Not only living things, but metal parts, castings, and other manufactured objects can be examined internally. The equipment used and how it works.

By JOHN R. COLLINS

INDUSTRIAL X-RAY APPARATUS

AT ABOUT the same time that Marconi was experimenting with radio waves, a German scientist named Roentgen discovered x-rays, another kind of electromagnetic radiation. While less striking, perhaps, than developments in radio communications and radar, recent advances in x-ray techniques have multiplied the uses of x-ray for industrial purposes. Improvements have been made in traditional x-ray fields and, in addition, new applications have been found.

Although many of the rules are the same for x-ray as for other types of electronic equipment, radio technicians usually need help in adapting their knowledge to the maintenance of x-ray apparatus.

Most people associate x-ray with its use in hospitals and doctors' offices for such things as detecting broken bones, diagnosing tuberculosis through chest x-ray, treating cancer, and fluoroscoping the stomach. Dental x-ray is also familiar.

The industrial use of x-ray has increased as a result of improved apparatus that permits the non-destructive examination of welds and castings of even the thickest steel, and portable equipment provides a convenient means of checking pipelines, bridges, and other construction projects on the spot. In addition, x-ray spectroscopes and x-ray diffraction apparatus have opened up new avenues in basic research.

The method of locating a defect in a casting with x-ray is not very different from finding a break in a bone. An x-ray beam is directed through the casting and detected on the far side, usually by means of photographic film. For a beam of given intensity, the amount of radiation reaching the film in a given time depends on two factors: the kind of material used for the casting and its thickness. If the casting is uniform throughout, the developed film will be of uniform density. However, an air bubble, being less dense than the

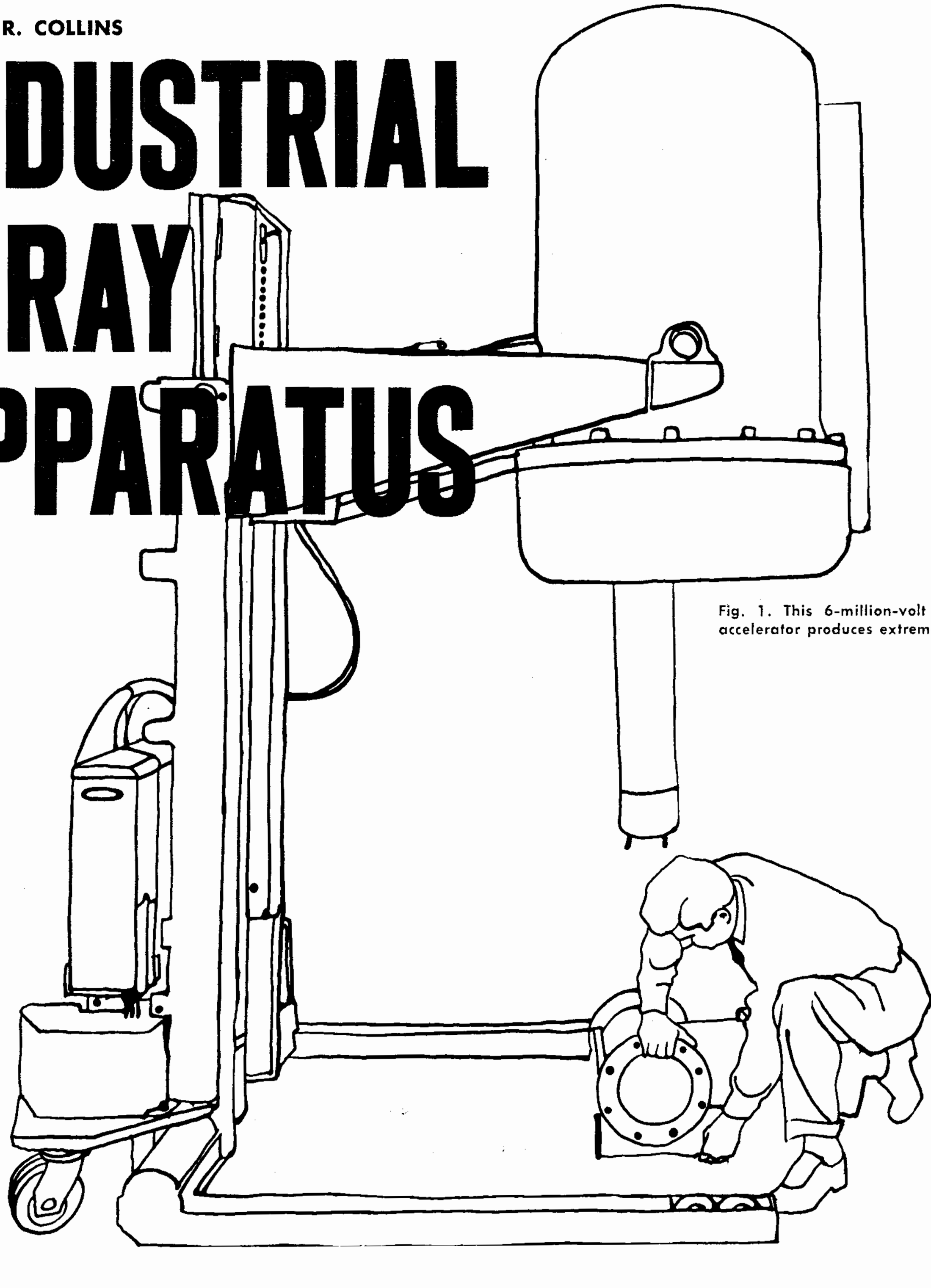

Fig. 1. This 6-million-volt Van de Graaff accelerator produces extremely "hard" rays.

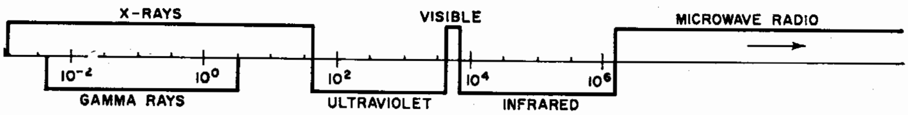

Fig. 2. Place of x-rays in electromagnetic spectrum. Wavelengths are in angstrom units.

steel, would permit more radiation to pass and would show up on the film as a dark spot. Similarly, any foreign matter having absorbing qualities different from steel and any irregularities in thickness would be displayed on the film as dark or light areas.

The process of producing x-ray photographs is called radiography. Microradiography concerns the x-raying of small objects, where the detail is too fine to be seen by the unaided eye, and the picture must either be enlarged or examined with a low-power microscope. The technique has been used for such diverse purposes as distinguishing between natural and cultured pearls, examining biological specimens (*e.g.*, insects, leaves, seeds) and in metallurgical laboratories for determining minute discontinuities and the separation of metals making up alloys.

Fluoroscopy is the same as radiography, except that the image appears on a fluorescent screen instead of a photographic film. It is fast and inexpensive, but lacks fine detail and does not provide a permanent record. It is most useful, therefore, for a fast examination for gross defects—like finding hairpins in candy bars.

General Theory

X-rays are a form of radiant energy having properties similar to visible light. Because of their extremely short wavelength, however, they are able to penetrate materials that absorb or reflect visible light. They are produced by collisions between electrons traveling at high speed and some form of matter.

Fig. 2 shows the place occupied by x-rays in the electromagnetic spectrum. Since they are far shorter than even the shortest radio or radar wave, it is inconvenient to measure their wavelength in meters. The usual standard of measurement is the angstrom unit, equal to 1/100,000,000 centimeter. The wavelength of visible light ranges from about 4000 to 7500 angstrom units. The wavelengths of x-rays vary from under 00 angstrom units to a tiny fraction of angstrom unit.

The wavelength is related to the ed the electrons are traveling when strike matter. So-called *soft* x-rays relatively long wavelengths and roduced by moderate accelerating als. They have little penetrating and have difficulty in escaping x-ray tube. *Hard* x-rays are by higher accelerating potenremely hard x-rays, such as uced by Van de Graaff accel. 1), can readily penetrate of steel.

tice that *gamma* rays me range as x-rays e same characterhed from x-rays an by nature,

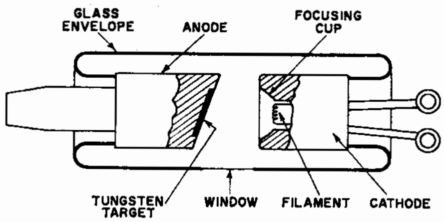

Fig. 3. The cut-away view shows the elements in a stationary-anode x-ray tube.

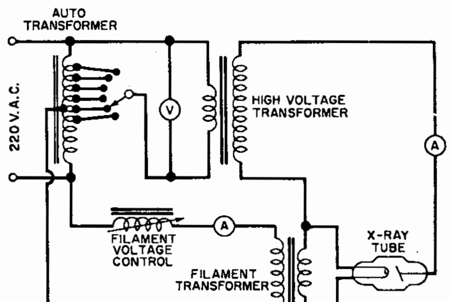

Fig. 4. Basic, high-voltage, x-ray circuit. Tube itself serves as rectifier.

being emitted by radioactive substances. Some *gamma*-ray sources are natural, such as radium; others, like cobalt-60, are artificially produced and do not occur in nature.

X-Ray Tubes

The principal features of an x-ray tube are shown in Fig. 3. It has a cathode to emit electrons and an anode to attract them. The electrons are concentrated in a narrow beam by the focusing cup and directed against the target on the anode. Their velocity is determined by the voltage applied to the anode. The sudden stopping of the electrons on striking the target causes x-rays to be produced.

Only about 1 per-cent of the energy resulting from the impact of the electrons on the target is given off in the form of x-rays, the rest being wasted as heat. Excessive heat can readily melt the tube and it is necessary to dissipate it efficiently. Tungsten is used as the target material not only because of its high melting point (3370 degrees C) but also because it has a high atomic number (74), and elements with the highest atomic numbers are most efficient in producing x-rays. The tungsten target is mounted on a copper base, a good heat conductor, which is brought out to external radiating vanes. In many tubes, oil or water is circulated through the anode to carry off heat.

A further aid to heat dissipation is the rotating-anode tube (Fig. 5). The anode is a large disc of pure tungsten with a beveled edge, connected to a motor. The electron beam is directed against the beveled edge while the disc rotates at high speed. The effect is to increase the area of the target and to lessen the chance of overheating. It permits the use of a smaller focal spot and higher accelerating potential without damaging the tube than would be possible in a stationary-anode tube.

X-rays do not travel from the target in a single beam. Instead, they are scattered and, like light rays, "illuminate" a considerable area. To prevent scattered radiation from endangering operating personnel and others, x-ray tubes are encased in shockproof metal enclosures lined with lead. An aperture is provided through which the x-rays can emerge in the desired direction.

Tubes for low-intensity or soft x-rays are made with special windows to permit the radiation to escape with little loss. A window is usually either an exceptionally thin area in the glass or an insert of beryllium metal. Beryllium has the characteristic of being transparent to x-rays, just as clear glass is to light.

The high voltage applied to an x-ray tube is expressed in peak kilovolts (rather than r.m.s.) and is abbreviated k.v.p.

Circuits

An elementary circuit for an x-ray machine is shown in Fig. 4. Basically, it is simply a power supply designed to furnish the filament and plate voltages needed to operate the x-ray tube. The principal components, other than the x-ray tube, are an autotransformer, a high-voltage transformer, a filament transformer and, sometimes, a rectifier unit with one or more rectifier tubes. The autotransformer (so called because both primary and secondary are combined in a single winding) permits the 220-volt source to be varied in steps over a considerable range. The voltage thus selected becomes the input to the high-voltage transformer, which supplies plate voltage for the x-ray tube. In this way the plate voltage can be adjusted by adjusting the autotransformer.

The filament voltage for the x-ray tube is furnished by a low-voltage stepdown transformer which provides from 4 to 12 volts at a few milliamperes. The secondary winding of the stepdown transformer is heavily insulated from the primary and from the iron core so that the high voltage to the x-ray tube will not get back into the supply lines of the machine.

The filament voltage is controlled by an adjustable iron core and coil in the primary circuit of the filament transformer. When the core is inserted all the way in the coil, its inductive reactance is high and a large part of the supply voltage is dropped across the coil instead of the transformer primary. When the iron core is withdrawn, the voltage drop is almost all across the transformer primary. A knob on the control panel usually provides this adjustment.

When only moderate power is handled, it is usual to employ self-rectification, in which the x-ray tube itself acts as a rectifier. The high voltage is applied directly to the x-ray tube, and the anode becomes alternately positive and negative with respect to the cathode during each half-cycle. When the anode is positive, the electrons emitted from the cathode are attracted to it and there is current flow in the tube. When the anode is negative, the electrons are not attracted to it and there is no current flow. Self-rectification is common in portable, bedside, and dental units.

X-ray machines of greater power usually employ rectifier tubes to prevent the inverse voltage from being applied to the anode. The rectifier circuit and its operation are conventional. A rectifier tube absorbs little of the power that it handles, so the heating problem encountered with x-ray tubes is not present. More efficient circuits use four rectifier tubes for full-wave rectification, in order to utilize the inverse voltage.

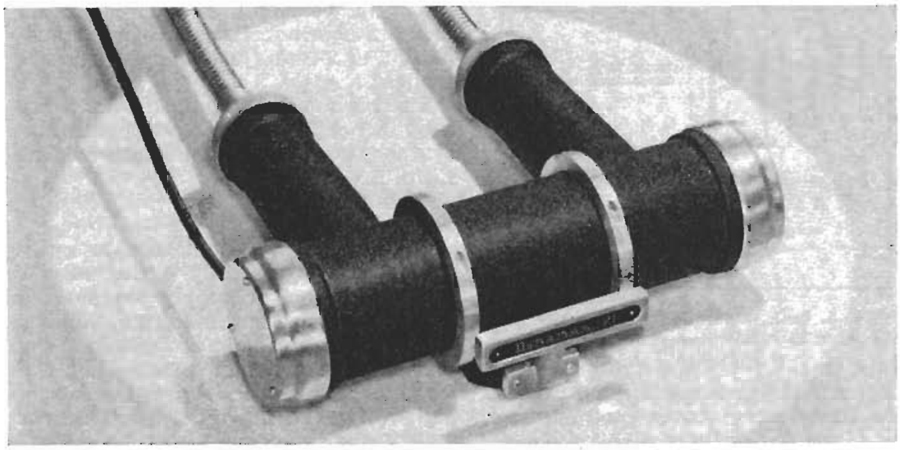

Fig. 5. A rotating-anode x-ray tube that can handle a high voltage of 100 peak kilovolts, made by Machlett Laboratories. It is suitable for general diagnostic service.

Unlike other electron tubes, the operating voltages of x-ray tubes are adjusted for each individual job. When the voltage is increased on the filament, the effect is to cause more electrons to be emitted. This is equivalent to providing greater illumination, and the process can be visualized as increasing the brightness. The variations in the intensity of rays passing through the subject is not changed, however, so contrast remains the same. Since x-rays, like light rays, travel in diverging straight lines, the brightness can also be increased by moving the tube closer to the subject. Numerically, the variation is inverse with the square of the distance, so brightness is increased four times by reducing the distance by one half.

Increasing the anode voltage increases the penetrating power of the x-rays. However, it also results in a decrease in contrast, so the kilovoltage is not increased beyond the point needed to achieve the necessary penetration.

Portable Equipment

Special lightweight equipment that can be moved readily from place to place is valuable for use around airplane factories, shipyards, and similar places to inspect welds, joints, and parts during construction. The apparatus shown in Fig. 6 is made in two pieces for easy handling. The control unit (right) is housed in a steel case and is connected to the power unit by means of a multiconductor cable. The x-ray generator and tube are encased in a shockproof and radiation-proof steel tank weighing 55 pounds. The high voltage can be varied continuously from 30 to 100 k.v.p.

Some portable units employ *gamma* radiation from cobalt-60 instead of x-rays. Other materials (radium, thulium-170, iridium-192, cesium-137) are sometimes used, but cobalt-60 is popular because of its high-power continuous radiation. Cobalt-60 is produced in unlimited quantities by exposing cobalt to radiation in a nuclear reactor. Its characteristics are subject to change with age. Its half-life is 5.3 years, indicating that the original intensity declines to one half in that period.

Fig. 6. Portable x-ray apparatus of this type is common in industrial radiography.

Gamma-ray radiographic equipment is contrived so that the cobalt-60 capsule can be remotely withdrawn from its protective cannister, exposed for any desired time, then drawn back into the shielded container. It is effective for x-raying even the heaviest castings when exposed for a sufficient period. About 15 minutes is normally needed to x-ray a 6-inch steel casting.

Gamma-ray apparatus has the advantage that no power supply is needed and it is therefore easily portable. The chief limitation is the fact that, unlike x-ray apparatus, the intensity of the beam cannot be varied to suit the requirements of a particular job.

Maintenance

X-ray circuits are relatively simple and straightforward. Most difficulties result from the exceptionally high voltage and heat. While maintenance procedures will vary with individual units, certain principles are common to all and can be used for general guidelines.

It is good practice to check the operation of an x-ray machine whenever the x-ray tube has to be replaced. As far as possible, the circuit is examined without connecting the high voltage. Whenever the high voltage is on and the x-ray tube is operating, the technician must be especially careful to avoid exposure to radiation. This means keeping clear of the active beam and also making sure that all shielding is in place. Furthermore, when it is necessary to check an operating machine, it is good practice to observe the one-hand-in-the-pocket rule to minimize the chance of having the body form part of a circuit for the high voltage. Some x-ray machines use an arrangement of capacitors to aid in building up the high voltage; when these are encountered, care must be taken to discharge them before touching the high-voltage circuit, even when the machine is not operating and is disconnected.

Arcing in the high-voltage section, a problem familiar to all television technicians, is even more of a problem in x-ray since the high voltage is many times greater than in television. Arcing may appear in a cable insulator, a socket, or in a rectifier tube. It can trip a circuit breaker, and the trouble may be attributed to a defective x-ray tube unless the cause is discovered.

An examination of the tube to be replaced will often uncover a defect in the equipment or the way it has been operated. Early failure may be due to any one of a number of causes. If the tube seems otherwise in good condition but is filled with oil, the trouble may be a puncture, probably caused by overload, excessive voltage, or instability. A cracked or broken tube would suggest careless handling. Filament burn-out would indicate a check of the filament boost circuit. Target damage would point to work overloads, such as too long or too heavy an exposure, or an excessive number of exposures without time to cool. Stationary molten spots on the target of a rotating-anode tube would indicate that the motor or motor control circuits are faulty.

A check may show that it is necess[illegible] to advance the filament voltage of x-ray tube to a higher value than [illegible] fied to obtain a certain current [illegible] x-ray tube. When this occurs i[illegible] indicate a loss of emission in the [illegible] fier tubes which, in turn, limits [illegible] flow in the x-ray tube. The [illegible] to operate the rectifiers a[illegible] filament voltage or (usual[illegible] them.

Most other checks [illegible] tracing that any [illegible] nician can hand[illegible]