X-rays in Industry.¹

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THERE are few more stimulating pages in the history of scientific endeavour than those which record progress in the field of X-ray investigation and application.

Physical research has spread itself over 60 octaves or more of electromagnetic waves which are now known to stretch without break from wireless waves 25 miles or more in length through heat waves, visible light waves, ultra-violet waves, and X-rays to gamma-rays of wave-lengths of the order of a ten-thousand-millionth of an inch. In this gigantic gamut of natural activity that group of radiations encroaching into and extending some thirteen octaves beyond the ultra-violet, and possessing wave-lengths ranging from about 5×10^{-6} to 5×10^{-10} cm., is now generally styled X-rays. Of these thirteen octaves, ten are extremely absorbable, but the remaining three possess those remarkable powers of penetrating matter which made Röntgen's discovery so arresting and monumental when it was announced exactly thirty years ago. If we include the gamma-rays of radium, this gives us a total of nearly six octaves of radiation with which the science of medical and technical radiology of the present day does its work.

The differential absorption of X-rays by matter of different densities (which makes the work of the medical radiologist possible), and the diffraction of X-rays, are phenomena which have been turned to account in the industries and arts in a diversity of directions. At the outset mention should be made of the dangers arising from X-rays. These are well known and have caused many casualties in the past. They can, however, be wholly avoided by common-sense protective measures which consist in the main of interposing lead sheet or the like, properly disposed and sufficiently thick, between the X-ray tube and the operator. The reports of the X-ray and Radium Protection Committee should be consulted for details by which complete safeguards can be secured.

RADIOGRAPHY.

One other practical precaution arises in industrial radiography, and that is the necessity for taking account of the scattering of the X-rays. Three things may happen to a beam of X-rays when it passes through a material. Part of it emerges undisturbed and undeviated, and outlines the shadow picture on the photographic plate. Part of it is absorbed with the liberation of characteristic X-rays and electrons. The rest is scattered or dispersed, which is equivalent to stating that, while the rays are not altered in quality or but slightly so, a considerable proportion of them have their direction altered to a greater or less extent. In some cases it is estimated that, of the energy received at a point well within or beyond a mass of material, the fraction arriving by devious routes may be equal to or several times greater than that by the direct route. This proportion may be lessened by narrowing the width of the beam of incident rays, but the size of the aperture is usually prescribed by the size of the object and, in general, the X-ray beam does not approximate to a pencil. Scattering thus produces a sort of halation or

fogging of the main image on the photographic plate. The effect may be troublesome enough, even with lesser thicknesses, to impair definition in the absence of suitable precautions, but increases to such an extent with greater thicknesses as to render the method nugatory or nearly so.

Many of the various applications of radiography to industry have come about owing to the fact that the method does not injure the specimen in any way. Further, it provides in many cases the only means, independent of human judgment, of detecting concealed defects in a material or of scrutinising a structure or sealed enclosure the disposition of component parts which are hidden from view. Incidentally, the mere existence of the method is not without its moral value as regards workmanship. Radiography is, of course, inoperable in those cases where the shape of the object prevents the right disposition of X-ray tube and film.

The X-rays found little effective scope in industry until the invention of the Coolidge tube, which permitted the utilisation of high voltages with standardised procedure. Experience differs as to the sensitiveness of the method, but, depending on the area of the inclusion, probably a variation in density equivalent to 2 to 5 per cent. of the thickness is necessary to be detected on the photographic plate. These figures require to be increased for fluoroscopy, but much depends on the luminosity and on the visual acuity of the observer. Definition is, of course, dependent, among other things, on the size of the focal spot in the X-ray tube. If a body has tapering edges, this will normally result in a nebulous radiographic outline. Exposures naturally depend on the conditions, and may vary from a few seconds to an hour or more. Stereoscopic radiography is sometimes useful in estimating depth.

If the intrinsic value of a specimen is low, or if "mass inspection" is contemplated, then visual inspection with a fluorescent screen is the only practical policy. It is not always satisfactory, but the more expensive and protracted process of photography has to be justified by the value of the specimen, or the importance of the job for which it is intended, or the desirability of confirming the fluoroscopic diagnosis by a permanent record. For some industrial purposes Dauvillier employs an exploring ionisation chamber filled with xenon, the ionisation currents being readily measured by a galvanometer.

The shape of the specimen may be such as to emphasise the evils of scattered radiation. If the object is continuous, with one side flat, there is no difficulty; for the flat side can be brought into close contact with the photographic plate. The same end can be achieved with bodies of regular shape, such as cylinders or spheres, by resting them in closely fitting solid metal "cradles" with flat bases. If the body is irregular in contour, something may be done by filling up pockets or hollows with wax or plasticene and placing a "mask" of lead or lead powder round the specimen. With hollow bodies a film may sometimes be placed inside and sprung against the interior face, though parallax is often exaggerated. In all cases the

¹ From a public lecture delivered at the University of Leeds, November 30.

photographic plate or film should be backed and framed with lead foil.

It should be realised that, while X-rays have proved of considerable value in many directions, their use in radiographing steel is limited at present. While both in Great Britain and America X-rays have been detected photographically after passing through 4 inches of steel, the result has little or no practical value. The present practicable limit is more nearly 2 inches for photography and less than half an inch for fluoroscopy. Incidentally, the corresponding limit for solid masonry is about a foot.

The quality or mean wave-length of the X-rays used depends on the requirements. For very transparent objects X-rays excited by fifty thousand volts or less may suffice. For the more opaque materials we require rays excited by up to 200,000 volts, which is as near to the present upper limit as any present-day X-ray tube will stand. Approximately double this voltage will be required to test so much as 6 inches of steel. The electrical engineer can, of course, generate such voltages, but an X-ray tube has yet to be designed which is capable of turning them to account. The task is not proving easy of solution, and the fact has a bearing on the possible extension of radiometallography to heavy engineering. With such high voltages the scattering effect may be somewhat reduced, and the attendant dangers could doubtless be countered if the results warranted the expense.

Within its limitations, however, radiography is very sensitive; for example, fine tool or mould marks and similar surface irregularities are frequently displayed in radiographs. Blowholes in castings show up as light spots. Cracks are occasionally revealed, though, if they are filled with material of density not very different from its surroundings, or if the cracks are fine or tortuous (hair cracks), the method normally fails. A negative result does not, in fact, afford a positive answer. Inclusions of sand, etc., are registered as cloudy, indefinite areas. The method has been proved to be of value in suitable cases for checking up steel castings and so preventing the machining of defective castings.

If the specimen is of large area, such as a turbine disc, to radiograph the whole disc is a costly and protracted operation which has, however, on occasion been carried out in its entirety in Great Britain. But normally in such cases the X-ray method would be used only when the material is already under suspicion by the use of other tests.

X-ray photography of steel welds has been used successfully for thicknesses up to about 1 inch. Welding is discredited for some purposes, for it is easy to scamp such work, but the X-rays are a somewhat severe critic in displaying blisters, blowholes, and lack of bonding. Skilled experience can usually say whether any imperfections indicated in the radiograph are sufficiently serious to disqualify a weld for its purpose. The method will not, however, indicate a common defect of welding—the burning of the adjacent metal.

The X-rays have become a useful adjunct in the photography of a variety of subjects in the laboratory and in the industries. The manufacturers of electrical insulators—ebonite, built-up mica, fibre, paper—find

the X-rays useful for detecting the presence of metallic particles, particularly if a high-grade product is desired. Fibre is frequently made from pulped rags and so may contain foreign metallic matter. Feminine labour has been occasionally responsible for the presence of hairpins in the finished product.

The centrality of the core of a heavily insulated electric cable can be tested by this means. In such a case as this, to secure both a sharp outline of the opaque core as well as clear detail of the more transparent insulation, a good plan is to make the exposure partly at a high exciting voltage and partly at a low voltage. The soundness of steel balls intended for ball bearings; the differentiation of lead-glass from soda-glass stems of clinical thermometers—now a routine test at the National Physical Laboratory—the centrality of the cores of golf balls; the test of the fit of a new shoe on the foot as now met with in many shoe shops; the nature of certain defects in artificial teeth; the proportion of ash in samples of coal, are among recent examples of the use of the method.

Aircraft materials afford scope for the X-rays as a testing agent. Aluminium alloys are very transparent, and so lend themselves to radiography, while if steel is used, its greater trustworthiness is offset by the necessity of keeping the weight down. The main difficulty, in fact, with aircraft components is usually their shape rather than their thickness. Timber offers no difficulty, of course, and the use of X-rays in this connexion, more particularly as regards aeroplane parts, was demonstrated during the War.

If a material is very transparent, its opacity may sometimes be increased much as a medical radiologist uses bismuth meals to watch processes in the alimentary canal. For example, the Dunlop Research Laboratory, by previously impregnating selected canvas threads with lead chromate, was able to test whether the stretch during the successive processes of manufacture of a tyre was within the limits tolerated by the yarn. Similarly, if it is desired to watch the behaviour of glued joints or splices while under stress, the radiography is facilitated if a little lead salt is added to the glue.

X-ray photography is at times particularly useful for displaying the construction of apparatus, the interior of which is hidden from view by thin metal or other opaque container. Among examples which may be cited are the counting of the turns of wire in a coil heavily covered with insulation; the details of the design of opaque vacuum pumps and radio valves; the interior detail of opal-glass electric lamps; the construction of selenium cells; the internal diameter of metallic tubing; and the interior construction and accuracy of assembly of explosive devices—this last by the Research Department at Woolwich Arsenal.

In quite another direction radiographs recently taken in Chicago of Egyptian and Peruvian mummies showed that rickets, bony tumours, pyorrhœa, caries of the teeth, were common conditions of disease, as nowadays. It was further found possible to gather something definite about the age and sex, and the nature of any injuries received. A recent attempt to X-ray the mummy of Tutankhamen was nullified mainly by the heavy gold "armouring" of the body.

Finally, one other application of radiography may be

referred to. As is well known, the forging of valuable pictures and antiques has always been a flourishing industry. One estimate puts the number of Rembrandts in existence at four to five thousand, yet, so far as is known, Rembrandt painted about 700 in his lifetime. We know that Sheraton had a little shop and did most of his work himself with only occasional help from a few expert artisans, but the amount of Sheraton furniture in existence belies the truth of this.

The X-rays have shown that they can sometimes usefully supplement the tests which are commonly resorted to for detecting fraud in old Masters and antiques. A radiograph will sometimes reveal constructional or other detail sadly out of tune with the reputed period. In the case of pictures or panels, the X-rays may give instructive information on the pigments which, in general, are more opaque in old pictures than in new, on the priming, which is commonly more opaque in new pictures than in old, and on the canvas, wood, or other surface painted on. Thus it happens that in the case of an old painting the X-rays can sometimes be employed as a means of detecting alterations or restorations or of identifying a modern fake.

Radiography could similarly be used to establish the identity of originals of modern pictures or panels, forgers of which are therefore not prevented from simulating closely the canvas, wood, and pigments. But in a radiograph the fine details of the canvas, or of grain and knots in the case of wood, are so characteristic as to be impossible of exact copying. If such records were normally taken, the method would also be of service in differentiating between the original and the copies painted by the artist himself. Furthermore, tentative detail ultimately painted out is sometimes revealed in the original painting which naturally is not repeated in the copies.

X-RAY DIFFRACTION

From Laue's momentous discovery in 1912 of the diffraction of X-rays, the science of X-ray spectrometry has grown to great proportions. The main developments deal with emission and absorption spectra, with crystal analysis and with the structure of atoms. Naturally, with the growth of the subject, special apparatus and technique have been developed.

In optical spectra the number of lines peculiar to an element are frequently numerous and their numerical relations complicated. X-ray spectra, on the contrary, are noteworthy for their simplicity, the number of lines characterising an element being relatively few, readily recognisable, and measurable with a precision not inferior to that which obtains in optical spectra. Moseley's great discovery in 1913 established a simple proportionality between the atomic number of an element and the square root of the frequency of a characteristic radiation or of an absorption limit. Moseley's law holds for all the known elements, and so it is possible to interpret new spectral lines with ease. It was by X-ray spectrometry that the element hafnium was discovered in 1923; and only recently Nonnack and Tacke announced the discovery by X-ray analysis of two new elements which they called masurium and rhenium. Thus 89 out of 92 elements are now known, and the spectral lines of the missing

three elements (Nos. 61, 85, 87) are predictable with certainty.

X-ray absorption spectra are very simply obtained by passing a pencil of X-rays through a sample of the matter and examining the transmitted beam by a crystal spectrometer. The X-rays should be excited by a suitably high voltage. It is best to have the substance in finely powdered form deposited on, say, paper. Very little material will suffice if the absorbing screen is placed at the slit of the "collimator." Solutions can also be tested, though not so readily. The method is specially applicable to all elements with a strong *K* absorption band, *i.e.* the iron group and heavier elements. For the elements of high atomic number the *L* band is also convenient. In the case of mixtures of adjacent elements the several absorption bands may tend to obscure one another, and for this reason the method excels in detecting traces of heavy elements in light elements.

Emission spectra are conveniently excited by mounting the material on the face of the target of an X-ray bulb and applying a suitably high voltage. In such spectra every element present is recorded with an intensity which depends only on its concentration and is independent of the presence of any other elements with which it may be mixed or combined. Such intensities are measured with a microphotometer. The method thus enjoys great advantages over optical spectroscopy. The test is a very sensitive one and, although not suitable for the very light elements, has found commercial application in analysis of the platinum group of metals and the rare earths. An alternative method, though not so effective, is to bombard the test material with X-rays, as in Barkla's original method of exciting characteristic X-rays. This can be readily made the basis of a method for analysing mineral salts.

The aim of X-ray crystal analysis is to determine the grouping of the atoms and molecules in the crystal unit, and so to account for the properties of the crystal. There are three main experimental methods:

(a) Laue's method, in which a narrow pencil of heterogeneous rays is passed through a single crystal.

(b) The Hull-Debye-Scherrer method, where homogeneous rays are passed through a thin rod of crystalline powder.

(c) The Bragg spectrometer method, in which a "slit" of homogeneous rays is reflected from a single crystal.

Many variations in the technique of these methods have been developed, some of which are becoming of industrial importance. For example, the Laue method may be arranged to test the general orientation or symmetry of crystal aggregates, in which case homogeneous rays are advantageous. The Bragg method is also applicable to a conglomeration of minute crystals. In many of these methods the specimen is kept in continual rotation or oscillation (de Broglie).

Our knowledge of the atomic structure of the solid state of matter owes more to X-ray analysis than to any other means. For example, most chemical elements, including solidified gases, have been shown to crystallise in the cubic or hexagonal system. Already nearly half the elements have been examined, including those allotropes which can arrange themselves in more than one kind of space lattice. As regards alloys—solid solutions and intermetallic compounds—the

X-rays have thrown light on and tested the truth of the existence of the several phases of steel and other alloys which metallurgists had differentiated by other means. The method has also indicated the atomic features which go hand in hand with ductility, hardness, etc. It has also been shown that in a solid solution of two elements the replacement of one atom by another is effected by substitution in and distortion of the lattice and not by interstitial insertion (Owen and Preston at the National Physical Laboratory). Other points which have been worked on are the effect of annealing, tempering, rolling, or other working; the mechanism of deformation and slip in metals; and the general shapes and sizes of atomic domains.

By the use of X-rays Sir William Bragg has shown that a diamond has an atomic bonding perfect in its symmetry and so possessing intense hardness. On the other hand, graphite (another variety of carbon) with unsymmetrical atomic linking, with weak linking and greatest separation between cleavage planes, is a good lubricant. So-called amorphous carbon is found to consist of minute graphite crystals. The fragility of annealed tungsten lamp filaments is explained by the gradual transformation to a number of single crystals of large dimensions.

The X-rays have demonstrated that almost every solid substance in Nature shows crystalline form, including such apparently amorphous materials as rubber, cellulose, soap, leather, bamboo, and talc. Müller and Shearer have shown that the fatty acids

give characteristic spectra which enable them to be identified in mixtures. This work was done at the Davy Faraday Laboratory where, under Sir William Bragg's guidance, the structures of many organic and inorganic crystals have been elucidated. Colloidal metals are shown to be made up of minute yet perfect crystals so small that they contain only a few score atoms. The molecular arrangements in thin metal and liquid films have been ascertained. In gold leaf, for example, the cubic crystals are found to have their cube faces parallel to the sheet. The Laue method has been used at the National Physical Laboratory to ascertain the crystal axes of jewel bearings. Within the last few months Dauvillier and Shaxby have ascertained the structure of pearls and shown that the Laue method, using homogeneous rays, affords a trustworthy and valuable criterion between the true natural pearl and the cultivated Japanese pearl, consisting of a thin pearly covering on a sphere of mother-of-pearl as a nucleus.

These are but a few of many examples which indicate that the several processes of X-ray spectroscopy are not only a valuable scientific tool for the physicist, but also that they are destined to play an important rôle in many industrial processes of the future. There are grounds for hoping that light may be thrown on the mechanism of such properties as magnetism, electrical and thermal conductivity, contact and thermal electromotive forces, dielectric capacity, fluorescence, the various types of elasticity, cohesion, diffusion, adsorption, etc.

Mineral Industries of the United States during the War.

THE mineral resources of the United States are of primary importance, for in 1915 that country produced 40 per cent. of the world's output of coal, 40 per cent. of its iron ore, 32 per cent. of its lead and zinc, 60 per cent. of its copper, and 66 per cent. of its petroleum. Since then, some of these proportions have increased. The data for the history of the mineral development of the United States during the War have now been issued in seven thick volumes,¹ which contain for each year the full record of the United States output of all important economic minerals, with shorter accounts of the contributions of other countries. The volumes consist mainly of compilations of mineral statistics accompanied by the statement of such geological and economic facts as are necessary to their interpretation. In each volume some chapters, in addition to the annual statistics and record of the year's development, contain a general review of the subject with reference to the current literature and geological descriptions of the chief mining fields. These monographic chapters include those on chromite by J. S. Diller, on graphite, with interesting accounts of its mining in Ceylon and Madagascar, by H. G. Ferguson, on molybdenum by F. L. Hess, on potash by W. B. Hicks, on American utilisation of peat by C. C.

Osbon, and on quicksilver by F. L. Ransome. In view of the importance and variety of the American yields, the especially important sections are those dealing with coal, petroleum, and the five metals which are so closely associated that they are recorded together—gold, silver, lead, copper, and zinc.

We find in these volumes, in addition to the record of the normal development of the mining industry, an account of the more sensational temporary effects of the War, which were often bewilderingly unexpected and contrary. Prices rose and fell in a manner that was at the time inexplicable, and in some cases is still obscure. The answer may be simple, though not obvious at the time; thus, although cadmium is more expensive than tin it was used in solders as a substitute, so that tin might be reserved for purposes for which it was indispensable. Some of the uses to which cadmium was put are still unrevealed, and Mr. Siebenthal, the author of the chapters on that metal, reports that a German firm in 1913 advertised for the purchase of unlimited supplies, and refused to answer inquiries as to the purpose for which it was wanted. It was certainly used in Germany during the War as a substitute for tin, but other uses by the belligerents on both sides have not yet been revealed.

The War, by its increased demands for metals, helped some branches of mining, but hampered others; thus the unlucky antimony miners of China, who produce the bulk of the world's supply, suffered both from the fall in price of their product and from the rise in the price of silver, which added to their working costs. In the case of some metals a fall in prices appeared to

¹ Dept. of the Interior, United States Geol. Survey. Mineral Resources of the United States:

1915. Part I., Metals, 1917, iv, 99a, 1000+3 pl.

1916. Part I., Metals, 1919, v, 73a, 871+3 pl.

1916. Part II., Non-Metals, 1919, v, 1115+4 pl.

1917. Part I., Metals, 1921, v, 79a, 980+8 pl.

1917. Part II., Non-metals, 1920, vi, 1293+1 pl.

1918. Part I., Metals, 1921, iv, 149a, 1096+9 pl.

1918. Part II., Non-metals, 1921, viii, 1557+16 pl.

Washington: Government Printing Office.