fortnights.

Sisters and nurses, employed as whole-time workers in X-ray and radium departments, should not be called upon for any other hospital service.

Protective Measures.

It cannot be insisted upon too strongly that a primary precaution in all X-ray work is to surround the X-ray bulb itself as completely as possible with adequate protective material, except for an aperture as small as possible for the work in hand.

The protective measures recommended are dealt with under the following sections :—

I. X-rays for diagnostic purposes.
II. X-rays for superficial therapy.
III. X-rays for deep therapy.
IV. X-rays for industrial and research purposes.
V. Electrical precautions in X-ray Departments.
VI. Ventilation of X-ray Departments.
VII. Radium therapy.

It must be clearly understood that the protective measures recommended for these various purposes are not necessarily interchangeable; for instance, to use for deep therapy the measures intended for superficial therapy would probably subject the worker to serious injury.

I. X-Rays for Diagnostic Purposes.

1. *Screen Examinations.*

(*a*) The X-ray bulb to be enclosed as completely as possible with protective material equivalent to not less than 2 mm. of lead. The material of the diaphragm to be equivalent to not less than 2 mm. of lead.

(*b*) The fluorescent screen to be fitted with lead glass equivalent to not less than 1 mm. of lead, and to be large enough to cover the area irradiated when the diaphragm is opened to its widest. (Practical difficulties militate at present against the recommendation of a greater degree of protection.)

(*c*) A travelling protective screen, of material equivalent to not less than 2 mm. of lead, should be employed between the operator and the X-ray box.

(*d*) Protective gloves to be of lead rubber (or the like) equivalent to not less than ½ mm. of lead, and to be lined with leather or other suitable material. (As practical difficulties militate at present against the recommendation of a greater degree of protection, all manipulations during screen examination should be reduced to a minimum.)

(*e*) A minimum output of radiation should be used with the bulb as far from the screen as is consistent with the efficiency of the work in hand. Screen work to be as expeditious as possible.

2. *Radiographic Examinations* ("*overhead*" *equipment*).

(*a*) The X-ray bulb to be enclosed as completely as possible with protective material equivalent to not less than 2 mm. of lead.

(*b*) The operator to stand behind a protective screen of material equivalent to not less than 2 mm. of lead.

II. X-Rays for Superficial Therapy.

It is difficult to define the line of demarcation between superficial and deep therapy.

For this reason it is recommended that, in the re-organisation of existing, or the equipment of new, X-ray Departments, small cubicles should not be adopted, but that the precautionary measures suggested for deep therapy should be followed.

The definition of superficial therapy is considered to cover sets of apparatus giving a maximum of 100,000 volts (15 cm. spark-gap between points; 5 cm. spark-gap between spheres of diameter 5 cm.).

Cubicle System.

Where the cubicle system is already in existence it is recommended that:—

1. The cubicle should be well lighted and ventilated, preferably provided with an exhaust electric fan in an outside wall or ventilation shaft. The controls of the X-ray apparatus to be outside the cubicle.

2. The walls of the cubicle to be of material equivalent to not less than 2 mm. of lead. Windows to be of lead glass of equivalent thickness.

3. The X-ray bulb to be enclosed as completely as possible with protective material equivalent to not less than 2 mm. of lead.

III. X-Rays for Deep Therapy.

This section refers to sets of apparatus giving voltages above 100,000.

1. Small cubicles are not recommended.

2. A large, lofty, well-ventilated and lighted room to be provided.

3. The X-ray bulb to be enclosed as completely as possible with protective material equivalent to not less than 3 mm. of lead.

4. A separate enclosure to be provided for the operator, situated as far as possible from the X-ray bulb. All controls to be within this enclosure, the walls and windows of which to be of material equivalent to not less than 3 mm. of lead.

IV. X-Rays for Industrial and Research Purposes.

The preceding recommendations for voltages above and below 100,000 will probably apply to the majority of conditions under which X-rays are used for industrial and research purposes.

V. Electrical Precautions in X-Ray Departments.

The following recommendations are made :—

1. Wooden, cork, or rubber floors should be provided; existing concrete floors should be covered with one of the above materials.

2. Stout metal tubes or rods should, wherever possible, be used instead of wires for conductors. Thickly insulated wire is preferable to bare wire. Slack or looped wires are to be avoided.

3. All metal parts of the apparatus and room to be efficiently earthed.

4. All main and supply switches should be very distinctly indicated. Wherever possible double-pole switches should be used in preference to single-pole. Fuses no heavier than necessary for the purpose in hand should be used. Unemployed leads to the high-tension generator should not be permitted.

VI. Ventilation of X-Ray Departments.

1. It is strongly recommended that the X-ray Department should not be below the ground level.

2. The importance of adequate ventilation in both operating and dark rooms is supreme. Artificial ventilation is recommended in most cases. With very

high potentials coronal discharges are difficult to avoid, and these produce ozone and nitrous fumes, both of which are prejudicial to the operator. Dark rooms should be capable of being readily opened up to sunshine and fresh air when not in use. The walls and ceilings of dark rooms are best painted some more cheerful hue than black.

VII. Radium Therapy.

The following protective measures are recommended for the handling of quantities of radium up to one gram :—

1. In order to avoid injury to the fingers the radium, whether in the form of applicators of radium salt, or in the form of emanation tubes, should always be manipulated with forceps or similar instruments, and it should be carried from place to place in long-handled boxes lined on all sides with 1 cm. of lead.

2. In order to avoid the penetrating rays of radium all manipulations should be carried out as rapidly as possible, and the operator should not remain in the vicinity of radium for longer than is necessary.

The radium when not in use should be stored in an enclosure, the wall thickness of which should be equivalent to not less than 8 cm. of lead.

3. The handling of emanation should, as far as possible, be carried out during its relatively inactive state. In manipulations where emanation is likely to come into direct contact with the fingers thin rubber gloves should be worn. The escape of emanation should be very carefully guarded against, and the room in which it is prepared should be provided with an exhaust electric fan.

Existing Facilities for Ensuring Safety of Operators.

The governing bodies of many institutions where radiological work is carried on may wish to have further guarantees of the general safety of the conditions under which their personnel work.

1. Although the Committee believe that an adequate degree of safety would result if the recommendations now put forward were acted upon, they would point out that this is entirely dependent upon the loyal co-operation of the personnel in following the precautionary measures outlined for their benefit.

2. The Committee would also point out that the National Physical Laboratory, Teddington, is prepared to carry out exact measurements upon X-ray protective materials and to arrange for periodic inspection of existing installations on the lines of the present recommendations.

3. Further, in view of the varying susceptibilities of workers to radiation, the Committee recommend that wherever possible periodic tests, e.g. every three months, be made upon the blood of the personnel, so that any changes which occur may be recognised at an early stage. In the present state of our knowledge it is difficult to decide when small variations from the normal blood-count become significant.

July, 1921.

MEMORANDUM NO. 2.

In view of the widespread uncertainty and anxiety as to the efficacy of the various devices and materials employed for the purposes of protection against X-rays, the X-ray and Radium Protection Committee strongly advises that the Heads of X-ray Departments of hospitals and other institutions should safeguard themselves and their staff on this score by recommending to the hospital authorities the adoption of the following precautions:—

1. The various protective appliances should be inspected and reported on by the National Physical Laboratory (N.P.L.), Teddington. In the event of an

adverse report, early steps should be taken to carry out the recommendations of the Laboratory. The Laboratory is prepared, wherever possible or expedient, to engrave (or otherwise suitably mark) the N.P.L. monogram and year of test on such appliances as provide the full measure of protection laid down in the Preliminary Report (Memo. No. 1, July, 1921) of the Protection Committee. It should be pointed out that, in the case of materials which may deteriorate, e.g. lead rubber, such inspection should be periodic, say every twelve months.

2. Within the Committee's recent experience, the working conditions of X-ray Departments, e.g. lay-out of installations, degree of scattered radiation, ventilation, high-tension insulation, etc., are often unsatisfactory. It is recommended that such conditions be inspected by the N.P.L., and that early steps be taken to give effect to such alterations as may arise out of their report. It is advised that, in the planning of new radiological departments, advantage be taken of the facilities available at the N.P.L.

3. Manufacturers of X-ray apparatus are also invited to assist in reassuring the public by actively co-operating with the Committee in its recommendations. It is suggested that protective materials or equipment should not be sold or incorporated into an installation unless accompanied by a specification based upon an N.P.L. certificate or report stating, in terms of the equivalent thickness of lead, the degree of protection afforded.

In the interests of both the trade and profession, it is urged that manufacturers should put themselves into a position to be able to guarantee that their apparatus complies completely with the recommendations of the Committee.

4. The Committee recommends that the various instruments dealing with the measurement of current (ammeters and milliammeters) and voltage, be standardised by the N.P.L. With reference to the measurement

of secondary voltage, the Committee recommends that every installation should be provided with adequate means for enabling this to be easily effected, e.g. by kilovoltmeter, sphere-gap voltmeter, or the like.

5. The Committee would further urge that Heads of X-ray Departments should insist upon complete N.P.L. inspection of imported materials and apparatus.

December, 1921.

APPENDIX NO. II.

X-RAY AND ELECTRO-MEDICAL NOMENCLATURE.

The following list of definitions includes those approved by the British Engineering Standards Association.

I. X-RAYS.

Absorption Coefficient.—The ratio of the distance-rate of change of intensity of a particular quality of X-rays at a point in a specified material to the intensity at that point.

Anode.—The positive (or the incoming current) electrode in a discharge tube.

Anticathode.—The target on which the cathode rays are focussed in an X-ray tube, and which forms the source of emission of the X-rays.

Auto-transformer.—A static transformer consisting of a primary winding (on an iron core), the winding having a number of tapping-off wires at various points for obtaining a gradation of voltages.

Brush Discharge (Corona).—An intermittent hissing discharge due to local ionisation of the air by voltages insufficient to produce a true spark discharge. The effect is emphasised in the regions of points, sharp corners, etc.

Cathode.—The negative (or the outgoing current) electrode in a discharge tube.

Cathode Rays.—A stream of negatively charged electrons emitted with high velocity from the cathode when an electric discharge is passed in an evacuated tube.

Cathode Dark Space (Crookes Dark Space).—A non-luminous region which envelops and follows the outline of the cathode in a discharge tube at moderately low pressures.

Characteristic X-Rays.—X-rays which are wholly characteristic of or peculiar to a particular element.

Condenser.—A device possessing electrical capacity which works in conjunction with an induction coil and mechanical interrupter. Normally constructed of tin-foil and paraffined paper.

Coolidge Tube.—A type of hot-cathode tube.

Crookes Tube (Vacuum Tube ; Discharge Tube ; Geissler Tube).—An electric discharge tube provided with electrodes and exhausted to a low gas pressure.

Dosemeter.—A device for indicating the length of exposure required in the use of X-rays for treatment purposes.

Electrometer (Electroscope). — An instrument for measuring potential differences by electrostatic means.

Electron.—The fundamental carrier of unit negative electric charge.

Fluorescent Screen.—A screen coated with a finely divided substance which fluoresces under the influence of X-rays.

Gas Tube.—An X-ray tube which depends for its action on the presence of the residual gas in the tube and in which the anticathode is usually connected electrically to the anode.

Hardness of X-Rays.—The quality (or wave length) of X-rays. The "harder" the rays, the shorter the wave length.

Hardness of X-Ray Tubes.—The degree of vacuum in an X-ray tube. The "harder" the tube, the higher the vacuum.

Hot-Cathode Tube.—A tube in which electrons are produced by an electrically heated cathode. The vacuum is so high that the residual gas plays no active part. The anticathode serves also as the anode.

Induction Coil (Ruhmkorf coil).—An open-core high-tension static transformer with independent interrupter (see Transformer).

Influence or Static Machine.—A high-potential generator which depends for its action on electrostatic means.

Intensifying Screen.—A thin screen coated with a finely divided substance which fluoresces under the influence of the X-rays and which is mounted in close contact with the emulsion of a photographic plate or film for the purpose of reinforcing the image.

Intensity of X-Rays.—The X-ray energy per unit area of a receiving surface normal to the rays.

Interrupter (or Break).—An apparatus for mechanically interrupting the primary current of an induction coil.

Ion.—A molecular or atomic aggregate consisting of one or more molecules or atoms which carries either a positive or negative electrical charge. At low pressures the negative ion exists as the electron.

Ionisation.—The temporary conductivity imparted to a gas by the presence of ions produced by X-rays, radium rays, etc.

Ionisation Chamber.—A piece of apparatus for measuring the degree of ionisation in a gas. It is commonly used as a means of determining the intensity of X-rays.

Negative Glow.—The luminous glow which envelops the cathode in a discharge tube at moderately low pressures.

Oscilloscope.—An accessory discharge tube in which the length of the negative glow affords an indication of the amount of current passing.

Peak Voltage.—The maximum voltage corresponding to the peak or crest of the potential wave in alternating or pulsating current.

Penetrometer (or Qualimeter).—An instrument for measuring the penetrating power or quality of X-rays.

Positive Rays.—A stream of positively charged atoms which travel mainly towards the cathode when an electric discharge is passed in an evacuated tube.

Quantum Limit.—The short wave-length boundary to a spectrum of general X-rays. Its position is accurately defined by Planck's quantum relation.

Radiograph (Radiogram, Skiagraph, Skiagram. In America, Roentgenogram).—An image produced on a photographic plate by the action of X-rays.

Radiography.—The taking of X-ray photographs.

Radiology.—The science and practice of X-rays, radium rays, etc.

Radiometallography.—The radiography of metals.

Rectifier.—A device either mechanical or of valve-tube type for suppressing or inverting the "non-useful" part of an alternating or pulsating current loop.

Scattered X-Rays.—Those rays which having encountered a material are deviated in direction but have the same quality as the original beam.

Spark-gap.—The maximum sparking distance between point, spherical or other electrodes, the degree of separation being a measure of the applied voltage.

Target.—See Anticathode.

Transformer.—A static closed-core high-tension transformer for converting alternating low-voltage current to high-voltage current of the same frequency.

X-Rays (Röntgen Rays).—Electromagnetic waves of very short wave length which are set up when electrons have their velocities altered.

X-Ray Crystallography.—The method of revealing the arrangement of the atoms in a crystal by "reflecting" monochromatic X-rays from the several faces of the crystal.

X-Ray Spectrum.—The spectrum produced by splitting up a heterogeneous beam of X-rays by means of "reflection" at a crystal face.

X-Ray Tube.—An electric discharge tube of appropriate design in which is maintained a vacuum suitable for the production of X-rays.

II. ELECTRO-MEDICAL.

Diathermy.—The therapeutic use of very high-frequency sustained and undamped oscillations of comparatively low voltage and relatively high amperage. The term is used in recognition of the marked heating effect produced throughout the tissues.

Faradism.—The therapeutic use of the interrupted current from an induction coil, usually from the secondary though occasionally from the primary. The object is the stimulation of muscles and nerves.

Galvanism.—The use of direct current for therapeutic purposes.

"*High-Frequency*" *Treatment* (D'Arsonvalism).—The therapeutic use of very high-frequency intermittent and isolated trains of heavily damped oscillations of very high voltage and relatively small amperage.

Medical Ionisation (*Ionic Medication*).—The therapeutic use of an electric current for the purpose of introducing the ions of soluble salts into the tissues.

Radiotherapy.—The treatment of disease by radiation.

Sinusoidal Current.—A single-phase alternating current of sine wave-form and of a periodicity adapted to the purpose in hand.

Static Breeze (static brush).—The therapeutic use of the brush discharge.

Static Induced Current.—The current which passes through a "patient" connecting the outer coatings of two Leyden jars, the inner coating of one of which is connected to the positive terminal of an influence machine, and the inner coating of the other to the negative terminal, the two inner coatings being periodically discharged.

Static Wave Current.—The current resulting from the sudden periodic discharging of a "patient" raised to a high potential by means of an influence machine.

APPENDIX III.

ATOMIC NUMBERS.

THE order of the elements in atomic number is that obtained by Moseley from his experiments on X-ray spectra. The order agrees with that of atomic weight except in the cases of argon, cobalt, and tellurium. Excepting the radioactive elements, there remain only three ordinal numbers—43, 61, 75—whose places are as yet unrepresented by elements.

Atomic No.	Atomic Weight (1922) O = 16.	Name.	Symbol.	First Isolated by	Date.
1	1·008	Hydrogen .	H	Cavendish	1766
2	4·00	Helium . .	He	Ramsay and Cleve *	1895
3	6·94	Lithium . .	Li	Arfvedson	1817
4	9·1	Beryllium .	Be §	Wöhler and Bussy	1828
5	10·9	Boron . .	B	Gay-Lussac & Thénard	1808
6	12·005	Carbon . .	C	—	P.
7	14·08	Nitrogen . .	N	Rutherford	1772
8	16·00	Oxygen . .	O	Priestley and Scheele	1774
9	19·0	Fluorine . .	F	Moissan	1886
10	20·2	Neon . .	Ne	Ramsay and Travers	1898
11	23·00	Sodium . .	Na	Davy	1807
12	24·32	Magnesium .	Mg	Liebig and Bussy	1830
13	27·1	Aluminium .	Al	Wöhler	1827
14	28·3	Silicon . .	Si	Berzelius	1823
15	31·04	Phosphorus .	P	Brand	1674
16	32·06	Sulphur . .	S	—	P.
17	35·46	Chlorine . .	Cl	Scheele	1774
18	39·9	Argon . .	A	Rayleigh and Ramsay	1894
19	39·10	Potassium .	K	Davy	1807
20	40·07	Calcium . .	Ca	Davy	1808
21	44·1	Scandium . .	Sc	Nilson and Cleve	1879
22	48·1	Titanium . .	Ti	Gregor	1789
23	51·0	Vanadium .	V	Berzelius	1831
24	52·0	Chromium .	Cr	Vauquelin	1797
25	54·93	Manganese .	Mn	Gahn	1774
26	55·84	Iron . . .	Fe	—	P.
27	58·97	Cobalt . .	Co	Brand	1735
28	58·68	Nickel . .	Ni	Cronstedt	1751
29	63·57	Copper . .	Cu	—	P.
30	65·37	Zinc . .	Zn	Ment. by B. Valentine	15 cent.
31	70·1	Gallium . .	Ga	L. de Boisbaudran	1875
32	72·5	Germanium .	Ge	Winkler	1886
33	74·96	Arsenic . .	As	Albertus Magnus	13 cent.
34	79·2	Selenium . .	Se	Berzelius	1817
35	79·92	Bromine . .	Br	Balard	1826
36	82·92	Krypton . .	Kr	Ramsay and Travers	1898
37	85·45	Rubidium .	Rb	Bunsen and Kirchhoff	1861
38	87·63	Strontium .	Sr	Davy	1808
39	89·33	Yttrium . .	Y	Wöhler	1828
40	90·6	Zirconium .	Zr	Berzelius	1825
41	93·1 ‡	Niobium . .	Nb	Hatchett	1801
42	96·0	Molybdenum .	Mo	Hjelm	1790

P., Prehistoric; * Lockyer (in sun), 1868; § Be or Ge; N ‡ Nb or Cb.

Atomic No.	Atomic Weight (1922). O = 16.	Name.	Symbol.	First Isolated by	Date.
44	101·7	Ruthenium . .	Ru	Claus	1845
45	102·9	Rhodium . .	Rh	Wollaston	1803
46	106·7	Palladium . .	Pd	Wollaston	1803
47	107·88	Silver . . .	Ag	—	P.
48	112·40	Cadmium . .	Cd	Stromeyer	1817
49	114·8	Indium . . .	In	Reich and Richter	1863
50	118·7	Tin . . .	Sn	—	P.
51	120·2	Antimony . .	Sb	Basil Valentine	15 cent.
52	127·5	Tellurium . .	Te	v. Richenstein	1782
53	126·92	Iodine . . .	I	Courtois	1811
54	130·2	Xenon . . .	Xe	Ramsay and Travers	1898
55	132·81	Caesium . . .	Cs	Bunsen and Kirchhoff	1861
56	137·37	Barium . . .	Ba	Davy	1808
57	139·0	Lanthanum . .	La	Mosander	1839
58	140·25	Cerium . . .	Ce	Mosander	1839
59	140·9	Praseodymium .	Pr	Auer von Welsbach	1885
60	144·3	Neodymium . .	Nd	Auer von Welsbach	1885
62	150·4	Samarium . .	Sa	L. de Boisbaudran	1879
63	152·0	Europium . .	Eu	Demarçay	1901
64	157·3	Gadolinium . .	Gd	Marignac	1886
65	159·2	Terbium . . .	Tb	Mosander	1843
66	162·5	Dysprosium . .	Dy	U. & D.	1907
67	163·5	Holmium . .	Ho	L. de Boisbaudran	1886
68	167·7	Erbium . . .	Er	Mosander	1843
69	168·5	Thulium . .	Tm	Cleve	1879
70	173·5	Ytterbium (Neo, Yb)	Yb	Marignac	1878
71	175·0	Lutecium . .	Lu	Urbain	1908
72	—	Celtium . . .	Ct	Urbain	1908
73	181·5	Tantalum . .	Ta	Eckeberg	1802
74	184·0	Tungsten . .	W	Bros. d'Elhujar	1783
76	190·9	Osmium . . .	Os	Smithson Tennant	1804
77	193·1	Iridium . . .	Ir	Smithson Tennant	1804
78	195·2	Platinum . .	Pt	—	16 cent.
79	197·2	Gold . . .	Au	—	P.
80	200·6	Mercury . . .	Hg	Md. by Theophrastus	300 B.C.
81	204·0	Thallium . .	Tl	Crookes	1861
82	207·20	Lead . . .	Pb	Mentd. by Pliny	P.
83	208·0	Bismuth . . .	Bi	Mtd. by B. Valentine	15 cent.
84	—	Polonium . .	Po	M. & Mme. Curie	1901
86	222	Radium Emanation (Niton) . .	Nt	M. & Mme. Curie	1900
88	226·0	Radium . . .	Ra	Curies and Bemont	1902
89	230 ?	Actinium . .	Ac	Debierne	1898
90	232·15	Thorium . .	Th	Berzelius	1828
91	—	Uranium Y . .	UY	Antonoff	1911
92	238·2	Uranium . .	U	Peligot	1841

P., Prehistoric; U. & D., Urbain & Demenitroux.

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