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ROENTGENOLOGY

G. W. C. KAYE

ROENTGENOLOGY

"Come, come, and sit you down: you shall not budge;
You go not till I set you up a glass
Where you may see the inmost part of you."

HAMLET, ACT III, SCENE 4

(*Frontispiece*)

Wilhelm Konrad Roentgen (1845–1923).

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ROENTGENOLOGY

ITS EARLY HISTORY, SOME BASIC PHYSICAL PRINCIPLES AND THE PROTECTIVE MEASURES

BY

G. W. C. KAYE

O.B.E., M.A., D.Sc., F.Inst.P.

WITH FORTY-NINE ILLUSTRATIONS

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DEDICATED TO
DR. A. HOWARD PIRIE

PREFACE

THE writer was accorded in 1927 the privilege of giving before the American Roentgen Ray Society's meeting in Montreal the Caldwell Lecture founded in memory of the late Dr. Eugene Caldwell whose name is inscribed on the long roll of roentgen-ray martyrs.

In the present volume the text of the lecture has been expanded somewhat, particularly in the earlier chapters which touch on certain historical and physical aspects of roentgen rays. The later chapters will, it is hoped, be found of service to hospital authorities who seek to improve the working conditions in their roentgen-ray departments.

The opportunity has been taken to include the International Recommendations for X-Ray and Radium Protection which were adopted at the Second International Congress of Radiology held in Stockholm in July, 1928.

The author is indebted to a number of friends, and in particular to Prof. E. N.

daC. Andrade, for kindly contributions to the collection of historical prints which are included in the volume.

G. W. C. Kaye.

September, 1928

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ROENTGENOLOGY

Chapter I

SOME EARLY PHILOSOPHERS

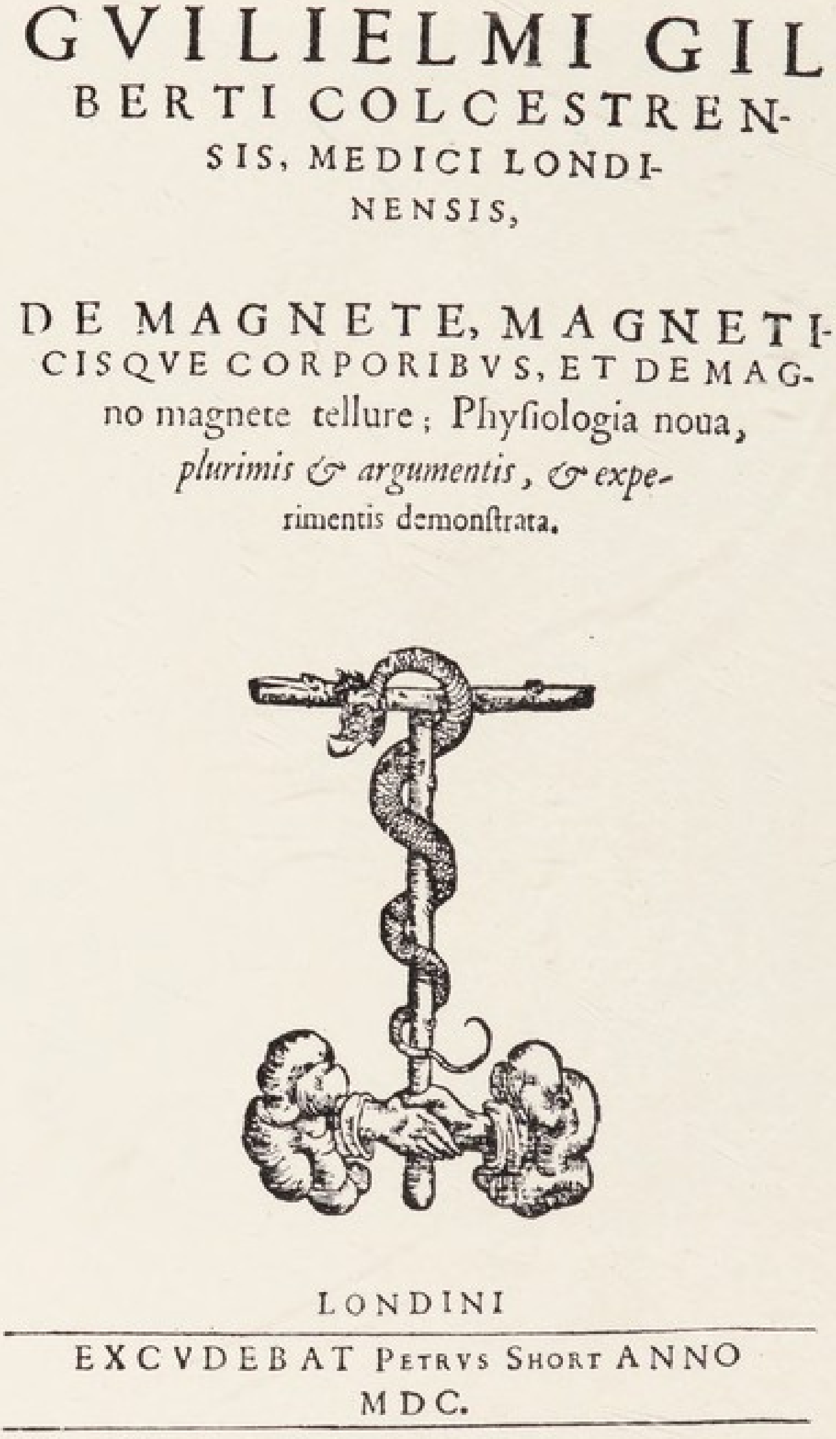
On November 8, 1895, Professor Wilhelm Konrad Roentgen of Würzburg, Bavaria, discovered the rays which now bear his name. The journals of 1896 bear ample testimony to the excitement which Roentgen's discovery caused at the time. A very natural scepticism was quickly followed by a great stimulus in science and medicine as the wonderful claims which Roentgen had made for his new rays were substantiated and extended in many quarters.

Roentgen's discovery was made by applying some thousands of volts to an exhausted discharge tube, and the X-rays, as Roentgen called them, were found to start from the region of impact of the high speed electrons or cathode rays on the walls of the tube.

The discovery of the roentgen rays was one of the momentous milestones in the history of the discharge tube. For a proper appreciation of its significance we should, I think, find it instructive and not uninteresting to spend a few minutes with some of those pioneer philosophers mainly of the 17th and 18th centuries who, toiling patiently, often in the face of the greatest difficulties, devised apparatus and developed theories which eventually led them to the electric discharge tube. It mattered little that few of the theories stood the test of time for, to quote Sir J. J. Thomson's aphorism in his Silvanus Thompson lecture before the Röntgen Society in London: "A scientific theory is a policy and not a creed." Moreover, theories, particularly if they are simple and easily visualized, serve to stimulate inquiry and systematize experiment. Furthermore, even when a theory is ultimately wrecked, there is not unusually a little salvage to incorporate into the next tentative working hypothesis.

It is interesting and curious that the very earliest records of electrical phenomena are in some way associated with medicine. For example, Pliny and other classical writers described the remedial uses of the electric torpedo fish. Again in the middle ages the confused notions of the alchemists were first clarified by Gilbert (1540–1603), physician to Queen Elizabeth and president

FIG. 1. Dr. William Gilbert (1540–1603).



GVILIELMI GILBERTI
COLCESTRENSIS, MEDICI
LONDINENSIS,

DE MAGNETE, MAGNETICISQVE CORPORIBVS, ET DE MAGNO
magnete tellure; Phyſiologia noua,
plurimis & argumentis, & experimentis demonſtrata.

LONDINI

EXCVDEBAT PETRVS SHORT ANNO
MDC.

FIG. 2. Reproduction of the title page of Gilbert's "De Magnete," 1600.

Fig. 3. Otto von Guericke (1602–1686).

of the Royal College of Physicians. It is acknowledged that Gilbert, to whom we owe the word electricity (though in the adjective), laid the foundations of the science of electricity in his monumental work "De Magnete"; it was a grievous loss when his apparatus and books were destroyed in the Great Fire of London in 1666.

FIG. 4. Von Guericke's experiment of using a water pump to draw water from a full cask in the attempt to create a vacuum.

We may pass to Torricelli, friend and pupil of Galileo, who in Italy in 1643 discovered the vacuum produced by a barometric column of mercury. This discovery laid the foundation of the many kinds of mercury pumps which were designed during the 18th and 19th centuries. The two outstanding examples of such pumps, the one due to Töpler (1862), the other to Sprengel (1865), were used to exhaust the tubes of all the early roentgen-ray workers.[35]

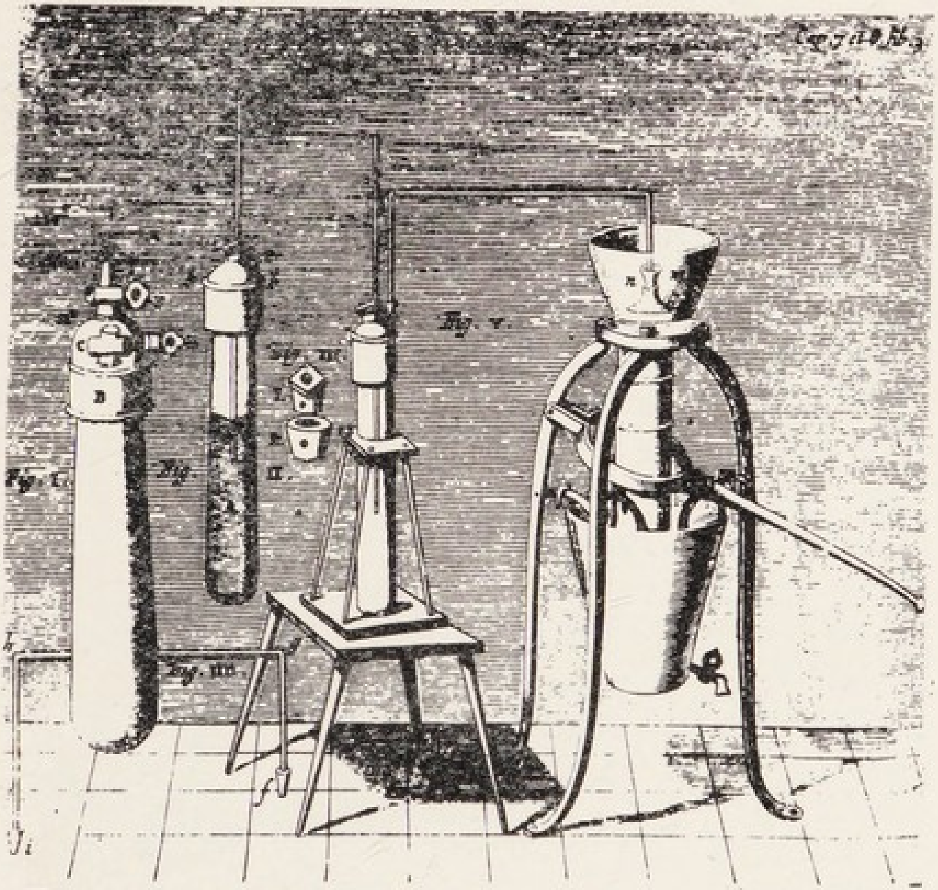


FIG. 5. Von Guericke's mechanical air pump, 1650.

A contemporary of Torricelli, but working quite independently, was Otto von Guericke, who in Germany about 1650 not only constructed the first mechanical air pump* but devised the first frictional electrical machine—two events of the first

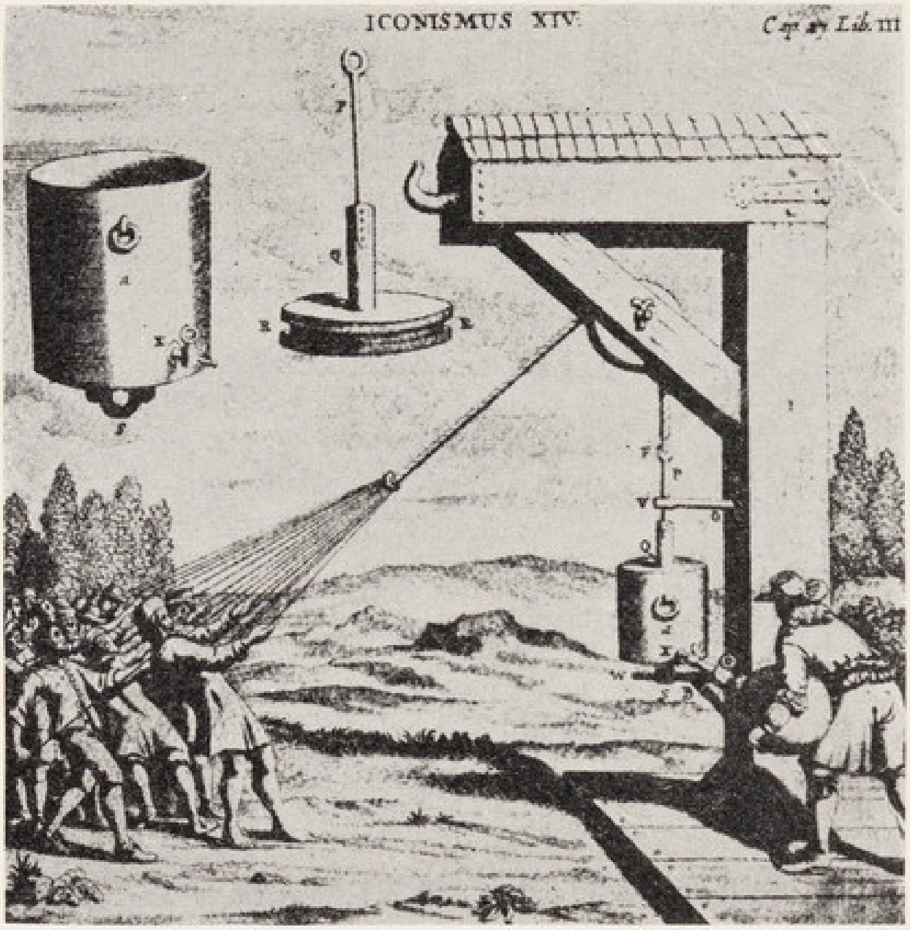


Fig. 6. Von Guericke's experiment to demonstrate the force upon the piston of a cylinder from which air is suddenly extracted.

importance in the genesis of the discharge tube. Von Guericke had a curious idea in his mind which he hoped to settle when he

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* Guericke's first pump is described in Schott's "Mechanica Hydraulico Pneumatica," 1658. See also Guericke's "Experimenta Madgeburgica de Spatio Vacuo," 1672

devised the air pump. He had long been interested in the motion of the stars in the heavens and had come to the conclusion that they must be moving through an empty space, for otherwise they would gradually be stopped by the resistance of the air. He therefore decided to try to make an empty space, the better to study the question at close quarters. He began by using a piston water-pump to suck out the water from a completely filled, closed cask, in the hope of leaving an empty space behind. When this failed, he developed his air pump which was much like the piston water-pump from which it was presumably derived. As regards von Guericke's electrical machine, it consisted of a ball of sulphur which could be rotated in bearings while the hand was pressed against it. Von Guericke enjoyed the patronage of the King of Prussia. Figures 6 and 7 show two dramatic experiments arranged for the edification of his royal patron.

Von Guericke was followed by, among others, Robert Boyle (about 1660) who, having read of von Guericke's pump, set to work to construct one. He used an improved form of this "wind pump," as he called it, in his classic experiments in 1661 on the "spring and weight of air."

FIG. 7. Von Guericke's experiment of the Madgeburg hemispheres, 1654.

FIG. 8. Robert Boyle (1627–1691).

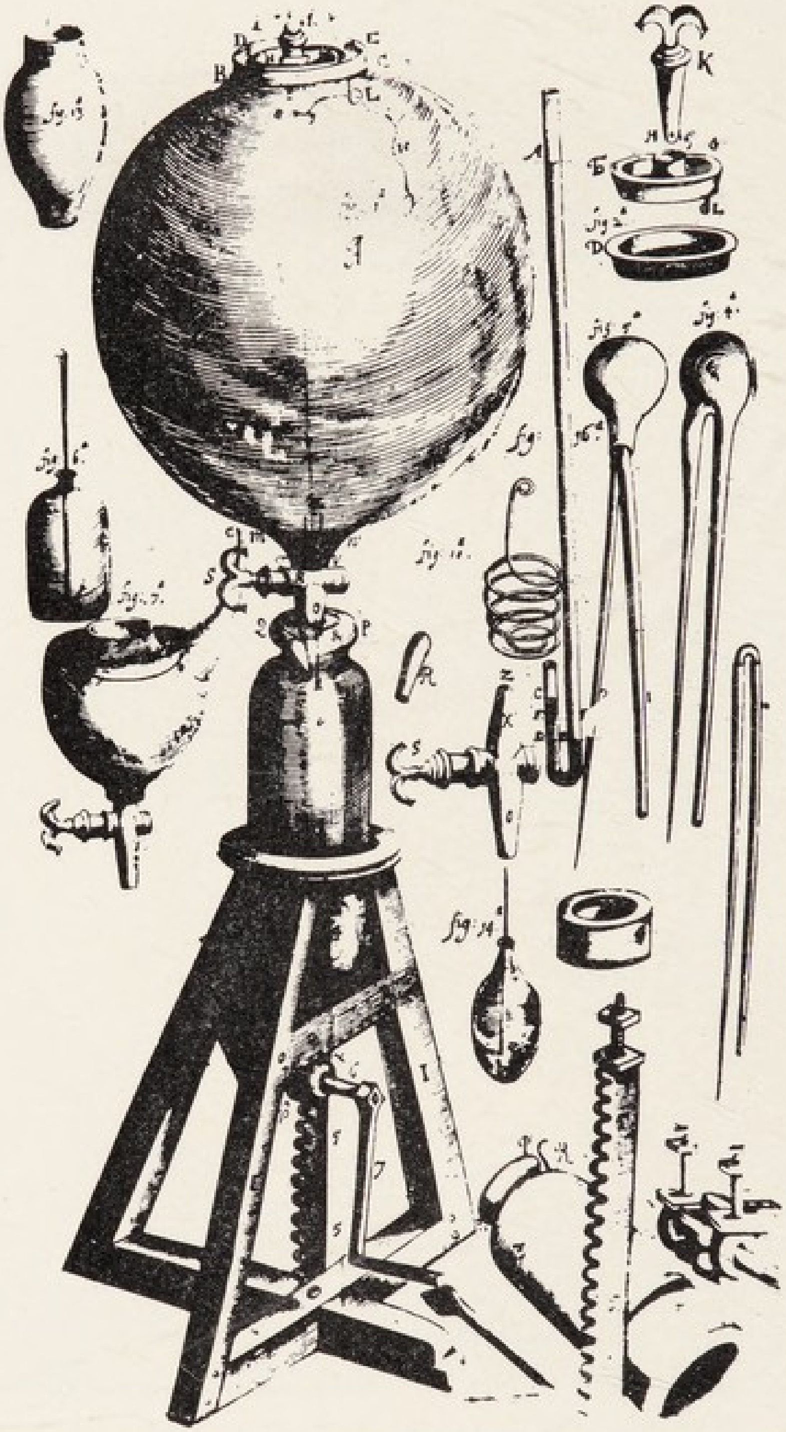

Fig. 9. Boyle's air pump or pneumatic engine, 1660

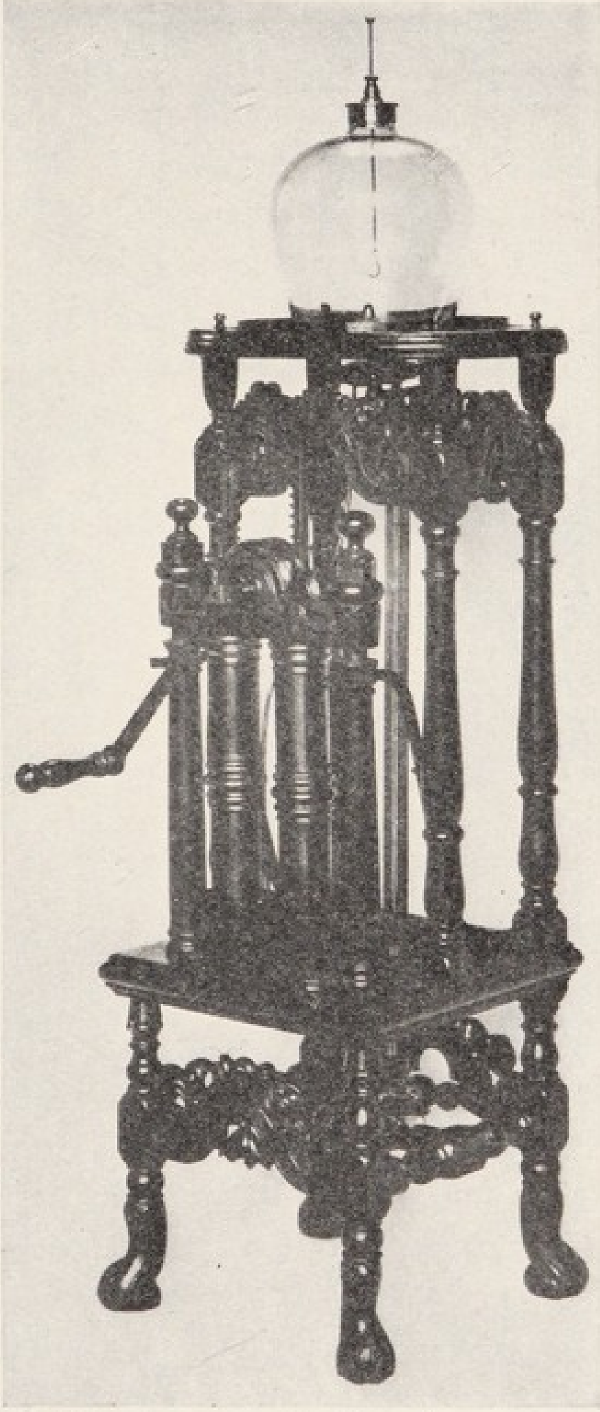

Fig. 10. Hauksbee's two-cylinder air pump, made before 1709, still in the possession of the Royal Society.

Incidentally, we owe to Boyle the use of the term "barometer." Hauksbee (about 1705), sometime Curator of Experiments to the Royal Society in London, was probably the first to conduct experiments on electric discharges *in vacuo.* This came about from his curiosity concerning the curious flickering luminescence which is occasionally seen in the vacuum of a barometer tube, when the mercury is caused to oscillate in the dark—an effect frequently referred to in the writings of the times.* "Mercurial phosphorus" it was called. Hauksbee devised a number

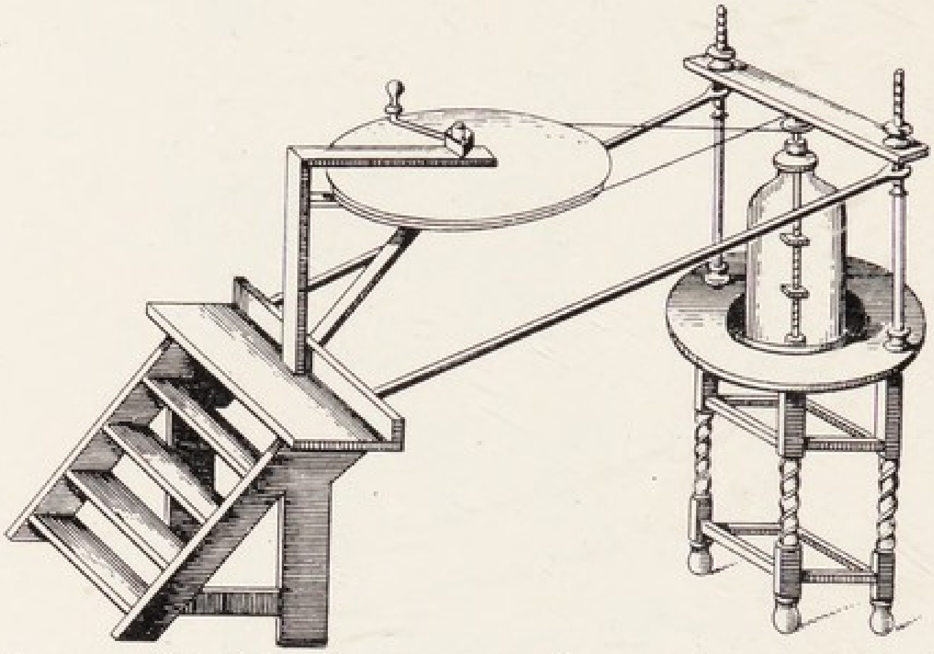

FIG. 11. Hauksbee's apparatus for rotating an electric machine within a vacuum, 1705.

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* I have traced it as far back as 1676 to Picard in France.

of arrangements for agitating mercury in exhausted vessels. Subsequently, in the belief that the explanation lay in some electrical action, he succeeded in simulating the effect by holding the hand against a rotating evacuated glass globe. Later he obtained "a fine purple light" by rotating within an exhausted bell jar, a small electrical machine depending on the "attrition" of wool against glass or amber. "Sometimes," he says, "I have observed the light to break from the agitated glass in as strange a form as lightning." Possibly the first reference in literature to electric sparks appears in Hauksbee's writings: "If a hand was held near the fricated glass a light would be seen to dart from it with a noise like that of a green leaf in the fire." Hauksbee was inclined to attribute the release of the electric "effluvium" to the heating produced. His beautiful two-cylinder vacuum pump* is happily still in the possession of the Royal Society. It was carefully overhauled in 1926 and, although over two hundred years old, is even now capable of pumping down to about 1 inch of mercury. Hauksbee also spent much time experimenting with mercury pumps, and summed up his experiences in the remark: "Such a dense and

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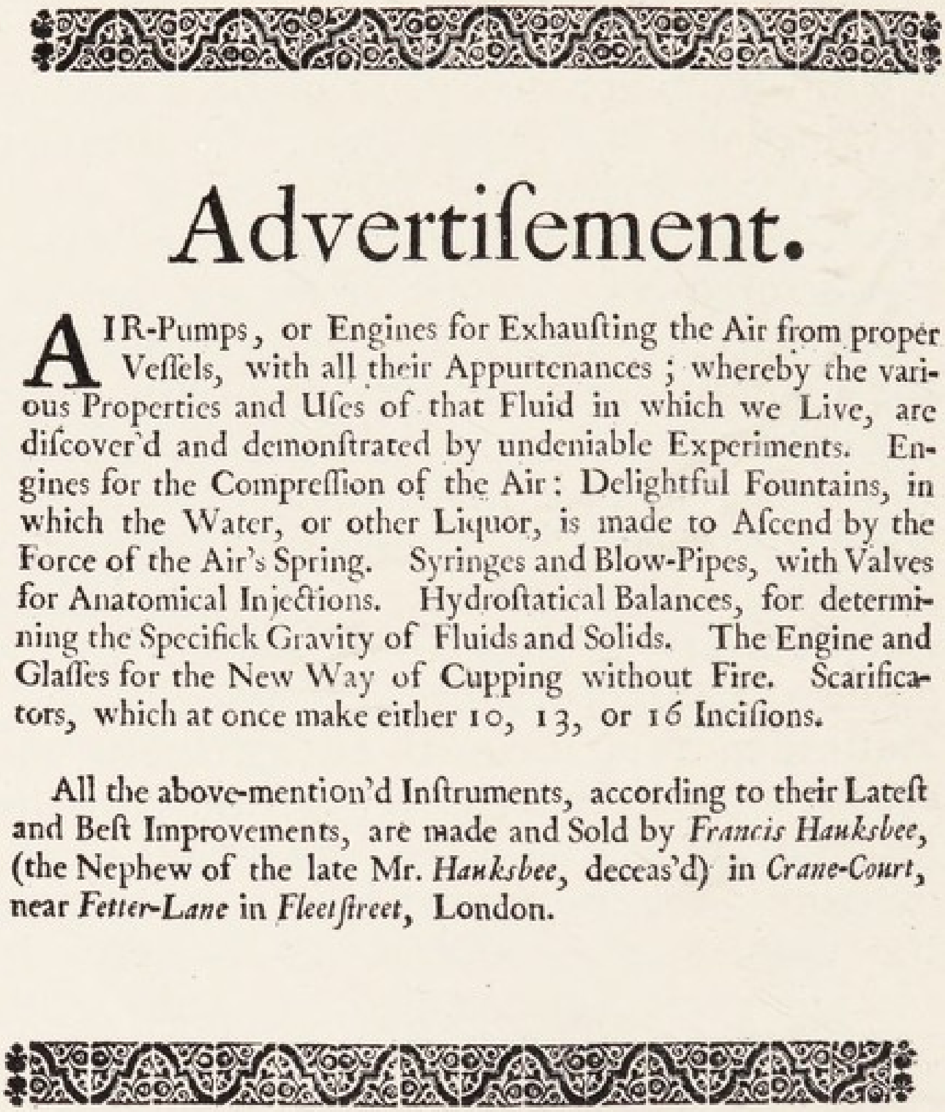
* See Hauksbee's Physico-Mechanical Experiments, 1709.

polite Body is Mercury; such a subtile Mover is Air; and such an apt Repository is an Exhausted Receiver."



Advertiſement.

AIR-Pumps, or Engines for Exhauſting the Air from proper Veſſels, with all their Appurtenances; whereby the various Properties and Uſes of that Fluid in which we Live, are diſcover'd and demonſtrated by undeniable Experiments. Engines for the Compreſſion of the Air: Delightful Fountains, in which the Water, or other Liquor, is made to Aſcend by the Force of the Air's Spring. Syringes and Blow-Pipes, with Valves for Anatomical Injections. Hydroſtatical Balances, for determining the Specifick Gravity of Fluids and Solids. The Engine and Glaſſes for the New Way of Cupping without Fire. Scarificators, which at once make either 10, 13, or 16 Inciſions.

All the above-mention'd Inſtruments, according to their Lateſt and Beſt Improvements, are made and Sold by *Francis Hauksbee*, (the Nephew of the late Mr. *Hauksbee*, deceas'd) in *Crane-Court*, near *Fetter-Lane* in *Fleetſtreet*, London.

FIG. 12. Copy of announcement about Hauksbee's air pumps.

Wall, a contemporary of Hauksbee, was evidently somewhat successful in generating electric sparks in air by the rubbing of amber with wool. "Five or six cracklings or more, full as loud as that of charcoal on fire, have been produced. They seemed," he says, "in some degree to represent thunder and lightning." He concluded that "the best time of making these experiments is when the sun is 18 degrees below the horizon"!

In 1730 Stephen Grey, a Pensioner in the Charterhouse in London, discovered that metal wires conducted electricity, and in 1740 the Abbé Nollet, (1700–70), professor of philosophy at the College of Navarre, and preceptor in natural philosophy to the French Royal Family, realizing it was now no longer necessary to place the electrical machine within the vacuum, obtained Hauksbee's results by connecting a frictional electrical machine by wires to an exhausted egg-shaped vessel. "The electric egg" Nollet called it, and the term, which persisted for many years, was not an unsuitable one for the prototype of the roentgen-ray bulb.

That great American philosopher and statesman, Benjamin Franklin (1706–90), is intimately associated with the succeeding developments in static electricity. His famous and daring kite experiment in 1749, to demonstrate the electrical nature of lightning, is known to every schoolboy.

He formed the opinion that "the electrical matter consists of particles extremely subtle," and he clearly recognized the properties of metallic points "in drawing on and throwing off the electrical fluid." Franklin's one-fluid theory of electricity commanded acceptance for over 150 years, though incidentally at the time it gave great offence to the Abbé Nollet, who was the protagonist of other views. There seem

FIG. 13. Abbé Nollet (1700–1770).

to have been three kinds of electricity in those days: Franklin electricity, Nollet electricity and Italian electricity, the last variety, "enjoying the prerogatives," as Nollet sarcastically puts it, of transmitting odors and drugs through the walls of glass phials or along chains, and indeed into the human system if the phial or chain were held in the hand!

The Leyden jar was discovered in 1745, and Franklin was persuaded about 1757 to investigate the curative value of Leyden jar discharges, miraculous claims for which were then being made. His sober and candid conclusions stand out in marked contrast to some of the exaggerated statements of the time. However, it was not all time wasted, for Franklin extended his experiments to fowls and, as he "conceited that birds killed in this manner eat uncommonly tender," he arranged "an electrical dinner" for his friends, in which a turkey, killed by an electrical shock, was subsequently roasted in front of an electrically ignited fire!

In 1751 Watson constructed a discharge tube 3 feet long. "It was a most delightful spectacle," he says; "the coruscations were of the whole length of the tube, were of a bright silver hue . . . and resembled very much the most lively coruscations of the aurora borealis."

It seems not unlikely that the first experimenter to generate X-rays—had he but known it—was Morgan, who in London in 1785, by previously boiling and so outgassing the mercury in a barometric "gage," was able to obtain so good a Torricellian vacuum that an electric discharge was prevented from passing. This was a big advance in vacuum technique. Morgan used a piece of tin foil wrapped outside the tube as one terminal. The tube presently cracked and we read that he obtained "a beautiful green electric light" followed by blue and purple colors which he suggested could be used as an index to the pressure.

Thus by the end of the 18th century the electric discharge tube was an established thing. Progress was more rapid during the 19th century when numerous workers with honored names helped to further the development.

At the Royal Institution in London, Davy in 1821 and Faraday in 1838 experimented with discharge tubes. Faraday's name has become associated with a dark space near the cathode. In 1838 Geissler in Germany was responsible for originating discharge tubes with sealed-in terminals of platinum wire, a device which added greatly to the life of the tubes. Plücker in

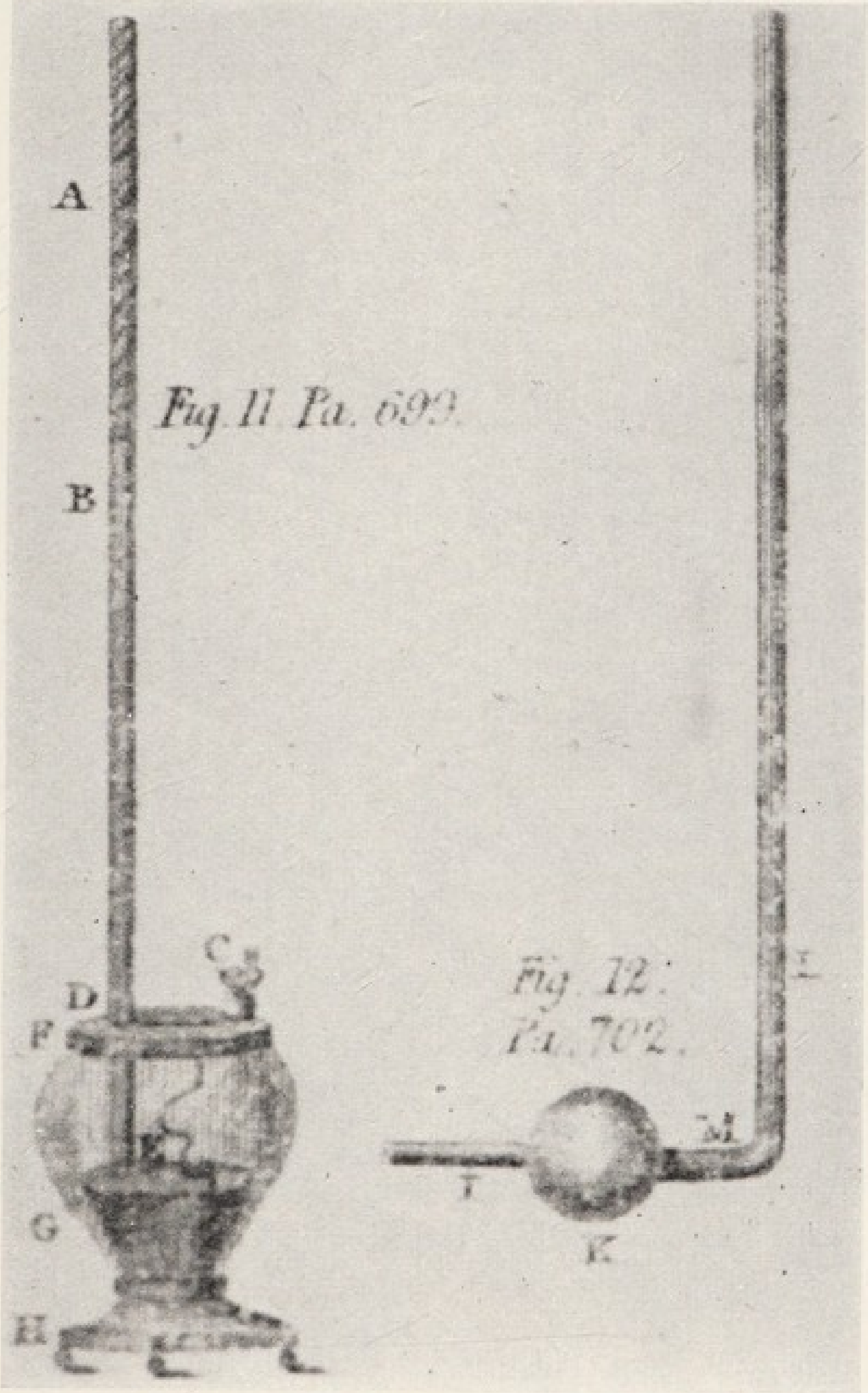


Fig. 14. Morgan's experiment with a barometric "gage," 1785.

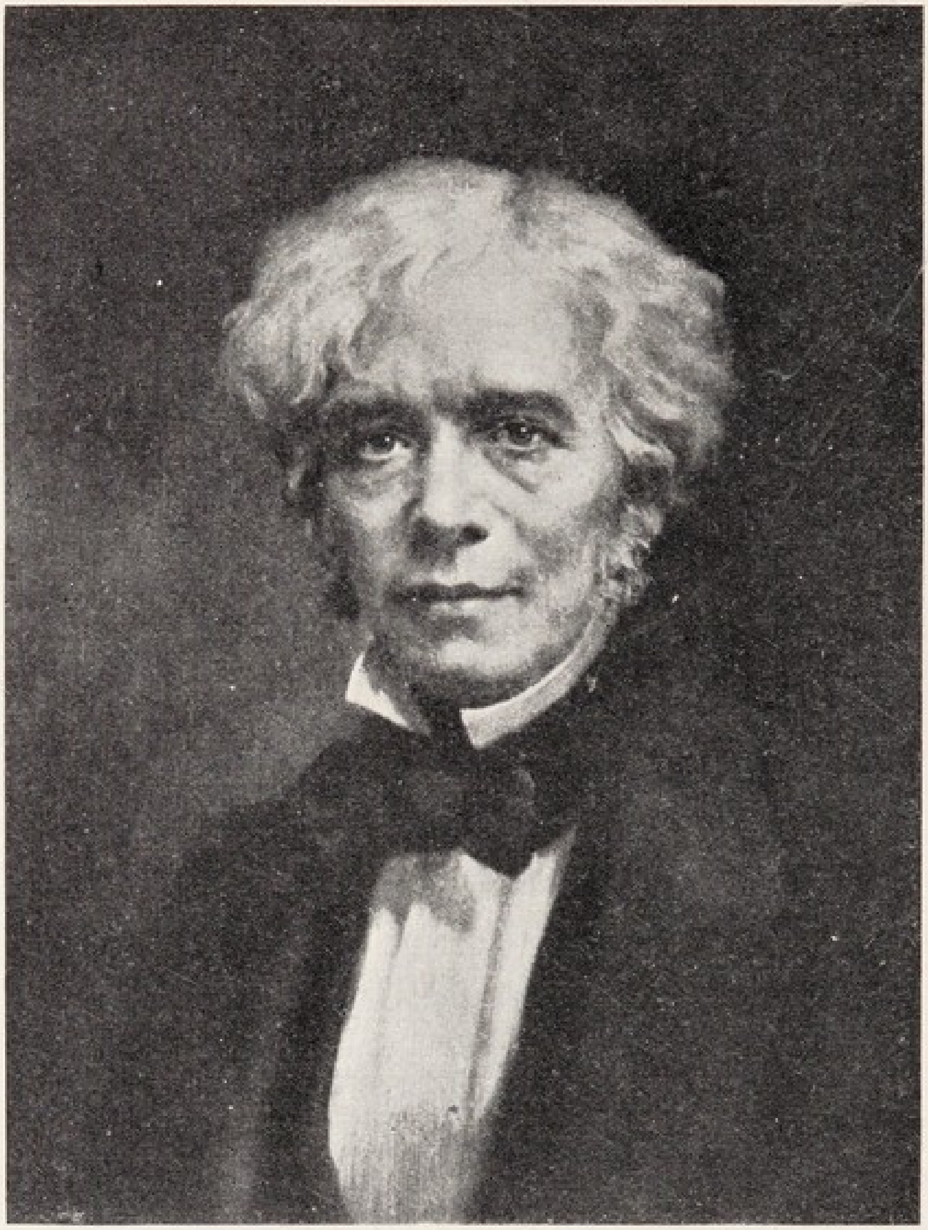


FIG. 15. Michael Faraday (1791–1867).

1859 systematically studied the green fluorescence of the glass, first remarked by Morgan at low pressures.

Fig. 16. Joseph Henry (1797–1878).

The researches of Faraday and Henry had by now led to the induction coil (with which the name of Ruhmkorff is associated) and by its aid, Plücker, Ruhmkorff, Grove and others noticed, about 1860, that under certain conditions the discharge was striated. Gassiot was the first to use high tension batteries (yielding possibly

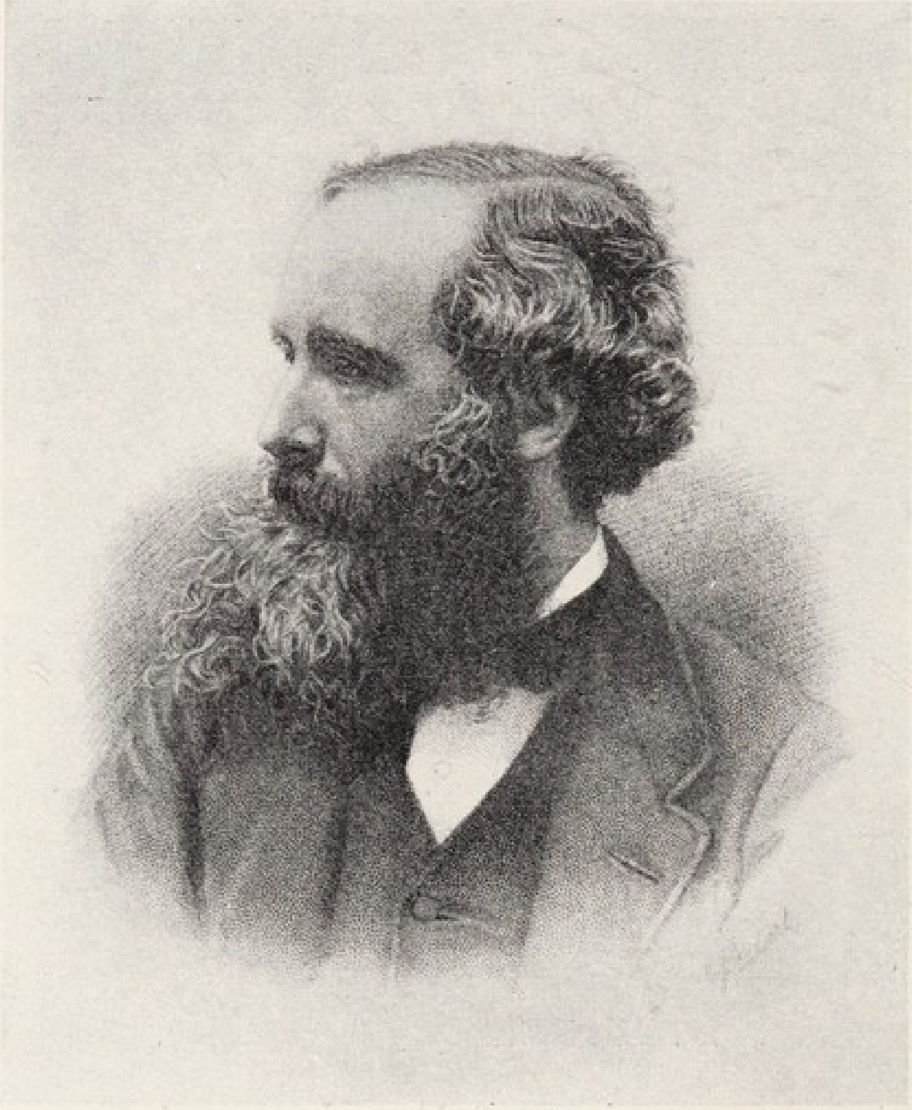


Fig. 17. James Clerk Maxwell (1831–1879)

FIG. 18. Exterior of Physics Laboratory, University of Würzburg. The plaque reads: "In diesem Hause entdeckte W. C. Röntgen in Jahre 1895 die nach ihm benannten Strahlen." (In this building W. C. Roentgen discovered in the year 1895 the rays which now bear his name.)

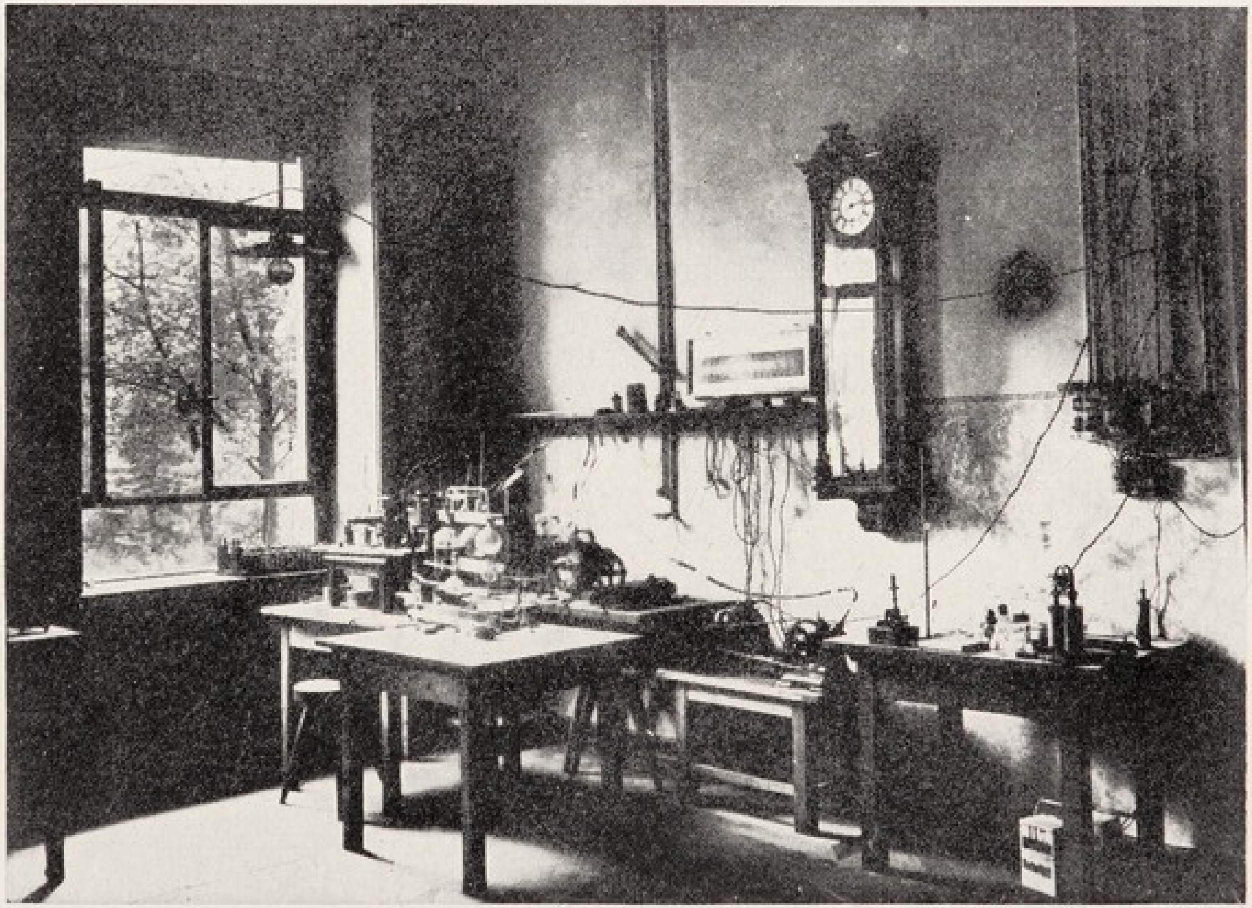


FIG. 19. Interior of Roentgen's laboratory at Würzburg. The laboratory is in active use today but is said to be practically unchanged.

FIG. 20. The famous door which Roentgen is said to have dismantled to determine why X-ray photographs taken through it showed streaks and bands of decreased density. He demonstrated that the marks were shadows cast by white lead used in cementing the panel mouldings.

several hundred volts) for the purpose and found the striations again occurred, which he regarded as evidence of an intermittent discharge.

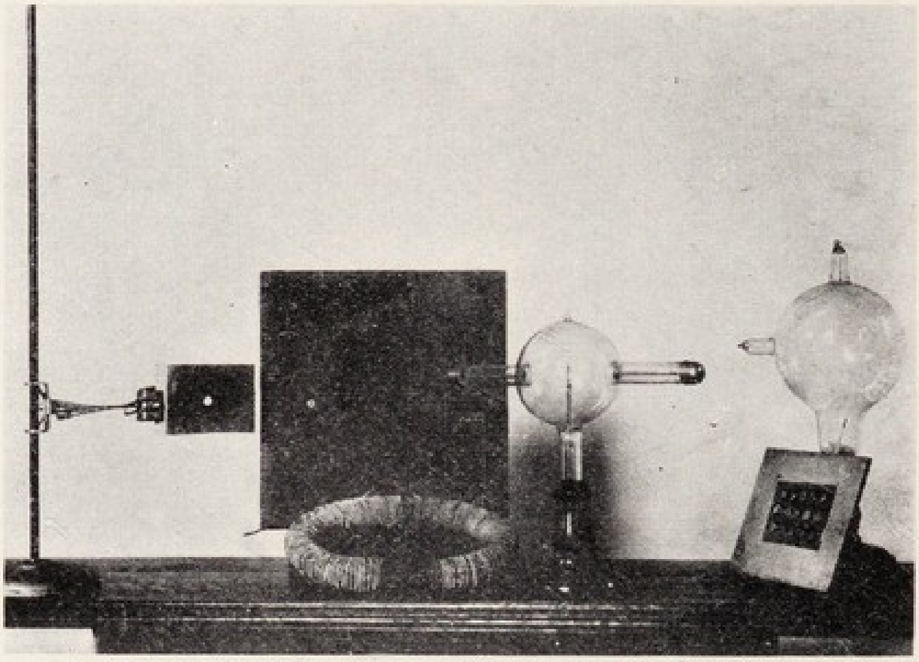


FIG. 21. Tubes, targets, screens and magnets used by Roentgen in his early work.

In 1865 Hittorf, a pupil of Plücker, discovered the stream of radiation from the cathode which we now call the cathode rays, his observations being extended in 1876 by Goldstein. De la Rue, Müller and Spottiswood in 1877 examined the striations with a revolving mirror. They remarked the effect of the bore of the tube on the striae which originated, they concluded, at the anode.

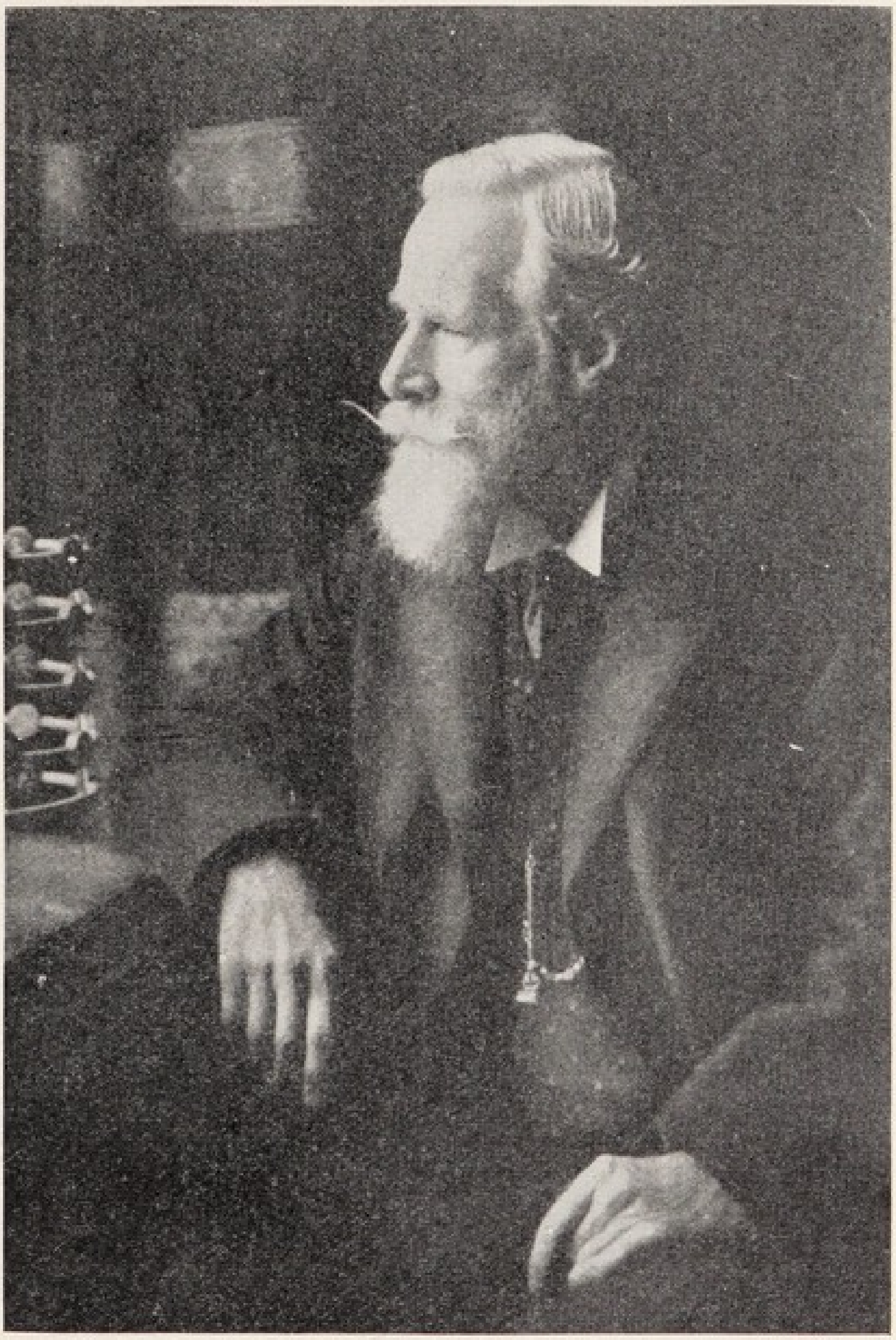


FIG. 22. Sir William Crookes (1832–1919).

By now the significance of the discharge tube phenomena was beginning to be generally appreciated and in 1873 we

Fig. 23. Print from the first roentgen-ray negative of the human hand made in England on January 13, 1896, by A. A. Campbell Swinton and shown by him at the Camera Club on January 16, 1896. Exposure: Twenty minutes through an aluminum sheet .0075 in. thick.

Fig. 24. Right hand of the late Lord Lister, taken by C. Thurstan Holland, September, 1896.

find Maxwell predicting that "when they are better understood, they will probably throw great light on the nature of electricity, as well as on the nature of gases and of the medium pervading space."

In the early eighties Crookes carried out his well known and memorable researches with the discharge tube, and with the aid of more efficient exhausting devices observed the dark space which closely envelopes the cathode and which is now associated with his name. He was led in his subsequent work to adopt the charged particle theory of the nature of cathode rays. Lenard succeeded in transmitting the rays through thin aluminum windows.* There followed the famous controversy between English and Continental physicists[36] as to the nature of cathode rays which was only settled in 1897 by Sir J. J. Thomson's discovery of the electron. In the meantime Roentgen, working in his laboratory at Würzburg in a search for "invisible rays" from the discharge tube, had discovered the roentgen rays; and the science of radiology or roentgenology was brought into being.

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* Coolidge has recently extended Lenard's experiments, using cathode rays excited by nearly a million volts. These rays have a range in air of 6 to 8 feet.

CHAPTER II

THE NATURE OF ROENTGEN RAYS

One is tempted to dwell on the subsequent growth of as fascinating a subject as any which science has revealed to us, but the story of the development of the art and practice of roentgen rays subsequent to 1895 has been told so often that we must confine ourselves to a few very recent fundamental features.

In passing, however, we may note the rapid development in the art of roentgen-ray photography, as exemplified by Figures 23 and 24. The former was taken in London in January, 1896, by Mr. Campbell Swinton; the latter at Liverpool in September, 1896, by Dr. Thurstan Holland, subsequent to the development of the focus tube by Sir Herbert Jackson in March. It may be added that within a few days of Roentgen's announcement and before any details had been transmitted from Germany, Professor Cox of McGill University, Montreal, successfully generated the rays and turned them to practical account.

It was Roentgen himself who styled his new and unknown radiation the "X rays"; and the name has persisted, for it was not till 1912 that the complete answer to the problem of the nature of the rays came with the experimental demonstration in Germany by Friedrich and Knipping of the correctness of von Laue's masterly conception of the probability of their diffraction by the orderly spacing of the atoms in crystals. As he anticipated, the results went to show that the wave length of ordinary roentgen rays is of the same order as the atomic spacings, that is, about 10^{-8} cm. or 1 Angström unit.

The roentgen rays have now taken their place in that great array of ethereal vibrations, the various groups of which are each associated with some outstanding physical property. The spectrum of radiations (Fig. 25) extends without break over a range of 60 octaves—from radio or wireless waves, through heat waves, visible waves, ultra-violet waves, roentgen rays and gamma rays. Then follows a gap of about 2 octaves before we come to the "cosmic rays" first demonstrated in 1902 by Cooke and Rutherford at Montreal, and by McLennan and Burton at Toronto, subsequently investigated among others

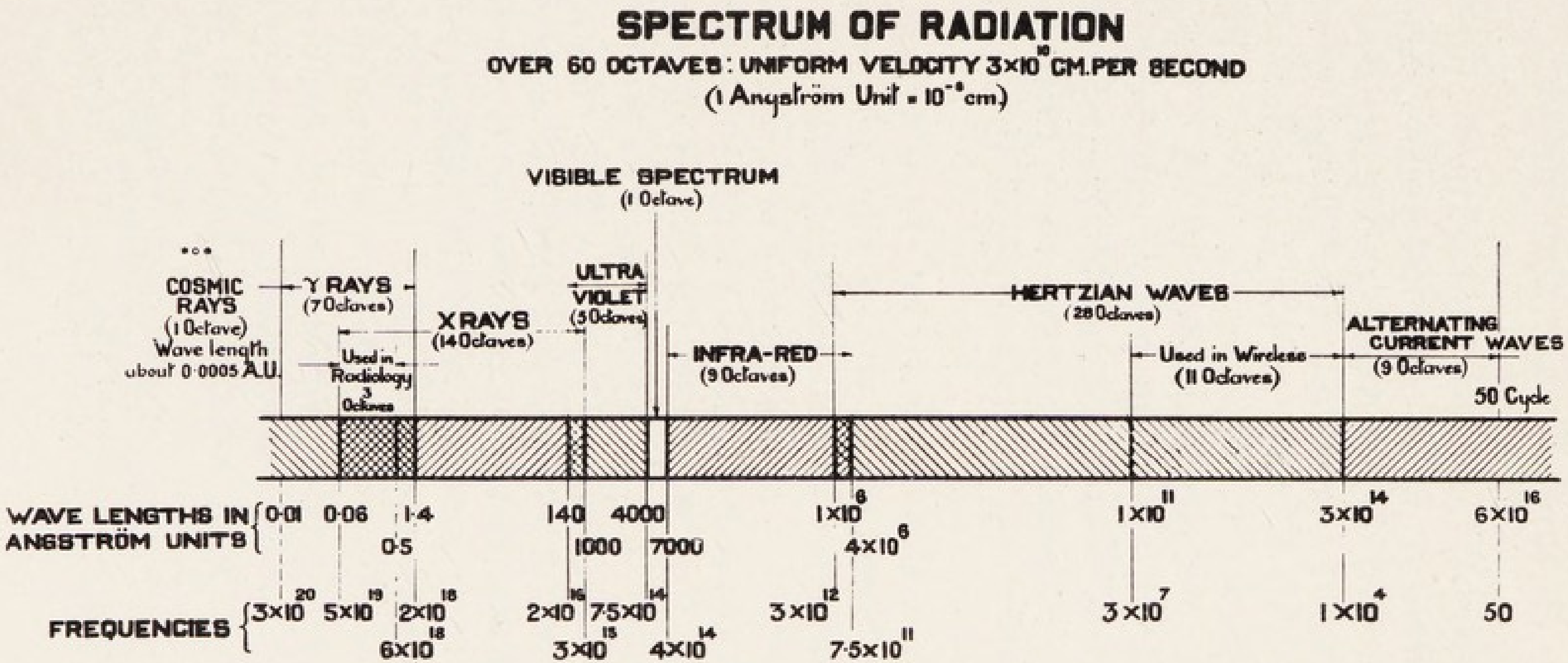
SPECTRUM OF RADIATION
OVER 60 OCTAVES: UNIFORM VELOCITY 3×10^{10} CM. PER SECOND
(1 Angström Unit = 10^{-8} cm)
VISIBLE SPECTRUM
(1 Octave)
COSMIC RAYS
(1 Octave)
Wave length about 0·0005 A.U.
γ RAYS
(7 Octaves)
Used in Radiology
3 Octaves
X RAYS
(14 Octaves)
ULTRA VIOLET
(5 Octaves)
INFRA-RED
(9 Octaves)
HERTZIAN WAVES
(28 Octaves)
Used in Wireless
(11 Octaves)
ALTERNATING CURRENT WAVES
(9 Octaves)
50 Cycle
WAVE LENGTHS IN ANGSTRÖM UNITS
0·01
0·06
0·5
1·4
140
1000
4000
7000
1×10^{6}
4×10^{6}
1×10^{11}
3×10^{14}
6×10^{16}
FREQUENCIES
3×10^{20}
5×10^{19}
2×10^{18}
6×10^{18}
2×10^{16}
3×10^{15}
$7{\cdot}5\times10^{14}$
4×10^{14}
3×10^{12}
$7{\cdot}5\times10^{11}$
3×10^{7}
1×10^{4}
50

FIG. 25.

by Wright in the Antarctic, and by Kohlhörster with balloon observations, and recently confirmed and extended by Millikan at Pasadena. The gamut of wave lengths of this spectrum of radiations is truly gigantic, amounting to a million, million, million fold, for the wave lengths range from about 30 kilometers (20 miles) in the case of radio waves, to about 5×10^{-11} cm. in the case of gamma rays, and about 5×10^{-12} cm. in the case of the cosmic rays.

Within the last two or three years the gap between radio waves and heat waves has been closed, while the gap between the ultra-violet and roentgen-ray groups has been bridged by the aid of vacuum spectrometers and photoelectric methods of analysis. This latter intervening group of very absorbable radiations, for which incidentally we need a handy and distinctive name,* have been shown to conform to the established roentgen-ray laws throughout their range right into the ultraviolet. Sir J. J. Thomson[1] has recently demonstrated that these very soft roentgen rays are generated within an ordinary discharge tube, but they are so absorbable that they never

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* In the absence of a better suggestion it might perhaps be remarked that, as there are U.V. rays on the one side and X rays on the other, the alphabetical sequence would be complete if these absorbable rays were called W rays.

emerge through the walls of the tube as ordinarily constructed. They possess pronounced ionizing ability, and it is not impossible that the more penetrating of these border-line radiations might, under proper conditions, prove to possess useful properties in superficial treatment.

Now, although the complete identity of roentgen rays and light waves was not established until just before the war, it had been correctly inferred by one school of workers on the score of the several features of resemblance, for example, their linear propagation, their ionizing, fluorescing and photographic activities, and their electrically neutral character. Furthermore, Barkla (1905) in England and his contemporaries had succeeded in establishing a partial polarization in the case of scattered roentgen rays somewhat akin to that of light.* Then, too, Marx in Germany carried out elaborate and ingenious experiments in 1906 which he claimed established the agreement of the velocity of roentgen rays with that of light. The experimental arrangements were the subject of criticism at the time, and Marx repeated his experiments in 1910. The correctness of the result

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* Since then with improved experimental arrangements Compton and Hagenow[2] have obtained almost complete polarization of scattered rays. Further, Bishop[3] has recently obtained results which indicate partial polarization of characteristic roentgen rays.

is no longer in doubt, though no recent work on the subject appears to have been done. Again, Haga and Wind conducted very difficult experiments in 1899–1901 to try to detect diffraction fringes by passing heterogeneous roentgen rays through a very narrow slit. They obtained a broadening of the image on a photographic plate which led them to a value in the neighborhood of 10^{-8} cm. for the wave length of roentgen rays. The experiments were adversely criticized by Walter and Pohl on the strength of more refined measurements made in 1909, but some three years later Sommerfeld redigested Walter and Pohl's own data and found support for Haga and Wind's conclusions. Wave lengths agreeing with present-day order of values were also derived by Wien in 1907, and Stark in 1908 from calculations based on Planck's theory of radiation.

The parallelism of light and roentgen rays was later emphasized by the discovery that roentgen rays yield both emission and absorption spectra. But in some other respects the correlation of light and roentgen rays seemed in the early days to be incomplete, for example, as regards reflection and refraction. Among others, Roentgen himself endeavored in 1896 to test the refrangibility of roentgen rays, employing for the purpose prisms of carbon bisulphide, water, ebonite, aluminum and heavier metals. He further tried to focus the rays with lenses of ebonite and glass.

We now know that such experiments were not of a kind to justify any hope of success, but searching attempts were made by later workers in the light of the Drude-Lorentz theory of dispersion. For example, Barkla[4] attempted to refract with a 90° prism of potassium bromide crystal a narrow pencil of heterogeneous roentgen rays of a range of frequencies including the resonance frequency of bromine (wave length about 0.5 Å). He could, however, detect no sign of refraction and concluded that the refractive index differed from unity by less than 0.000005—a figure of the right order, as we shall presently see.

It is only within the last few years that success has been attained. A. H. Compton at Chicago (1922), Siegbahn in Sweden, Bergen Davis in New York and others have displayed the specular reflection of roentgen rays, the refraction by prisms, and, furthermore, the diffraction by ruled gratings. These experiments are of great fundamental interest to all roentgen-ray workers. Some of the results form part of the rich harvest which is being gleaned from the large amount of roentgen-ray research now being carried out in the great industrial and university laboratories of America and Europe.

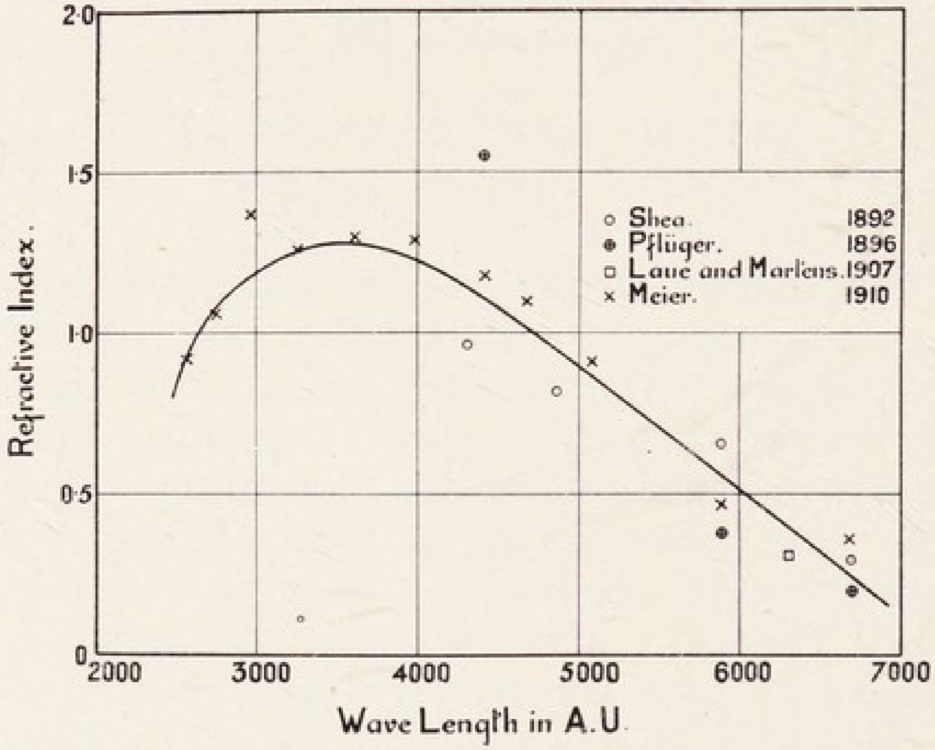
CHAPTER III

TOTAL REFLECTION OF ROENTGEN RAYS

It follows from the classical Drude-Lorentz theory of dispersion that, if the frequency of the incident radiation is large compared with the natural frequency of the electrons encountered in a medium—as is the case when roentgen rays of ordinary wave length are incident on light atoms—then the refractive index of the medium increases with the frequency of the radiation but is always less than unity. In other words, the velocity of roentgen rays is greater in the medium than *in vacuo*. This presents an interesting case of the difference between wave velocity and group velocity. Refractive indices less than unity are, of course, also known in the transmission of visible light by metals. For example, see Figure 26 which refers to the case of gold.

The value of the refractive index μ for roentgen rays in the circumstances stated is given approximately by the Lorentz theory as

$$\mu = 1 - \frac{ne^2}{2\pi m \nu^2}$$



Refractive Index of Gold

Fig. 26.

where n is the number of active electrons per unit volume, e is the charge on the electron, m is the mass of the electron, and ν is the frequency of the radiation.

Compton[5] computed by this formula the theoretical values of μ for calcite. They proved to be less than unity by quantities of the order of 10^{-6}, the refractive indices ranging from 0.999992 to 0.999996 for wave lengths from 1.47 to 1.10Å.

But other evidence had also been accumulating, for if roentgen rays have an appreciable refractive index, then, as Darwin[6] at Edinburgh had pointed out some years previously, Bragg's well-known simple relation for crystal reflection

$$n\lambda = 2d \sin \theta_n{}^*$$

will not be strictly obeyed. That is, the ratio

$$\frac{\lambda}{2d} = \frac{\sin \theta_n}{n}$$

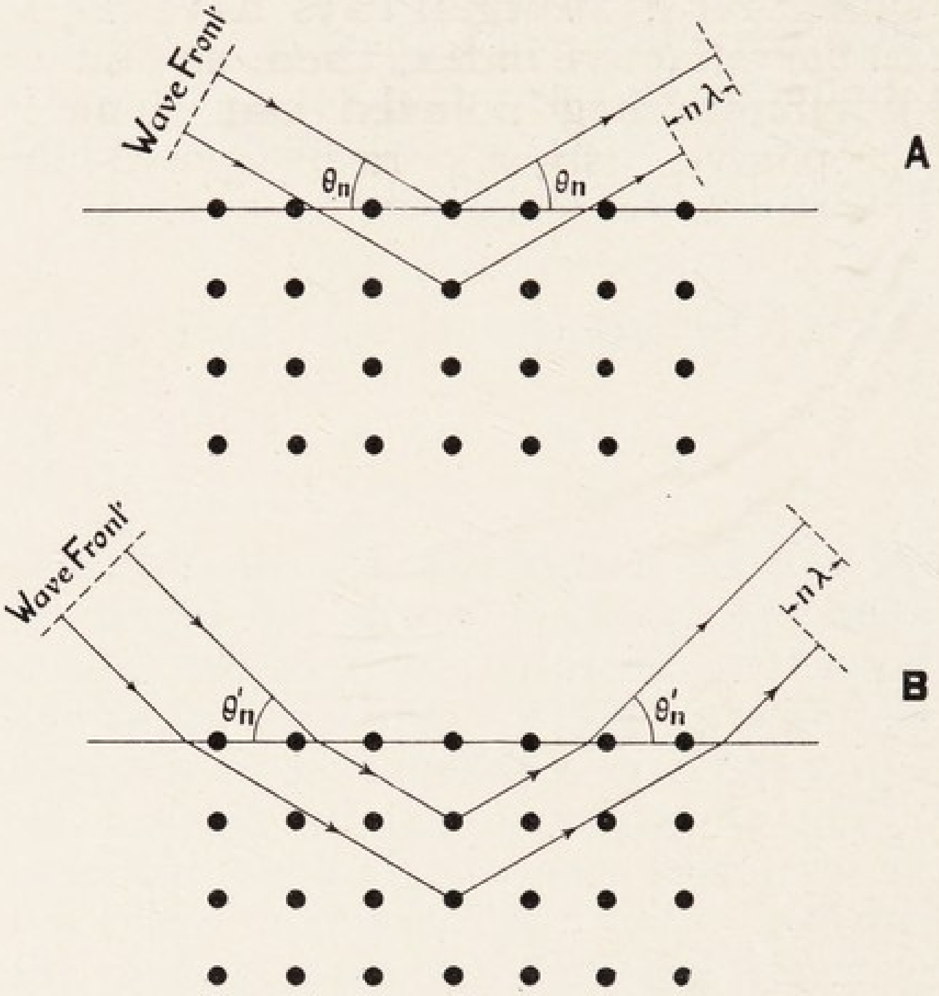
will not be a constant for all orders of reflection. In other words, as Figure 27 shows, the measured value of the reflecting angle θ_n will be slightly too great and so give too large a value of the wave length λ. The discrepancy will be greatest for the first order spectrum, but as θ_n increases with the order the refraction will exert relatively less and less effect and so the error in λ will be proportionately reduced. Darwin's correction leads to an amended form of Bragg's relation

$$n\lambda = 2d \sin \theta_n \left(1 - \frac{1 - \mu}{\sin^2 \theta_n} \right)$$

---

* d is the atomic spacing.
θ_n is the reflecting angle for the nth order.
λ is the wave length.

Increasing precision in roentgen-ray spectrometry by Stenström in Sweden in 1919, Duane and Patterson at Harvard in 1920, and Siegbahn in 1921, confirmed the

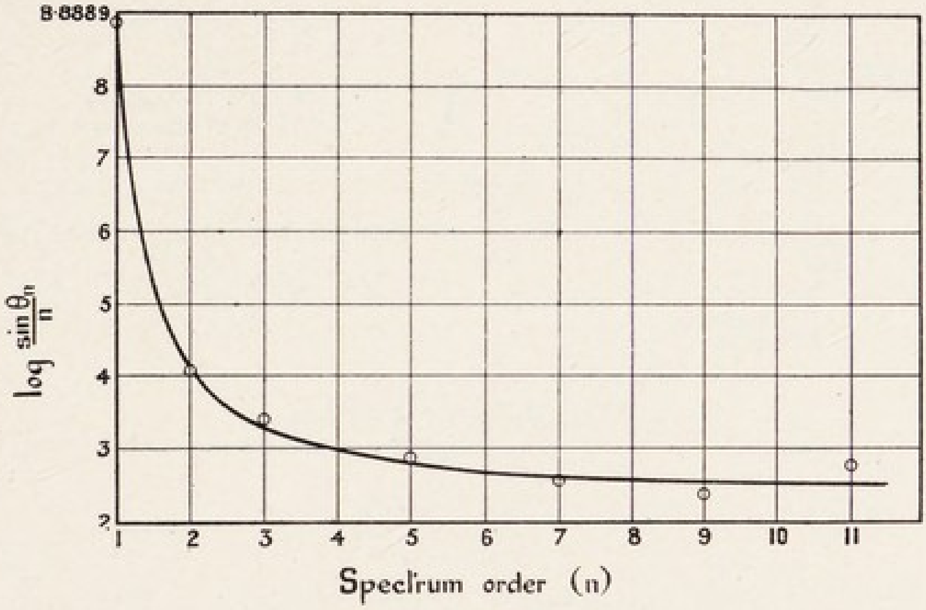


A. Illustrating Bragg's law of Crystal Reflection
$n\lambda = 2d \sin \theta_n$

B. Illustrating the effect of refraction in slightly increasing the measured value of θ_n

Fig. 27.

point experimentally: the ratio sin θ_n/n is not quite constant, but decreases slightly as n increases. This is well illustrated in

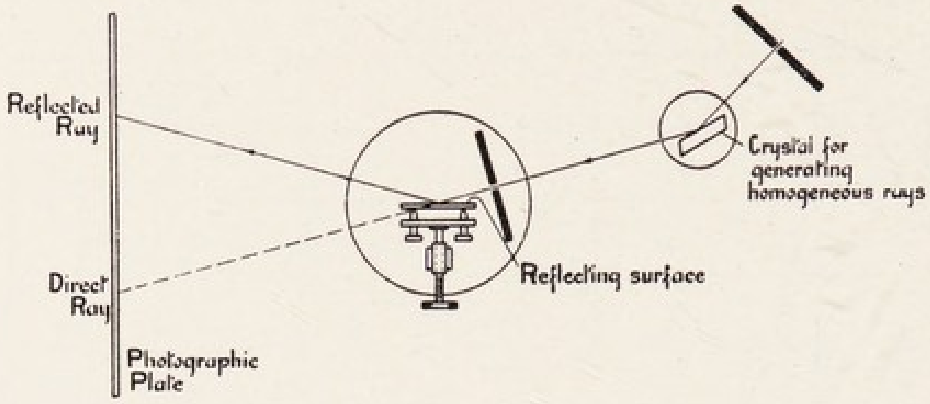


Mica: Cu Kα_1 radiation. (Larsson)

FIG. 28.

Figure 28 based on the results for mica obtained by Larsson[7] in Siegbahn's laboratory. The correspondence between the experimental values of sin θ_n/n (for different orders from the first to the eleventh) and the theoretical curve embodying Darwin's correction is very close.

Furthermore, Compton[5] computed the values of μ by the modified Bragg equation, utilizing Duane and Patterson's data for calcite, and found results in excellent agreement with those calculated, as mentioned above, from the Lorentz theory. We may take it as established that refraction is the true explanation of the consistent dependency of the apparent wave length upon the order of reflection.



Total Reflection of X Rays.
Compton and Doan.

FIG. 29.

Now, since the refractive index of roentgen rays is less than unity, then if the glancing angle θ in the case of rays travelling in air and incident on the medium is such that

$$\cos\theta = \mu$$

then the rays should, as in the case of light, be totally reflected, no matter whether the medium is crystalline or amorphous. Let us take the case of a crown-glass mirror of density 2.52 and roentgen rays of wave length 1.28 Å, then the Lorentz dispersion formula above gives $\mu = 0.999995$, so that the critical glancing angle $\theta = 11$ minutes of arc. On putting the experiment to the test, Compton, using an ionization method and a very narrow roentgen-ray beam, was able to detect specular reflection close to the position predicted. Energy measurements showed that almost all the incident energy was reflected, as would be anticipated in a case of true total reflection.

It may be of interest to give Compton's experimental values of the refractive indices and the critical glancing angles:

Substance	Density	Wave Length Å	Critical Glancing Angle θ	Refractive Index μ
Glass.........	2.52	1.28	10′	0.999996
Glass.........	2.52	0.52	4′	0.999999
Silver.........	10.5	1.28	22.5′	0.999979

Incidentally, Compton's measurements afford an independent and reliable confirmation of the accepted result that the number of active electrons in the extra nuclear region of the atom is equal to the atomic number. Furthermore, the phenomenon of total reflection provides a means of filtering out the *short* waves from a composite beam of rays, a thing not possible with absorption filters. Surfaces of the heavier metals are more convenient for the purpose, as the critical glancing angles are rather larger. Unfortunately, from a practical point of view, the method is only applicable to very narrow pencils of rays.

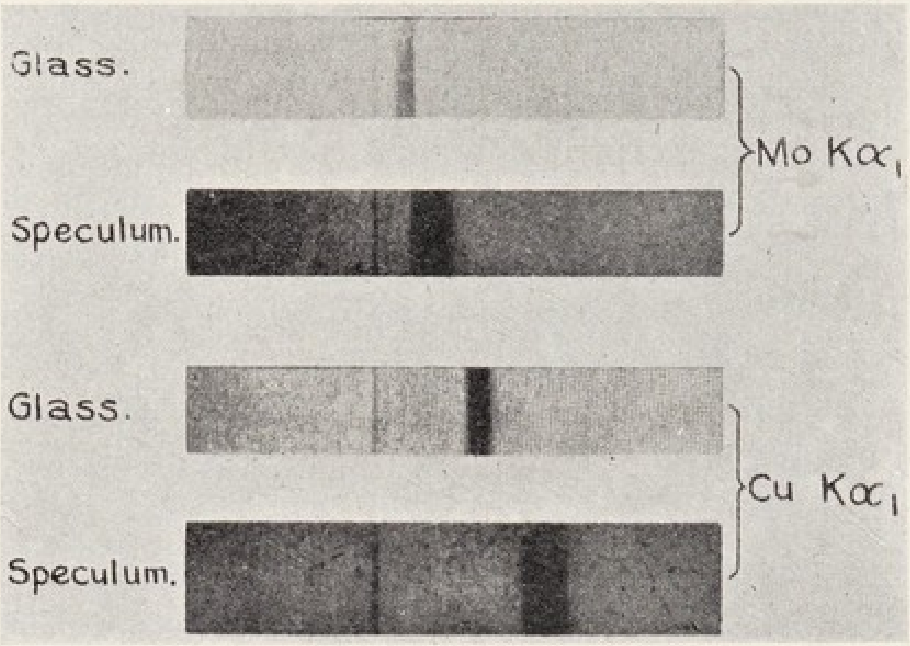


FIG. 30. (From Doan.)

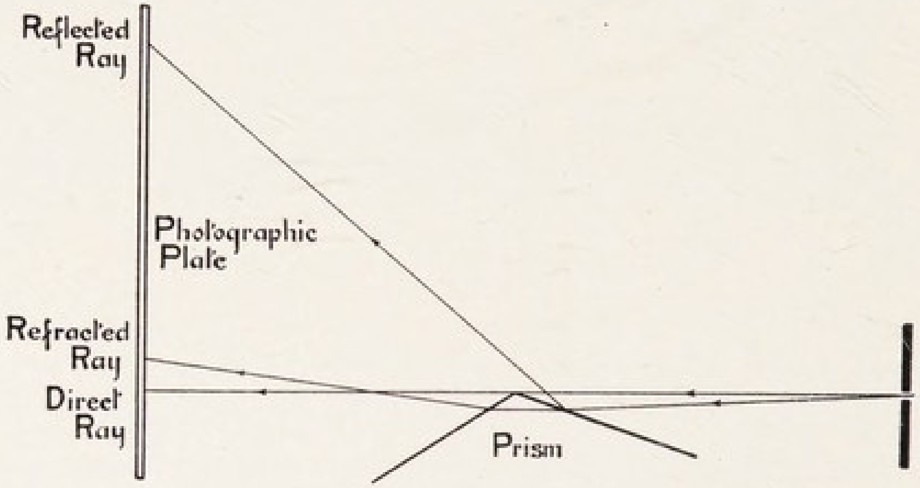
Kirkpatrick[8] in Hawaii subsequently obtained photographs of total reflections from surfaces of lead and sputtered platinized glass. Doan[9] at Chicago, also using a photographic method, has recently extended the scope of Compton's work on total reflection to include a number of sputtered metal surfaces, e.g., copper, silver, nickel, gold and speculum. Of these gold exhibited the largest critical glancing angle (31′ 24″ for Cu Kα_1 radiation) and the smallest refractive index (0.999958 for Cu Kα_1 radiation). Figure 29 shows Doan's experimental arrangements and Figure 30 some of the photographs obtained. In practice it is found that both the sharpness and intensity of the reflected spectrum depend upon the degree of polish of the surface.

More recently Prins[10] at Groningen has succeeded in producing multiple reflection of roentgen rays between two parallel stainless-steel mirrors about 0.005 cm. apart.

CHAPTER IV

PRISMATIC REFRACTION OF ROENTGEN RAYS

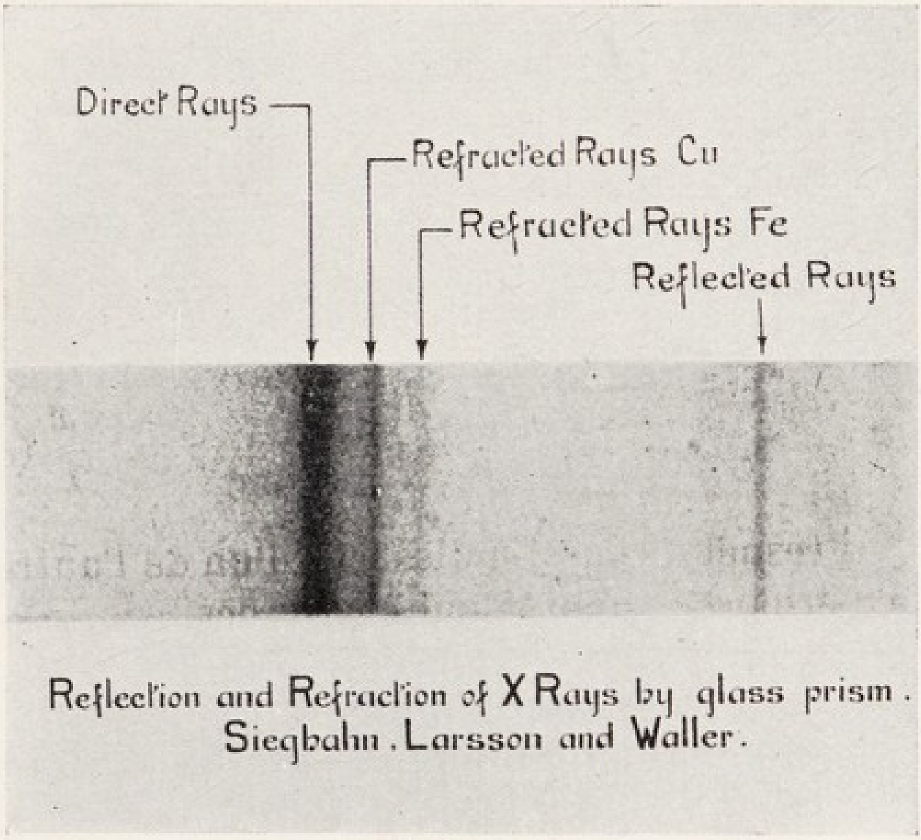
Now that we know the extent of the very small divergence of the refractive index of roentgen rays from unity, it should be possible to arrange the conditions so that the minute prismatic bending of the rays may be detected. This was first



Reflection and Refraction of X Rays by glass prism
Siegbahn, Larsson and Waller.

FIG. 31.

accomplished photographically by Siegbahn, Larsson and Waller.[11] They used heterogeneous rays and a glass prism, the refracting angle of which was large so as to enhance the deviation. Figure 31 shows the arrangement. If the glancing angle is very small two lines appear on the photographic plate due to the direct and reflected beams respectively. As the glancing angle is increased through the critical angle, the reflected ray disappears and a refracted ray appears in a position indicating a



Reflection and Refraction of X Rays by glass prism.
Siegbahn, Larsson and Waller.

FIG. 32.

bending of the beam in a direction opposite to that of normal optical refraction. Figure 32 shows on the one plate the direct and reflected rays as well as the refracted spectrum of a pencil of rays which includes the Kα rays of copper and iron. The refractive index of the glass prism (density 2.55) was found to differ from unity by from 1 to 12 in the 6th place for wave lengths ranging from 0.63 to 1.93 Å.

Davis and Slack,[12] and Slack,[13] using the double ionization spectrometer, found the deviation when roentgen rays were refracted by a number of metal prisms to be only a few seconds of arc. The following are some of their results:

Substance	Wave Length Å	Prism Angle	Angle of Deviation	Refractive Index μ
Silver	0.708	63.5°	2.4″	0.999994_1
Copper	0.708	60.0	2.1	4_0
Sulphur	0.708	168.3	5.4	8_6
Aluminum	0.708	166.0	5.6	8_3
Carbon	0.708	86.4	4.0	8_8

Incidentally, Davis greatly increased the deviations with certain crystals by grinding the reflecting planes to suitable angles. Mention may also be made of the application of roentgen-ray refraction by Davis and Nardroff[14] to the measurement of the size of small particles. The method appears to afford some hope of measuring in certain cases the size of small particles far beyond microscopic size, possibly as small as 10^{-7} cm.

Chapter V

DIFFRACTION OF ROENTGEN RAYS BY RULED GRATINGS

Until recently, roentgen-ray spectroscopy rested entirely upon diffraction by crystals, after the method due to Bragg. For this we require a knowledge of the atomic spacing which it will be recalled is calculated in the case of some standard crystal such as calcite or rock salt by means of the relation which, in its simplest form, is

$$d^3\rho = M$$

where d is the atomic spacing in cm., ρ is the density (gram/c.c.), M is the weight of the molecule in grams.

By this means W. L. Bragg[15] first found the atomic spacing for rock salt, the latest value of which is

$$d = 2.814 \times 10^{-8} \text{ cm.}$$

while Siegbahn's latest figure for calcite (cleavage face) is

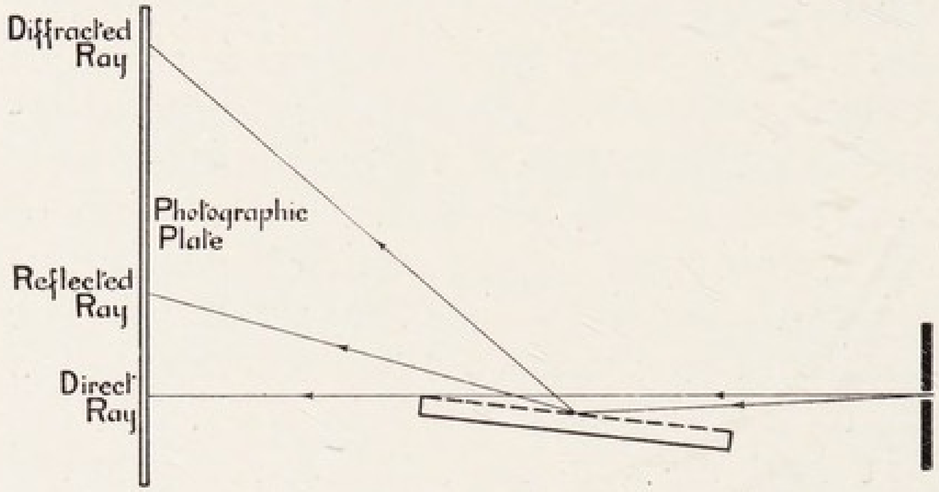
$$d = 3.029 \times 10^{-8} \text{ cm.}$$

and these are generally adopted as standard values.

The value of M is dependent on that adopted for the Avogadro number, i.e., the number of molecules per cubic centimeter of a gas, and, as Siegbahn has pointed out, the technique of roentgen-ray spectrometry has now reached a stage of development when the accuracy of measurement of the angle of reflection is greater than that attainable in the calculation of the atomic spacing, for which the accumulative uncertainty in the value of the density, the charge on the electron, etc., amounts to about 2 parts in 3000.

It had always been taken for granted that ordinary optical diffraction gratings were much too coarsely ruled for dealing with waves as short as roentgen rays; but it is evident that, by employing extremely small glancing angles, the difference in the paths of the waves reflected by adjacent rulings will become such that the diffraction of roentgen rays may be rendered possible—a suggestion which was first put forward by Carrara.[16]

The production of such spectra was, however, first demonstrated by A. H. Compton with Doan[17] who used a reflection grating on speculum metal with 500 lines to the centimeter. If any considerable fraction of the energy is to be reflected, it is necessary to work within the critical glancing angle for total reflection, i.e., about 25′ for wave lengths less than 1.6 Å. By the use of a photographic method under



Reflection and Diffraction of X Rays by ruled grating.

FIG. 33. (From Thibaud.)

these conditions the diffraction effect was completely established.

Compton and Doan cite the following example of the agreement between the results of the ruled grating and the crystal grating methods in the case of the molybdenum $K\alpha_1$ line:

By ruled grating $\lambda = 0.707 \pm 0.003$ Å
By crystal grating $\lambda = 0.7078 \pm 0.0002$ Å

Thibaud[18] has recently extended Compton's work, using a glass reflecting grating with 2000 lines per cm. Figure 33 shows the experimental arrangement, and Figure 34 is a typical photograph showing the direct beam of rays, the totally reflected

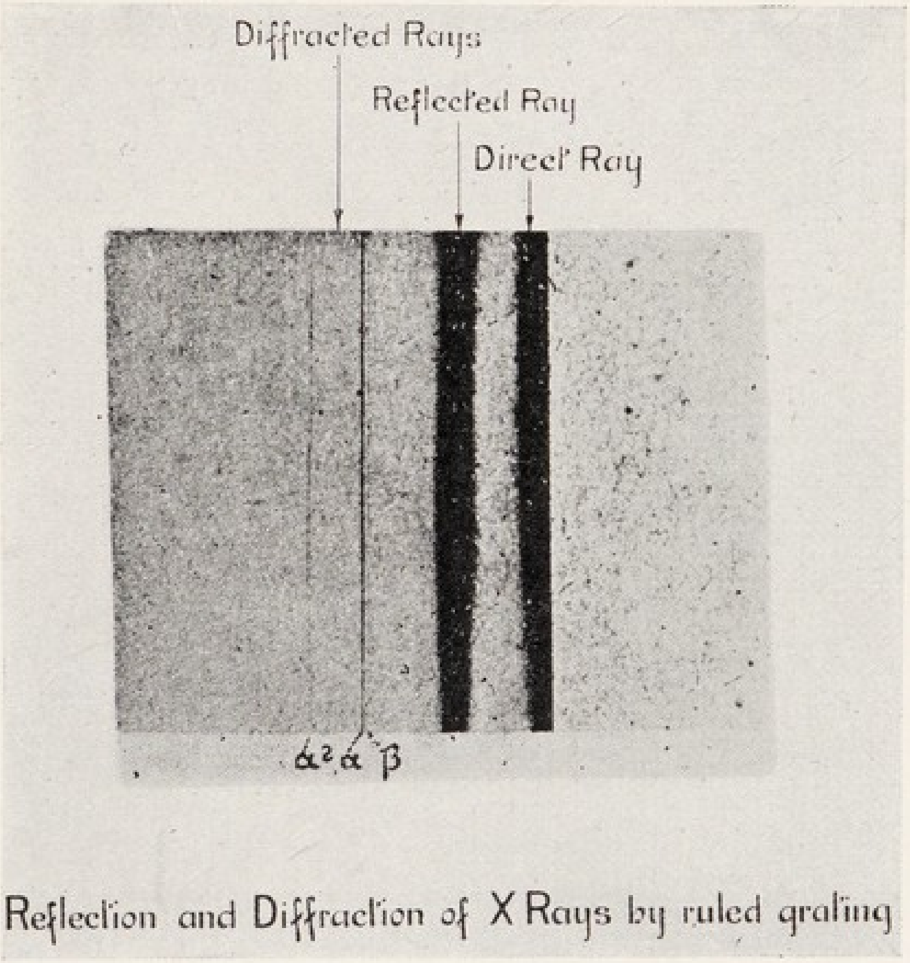


Fig. 34. (From Thibaud.)

beam, and the diffracted spectrum, the sharp lines of which include the α and β lines of the CuK series. As the glancing angle is increased through the critical value the reflected and diffracted beams disappear simultaneously. Thibaud gives the following results for the CuKα line:

By ruled grating λ = 1.540 Å (to about 1%)
By crystal grating λ = 1.538 Å

We are thus no longer wholly dependent on the crystal grating method for measuring roentgen-ray wave lengths; and when the technique and accuracy of the ruled grating method are improved, as they require to be, we shall be provided with a valuable alternative method which moreover is absolute. We can too, if we desire, conduct a direct comparison of roentgen-ray and optical wave lengths for the same grating. Incidentally, the agreement already obtained between the results given by the two kinds of gratings, provides assurance, if it were needed, of the sound foundations on which crystal analysis rests.

An obvious field for this ruled grating method is in the region between roentgen rays and ultraviolet rays. Apart from photoelectric methods, progress in this absorbable region has been chiefly effected by the use of crystal gratings of the fatty acids, such as lauric, palmitic and stearic acids, the interplane molecular spacings of which, as Müller and Shearer,[19] working at the Royal Institution in London, first showed, range up to 60 or 70 Å.

By mounting such crystals in a vacuum spectrograph Thoraeus,[20] working in Siegbahn's laboratory, has extended roentgen-ray wave length measurements up to the L series of chromium (21.5 Å) (Fig. 35). Early this year Dauvillier[21] also published results, taking matters considerably further into the region of longer waves.

Progress by such means is difficult, however, owing to the fact that a finite, if small, depth of the crystal must be penetrated to produce diffraction, and presently as the waves lengthen they become too absorbable to permit even this.

However, Thibaud[22] in a paper published very recently has successfully applied the ruled grating method to the absorbable region as far as 65 Å. Glass gratings were used having either 2000 lines per cm. or 11,800 lines per cm., the spacing being checked optically by one of the green mercury lines. The K lines of carbon and oxygen were obtained in sharp definition, the absolute accuracy being about 1 in 200 (Fig. 36).

Mention should also be made of the recent experiments of Walter[23] who in 1924 returned to his earlier investigations on the diffraction of roentgen rays by narrow slits. In this later work Walter, using homogeneous rays and slits as

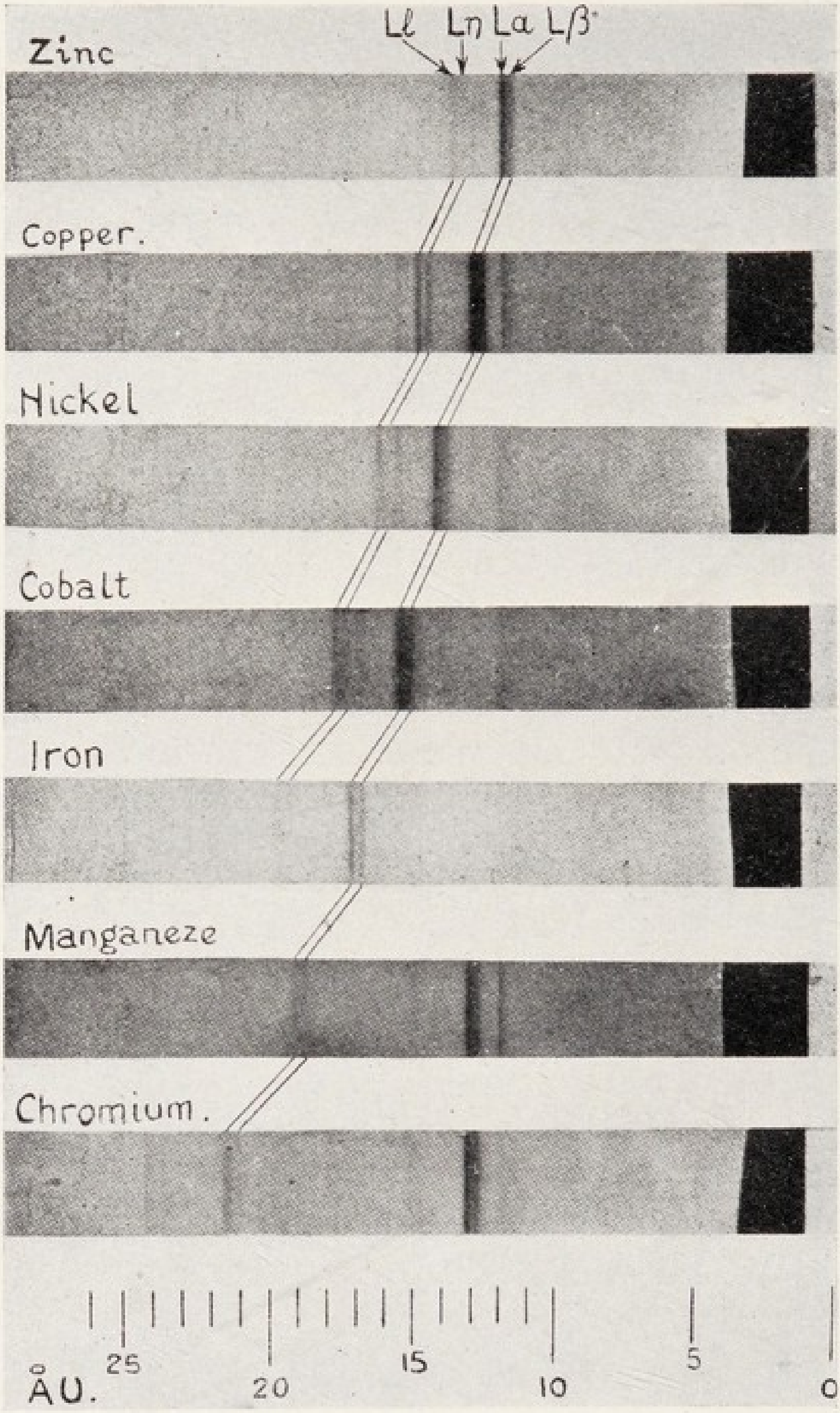
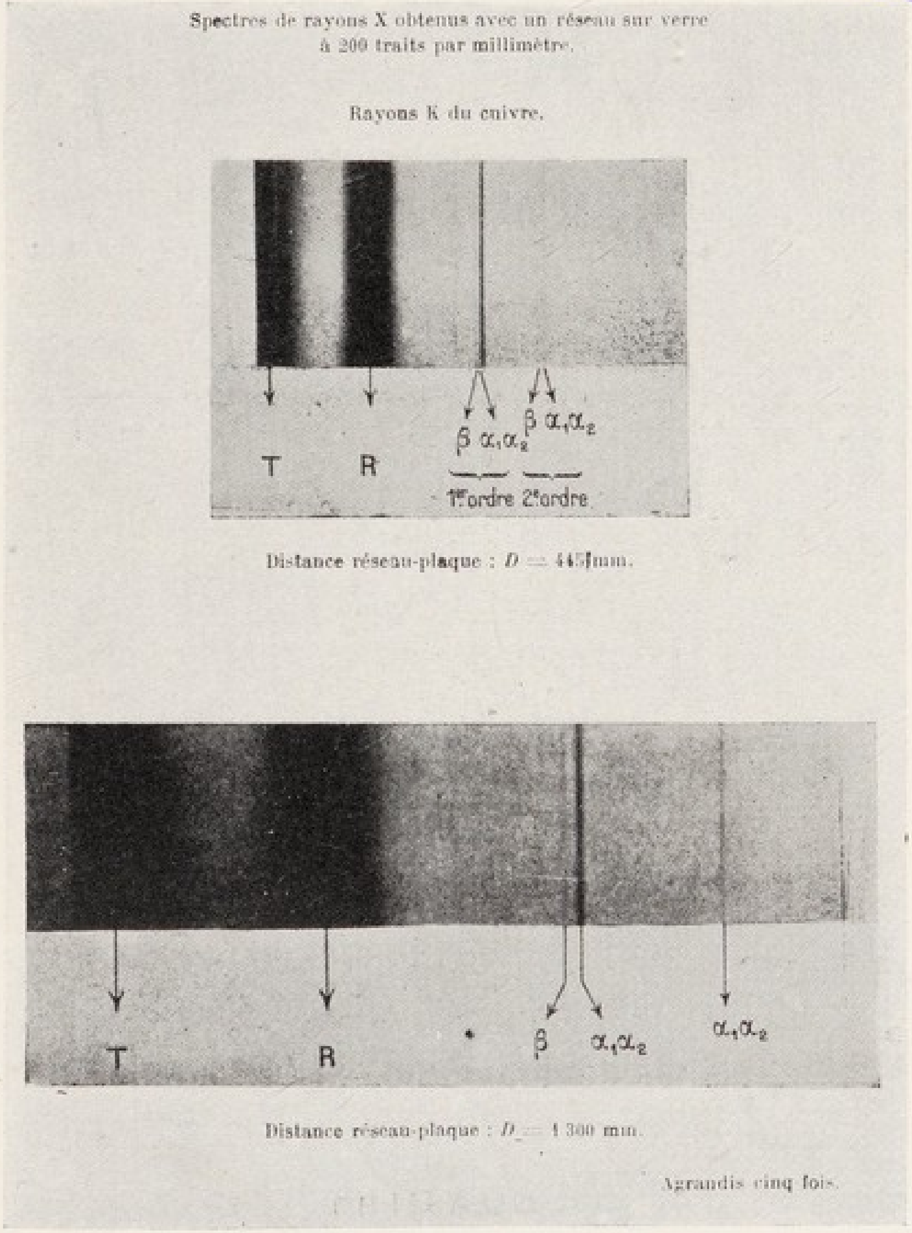


Fig. 35. (From Thoraeus.)



Spectres de rayons X obtenus avec un réseau sur verre à 200 traits par millimètre.

Rayons K du cuivre.

Distance réseau-plaque : $D = 445$ mm.

Distance réseau-plaque : $D = 1\,300$ mm.

Agrandis cinq fois.

FIG. 36. (From Thibaud.)

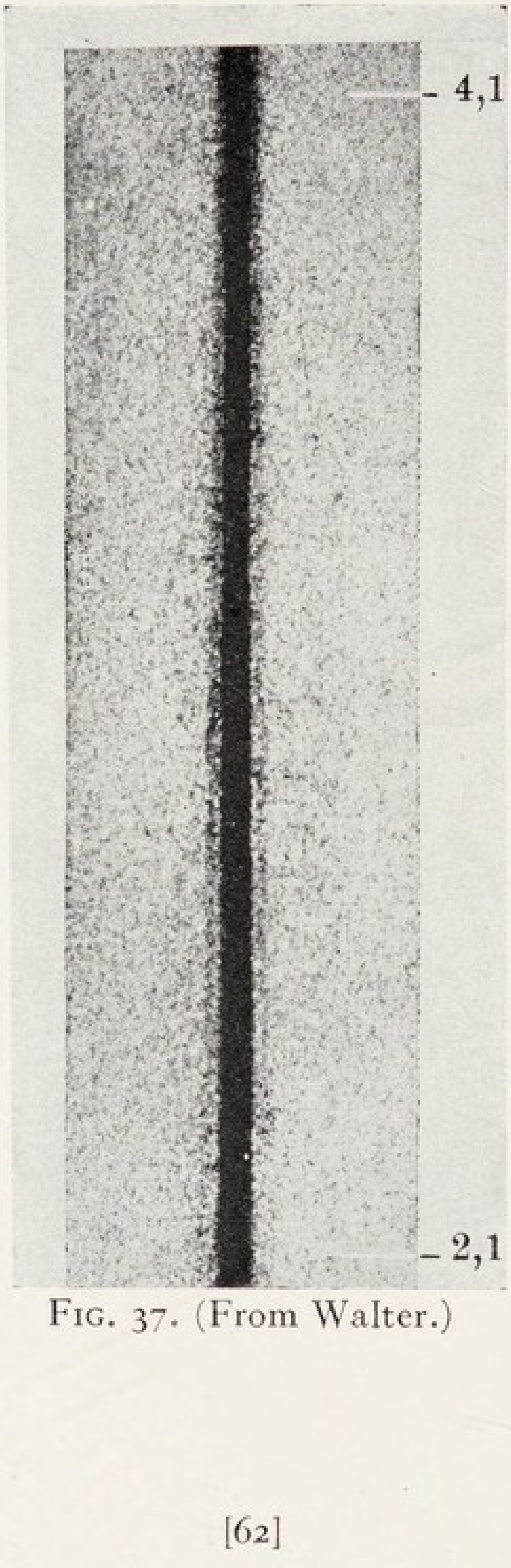


FIG. 37. (From Walter.)

narrow as 2×10^{-4} cm., obtained first and second order fringes giving wave lengths for copper K radiation within ± 10 per cent of the accepted figure (Fig. 37).

CHAPTER VI

THE NATURE OF RADIATION

Thus, to sum up, what may be called the optical requirements of the classical and long established electromagnetic wave theory are now completely met by the roentgen rays. This is not to say, however, that we are any nearer to a solution of the nature of roentgen rays or indeed of radiation in general. On the contrary, side by side with the above "optical" investigations have been developed other roentgen-ray researches equally fundamental, the results of which are not only unpredictable on a spreading wave theory but greatly strengthen the case for the quantum theory of radiation, which in effect regards roentgen rays as so many tiny projectiles or "quanta," much like the corpuscles in Newton's theory of light. The quantum theory contemplates these "projectiles" as possessing energy proportional to their frequency; and the theory achieves its greatest successes in explaining those electrical and energy phenomena which become more conspicuous as the frequency increases. The outstanding recent example is the Compton effect, that is, the small increase in wave length which is produced when hard roentgen rays are scattered by free electrons. The Compton effect is unexplained by the continuous wave theory, but receives very simple and quantitative explanation on the quantum theory by the notion that a quantum of roentgen rays may be scattered by a single electron, much as one billard ball is deflected by another. The roentgen-ray quantum loses a certain amount of energy in the encounter and this energy is taken up by the recoiling electron, the amount of energy transferred and the relative directions of the scattered quantum and the recoil electron depending on the conditions, such as the angle of scattering. This has been beautifully displayed by the cloud chamber method due to C. T. R. Wilson.

The intimate relationship between the two energy carriers, roentgen-ray quanta and electrons, is further emphasized by the recent results of Davisson[37] at the Bell Telephone Laboratories in New York. Davisson has shown that when slow-speed electrons are reflected by a single crystal of nickel, a kind of Laue pattern is formed, the electrons being reflected along definite tracks just as are roentgen rays. More recently G. P. Thomson has confirmed and extended these results photographically.[38]

The doctrine of discontinuity that the quantum theory of radiation postulates is an important example of a conception that is gradually permeating fundamental physics at the present time. Even the so-called laws of nature are beginning to be looked upon not so much as inherently simple and fundamental relations, but rather as mere expressions of something essentially statistical and which indicate nothing more than the most likely trend of events. We find another illustration in the primordial atom of Dalton which, small as it is (diameter 10^{-8} cm.), is, as is well known, no longer regarded as continuous in structure, but as consisting of electrons (of diameter about 3×10^{-13} cm.) and even smaller protons (with diameters estimated at about 6×10^{-16} cm.). Furthermore, there is no evidence that even the electron or the proton is structureless; and in the Silvanus Thompson lecture already referred to, Sir J. J. Thomson did not hesitate to take things a step further and to invoke the assistance of particles much smaller even than the proton. There is obviously no finality; it is all a question of the fineness of the test that we presently apply to our theory. Even Maxwell's famous sorting demon, though thoroughly at home with the doctrine of discontinuity, might wonder at the increasing elaboration of his former simple molecules.

To return to the physics of radiation, we see that the difficulties of the problem have not been clarified but rather accentuated by some of the recent investigations on roentgen rays. All the electrical and energy phenomena point to a quantum theory, but this, even on the assumption of a partial coherence of quanta, still fails to explain interference which is most adequately accounted for by the spreading wave theory. As Sir J. J. Thomson has remarked, the conflict between the two theories has some of the features of a fight between a tiger and a shark: each is supreme in its own element and helpless in the other. The master theory which will reconcile the modern and the classical points of view is not yet in sight, and we are left confronted with one of the two great problems of modern physics—the structure of the atom and the structure of radiation.

Chapter VII

ROENTGEN-RAY PROTECTION

I would like now to refer to the efforts which have been made in recent years to put an end to the danger of roentgen rays to those in their proximity, and to improve the general working conditions of the operator. I am aware that a good deal has been done in this connection in America, particularly by the Safety Committee of the American Roentgen Ray Society, but the reader will forgive me if my remarks refer mainly to the work carried out in England, because that is the side with which I happen to be most familiar.

The mischievous effects of the roentgen rays made themselves felt very early. In 1896 Edison and Dr. J. W. Morton experienced severe smarting of the eyes; the same year roentgen-ray dermatitis was noticed, the following year cases of pronounced constitutional symptoms were observed. Since then many cases resulting from overexposure under faulty working conditions have been recorded. It is estimated that well over a hundred of the earlier workers have succumbed to their injuries, while the large number of lesser casualties cannot be estimated. The great war must have added greatly to the list.

A succession of deaths from aplastic anemia brought matters to a head in England in 1921. Public opinion was stirred and the assurance companies began to regard the roentgen-ray worker with an unfavorable eye. Specific precautions were asked for, and accordingly by cooperative action between the various British radiological and physical institutions, a representative committee of radiologists, physicists and manufacturers was set up in April, 1921, under the chairmanship of Sir Humphry Rolleston, then President of the Royal College of Physicians, and three months later issued a series of recommendations. These recommendations (which are given *in extenso* in the Appendix), though naturally they have not wholly escaped criticism, have in the main been very favorably received and widely adopted. From personal experience I know they are leading to a great improvement in the working conditions of roentgen-ray operators in Great Britain and, thanks to the co-operation of the manufacturers, have influenced beneficially the design of much

British-made apparatus. Similar recommendations have since been made in a number of other countries,[*] and a considerable literature has resulted: over 120 papers have, I find, been published on the physics of protection alone. At a discussion at the First International Congress of Radiology held in London in 1925 the desirability of international agreement on, at any rate, the main questions of protection was suggested. Such international recommendations were adopted at the Second International Congress at Stockholm in 1928. (See Appendix B.)

It should be understood that there has been no question of legislation in England in this matter. The Ministry of Health and the Ministry of Pensions gave the recommendations their support, and the Home Office consulted the committee on the question of including roentgen-ray

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[*] So far as I am aware, the following committees have been appointed in different countries to deal with the question of protection:

England.	The X-Ray and Radium Protection Committee.
United States.	The Safety Committee of the American Roentgen Ray Society.
Germany.	Die Deutsche Roentgengesellschaft.
Sweden.	The X-Ray and Radium Protective Committee.
Norway.	De Norsk Forening for Medicinisk Radiologi.
Russia.	The Radiological Congress of the Soviet Federation.
Holland.	The Protection Committee of the Board of Health.

Austria has legalized certain protective measures.

dermatitis in the schedule under the Workmen's Compensation Act, a step which was ultimately taken in 1924.

It will not, I think, be without interest if I refer to some of the main points that guided the English Protection Committee in framing its recommendations, more particularly as regards roentgen rays.

A scheme of roentgen-ray protection which rests on a sound physical and biological basis involves:

(*a*) Measuring under specified conditions the intensity of roentgen rays in terms of a specifiable and reproducible physical standard expressed, if possible, in absolute units.

(*b*) Establishing a maximum tolerance dose in terms of a specifiable and reproducible biological standard and, if possible, expressing this biological standard in physical units.

(*c*) Establishing reliable figures for the transmission of roentgen rays of specified quality by lead and other absorbents.

(*d*) Calculating the thickness of absorbent necessary to reduce the intensity of a given beam of roentgen rays to that corresponding to the tolerance dose at some specified point.

The Committee was first confronted with the fact that (in 1921) there was no generally agreed physical unit of roentgen-ray intensity, nor an accepted method of measurement. (That was, in fact, the position, until 1928 when the unit "Röntgen" [r] was adopted at Stockholm.) The consequential difficulty of specifying a safe intensity was aggravated by lack of knowledge on what is a maximum tolerance dose and what relation it bears to the biological standard selected. For want of a better, the biological standard selected is the erythema dose (H.E.D.; or unit skin dose) which, however, is of variable and uncertain magnitude both biologically and physically. Moreover, while there is a consensus of opinion as to the cumulative biological effect of the rays and also as to the enhanced effect of a single dose as compared with that of the same dose when divided, the questions of the exact extent to which the effect of the divided dose is influenced by the magnitude of each fractional dose and the time interval between the fractional doses, also remain to be settled. Then, too, there is the problem of whether the biological effect is selective or not as regards wave length. Furthermore, the vexed question of idiosyncrasy to roentgen rays, whether acquired or congenital, has to be taken into account. Some radiologists hold the view that it is very exceptional, but Sir Humphry Rolleston,[24] in his Mackenzie Davidson Lecture given in London in 1927, concluded that, while examples of acquired sensitiveness to radiations appear to be rare, "it would appear to be impossible to deny the occurrence of an inborn hypersensitiveness to radiations though extreme degrees may be very unusual."

In the light of the above considerations, the protective values recommended had necessarily to be framed less from the biological aspect than from the point of view of physical measurements and the common practice and accumulated experiences of a considerable number of older workers. It was obvious that the protective values selected would have to be in the nature of a compromise, as considerations of weight and cost would preclude any attempt at stopping the rays virtually completely. Some small amount of radiation is bound to reach the operator, particularly during screening, but this should be made so small as to be innocuous.

It was, of course, realized that the precautions should be more comprehensive in a busy roentgen-ray department than in, say, a small country hospital where only occasional use is made of the apparatus, but it was felt that, if it could be devised, a very simple cut-and-dried scheme of protection, which could be easily understood and worked to, would be more generally acceptable than a "graded" system based wholly on working conditions. Furthermore, the demands on an apparatus normally tend to increase as time goes on and, unless there is close supervision, the resulting liability to misinterpretation and misuse, particularly in small isolated hospitals, might stultify the very object of the recommendations. Moreover, in large hospitals and particularly in factories using roentgen rays industrially, installations are not at all unlikely to be operated by men with little experience or knowledge. The Committee accordingly took the view that the recommendations should seek to ensure adequate protection on an installation, no matter what the conditions. As Rolleston[24] remarks: "It is important that the recommendations for protection should be based on the principle of absolute safety and so err, if they do so at all, on the side of excess."

At an early stage in its deliberations, the Protection Committee approached the National Physical Laboratory (that is, the British Bureau of Standards) and invited its close co-operation. In response, the Laboratory agreed to test protective materials and protective devices and to inspect and report on roentgen-ray departments of hospitals, etc., from the point of view of the Committee's recommendations. I may add that the Laboratory does not attempt to exercise discretionary powers in such work, but simply states in its reports whether or not the recommendations are complied with.

During the last few years over a hundred hospitals have been so inspected by my Department of the Laboratory, and many hundreds of protective materials and devices have been tested. In some cases we have been called in at several stages in the construction of a new roentgen-ray department, and the carrying out of the Committee's recommendations has thus been ensured from first to last. It may be added that the standing of the Laboratory and its impartial position as a Government institution have proved of peculiar assistance in this inspecting work. It has, for instance, been a matter of interest to us to notice how often our reports have been instrumental in influencing a situation and so assisting a hospital radiologist to obtain the new roentgen-ray department or the new equipment or the added protection he was only too well aware he sorely needed, but had not hitherto been able to get for some good reason from his governing body. That is, I think, an important aspect of the Protection Committee's work.

PROTECTIVE RECOMMENDATIONS

As regards protection, the simplest and most economical plan is to place the roentgen-ray tube within a tube box or shield which is as small as the design of tube will permit and which affords protection in all directions, except, of course, for a suitable working aperture. Supplementary protection for the operator and others in the vicinity may be provided, if necessary, by the walls of the room or by some alternative scheme. The protective values of building and other materials are dealt with in Chapter VIII.

As to the amount of protection, the Protection Committee took the view that the exciting voltage on the roentgen-ray tube was the most weighty factor on which to build a simple scheme of protective values based on the degree of absorption of different qualities of roentgen rays (Fig. 38). Accordingly two main groups of rays were first legislated for: (1) those generated by peak voltages under 100 kv. (covering the bulk of diagnostic work and superficial treatment); and (2) those generated by peak voltages exceeding 100 kv.

Since then these groups have been subdivided and the following protective values expressed in terms of the equivalent thickness of lead (which is adopted as the standard of reference) are those given in the International Recommendations:

Roentgen Rays Generated by Peak Voltages	Minimum Lead Equivalent
Not exceeding 75 kv.	1.0 mm.
Not exceeding 100 kv.	1.5 mm.
Not exceeding 150 kv.	2.5 mm.
Not exceeding 200 kv.	4.0 mm.

In addition, recommendations are made for protection of the operator against scattered radiation, the magnitude of which, particularly close to the patient, is often underrated. The above protective values are equally applicable to the protective glass of fluorescent screens, in view of the fact that, although screening examinations will naturally be conducted as rapidly as possible with minimum apertures, the operator is compelled to work in the direct beam, usually in close proximity to the roentgen-ray tube. In all other work the operator will naturally seek as great a distance as possible in as favorable a direction as the conditions permit and behind the target if possible. As regards protective gloves, they should afford protection both back and front, and the 0.5 mm. lead equivalent suggested should not lead to undue loss of suppleness.

While in some quarters it is held that the amount of protection recommended by the Committee is somewhat inadequate, particularly at high voltages, on the other hand, there are those who complain that it leads to heavy, unwieldy and cumbersome apparatus, to which the answer is that if the weight of the tube enclosure is kept to the minimum by bringing the protective material close up against the tube, there need be no difficulty on that score. In any event such difficulties are avoided by proper design; and already many roentgen-ray manufacturers have shown that the difficulties complained of are surmountable by designs which are not unduly costly.

It may here be added that such quantitative biological evidence as has been advanced since the recommendations were drafted is not unfavorable to the Committee's suggested protective values. Steps should be taken to correlate the experiences of all the older workers while they are still with us, for it must be recognized that as yet the evidence in question is based on restricted statistical and biological data. For example, Mutscheller[25] "from a limited number of typical examples" argues that the tolerance dose for an operator should not exceed $1/100$ of an erythema dose every thirty working days; that is, $1/1000$ of an erythema dose every three working days. He further refers to a simple expression, though one of admittedly doubtful validity, for the intensity of a roentgen-ray beam, which, written in the form

$$\frac{\text{milliamperes} \times \text{minutes}}{25\ (\text{distance in feet})^2}$$

gives, obviously only approximately, the number of erythema doses received at a given distance along the direct beam from a roentgen-ray tube. We can then calculate the amount of lead necessary to reduce this intensity to the tolerance dose.

Glocker and Kaupp[26] adopt Mutscheller's figures for the tolerance dose and incidentally conclude that the fluorescence which can just be seen on a screen in a completely dark room by a well-rested eye of good acuity corresponds approximately to the tolerance dose. Alternatively, they state, such a dose will only occasion barely visible blackening of a duplitized film after about an hour's exposure.

Sievert[27] adopts $1/10$ erythema dose a year as a safe dose, i.e., $1/1000$ erythema dose every three working days.

Solomon[28] expresses the opinion that an erythema dose spread over a time of the order of a year loses all biological significance. On the basis of a 300 working-day year this corresponds to a tolerance dose of 1/1000 erythema dose in 0.3 day.

The Protection Committee of the Dutch Board of Health recommended in May, 1926, that the operator should not receive an erythema dose within 90,000 hours: that is 1/1000 of an erythema dose in fifteen days (of six working hours). The corresponding period suggested for the casual occupants of adjacent rooms is 1.5 days.

Barclay* has recently suggested, on the basis of 2 cases, a figure of 0.284×10^{-3} erythema dose per day for the limit of safety, that is, 1/1000 of an erythema dose in 3.5 working days.

Thus we have the following estimates for the tolerance dose for the operator:

	1/1000 Erythema Dose in
Mutscheller	3 days
Sievert	3 days
Solomon	0.3 days
Dutch Board of Health	15 days
Barclay	3.5 days

We may take a round figure of five days as a mean value, which may be utilized in

---

* Barclay, A. E. *Am. J. Roentgenol. & Rad. Therapy*, 1928, xix, 551.

the following cases, for a fairly busy roentgen-ray department. In the absence of experimental data, we will make use for what it is worth of the formula on p. 79 to derive an approximate estimate of the intensity of the roentgen rays from a bulb in erythema units.

	Roentgenography	Screening	Deep Therapy
Peak voltage on tube	100 kv.	100 kv.	200 kv.
Current	25 ma.	4 ma.	4 ma.
Total exposure per day	5 min.	1 hour	8 hours
Distance of operator from target of tube	5 feet	2 feet	10 feet
No. of erythema doses in 5 days with no protection	1	12	4
To reduce to maximum tolerance dose divide therefore by	1,000	12,000	4,000
Minimum thickness of lead thus required (no scattering). See Table 1	1.2 mm.	2.1 mm.	2.5 mm.

If allowance is made for scattered rays the above thicknesses of lead will be increased to, say, 1½, 2½, and 3 mm. or more. It thus appears that, as far as such evidence goes, the protective values recommended by the English Protection Committee are reasonable and practical. It may be added that Behnken,[29] of the German Reichsanstalt, in a discussion on International Protective Measures in Berlin in 1925 expressed the same opinion from somewhat analogous reasoning.

CHAPTER VIII

MEASUREMENT OF PROTECTIVE VALUES

During the last few years measurements have been undertaken at the National Physical Laboratory* on the absorption of roentgen rays by a variety of protective materials including metals, plasters, bricks, concrete, etc. Transformer currents with peak voltages of 50, 100, 150 and 200 kv. and materials of thicknesses up to an equivalent of 3–4 mm. of lead, were normally employed. The cross section of the roentgen-ray beam and the area over which the transmitted energy was measured were each quite small (except for the more heterogeneous materials where a rather wider beam was employed), so that the results approximate to true absorption figures. If, on occasion, the effect of scattered radiation was also measured, this is stated. The results for each material are shown graphically and the values derived from the smooth curves are set out in Tables I and II.

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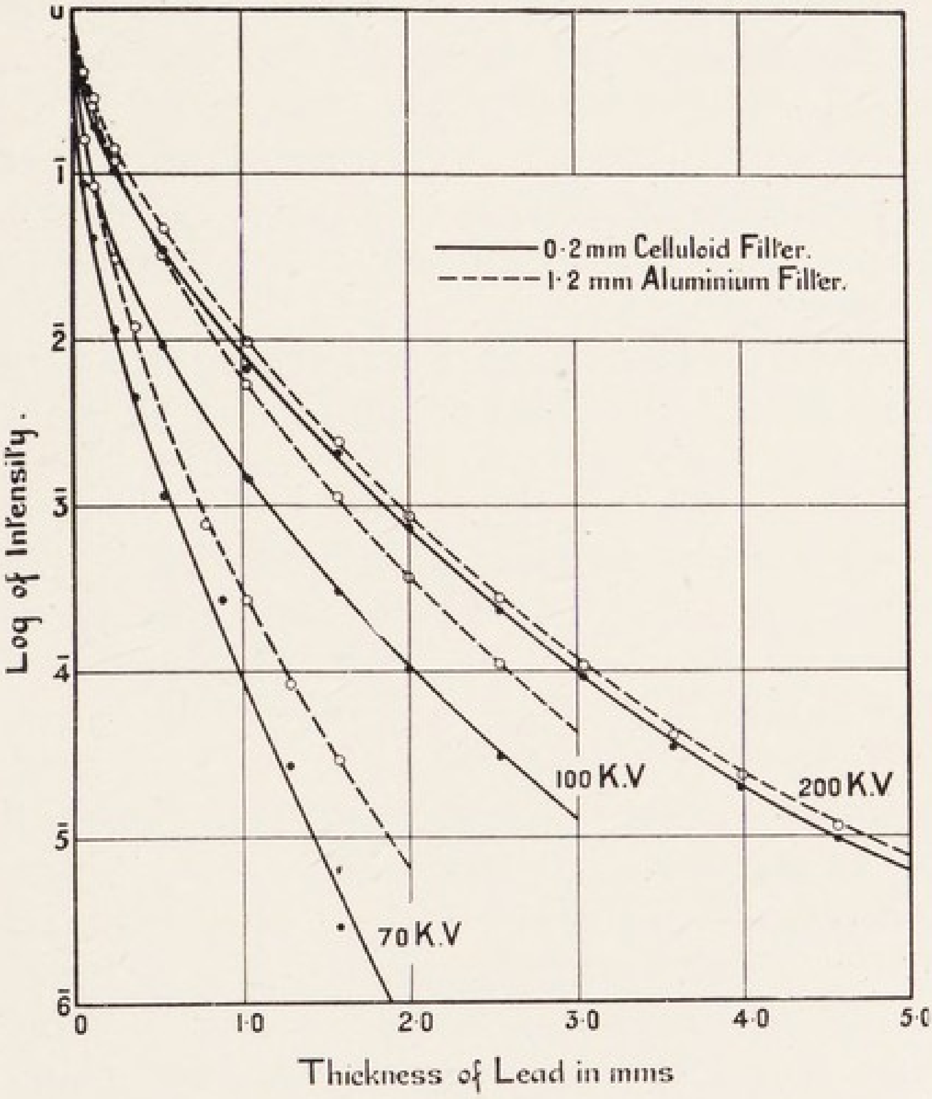
* Some earlier results are given in a paper by Kaye and Owen.[30]

PROTECTIVE METALS AND LEAD COMPOUNDS

Figure 38 and Table 1 show the absorption of roentgen rays by metallic lead



Absorption of X Rays by Lead

FIG. 38.

with a filter of 0.2 mm. of celluloid (that is, virtually no filter) and also with a filter of

1.2 mm. of aluminum. It will be noted that a reduction of intensity to 1/10,000 occurs with a 2 mm. screen at 100 kv., as also with a 3 mm. screen at 200 kv.

The absorption curves for the remaining materials are all referred to lead as a standard, the results being given in Table II. We may conveniently speak of either the lead equivalent or the lead coefficient of a material. These may be defined as follows:

The *lead equivalent* of a material of given thickness is the thickness of lead which has the same absorptive power as the given thickness of material.

The *lead coefficient* of a material is the thickness of lead which has the same absorptive power as unit thickness of the material. The coefficient is often expressed as a percentage.

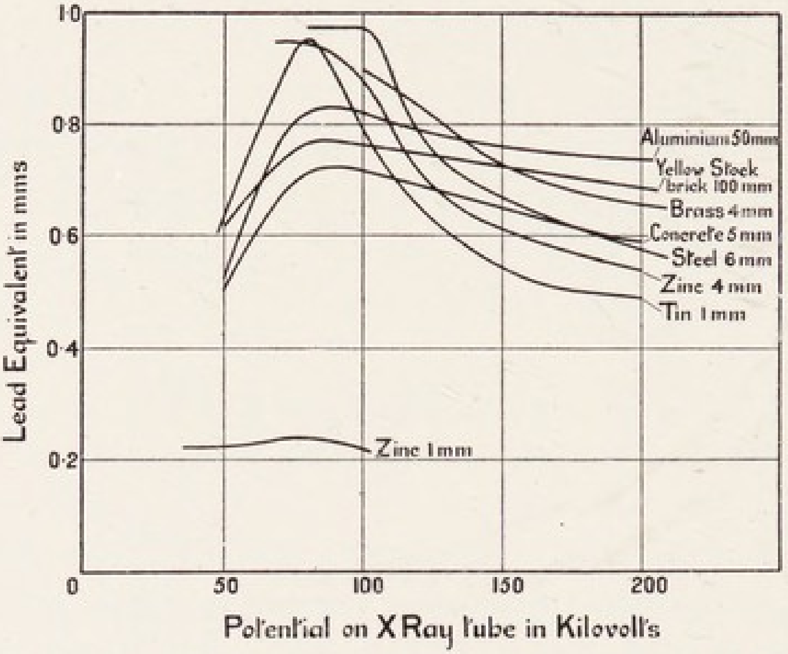
The various results show that, as would be anticipated, the lead equivalents of protective materials depending only on lead or lead salts as absorbents, are proportional to the thickness and do not vary with the exciting voltage. On the other hand, in the case of materials depending on elements lighter than lead as absorbents, it is found that (*a*) the lead equivalents vary with the voltage, reaching a maximum at 80–110 kv.; and (*b*) the lead

Table 1

TRANSMISSION OF ROENTGEN RAYS BY LEAD

Thickness of Lead, mm.	70 Kv.		100 Kv.		200 Kv.	
	X-Rays First Filtered by		X-Rays First Filtered by		X-Rays First Filtered by	
	0.2 Mm. Celluloid	1.2 Mm. Aluminum	0.2 Mm. Celluloid	1.2 Mm. Aluminum	0.2 Mm. Celluloid	1.2 Mm. Aluminum
0	1	1	1	1	1	1
0.2	0.0182	0.0407	0.0502	0.154	0.125	0.180
0.4	0.00325	0.00748	0.0175	0.0573	0.0533	0.0748
0.6	0.000805	0.00213	0.00741	0.0252	0.0264	0.0361
0.8	0.000257	0.000741	0.00343	0.0123	0.0141	0.0194
1.0	0.0000944	0.000294	0.00170	0.00612	0.00791	0.0109
1.2	0.0000391	0.000126	0.000891	0.00321	0.00470	0.00632
1.4	0.0000177	0.0000573	0.000491	0.00177	0.00286	0.00373
1.6	0.00000851	0.0000271	0.000282	0.00103	0.00179	0.00225
1.8	0.00000430	0.0000136	0.000169	0.000617	0.00114	0.00140
2.0	0.00000227	0.00000708	0.000103	0.000380	0.000736	0.000883
2.5	....	....	0.0000336	0.000124	0.000255	0.000294
3.0	....	....	0.0000119	0.0000445	0.0000957	0.000111
3.5	....	....	....	....	0.0000401	0.0000475
4.0	....	....	....	....	0.0000196	0.0000234
4.5	....	....	....	....	0.0000108	0.0000128
5.0	....	....	....	....	0.00000631	0.00000748
5.5	....	....	....	....	0.00000394	0.00000462

equivalents are not in all cases proportional to the thickness, thinner materials usually being relatively more absorbent than thick, the divergence from a linear relation being more pronounced at the higher voltages. In other words, short waves are cut off more effectively by lead than by lighter elements.

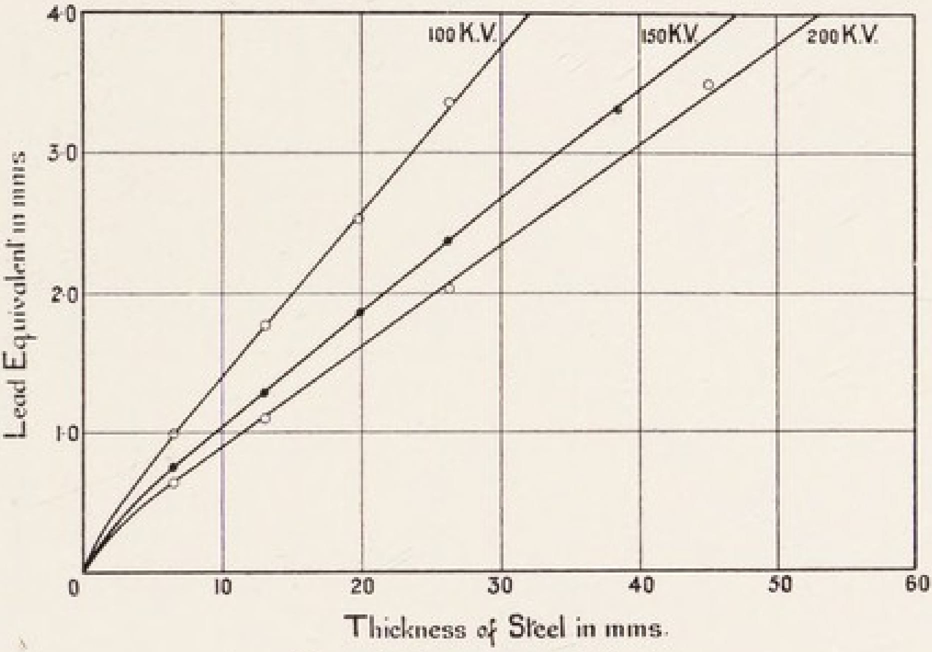


Variation of Lead Equivalent of different materials with voltage

FIG. 39.

The maximum lead equivalent is found to occur at about 90 kv. for all the materials tested, namely, aluminum, steel, brass, zinc, tin, barium sulphate, bricks and concrete (Fig. 39). We are led to look for a common cause in the K discontinuity of lead which occurs at about this voltage.

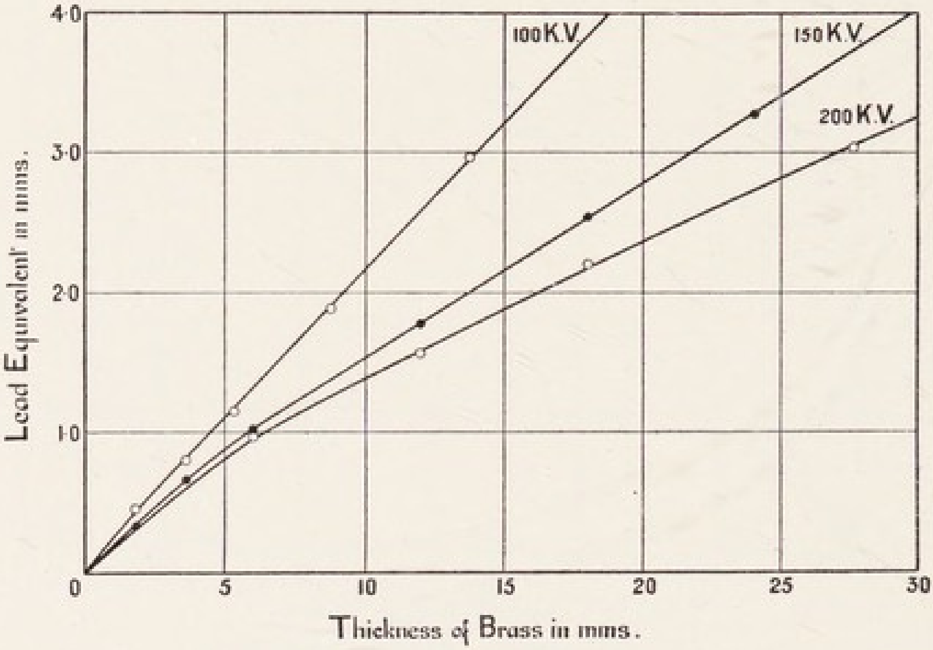
Figure 40 shows the lead equivalent curves for steel, and Figure 41 those for brass of density 8.4, the latter curves being sufficiently representative, for many purposes, of both copper and zinc which are largely used for filters.



Lead Equivalent of Steel

FIG. 40.

Figure 42 incorporates the measurements during the last six years at the National Physical Laboratory of the percentage lead coefficients and densities of several hundred samples of lead glass derived from many sources. The values are the same whether the exciting peak voltage is 100 or 200 kv. The PbO contents range from about 30 per cent to 60 per cent by weight, while the lead coefficients lie between 13 and 26 per cent. Such glasses can all be made clear and virtually colorless. It will

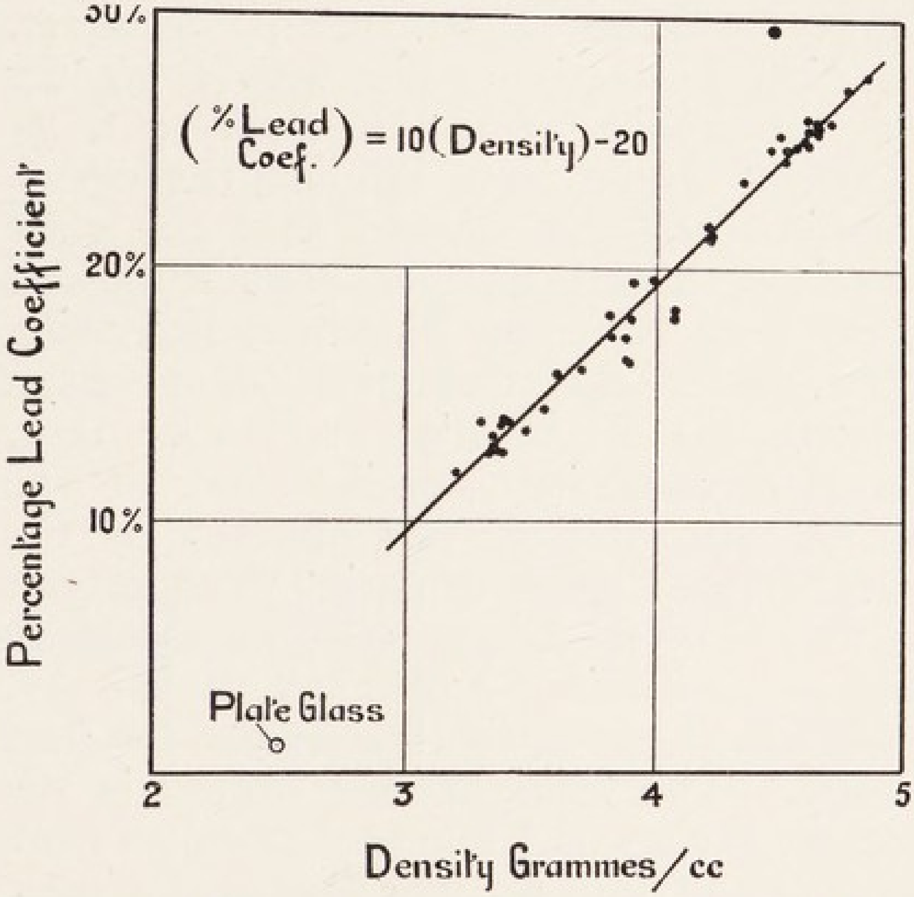


Lead Equivalent of Brass
FIG. 41.

be seen that, in general, there is a linear relationship between the density and the lead coefficient of lead glass as manufactured commercially, and we infer that, from a protection point of view, the lead content dominates the other elements present. The mean straight line of Figure 42 corresponds approximately to the relation:

$$\left(\begin{matrix}\text{percentage lead}\\ \text{coefficient}\end{matrix}\right) = 10\ (\text{density}) - 20$$

which gives us a very simple means of ascertaining the lead coefficients of glasses which owe their protective properties to



Lead Equivalent and Density of Lead Glass.

FIG. 42.

their lead content. If the line is produced, it passes close to the value for metallic lead (density 11.4).

Two points are shown in Figure 42 which are well off the line. One refers to ordinary plate glass of density 2.5, which had only a small proportion of lead in it. The other point refers to a clear, slightly yellowish glass of specific gravity 4.5, which proved to have the exceptionally high lead coefficient of nearly 30 per cent. Moreover, the high protective value was evidently not due solely to the lead present, or the point would have lain on the curve. Chemical analysis showed that the glass contained about 45 per cent PbO and 17 per cent BaO, the baryta contributing of course to the protective value. As a consequence of the high baryta content, the lead coefficient, unlike that of the normal lead glasses, was affected by the voltage, the figure dropping from about 30 per cent to 26 per cent as the peak voltage was raised from 100 to 200 kv.

Figure 43 gives similar results for lead rubber.* The straight line drawn is the average for several hundred samples from a variety of sources. The lead coefficients, which are the same for 100 kv. and 200 kv. peak, range between about 20 and 45 per cent and the specific gravities between about 3 and 6. Values for pure rubber are included, as well as an observation on a sample of lead rubber, with a

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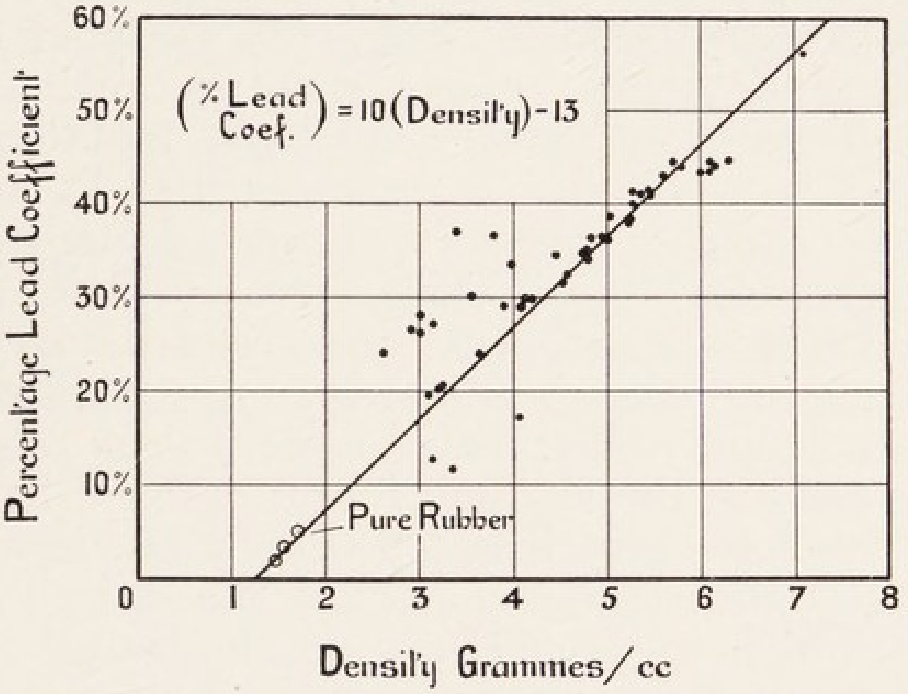
* Martin in 1904 in England, and Meisel in 1906 in Germany appear to have been the first to file patent specifications in connection with the incorporation of lead or other metals into rubber.

specific gravity of 7 and a lead coefficient as high as 56 per cent. This rubber was, however, so heavily loaded as to be brittle and devoid of insulating properties. The samples with the lower lead coefficients do not lie so well on the line as the denser samples. The mean straight line, which if produced passes through the value for metallic lead (density 11.4), leads to the approximate relation for lead rubber:



Lead Equivalent and Density of Lead Rubber.

FIG. 43.

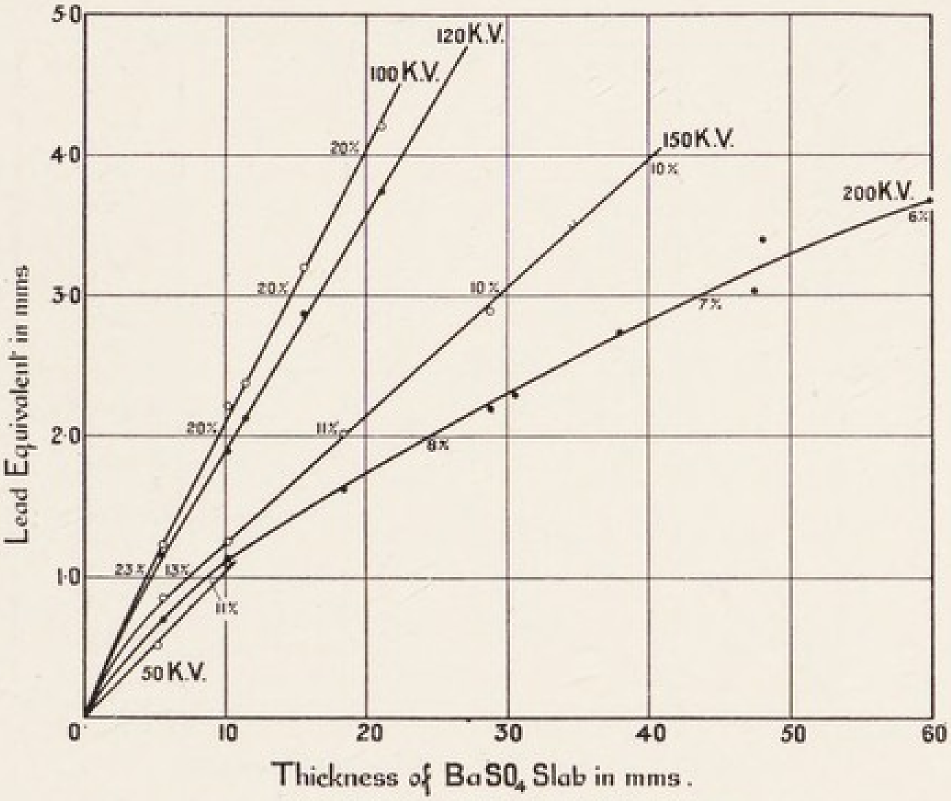
$$\left(\begin{matrix}\text{Percentage lead}\\ \text{coefficient}\end{matrix}\right) = 10\ (\text{density}) - 13$$

PROTECTIVE SLABS AND PLASTERS

The high cost of lead has led to the introduction of various types of protective slabs and plasters consisting of a compound of some heavy metal, such as galena, lead oxide or barium sulphate, together with some binding material such as Portland cement, gypsum (plaster of Paris), magnesium oxychloride, glue, shellac, bakelite, paxolin, wax, or sodium silicate. Sometimes the absorbent is simply packed into hollow walls; for example, galena was so used in the Radium Institute in Paris.

We have experimented at different times with most of these materials, the majority of which are ruled out on the score of cost or for other reasons, such as difficulty of application, or cracking on setting. Portland cement will not set when admixed with galena or the oxides of lead; magnesium oxychloride, plaster of Paris or glue may, however, be used as binders. Litharge also sets with glycerine, the mixture forming a lute which has long been known. Red lead is poisonous and, in common with litharge and galena, does not compete with metallic lead on the score of cost.

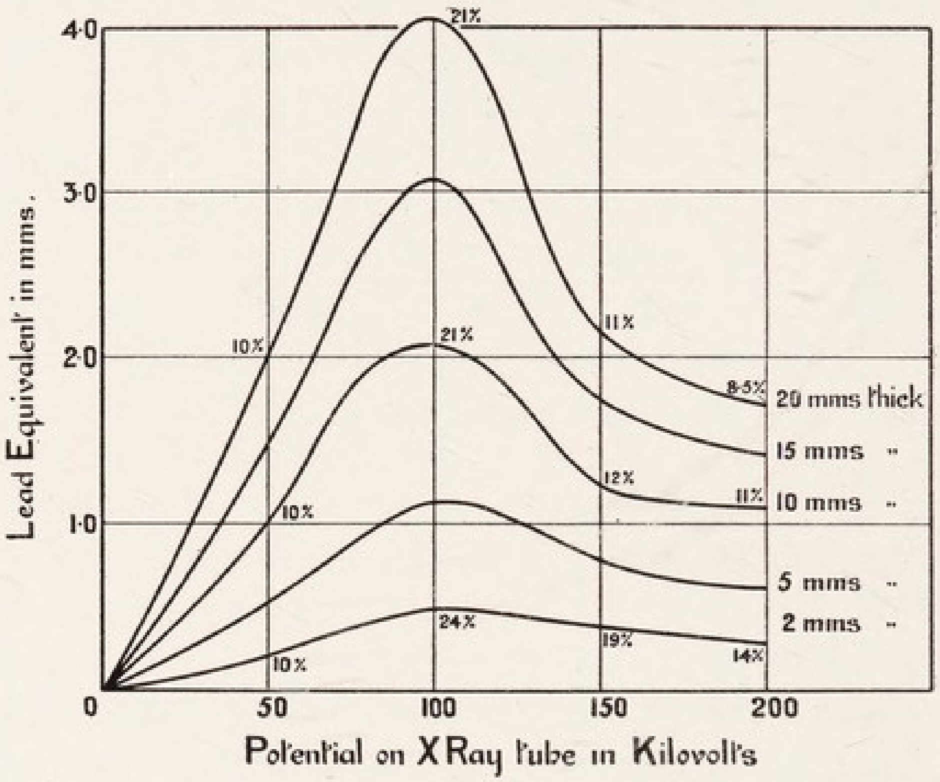
Of the various protective plasters and slabs, those which rest on the use of barium sulphate have found extensive commercial application. Lorey and Kämpe[31] in Germany in 1919 appear to have been the first to manufacture and use building material containing barytes. They were followed by H. Béclère, Chevrotier and Lumière,[32] who in 1922 devised bricks containing 66 per cent by weight of barytes.



Lead Equivalent of 75% (by vol.) $BaSO_4$ Slab.

FIG. 44.

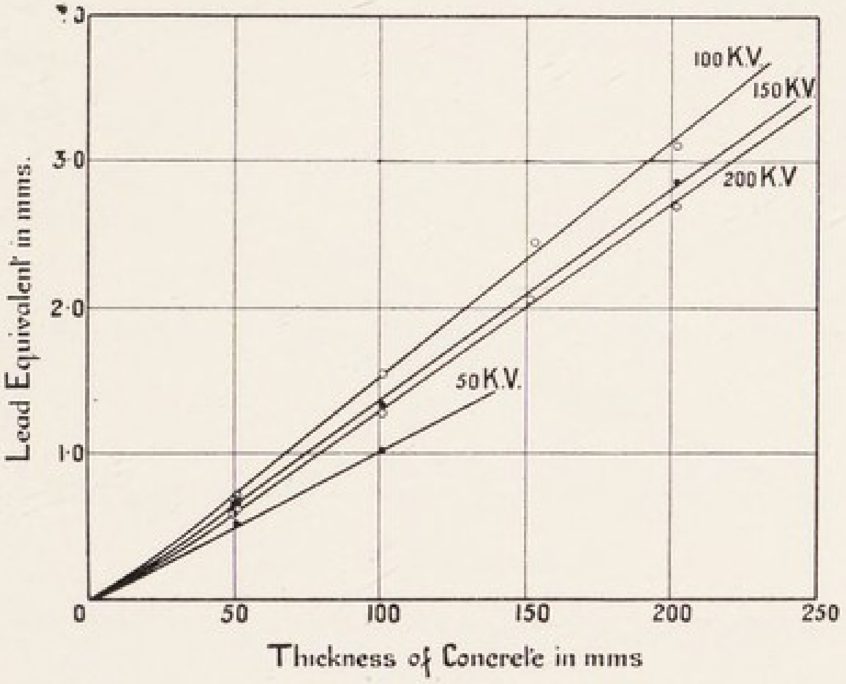
Since then barium sulphate plasters and slabs have been used in a good many hospitals in various countries. For example, a plaster containing 33 per cent of $BaSO_4$ (by volume) was used at the Manchester Royal Infirmary in 1922 and one of 40



Variation of Lead Equivalent of different thicknesses of 75% Barium Sulphate Slabs with different voltages.

FIG. 45.

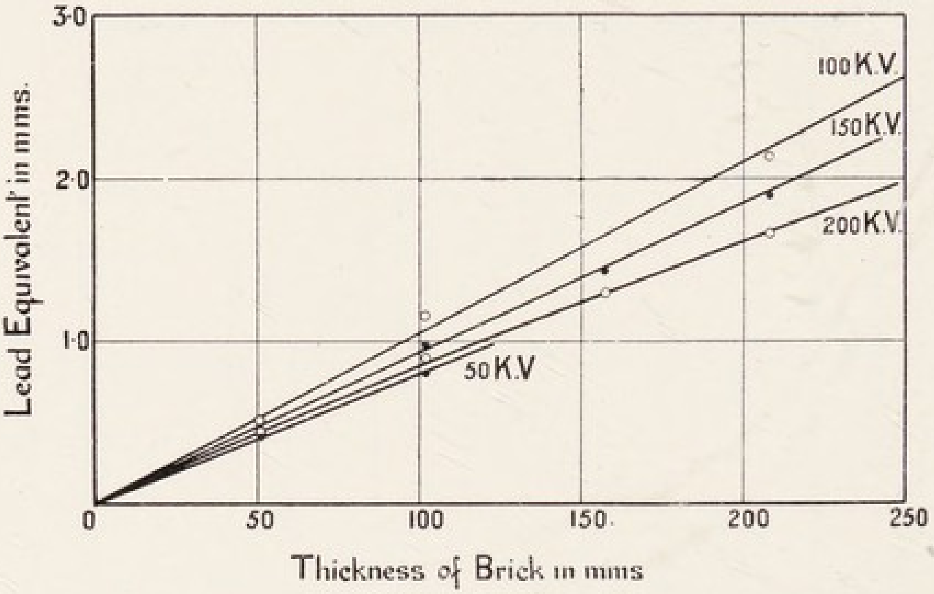
per cent at the Edinburgh Royal Infirmary in 1925. The highest proportion of barium sulphate that will make a satisfactory plaster with the Portland cement binder that is commonly used appears to be approximately 75 per cent by volume (about 85 per cent by weight). The well-known Kämpe-Lorey slabs have approximately this composition. About two-thirds of the barytes should be rather coarse grained to secure good binding qualities with the cement. The remainder should be finely ground to assist in securing uniformity of protection, for which of course good mixing is also essential. The barium plasters are equally suitable for wood or metal laths.



Lead Equivalent of Concrete (4 parts stone chippings. 2 parts washed sand. 1 part cement) Density 2·1 grm/cc

FIG. 46.

Figure 44 expresses the relationship between lead equivalent and thickness of barytes slab (75 per cent $BaSO_4$ by volume) for voltages between 50 kv. and 200 kv.* For all practical purposes we may take it that for voltages up to 120 kv. the lead equivalent is proportional to the thickness,



Lead Equivalent of Red Daneshill Brick Density 1·9 grm/cc
FIG. 47.

but at 200 kv. the greater thicknesses are relatively less effective than the smaller doubtless owing to the increased scattering, e.g., at 200 kv. the lead equivalent of a 10 mm. slab is 1.1 mm; of a 60 mm. slab 3.7 mm. We see, too, that the lead equivalent curve is steepest at 100 kv., the values being less for voltages both higher and lower than this, e.g., the lead equivalents for a 10 mm. slab are 1 mm. at 50 kv., 2.1 mm. at 100 kv.; and 1.1 mm. at 200 kv.

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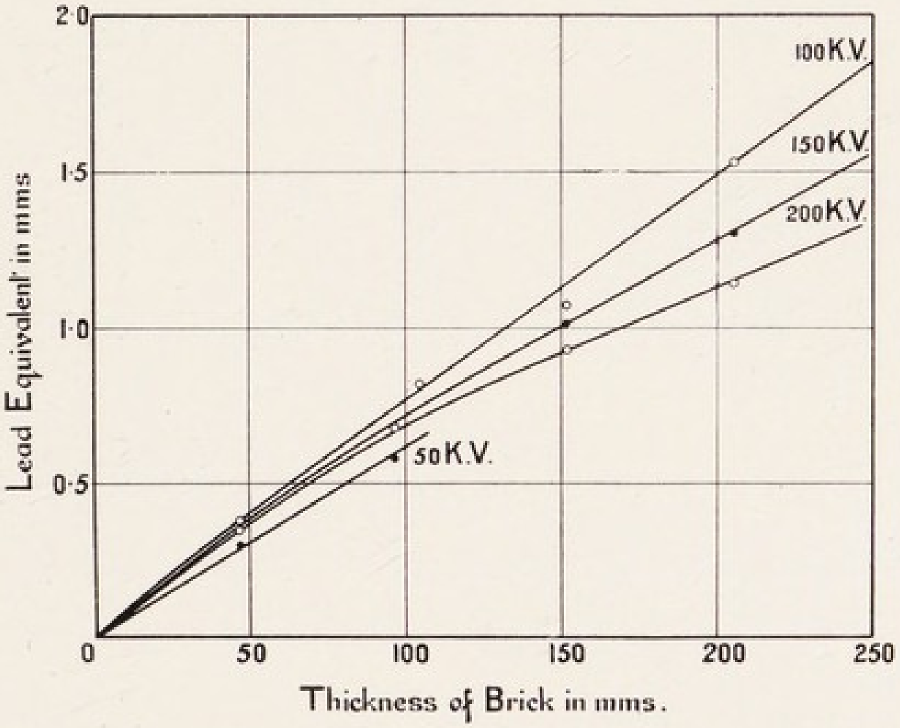
* A preliminary account of this was given in a paper before the First International Congress of Radiology in 1925. See Kaye.[33]

This maximum value at 100 kv. is also clearly displayed in Figure 45, the explanation doubtless being, as already remarked, the existence of the K discontinuity of lead at about 90 kv. emphasized by that of barium at about 40 kv. The percentage lead coefficients are indicated on the curves of Figures 44 and 45 at various points.



Lead Equivalent of Yellow Stock Brick Density 1·5 grm/cc.

FIG. 48.

In Table 11 the equivalent thickness of barium plaster should be increased by an amount up to 40 per cent if scattered radiation is to be allowed for. It may be noted that of two walls affording protec-

TABLE II. ROENTGEN-RAY

Material	Mean Density
	Gm./c.c.
Aluminum	2.7
Brass	8.4
Steel	7.8
Lead Glass	4.6 to 3.4
Lead Rubber	5.8 to 3.3
Barium Plaster	3.5
2 parts coarse $BaSO_4$	...
1 part fine $BaSO_4$	...
1 part Portland cement	...
Concrete	2.1
4 parts Stone Chippings	...
2 parts Sand	...
1 part Cement	
Concrete	1.5
4 parts Clinker	...
1 part Cement	
Concrete	2.1
4 parts Granite	...
1 part Cement	...
Coke Breeze	1.2
Daneshill Brick (red)	1.9
Stock Brick (yellow)	1.5

PROTECTIVE MATERIALS

Lead Equivalent	Equivalent Thickness of Material in Mm.			
	50 Kv.	100 Kv.	150 Kv.	200 Kv.
Mm.	Mm.	Mm.	Mm.	Mm.
1	96	60	65	70
2	.....	120	130	140
3	.....	180	195	210
1	6.5	4.5	6.0	6.5
2	.....	9	13.5	16
3	.....	14	21.5	27
4	.....	19	30	40
1	11.5	6.5	9.5	11.5
2	.....	15	21.5	25
3	.....	23.5	34	39
4	.....	32	47	53
1	4 to 7.5			
2	8 to 15			
3	12 to 22.5			
4	16 to 30			
1	2 to 5			
2	4 to 10			
3	6 to 15			
4	8 to 20			
1	10	4	7.5	9
2	.....	9	18	25
3	.....	14.5	29	43
4	.....	20	41	65
1	100	70	75	80
2	.....	130	145	150
3	.....	190	215	220
1	135	100	105	110
2	.....	200	210	220
1	110	70	80	85
2	.....	145	160	170
3	.....	215	240	260
1	200	110	.....	130
2	.....	220	.....	270
1	125	100	110	120
2	.....	200	220	250
1	170	130	150	170
2	.....	280	350	450

tion equivalent to 3 mm. of lead, one of metallic lead (density 11.4), the other of barium plaster (mean density 3.5), the latter will weigh about half as much again for 100 kv., and between 4 and 5 times as much for 200 kv. These ratios will be increased if allowance is made for scattering and the possibility of faulty mixing.

Figures 46, 47 and 48 give corresponding curves for a concrete and two different kinds of brick. The various thicknesses given in Table II should be increased by an amount up to about 30 per cent if scattering is allowed for.

CHAPTER IX

WORKING CONDITIONS IN ROENTGENOGRAPHIC DEPARTMENTS

In view of the accidents which have occurred in the past, the British Protection Committee was led to stress the dangers of high voltages, particularly with modern high-powered constant-potential outfits which utilize large condensers. Such dangers are minimized by the use of large and lofty rooms, the floors of which are covered with insulating material such as cork or rubber. Coronaless tubing at a height of not less than 9 ft. is recommended for the overhead conductors. There should be no dangling wires from the overhead conductors, and rheophores should have springs equal to keeping the connecting wire always taut. All metal parts of an apparatus or room should be grounded unless the considerations forbid. Earthed guard shields should be provided where possible for the more accessible parts of the high tension current. Switches should not be closed without ascertaining that nothing untoward is likely to occur. Other more detailed matters are also dealt with in the report.

Incidentally, there are many advantages from the point of view of noise, as well as ventilation, in mounting rotating machinery, and as much as possible of the high tension equipment, in an adjacent room. Switching on roentgen rays should be as devoid of incident for the patient as turning on an electric lamp.

VENTILATION, ETC.

The question of adequate ventilation has assumed an importance second only to that of protection, for the gases generated by high tension roentgen-ray equipment are responsible for much of the lassitude, debility, headaches and anemia experienced by many workers. Rooms should be spacious and lofty: the minimum area may well be taken as about 250 sq. ft. with a height not less than 11 ft.

But, as we have repeatedly noticed in our inspection work, large airy rooms are not in themselves sufficient, for it is difficult to make a roentgen-ray outfit completely coronaless, particularly at high voltages, and the high tension discharge speedily vitiates the air to an extent which calls for very efficient ventilating arrangements. Natural ventilation, even if ordinarily good, is rarely adequate for roentgen-ray rooms and moreover is apt to be unsatisfactory on windy, stagnant or very cold days. In any case, such ventilation is usually put out of action if the room is darkened. Artificial ventilation is practically always necessary for roentgen-ray and dark rooms and control cubicles.

In general, exhaust ventilation is to be preferred to pressure ventilation. A general ventilating scheme with ducts leading from the different rooms to a main air channel and a common fan is often likely to have its even distribution disarranged by an untoward opening of doors or windows, with the result that one room may get more than its share of fresh air at the expense of other rooms. If the conditions permit the windows to be opened widely so that fresh air may enter in abundance, this is to be encouraged but, to avoid the possibility of interfering with the ventilation of neighboring rooms, it may be better to fit each room with its independent ventilating arrangements. The initial outlay and running costs will, of course, be heavier.

In our experience the most effective and reliable form of ventilation for roentgen-ray and dark rooms is to provide each room with its own suction fan or fans, each fan to have its own outlet and to be mounted so as to extract air from near the ceiling, fresh air entering from without by inlets placed 2 or 3 feet from the floor and so placed as to secure crosswise ventilation. By this means the operators are working at a level where the air is freshest and less admixed with vitiated air. A number of distributed inlets should normally be provided and the area of both inlets and outlet should be ample, the total area of the former being several times that of the latter. The incoming air should, if necessary, be warmed by radiators or the like in cold or damp weather. Cooling would be equally desirable in hot weather if it were possible.

As a rule, we do not find roentgen-ray rooms with the ventilating arrangements reversed—i.e., with the suction outlet at low level and the inlets near the ceiling—to be so satisfactory. This latter arrangement is sometimes advocated in view of the fact that the deleterious gases produced by the high-tension discharge are somewhat heavier than air; but it is contrary to theory to anticipate that in such circumstances gravity would exercise any appreciable influence on the proportions of the gases present. On the contrary, the first tendency of the gases in question will usually be to rise rather than fall, owing to the warmth which may accompany their generation. This applies also to the products of respiration, and experience suggests that the direction of flow of the incoming air should also be upwards.

The enclosed-propeller type of fan is usually satisfactory. It should be quiet in running. Frequently the fan installed is under powered; its capacity should be such as to scavenge and renew completely the air throughout a room in about 5 or 6 minutes. This should be borne in mind when heating arrangements are being planned. A perceptible movement of the air, if it is not too cold, is pleasant and beneficial, provided the speed is not such as to cause draughts. According to the pamphlet on "Ventilation of Factories and Workshops" issued by the Home Office in England, the speed of the incoming air should not normally exceed 250 feet per minute. Incidentally, in some rooms both inlets and outlet may require to be light trapped, and the outlet may need to be shielded externally if the prevailing winds are unfavorable.

As regards the temperature of roentgen-ray departments, the work of Leonard Hill in England and of the U. S. Public

Health Service indicates that, on the whole, human activity reaches its height at temperatures in the region of 18°C. or 65°F. It is claimed that, under such conditions, there is least sickness, fewest accidents, metabolism is at its lowest and comfort is at a maximum. A rise of temperature above the optimum is more adverse to activity than a fall.

One of the traditions which dies hard in the majority of countries is the placing of roentgen-ray departments in basements. Much, of course, depends on the kind of basement, but, in general, roentgen-ray departments are far better placed at a higher level where, if properly designed and situated, they are sure of such sunshine as occurs, where the natural lighting and ventilation are more likely to be good and where it is more readily possible to open the windows at any time without sacrificing privacy or allowing dust to blow in from the ground level. Few basement sites permit these desiderata. Furthermore, on certain days of the year the normally somewhat lower temperature of basements may lead to prejudicial deposition of moisture on high-tension apparatus. If a building is of several stories, the top floor has much in its favor, as the protection of adjacent floors is simplified.

Top natural lighting is preferred by some workers, but is sometimes troublesome to darken and in our experience does not normally contribute so agreeably to the amenities of a room as do ordinary windows. Such windows, except where other considerations forbid, may well be of generous dimensions with clear glass and low sills so that the operator does not feel "cribbed, cabined and confined," a sensation apt to be fostered when top lighting alone is employed. A sunny aspect is preferable to north lighting which offers no advantages for roentgen-ray rooms.

The roentgen-ray department should be as bright and cheery in its scheme of decoration as any hospital ward. The dark room should be no exception; with good safe lights it is unnecessary to blacken the walls and ceiling for routine work. There should be a standing rule that roentgenographic, screening and developing rooms should be opened up to daylight and fresh air directly they are not in use. To this end, the shutters or dark blinds should be of a quick acting type which are not troublesome to operate. Developing rooms are often much too small: when a new department is being designed, not less than 100 to 150 square feet should be allotted to the dark room, and much more for a large department.

The Committee also made recommendations as to the working hours of whole-time roentgen-ray and radium workers and suggested a seven hour working day, a five day week (Sundays and two half-days off duty) and holidays amounting to a month in a year. The importance of an outdoor life when off duty was urged.

Finally, the fire risks with ordinary celluloid films are not negligible, and attention should be paid to ensure proper measures for storage and drying.

As an illustration of the value of the recommendations, I may cite the new roentgen-ray department at the Royal Infirmary, Edinburgh, probably the largest and finest example of its kind in Europe at the present time. Great care was taken in its design and equipment to conform to the recommendations of the Protection Committee. Dr. Woodburn Morison, the head of the department, permits me to quote the following:

> "The health of the workers in the new Radiological Department has been excellent, and it is particularly noticeable in the case of the old workers who, for so many years, were working under bad conditions, not only as regards protection from X-radiations, but as regards the light and ventilation of the Department. The case of Mr. W. Law, the senior lay

radiographer, is an excellent example. He began work in the old X-ray department of the Edinburgh Royal Infirmary in 1900, at the age of 16. For years his average weight was 9 st. and his health indifferent, except during holidays. He was on active war service from August, 1914 until March 1919, doing no X-ray work and living an open air life. His weight increased during this time to 11 st. 4 lbs. and his health was good. After the war he returned to the old X-ray Department and was working under the old conditions. He gradually lost weight until he reached his old average weight of 9 st. We transferred to the new Radiological Department in August 1926, and since then he has gradually put on weight and at the present time (July 7, 1927) is 11 st. 4 lbs., the weight which was his average during active service. With the increase in weight there has been a very noticeable improvement in his general health.

"I attribute this in the first place to the efficient protection of the apparatus and the building; in the second place to the efficient lighting and ventilation of the whole department; in the third place to the working hours not more than seven per day—Saturday afternoon, Sunday and one half day in the middle of the week off work. Also one month's holiday during the course of the year. It practically amounts to this that we have endeavoured to carry out in full the recommendations of the Protection Committee; not only as regards the protection of the instruments and the building, but what I think is equally important, the recommendations regarding the hours of work and holidays for all those engaged in X-ray work."

Other examples could be adduced, but this I think will serve.

To sum up, the Protection Committee concludes that "the dangers of over-exposure to X-rays and radium can be avoided by the provision of efficient protection and suitable working conditions." Radiology is, in fact, no more dangerous, under proper conditions, than scores of other professions. All honor to the pioneers for taking the risks they did in the service of humanity, but it is only too true that those risks need never have been taken had the knowledge been available as it is now.

It is not, however, in the interests of roentgenology that new cases of even minor casualties should be allowed to occur in the future through faulty working conditions. A succession of such casualties is bound to react unfavorably on the public (already a little uneasy), on other branches of the profession and, even more deplorable, on potential entrants to a radiological career. Furthermore, the ignorant, the inexperienced, the indifferent, the irresponsible, the scoffer and the foolhardy should be taught by practice and precept to realize that, apart from their own interests, such casualties are prejudicial to their fellow workers in that they tend to stiffen the backs of the insurance companies who, on both sides of the water, are, I understand, already somewhat disposed to consider roentgen-ray workers as abnormal risks.* We may consider such an attitude as unreasonable, but it is bound to take time to dispel, and it is obviously not only a duty, but good from every point of view that roentgenologists in charge of roentgen-ray departments should face the situation by allowing no loophole, and err, if need be, on the side of safety rather than by being content with the bare minimum of protective measures.

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* For example, see Melville.[34]

Chapter X

FUTURE OF ROENTGENOLOGY

To conclude, while the Protection Committee has attempted to outline an ideal set of working conditions, it is fully realized that, as time goes on, experience may indicate more clearly than we know now, in what directions, if any, some relaxation of the recommendations may be expedient and desirable.

The three phenomena of the differential absorption of roentgen rays by various kinds of matter, the biological effects of the rays and the diffraction of the rays by crystalline solids have already been turned to account in the arts, sciences and industries in many directions. The diversity of the applications of the roentgen rays has indeed become such that one scarcely envies the task of the future student of the subject. Specialization will become inevitable, as is apparent from the immense literature that has already come into being from the activities of the large body of workers who have been attracted by the various problems to which roentgen rays are being applied, whether medical, scientific or technical.

Our knowledge of the ultimate structure of the solid state of matter already owes more to roentgen-ray analysis than to any other means. As to the value of roentgenography to the surgeon, it is surely almost incalculable. On the biological side it would seem that, while wonderful results are achieved from time to time in therapy, progress is somewhat hampered by a number of factors. Quantitative measurements and physical units in which to express them will be bound up with future developments, despite the fact that the physics of such work is apt to be embarrassed by the power of selection and choice exhibited by the living cell. In the opinion of some authorities roentgenology in the future is likely to find its biggest field of development in the science of biophysics;* and closer cooperation between the roentgenologist and the physicist is bound to come. Of material assistance in this connection will be the establishment at the Second International Congress of Radiology at Stockholm in 1928 of the "Röntgen," the physical unit of X-ray intensity.

We may confidently look forward to continued progress in roentgenology, the developments of which, we are proud to think, have exerted in the past no small influence on the progress of civilization.

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* For example, see Rolleston.[24]

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APPENDIX A

RECOMMENDATIONS OF THE BRITISH X-RAY AND RADIUM PROTECTION COMMITTEE

THIRD REVISED REPORT

(May, 1927)

Chairman

Sir Humphry Rolleston, bt., k.c.b. (Regius Professor of Physic in the University of Cambridge; Past President of the Royal College of Physicians).

Members

Nominated by the British Institute of Radiology.

Robert Knox, m.d., m.i.e.e. (The Cancer Hospital (Free)).

Nominated by the Royal Society of Medicine.

Stanley Melville, m.d. (St. George's Hospital).

S. Gilbert Scott, m.r.c.s., l.r.c.p. (London Hospital).

Nominated by the Röntgen Society.

CUTHBERT ANDREWS, Esq.
G. HARRISON ORTON, M.D. (St. Mary's Hospital).

Nominated by the Institute of Physics.

Prof. SIDNEY RUSS, D.SC. (Middlesex Hospital).

Nominated by the Radium Institute, London.

J. C. MOTTRAM, M.B.

Nominated by the National Physical Laboratory.

G. W. C. KAYE, O.B.E., M.A., D.SC.

Co-opted.

A. E. BARCLAY, O.B.E., M.A., M.D. (University of Manchester).
C. THURSTAN HOLLAND, D.L., CH.M. (University of Liverpool).
J. M. WOODBURN MORISON, M.D. (University of Edinburgh).

Hon. Secretaries

STANLEY MELVILLE, M.D.
Prof. SIDNEY RUSS, D.SC.

At 32, Welbeck Street, London, W.1.

With the object of arresting the sequence of casualties to roentgen-ray and radium workers, the X-ray and Radium Protection Committee was formed in 1921 as the result of co-operative action between the Royal Society of Medicine, the Röntgen Society, the British Association for the Advancement of Radiology and Physiotherapy (now the British Institute of Radiology), the Institute of Physics, the Radium Institute and the National Physical Laboratory. The scope of the Committee was afterwards widened to include representatives from the provincial schools.

The Committee issued its first recommendations in July, 1921. A revised Report followed in December, 1923. The present (third) Report contains a number of alterations and additions based on the experience of the Committee and of the National Physical Laboratory in its inspection and testing work carried out in association with the Committee.

Copies of the Report may be had on application to the Hon. Secretaries of the Protection Committee or the Director, The National Physical Laboratory, Teddington, Middlesex.

INTRODUCTION

1. The danger of over-exposure to roentgen 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:

(*a*) Visible injuries to the superficial tissues, which may result in permanent damage.

(*b*) Derangements of internal organs and changes in the blood. These are especially important, as their early manifestation is often unrecognised.

PROTECTIVE MEASURES

2. It is the paramount duty of those in charge of roentgen-ray and radium departments to ensure efficient protection and suitable working conditions for the personnel. The protective measures recommended are dealt with under the following sections:

i. Roentgen rays for diagnostic purposes.
ii. Roentgen rays for superficial (low-voltage) therapy.
iii. Roentgen rays for deep (high-voltage) therapy.
iv. Electrical precautions in roentgen-ray departments.
v. Ventilation, lighting, etc., of roentgen-ray departments.
vi. Roentgen rays for industrial and research purposes.
vii. Radium therapy.
viii. Ultra-violet therapy.
ix. General.

3. 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.

4. The Protection Committee realise that in a busy roentgen-ray department the precautions should be more elaborate and extensive than in one where the apparatus is only occasionally used. There is, however, as yet no agreed unit of roentgen-ray intensity or standard method of measurement. There are, moreover, difficulties in the way of providing for widely varying conditions by a system of "graded" protection. The Committee's recommendations are accordingly framed with a view to ensuring adequate protection for the operator no matter to what extent an apparatus is used.

5. It should further be pointed out that the protective values of certain materials are much affected by a change in the voltage applied to the roentgen-ray tube. This applies particularly to materials in which lighter elements than lead furnish the chief protection. The importance of obtaining a National Physical Laboratory test in this connection is emphasised. In

the case of protective slabs or plasters made up of a mixture of materials, the difficulty of securing uniform mixing should be met by a generous margin of safety in estimating the required thickness.

6. It cannot be insisted upon too strongly that a primary precaution in all roentgen-ray work, whether with stationary or portable sets, is to surround the roentgen-ray bulb itself as completely as possible with adequate protective material, except for an aperture as small as possible for the work in hand. Wherever possible the roentgen-ray bulb should be so placed that the target points away from the operator's controls. If a ventilated tube-box is used the ventilation holes should be suitably baffled with protective material. If adjoining rooms are occupied the protection in the path of the emergent roentgen-ray beam may need attention. The value of distance as a protective measure should naturally be turned to account whenever possible.

7. The following working conditions are recommended for whole-time workers:

(*a*) Not more than seven working hours a day.

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

(*c*) An annual holiday of one month or two separate fortnights.

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

I. X-RAYS FOR DIAGNOSTIC PURPOSES

(A) Screen Examinations

8. 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 should be as expeditious as possible.

9. The roentgen-ray bulb should be enclosed as completely as possible with protective material equivalent to not less than 2 mm. of lead. The material of the diaphragm should be equivalent to not less than 3 mm. of lead. The design of the diaphragm should be such as to permit it to be completely closed. The rectangular diaphragm only should be used. To prevent the lateral escape of direct radiation, the diaphragm should be fitted within an enclosure, the sides of which should be completely closed with protective material. In the case of installations which are incapable of generating peak voltages exceeding 70,000, the lead value of the

tube enclosure may be reduced to 1.5 mm. and of the diaphragm to 2 mm.

10. The fluorescent screen, attached as a permanent fitting to screening stands, etc., should be fitted with lead glass equivalent to not less than 2 mm. of lead. This figure may advantageously be increased to 3 mm. wherever practicable. In all positions the lead glass should be large enough to cover the area irradiated when the diaphragm is opened to its widest. For screens of smaller area, the lead glass should be mounted in a frame of protective material which overlaps the screen and is of adequate width and thickness to afford protection in all positions of the screen. In the case of portable screens the lead glass should have an equivalent of not less than 2 mm. of lead. As far as possible the glass should be of uniform thickness and free from striations and air bubbles.

11. To afford protection from scattered radiation in the case of a couch, a protective screen, mounted on the carriage and of material equivalent to not less than 2 mm. of lead, should be employed between the operator and the roentgen-ray box. This screen should have a width of not less than 2 feet and should project sufficiently above the couch to afford adequate protection for the operator. In addition, a

device such as a "collar" of protective material between the tube box and the underside of the couch is effective. In the case of a screening stand, an "apron" of protective material of not less than 1 mm. lead equivalent should be attached to the lower edge of the screen.

12. Protective gloves should be of lead, rubber (or the like) as flexible as possible and should afford protection for both back and front of hand (including fingers and wrist). The protective value should be not less than ½ mm. of lead. Gloves should preferably 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.)

13. In those cases where the necessity is felt for even greater protection for the operator, goggles and aprons may advantageously be worn. The glass of the goggles should have a lead value not less than ¼ mm.; aprons should have lead values not less than ½ mm.

(B) Roentgenographic Examinations ("overhead" equipment)

14. The roentgen-ray bulb should be enclosed as completely as possible with

protective material equivalent to not less than 2 mm. of lead. This figure may be reduced to 1.5 mm. in the case of installations which are incapable of generating peak voltages exceeding 70,000. A sheet of mica, asbestos or the like should be mounted below the bulb.

15. The operator should be behind a protective screen as remote from the roentgen-ray bulb as is convenient. The material of the screen should be equivalent to not less than 2 mm. of lead. In general, such screens should not be less than 3 ft. 6 in. wide and 7 ft. high and should extend to within 1 inch of the ground. If an inspection window is provided, its lead equivalent should not be less than 2 mm. Its dimensions need only rarely exceed 9 in. × 6 in.

II. ROENTGEN RAYS FOR SUPERFICIAL (LOW-VOLTAGE) THERAPY

16. The definition of superficial therapy is considered to cover sets of apparatus giving a maximum peak voltage of 100,000 (15 cm. spark gap between points; 5 cm. spark gap between spheres of diameter, 5 cm.). It is difficult, however, to define the line of demarcation between superficial and deep therapy. For this reason it is recommended that, in the reorganization

of existing, or the equipment of new roentgen-ray departments, small cubicles should not be adopted, but that the precautionary measures suggested for deep therapy should be followed.

Cubicle System

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

(*a*) The cubicle should be well lighted and ventilated, and provided with an exhaust fan in an outer wall or chimney shaft. The controls of the roentgen-ray apparatus should be outside the cubicle.

(*b*) The roentgen-ray bulb should be enclosed as completely as possible with protective material equivalent to not less than 2 mm. of lead. This figure may be reduced to 1.5 mm. in the case of installations which are incapable of generating more than 70,000 volts. A sheet of mica, asbestos or the like should be mounted below the bulb.

(*c*) The walls of the cubicles should preferably not take the form of partitions, but should extend from floor to ceiling. If partitions are adopted, they should be not less than 9 feet in height and extend to floor level.

(*d*) Where necessary the walls (and doors), floor and ceiling of the cubicle should be of material equivalent to not less than 2 mm. of lead. Inspection windows should be of high quality lead glass of equivalent thickness. They need only rarely exceed 9 in. × 6 in. in dimensions. Care should be taken that the protective material overlaps at joints. It may be noted that, for peak voltages of 100,000, 5 inches of solid concrete or 10 inches of solid brickwork (yellow stock) are approximately equivalent to 2 mm. of lead.

III. ROENTGEN RAYS FOR DEEP (HIGH-VOLTAGE) THERAPY

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

18. The room should be large, lofty and well-ventilated, with good natural lighting. It should be provided with an exhaust fan communicating with an outer wall or chimney shaft. Small cubicles are not recommended.

19. The roentgen-ray bulb should be enclosed as completely as possible with protective material equivalent to not less than 3 mm. of lead. This figure may advantageously be increased to 4 mm. for peak voltages exceeding 150,000 (see paragraph 20). A sheet of mica, asbestos or the like should be mounted below the bulb.

20. The controls of the roentgen-ray apparatus should be outside the room. Additional protection should be afforded to the operator and, where necessary, to the occupants of any adjoining rooms, through the medium of the appropriate walls (and doors), floor and ceiling. This protection should be equivalent to not less than 2 mm. of lead, but should be increased, if necessary, to ensure that the total protection (including the tube-box) is equivalent to not less than 5 mm. of lead for peak voltages up to 150,000 volts, and not less than 6 mm. for peak voltages up to 200,000 volts. (See paragraph 19.) Inspection windows should be of high-quality lead glass of equivalent thickness. They need only rarely exceed 9 in. × 6 in. in dimensions. Care should be taken that the protective material overlaps at joints. It may be noted that for peak voltages of 200,000, 6 inches of solid concrete or 16 inches of solid brickwork (yellow stock) are approximately equivalent to 2 mm. of lead.

IV. ELECTRICAL PRECAUTIONS IN ROENTGEN-RAY DEPARTMENTS

21. Attention should be paid to the dangers of high voltages, particularly with present-day high-powered plants.

The floor area should be large enough to permit a convenient lay-out of the equipment. Wooden floors are suitable; existing concrete or similar floors should be covered with linoleum or rubber.

22. Stout metal tubes or rods terminating in spheres should be used instead of wires for overhead conductors. Overhead conductors should not be less than 9 feet from the floor level. The provision of thick-walled insulating tubing or an earthed "guard" to shield the more adjacent parts of the high-tension system is recommended. The connecting leads from the overhead conductors to the roentgen-ray tube should be brought down in positions as remote as possible from the operator and the patient. Thickly insulated wire is preferable to bare wire. Slack, looped or low-hanging wires should be avoided. Small spring tapes should be replaced by rheophores of robust design with heavily insulated wire, and springs of adequate strength.

23. All metal parts of the apparatus and room should be efficiently earthed. Main and supply switches should be very accessible and distinctly indicated. They should not be in the proximity of the high-tension system, nor should it be possible to close them accidentally. 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, together with quick acting double-pole circuit breakers. The possibility of unemployed leads to the high-tension generator should be prevented by interlocking high-tension switches or the like. In the case of some of the constant-potential generators, a residual charge is held by the condensers after shutting down. A suitable discharging device should therefore be fitted.

24. Adequate means for the measurement of high voltage should be installed, *e.g.*, kilovoltmeter, sphere-gap voltmeter, or the like. Spark gaps (preferably of the sphere type) should be furnished with cm. or inch scales, together with a voltage scale. The spark gaps should be situated in positions where they can easily be read and adjusted while the tube is in operation.

V. VENTILATION, LIGHTING, ETC. OF ROENTGEN-RAY DEPARTMENTS

25. It is strongly recommended that the roentgen-ray department should not be below the ground level. In general, ceilings should not be less than 11 feet in height. The presence of steam-piping and the like must be allowed for. Damp

rooms should be avoided. The heating arrangements should be adequate.

26. The importance of adequate ventilation in both roentgen-ray and dark rooms is supreme. Exhaust-fan ventilation is recommended in all cases. With very high potentials coronal discharges are difficult to avoid, and these produce ozone and nitrous fumes, which are prejudicial to the operator. Rotating rectifiers often require the provision of a special ventilating duct or like measure. Unenclosed rectifying spark gaps are better replaced by enclosed types. If vacuum valves are used, the fact that they may produce roentgen-rays should not be lost sight of.

27. Roentgen-ray departments should be well lighted, and all rooms, including dark rooms, should be capable of being readily opened up to sunshine and fresh air when not in use. The walls and ceilings of all rooms, including dark rooms, are best painted some light hue. Dark rooms should not be cramped in dimensions.

VI. ROENTGEN RAYS FOR INDUSTRIAL AND RESEARCH PURPOSES

28. The preceding recommendations will probably apply to the majority of conditions under which roentgen rays are used for industrial and research purposes.

VII. RADIUM THERAPY

29. Radium is used in the form of:

(A) Radium salts contained in tubes and applicators;

(B) Emanation contained in tubes.

(A) Radium Salts

30. Protection for radium workers is required from the effects of:

(*a*) Beta rays upon the hands;

(*b*) Gamma rays upon the internal organs, vascular and reproductive systems.

31. In order to protect the hands from beta rays, reliance should be placed, in the first place, on distance. The radium should be manipulated with long-handled forceps, preferably made of wood, and should be carried from place to place in long-handled boxes, lined on all sides with about 1 cm. of lead. All manipulations should be carried out as rapidly as possible.

32. Radium, when not in use, should be stored in a safe as distant as possible from the personnel. It is recommended that radium tubes or applicators be inserted into separate lead blocks in the safe, giving a thickness of protective wall amounting to 5 cms. per 100 milligrams of radium element.

33. A separate room should be provided for the "make-up" of screened tubes and applicators, and this room should only be occupied during such work.

34. In order to protect the body from the penetrating gamma rays during any handling of the radium, a screen of not less than one inch thickness of lead should be used, and proximity to the radium should only occur during actual work and for as short a time as possible.

35. The measurement room should be a separate room and it should contain the radium only during its actual measurement.

36. Nurses and attendants should not remain in the same room with patients undergoing radium treatment.

37. All unskilled work or work which can be learnt in a short period of time should preferably be carried out by temporary workers, who should be engaged on such work for periods not exceeding six months. This applies especially to nurses and those engaged in "making-up" applicators.

38. Discretion should be exercised in transmitting radium salts by post. In the case of small quantities it is recommended that the container should be lined throughout with lead not less than 3 mms. thick. It is more satisfactory to transport large

quantities by hand in a suitably designed carrying case.

(B) Emanation

39. In the manipulation of emanation, protection against the beta and gamma rays has likewise to be provided.

40. The handling of emanation should be carried out, as far as possible, during its relatively inactive state.

41. The escape of emanation should be very carefully guarded against, and the room in which it is prepared should be provided with an exhaust fan.

42. Where emanation is likely to come in direct contact with the fingers, thin rubber gloves should be worn to avoid contamination of the hands with active deposits. Otherwise, the protective measure recommended for radium salts should be carried out.

43. A separate pumping room should be provided with a connecting tube from the special room in which the radium is stored in solution. The radium in solution should be heavily screened to protect people working in adjacent rooms. This is preferably done by placing the radium in solution in a lead-lined box, the thickness of lead recommended being according to the following table:

Quantity of Radium Element	*Thickness of Lead*
0.5 gram	6 inches
1.0 ”	8 ”
1.5 ”	10 ”
2.0 ”	12 ”

VIII. ULTRA-VIOLET THERAPY

44. Almost without exception, the sources of ultra-violet rays are fed from the mains. Power is very often taken from the mains by means of wall plugs. It is well to have for each source a quick-release switch of an enclosed type which is only put into action after the plug is in position. Tests of polarity of a main circuit should not be entrusted to the nursing staff and, in no circumstances, should they be encouraged to handle open wires leading from the main circuit. All such matters, including the coupling up to the lamps, should be done by someone with technical knowledge.

45. Open and closed arcs yielding ultra-violet radiation are dangerous to look at with the naked eye; goggles of proved opacity to ultra-violet rays should be used both by patients and by operators. The opacity can only be proved satisfactorily by a spectroscopic test. Goggles which

transmit radiation shorter than 3,800 A.U. should not be used. The nursing staff should be warned of the pigmentation produced by repeated or prolonged exposures to ultra-violet radiation. Thin muslin worn over the face will prevent pigmentation.

46. Practically the only closed arc used is mercury in a quartz tube. The tube gets hot in action and sometimes cracks with the expulsion of hot mercury. It is recommended that these lamps should not be used for overhead work without some device for catching spilt mercury.

47. The open arcs most used are carbon, carbon-cored and tungsten. There is some danger to patients from small white-hot fragments spurted off open arcs on starting.

48. Ventilation is of great importance because all arcs produce deleterious gases; the open arcs also consume oxygen. The air of rooms devoted to such work should therefore be frequently changed yet adequately warmed, for patients exposed to the rays often have little clothing on. Exhaust fans communicating with an outer wall or chimney shaft are recommended for the purpose.

49. Though the dangers of errors in dosage are not so great as with roentgen rays or radium, every effort should be

made to get some measurement of the rays being administered. There is as yet no agreed unit of ultra-violet energy or standard method of measuring doses of these rays. It is, however, known that the yield of arc lamps increases proportionately with the power supplied to them, so that the volts and ampères in the circuit should be measured as a first check on the yield of radiation. The quartz in mercury vapour lamps gradually becomes more opaque to ultra-violet radiation, and so it becomes more necessary here to supplement the power observations by some device which will measure the radiation actually emitted by the lamp. Further precautions in the use of mercury lamps are necessary because, after these lamps are started, their output gradually decreases, but then increases to a steady value which may take 10 to 15 minutes to attain. Therapeutic work should therefore not be begun until this steady state is reached.

IX. GENERAL

50. 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.

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.

51. 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.

52. The Committee further advise that the heads of roentgen-ray departments of hospitals and other institutions should safeguard themselves and their staff by recommending to the hospital authorities the adoption of the following precautions:

(*a*) The various protective appliances and the working conditions of roentgen-ray departments, *e.g.*, lay-out of installations, degree of scattered radiation, ventilation, high-tension insulation, etc., should be inspected by the National Physical Laboratory, Teddington. Early steps should be taken to give effect to such recommendations as may arise out of their report. It is advised that, in the planning of new roentgenological departments, advantage be taken of the facilities available at the N.P.L.

(*b*) Protective materials or equipment should not be 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.

(*c*) In the case of imported materials and apparatus, complete N.P.L. inspection should be insisted upon.

The Protection Committee will welcome at any time suggestions or information which would tend to improve the scheme of protection outlined in their recommendations.

APPENDIX B

INTERNATIONAL RECOMMENDATIONS FOR X-RAY AND RADIUM PROTECTION

The following recommendations adopted at the Second International Congress of Radiology in Stockholm in 1928 are designed to unify protective measures and to improve the working conditions of X-ray and radium operators in all countries. The recommendations deal only with the more essential matters involved, minor questions of detail being left to each country to elaborate. The question of seeking legal authorisation for such recommendations was also left to each country to deal with as appears to it best.

1. The dangers of over exposure to X-rays and radium can be avoided by the provision of adequate protection and suitable working conditions. It is the duty of those in charge of X-ray and radium departments to ensure such conditions for their personnel. The known effects to be guarded against are:

(a) Injuries to the superficial tissues;

(b) Derangements of internal organs and changes in the blood.

I. WORKING HOURS ETC.

2. The following working hours etc. are recommended for whole-time X-ray and radium workers:

(a) Not more than seven working hours a day.

(b) Not more than five working days a week. The off-days to be spent as much as possible out of doors.

(c) Not less than one month's holiday a year.

(d) Whole-time workers in hospital X-ray and radium departments should not be called upon for other hospital service.

II. GENERAL X-RAY RECOMMENDATIONS

3. X-ray departments should not be situated below ground floor level.

4. All rooms, including dark rooms, should be provided with windows affording good natural lighting and ready facilities for admitting sunshine and fresh air whenever possible.

5. All rooms should be provided with adequate exhaust ventilation capable of

renewing the air of the room not less than 10 times an hour. Air inlets and outlets should be arranged to afford cross-wise ventilation of the room.

6. All rooms should preferably be decorated in light colours.

7. X-ray rooms should be large enough to permit a convenient lay-out of the equipment. A minimum floor area of 250 sq. feet (25 sq. metres) is recommended for X-ray rooms and 100 sq. feet (10 sq. metres) for dark rooms. Ceilings should be not less than 11 feet (3.5 metres) high.

8. A working temperature of about 18°C. (65°F.) is desirable in X-ray rooms.

9. Wherever practicable the X-ray generating apparatus should be placed in a separate room from the X-ray tube.

III. X-RAY PROTECTIVE RECOMMENDATIONS

10. An X-ray operator should on no account expose himself unnecessarily to a direct beam of X-rays.

11. An operator should place himself as remote as practicable from the X-ray tube. It should not be possible for a well rested eye of normal acuity to detect in the dark appreciable fluorescence of a screen placed in the permanent position of the operator.

12. The X-ray tube should be surrounded as completely as possible with protective material of adequate lead equivalent.

13. The following lead equivalents are recommended as adequate:

X-rays Generated by Peak Voltages	Minimum Equivalent Thickness of Lead
Not exceeding 75 kv.	1 mm.
Not exceeding 100 kv.	1.5 mm.
Not exceeding 125 kv.	2 mm.
Not exceeding 150 kv.	2.5 mm.
Not exceeding 175 kv.	3 mm.
Not exceeding 200 kv.	4 mm.
Not exceeding 225 kv.	5 mm.

14. In the case of diagnostic work, the operator should be afforded protection from scattered rays by a screen of a minimum lead equivalent of 1 mm.

15. In the case of X-ray treatment the operator is best stationed completely outside the X-ray room behind a protective wall of a minimum lead equivalent of 2 mm. This figure should be correspondingly increased if the protective value of the X-ray tube enclosure falls short of the values given in paragraph 13. In such event the remaining walls, floor and ceiling may also be required to provide supplementary protection for adjacent occupants to an extent depending on the circumstances.

16. Screening examinations should be conducted as rapidly as possible with minimum intensities and apertures.

17. The lead glass of fluorescent screens should have the protective values recommended in paragraph 13.

18. In the case of screening stands the fluorescent screen should, if necessary, be provided with a protective "surround" so that adequate protection against direct radiation is afforded for all positions of the screen and diaphragm.

19. Screening stands and couches should provide adequate arrangements for protecting the operator against scattered radiation from the patient.

20. Inspection windows in screens and walls should have protective lead-values equivalent to that of the surrounding screen or wall.

21. Efficient safeguards should be adopted to avoid the omission of a metal filter in X-ray treatment.

22. Protective gloves, which should be suitably lined with fabric or other material, should have a protective value not less than ½ mm. lead throughout both back and front (including fingers and wrist). Protective aprons should have a minimum lead value of ½ mm.

IV. ELECTRICAL PRECAUTIONS IN X-RAY ROOMS

23. The floor-covering of the X-ray room should be of insulating material such as wood, rubber or linoleum.

24. Overhead conductors should be not less than 9 ft. (3 metres) from the floor. They should consist of stout metal tubing or other coronaless type of conductor. The associated connecting leads should be of coronaless wire kept taut by suitable rheophores.

25. Wherever possible earthed guards should be provided to shield the more adjacent parts of the high tension system. Unless there are reasons to the contrary, the metal parts of the apparatus and room should be efficiently earthed.

26. The use of quick-acting double-pole circuit breakers is recommended. Over-powered fuses should not be used. If more than one apparatus is operated from a common generator, suitable overhead multi-way switches should be provided.

27. Some suitable form of kilo volt-meter should be provided to afford a measure of the voltage operating the X-ray tube.

V. RADIUM PROTECTIVE RECOMMENDATIONS

(A) Radium Salts

28. Protection for radium workers is required from the effects of:

(a) Beta rays upon the hands;

(b) Gamma rays upon the internal organs, vascular and reproductive systems.

29. In order to protect the hands from beta rays, reliance should be placed, in the first place, on distance. The radium should be manipulated with long-handled forceps, preferably made of wood, and should be carried from place to place in long-handled boxes, lined on all sides with about 1 cm. of lead. All manipulations should be carried out as rapidly as possible.

30. Radium, when not in use, should be stored in a safe as distant as possible from the personnel. It is recommended that radium tubes or applicators be inserted into separate lead blocks in the safe, giving a thickness of protective wall amounting to 5 cms. of lead per 100 milligrams of radium element.

31. A separate room should be provided for the "make-up" of screened tubes and applicators, and this room should only be occupied during such work.

32. In order to protect the body from the penetrating gamma rays during han-

dling of the radium, a screen of not less than one inch thickness of lead should be used, and proximity to the radium should only occur during actual work and for as short a time as possible.

33. The measurement room should be a separate room and it should contain the radium only during its actual measurement.

34. Nurses and attendants should not remain in the same room as patients undergoing radium treatment.

35. All unskilled work or work which can be learnt in a short period of time should preferably be carried out by temporary workers, who should be engaged on such work for periods not exceeding six months. This applies especially to nurses and those engaged in "making-up" applicators.

36. Discretion should be exercised in transmitting radium salts by post. In the case of small quantities it is recommended that the container should be lined throughout with lead not less than 3 mms. thick. It is more satisfactory to transport large quantities by hand in a suitably designed carrying case.

(B) Emanation

37. In the manipulation of emanation, protection against the beta and gamma rays has likewise to be provided.

38. The handling of emanation should be carried out, as far as possible, during its relatively inactive state.

39. The escape of emanation should be very carefully guarded against, and the room in which it is prepared should be provided with an exhaust fan.

40. Where emanation is likely to come in direct contact with the fingers, thin rubber gloves should be worn to avoid contamination of the hands with active deposit. Otherwise, the protective measure recommended for radium salts should be carried out.

41. A separate pumping room should be provided with a connecting tube from the special room in which the radium is stored in solution. The radium in solution should be heavily screened to protect people working in adjacent rooms. This is preferably done by placing the radium in solution in a leadlined box, the thickness of lead recommended being according to the following table:

Quantity of Radium Element	Thickness of Lead
0.5 gram	6 inches (15 cms.)
1.0 gram	6.6 inches (16.5 cms.)
1.5 gram	6.8 inches (17 cms.)
2.0 gram	7.2 inches (18 cms.)

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PAUL B. HOEBER, INC., 76 Fifth Avenue, New York