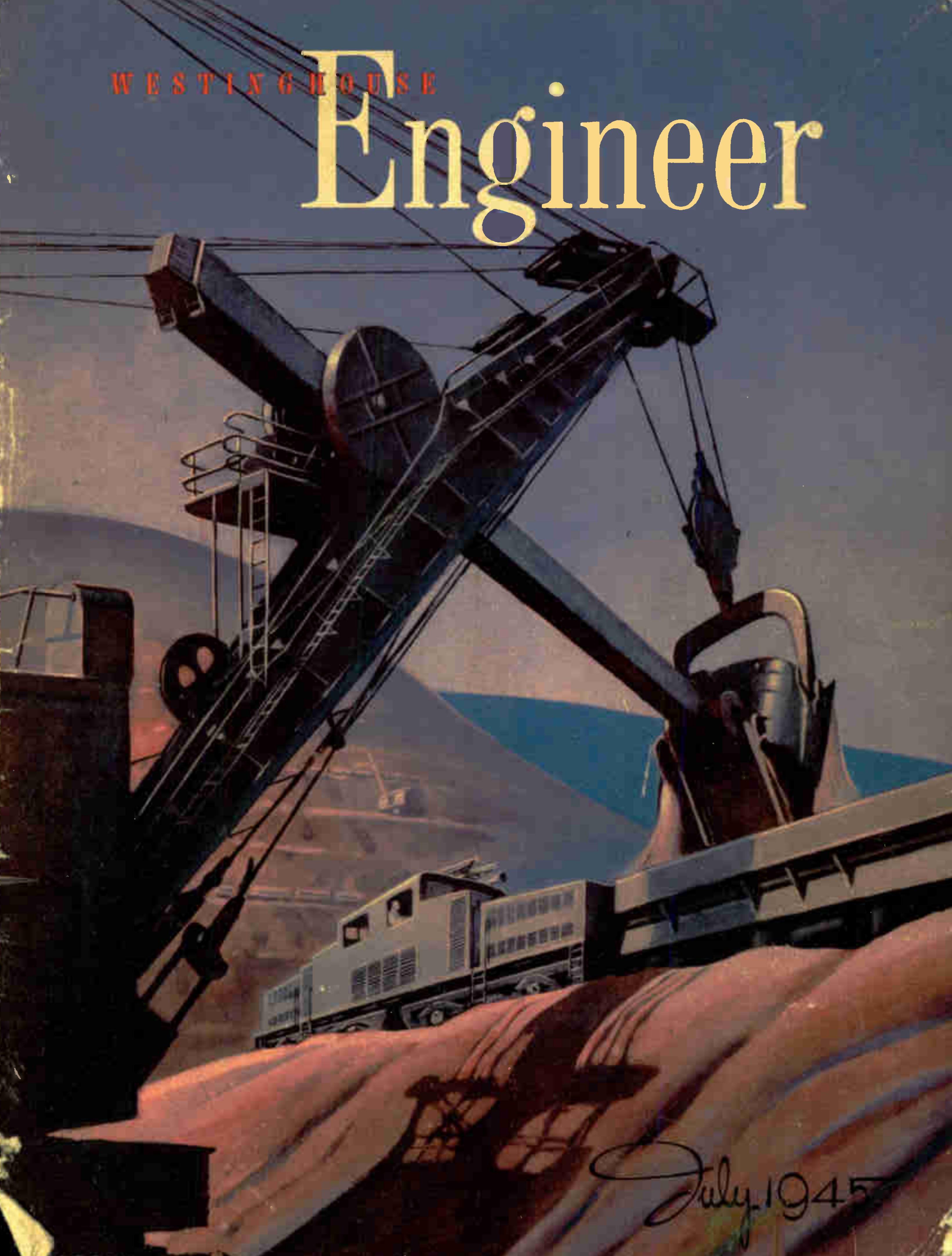
WESTINGHOUSE
Engineer



July 1945

Reducing the X of X-RAYS

X-rays probably set some sort of all-time record for brevity of time between discovery of a new phenomenon and its practical use. Wilhelm Konrad Röntgen, professor of physics at Würzburg, first observed them in 1895. Three months later x-rays were in use by surgeons in a Vienna hospital. So thorough was Röntgen that his first paper on the subject discussed nearly every basic property of x-radiation. A bibliography of scientific literature for the year 1896 lists 400 titles on x-rays, such was the great interest in this phenomenon.

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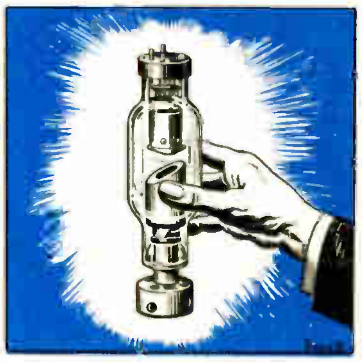
Röntgen dubbed his discovery x-rays, because the radiation was unknown as to source and nature. We now know that the effect is the result of hurling electrons at high speed against a "solid" wall. The electron beam is called a cathode ray, because it is a stream of electrons emanating from a cathode. The "wall" is a metal target, usually tungsten. When the fast-moving electrons are suddenly stopped a portion of their energy is released as the so-called x-radiation, which is electro-magnetic radiation of extremely short wavelength. X-ray wavelengths lie in the band from 120 to 0.02 Ångstroms. The quicker the electron is stopped, i.e., the greater the rate of deceleration, the higher the frequency, or, what is the same thing, the shorter the wavelength of the x-ray. This leads logically to the idea that the minimum wavelength of x-radiation is determined by the speed with which the electrons impinge on the target, which is directly proportional to the accelerating voltage. This is because the greater the speed of the electron the greater is the possible rate of deceleration. In other words, the minimum wavelength of the x-radiation is determined by the accelerating voltage. For example, a 500-kv tube produces radiations with wavelengths down to but not beyond 0.025 Ångstrom.



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The generation of x-rays is a random effect. Not by any means are all the electrons stopped "suddenly," as might be likened to a ball striking a wall. It is more like shooting BBs at a roll of chicken wire, if a bit of oversimplification can be permitted. A few shot strike the wire directly, and are decelerated with great suddenness. Most of them pass the first layer of wire, and are stopped by "installments" as they glance from one inner layer to another in every conceivable manner.

The target of an x-ray tube is not "solid," as we think of a solid surface. Actually it presents a front of relatively widely spaced atoms. In only a small portion of the cases do the electrons make "direct" hits with atoms. When they do, the energy is released as a radiation of the minimum wavelength characteristic of that accelerating voltage. Most of them strike "glancing" blows; perhaps they penetrate many layers of atoms before coming to a halt. The electrons that decelerate more slowly give up their energy as radiations of wavelengths longer than the minimum. Thus an x-ray tube produces radiation of all wavelengths above the minimum—through the ultraviolet region, and even past the visible into the infrared.

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The size of the target atoms has an effect on the intensity or amount of the x-radiation, but not on the minimum wavelength. This follows from the fact that the heavier or the larger the atoms, the greater the proportion of "direct" hits. For this reason x-ray targets are made from the element with the highest practical atomic number. Uranium, with atomic number of 92, would be best from the standpoint of efficiency of converting kinetic energy to x-radiation. But, uranium is not mechanically suitable. Tungsten is the usual target material. It is heavy (atomic number 74), can be readily worked into suitable shapes, has a high melting point, and conducts heat reasonably well.

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Some x-rays are produced in almost every electronic tube. Wherever high-speed electrons are decelerated quickly some x-radiation appears. However, in electronic tubes of ordinary voltages the electron velocities are small and hence the amount of x-radiation produced is so slight as to be inconsequential.

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Electron speeds as they strike the target in x-ray tubes are quite high. In a 300-kv tube, for example, electrons reach speeds of 149 000 miles per second or 80 percent of the velocity of light.

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The targets and x-ray tubes become hot very quickly. In ordinary radiographic tubes, the temperature at the tungsten surface rises to almost the melting point, which is 3300 degrees C, in a second or less. In the new high-speed tube the temperature rises to this value in one millionth of a second.

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Electromagnetic radiation in the x-ray spectrum differs sharply in an important respect from that in the visible region, in that the wavelength of x-rays is as short or shorter than the distance between atoms in a solid, whereas the wavelength of light extends over thousands of such atomic distances. Hence ordinary light can be reflected by ordinary smooth surfaces, and can thus be brought to a focus by concave mirrors, or can be refracted and thus be brought to a focus by lens-shaped transparent objects. X-rays, however, fall in between the atomic cracks, so to speak, and cannot be focused by such means.

The shortness of the x-ray also accounts for its ability to penetrate matter and why the shorter the wavelength (i.e., the "harder" the radiation) the greater the penetrating power. Obviously, then, x-rays to make good shadowgraphs of flowers or a man's chest need not be of as short wavelength as for steel.

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The x-ray tube is possibly the most inefficient of all electrical devices. Within the usual range of voltages, only a tiny fraction of one percent of the original energy in the cathode beam becomes available at the photographic plate or fluorescent screen. This is the result of a succession of losses.

In the first place, only a small percentage of the energy imparted to the electrons appears as radiation in the x-ray region. The great bulk of it comes out as heat—therefore, the cooling of x-ray anodes is a major problem in tube design. The higher the electron-accelerating voltage, the higher the efficiency of conversion to x-rays. At 100 kv, this efficiency is about one percent; at one million volts, five to ten percent.

Then, because x-radiation cannot be focused, only a small portion of the little bit developed at the target becomes the x-ray beam. All the remainder is unavoidably thrown away.

Finally, of this small proportion of the total usable x-rays taken from the target only a fraction get through the glass wall of the tube. The product of these small fractions, which is the overall efficiency, is a very small number.

WESTI

Engineer

VOLUME FIVE | JULY, 1945 | NUMBER FOUR

On the Side

The Cover—Utilization at low cost of the vast natural resources of minerals, such as those iron ore and copper deposits that lie close to the surface, is due in no small part to electric power as used by large shovels and locomotives. A representative open-pit operation is depicted by our artist, F. G. Ackerson.

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The geared-turbine steam locomotive described in detail in the March issue has completed, with marked success, both heavy-freight trials and operation in high-speed passenger service. The Pennsylvania Railroad has announced preliminary plans to have built a still larger geared-turbine locomotive with several novel features. It will have two turbines totaling 9000 hp. Instead of the usual locomotive arrangement, the coal compartment and engineer's cab will be at the front and the turbines and boilers in sections at the rear.

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The Chesapeake and Ohio Railroad has let contracts with Baldwin Locomotive Works and Westinghouse for three turbine-electric locomotives. Each unit is to have a 6000-hp turbine driving two direct-current generators that supply power to eight d-c motors on separate driving axles. These locomotives will be fully streamlined, with cab in front and are intended primarily for high-speed passenger service.

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The all-American gas-turbine drive for Navy planes developed by Westinghouse is already in production at South Philadelphia. The Navy and Westinghouse this year are jointly investing $9 000 000 for further laboratory development and manufacturing facilities of this revolutionary type of airplane drive in the new Aviation Gas Turbine Division.

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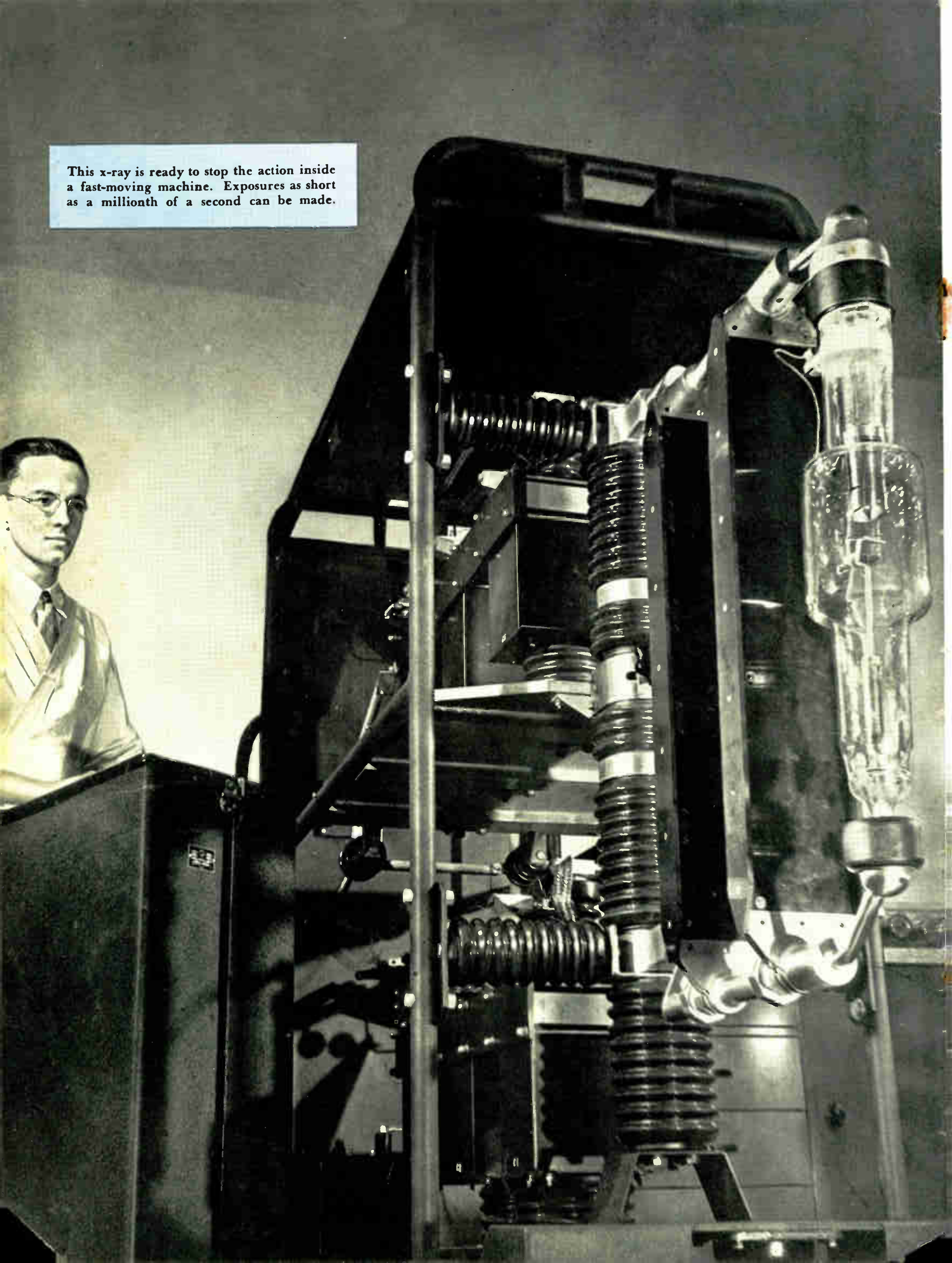

This x-ray is ready to stop the action inside a fast-moving machine. Exposures as short as a millionth of a second can be made.

Millionth-of-a-Second X-ray Snapshots

Man's personal experience in matters of time is confined to events that occur within narrow limits—from a fraction of a second to about a hundred years. For happenings of longer duration he must examine the records of man or nature. To explore those vast worlds of events that complete their full cycle in small fractions of a second he must build special tools, such as the new ultra-high-speed x-ray machine. It freezes for direct and leisurely examination all sorts of ultra-rapid actions of machines, of impacts, and perhaps even of chemical reactions. It opens a wide door to an entirely new "world" of time in mechanical phenomena.

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Westinghouse Electric Corporation

X-RAY pictures of a golf ball as it is struck, a football and the foot that kicks it, a glass bulb as it is shattered by a missile are spectacular, interesting, but perhaps not too important. They are indicative, however, of the capabilities of a new type of high-speed x-ray machine, which offers a prospect of major importance to every engineer concerned with machines in motion, impacts, vibrations or other occurrences that are too fast for observation or are obscured from view of eyes or camera. Furthermore, taking of such high-speed x-ray pictures does not necessitate highly specialized laboratory technique or complex, cumbersome laboratory apparatus. The new high-speed x-ray machine is a compact unit on wheels, with simple controls. It is actually simpler in its principle of operation than the conventional x-ray machine. It is a practical industrial tool. It is self-contained, requires no special source of power, and is suitable for either special or routine investigations.

The high-speed x-ray is not an ordinary industrial x-ray machine "souped up" for ultra-fast operation. That is impossible. The high-speed x-ray machine employs a tube using a new type of electron emitter and is supplied with power from a stored-energy source, instead of drawing it from a power line as used.

In taking a radiograph, the time of exposure at any given voltage is determined by the intensity of the x-ray beam, which in turn is dependent on the magnitude of the current through the tube. For normal exposures, which range from a few seconds to perhaps minutes in duration, the tube current is several milliamperes. To make a suitable exposure at one millionth of a second, a current a million times greater than the usual current, i.e., some thousands of amperes, must be passed through the tube. Currents of this magnitude cannot be obtained from a heated tungsten filament. Some other source of electrons is required.

The search for a new method of supplying such an inordinately large current led, curiously, to utilization and encouragement of a phenomenon previously considered a weakness or defect in high-vacuum electronic tubes, and consequently was studiously avoided—that of random discharge. This emission abnormality had been previously thought to result from an increase in the gas pressure in the tube. In a simple two-electrode tube filled with gas at or about atmospheric pressure, the voltage required to produce a discharge is large. As the pressure is reduced, the discharge voltage also decreases until a certain minimum is reached, after which further decrease in pressure causes the voltage to rise again. This is in accordance with Paschen's law. As the high-vacuum portion of the curve is approached, the slope becomes extremely steep, leading to the expectation that the voltage should reach infinity at extremely low pressures. Furthermore, x-ray tubes were known to operate at higher and higher voltages as the vacuum improved. Reasoning along these lines, it has generally been concluded that when a tube fails to withstand high voltage it is because the vacuum has become impaired. The tube is said to be "gassy."

Physicists now recognize that irregularities in operation often occur in tubes having the highest of vacuums and that gas is not responsible for the phenomenon. Illustrative of this, a deep-therapy x-ray tube was provided with an ionization gauge and sealed off with a neon pressure of three microns. The tube operated satisfactorily for some hundreds of hours. When arc-overs, usually attributed to gas, did develop

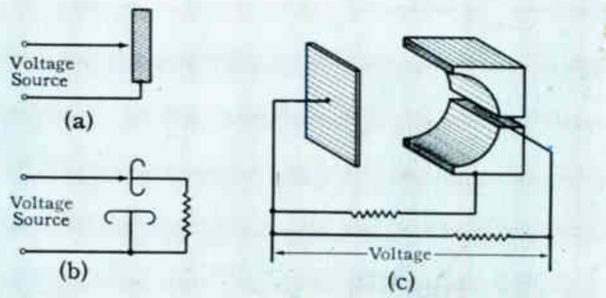

Fig. 1—These successive steps led to the cathode construction that has proved effective in the high-speed x-ray unit. The point-to-plane cathode of (a) is inconsistent in performance. That of (b) is much better, the emission first occurring at the point to plane but quickly breaking down into an arc. The series resistance is high enough to cause a stable, reliable discharge between the two planes. The cathode of (c) carries out the idea developed in (b) and provides, by its cup shape, a means of focusing the electrons toward the anode.

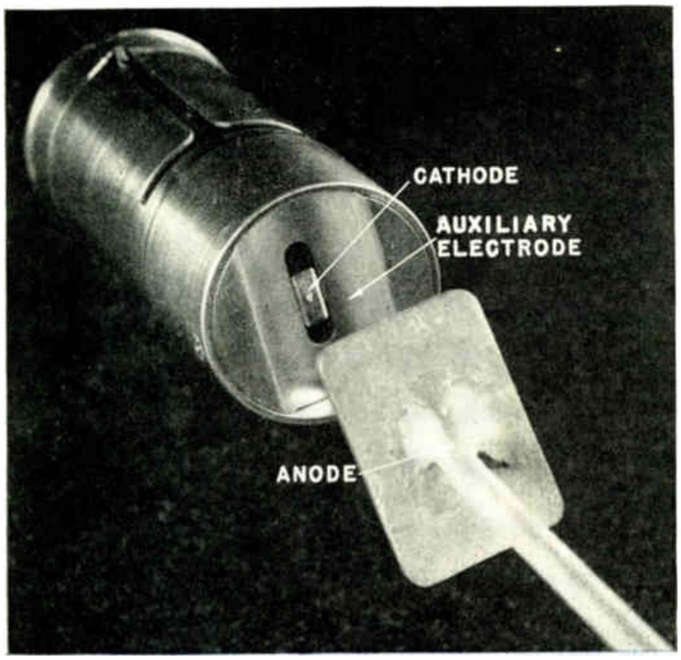

Fig. 2—The practical form of the cathode and anode construction used in the high-speed x-ray tube. The cathode is a sharp-edged paddle set in a slot in the trough-shaped auxiliary electrode, the shape of which provides a focusing cup.

the actual pressure as indicated by the ionization gauge, instead of increasing, declined to 0.01 micron.

The erratic behavior of tubes, referred to as gassy, is apparently not caused by the gas content of the tube but by the emission of electrons under the influence of high electric fields that exist at points other than the heated cathode. Sharp corners and points on the tube parts tend to accentuate the voltage gradients; impurities or occluded gas tend to lower the work function of the surface and make it easier for the electrons to escape. Such bursts of electrons by cold emission occur at voltages far less than those calculated to be necessary for their production from pure metals. This phenomenon is not limited to x-ray tubes but applies to all high-vacuum electronic tubes and is the cause of a large part of the irregularities in such tubes, particularly where the voltage rating is exceeded.

The magnitude of these bursts of electrons was surprisingly large, of the order of several amperes. Inasmuch as the effect was so large in tubes designed especially to avoid them, the possibility presented itself of increasing them by deliberate design to the point where some useful purpose might be served by the sudden flow of large amounts of current.

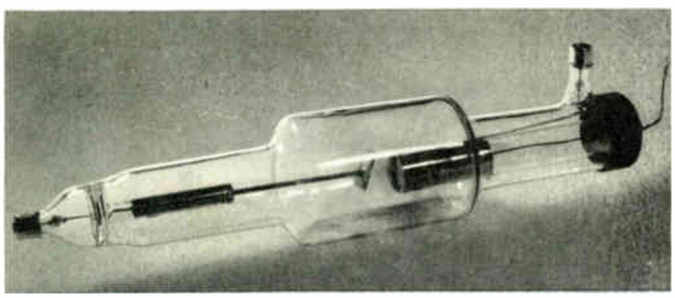

Fig. 3—In this tube controlled bursts of extremely high emission currents produce x-radiation of such great intensity that exposures of one-millionth of a second are possible.

The first trial was made with a single-point tungsten cathode placed approximately one millimeter from a flat anode, Fig. 1(a). With this arrangement several thousand amperes could be drawn from a condenser charged to 50 000 volts. Some x-rays were produced but, in general, the behavior was erratic. If the point was too close to the anode, an arc was formed that allowed such large currents to pass that most of the energy was dissipated in the circuit rather than in the tube. As the wire was moved farther back, the peak current diminished and the production of x-rays increased, but the initiation of the discharge became uncontrollable, the tube often refusing to fire. Many shapes and types of material were tried, but the results were much the same in each case.

This difficulty was overcome by the introduction of a third electrode, Fig. 1(b), spaced close to the cathode and connected to the anode through a high resistance. This electrode served to concentrate a high field at the cathode and initiate the discharge that is then forced by the voltage drop across the high resistance to transfer to the anode. As soon as this auxiliary electrode has performed its job of starting the discharge, it assumes a potential close to that of the cathode and consequently, if shaped correctly, as in Fig. 1(c), focuses the electrons on the desired region of the anode. By this arrangement currents of several thousand amperes essential to the production of intense x-ray outputs required for extremely fast radiography are regularly obtained.

The tube structure used is illustrated in Fig. 2. The tungsten point is replaced by a small rectangular piece of molybdenum, which acts as the cathode. The auxiliary cathode consists of the trough-shaped block, which provides a focusing cup. The sharpened edges of the molybdenum cathodes are located close to the edge of the slot in the auxiliary electrode so that the high-potential gradient thus obtained is sufficient to initiate a cold-emission discharge. The auxiliary electrode also acts to focus the electron beam so that an approximately rectangular focal spot is produced on the anode.

The target consists of a rectangular slab of tungsten 1 by 1½ by ⅛ inches thick. Tungsten is desirable because of its relatively high efficiency of x-ray production as well as its high melting point and good heat conductivity. Although the exposure time is only one microsecond, a large amount of energy is put into the focal spot during this time. Theoretical considerations show that heat conduction plays the major role in dissipating the energy delivered to the focal spot area. Because the amount of heat conducted from this area depends on time and the difference in temperature, the heat-dissipating ability of a focal spot decreases as the exposure time decreases. Thus heat conduction would seem to be quite small for exposure times of one microsecond such as are considered here. Fortunately the heat dissipated varies with the square root of the exposure time.

Even calculated on this basis, focal spots far larger than those in use would be necessary to dissipate the energy without vaporization of the target. However, in practice, while some vaporization does occur within the small focal areas, several thousand exposures can be made before the deposit of metal on the glass becomes heavy enough to interfere with the operation of the tube.

These conditions indicate that the focal spot (hence the obtainable definition) cannot be made as fine in a tube operating at these extremely short exposure times as in tubes operating in the conventional manner. However, adequate definition for most purposes is easily obtained and rather fine definition can be secured in one direction by taking the x-rays off the target at or near grazing incidence.

Development of these high currents in the x-ray tube, shown in Fig. 3, requires a large but brief rate of power flow. During the period of peak operation the amount of power flowing to the tube is of the order of 600 000 kilowatts. Its total duration, of course, need be but a few microseconds. Clearly, then, stored energy is demanded. This requirement is fulfilled by a surge generator, such as is commonly used for simulated lightning studies.

The surge generator built to operate the high-speed x-ray tube is shown in Fig. 4. Six 0.04-μf condensers are arranged in a Marx circuit substantially as illustrated in Figs. 5 and 6. The exceedingly rapid breakdown of the x-ray tube has permitted closer spacing of the condensers than is normally the case so that a relatively compact design has been achieved. The condensers have been separated into two groups or levels of three each. Each of the condensers can be charged to a potential of 50 kv, thereby resulting in an output potential of 300 kv across the tube. A stabilizing resistor is added across the x-ray tube to facilitate consistent firing. Without this resistor, the surge generator would be feeding into an unknown resistance because of the varying characteristics of the vacuum space within the tube, which is part of the circuit. The condensers are arranged to be charged in parallel through resistance high enough (10 000 ohms) that when they discharge in series through the sphere gaps, no appreciable loss of energy occurs in the resistors.

The first condenser is connected directly to the anode of the x-ray tube. C6 is connected to the cathode of the x-ray tube through a sphere gap. Condenser C3 is grounded and the cans of condensers C2 and C1 are connected to each other through series resistors. The metal cases of C4, C5, and C6 are connected together through resistors and connect to the positive input potential from the high-tension transformer. The three upper gaps are linked together and are adjustable by means of a special micrometer, operable from the front panel of the generator. The lower two gaps are connected in like fashion, and can be adjusted by a similar micrometer mechanism. The gap on the condenser C3 is made non-adjustable and serves as the triggering gap for the surge generator; that is, the output of the trigger potential transformer is con-

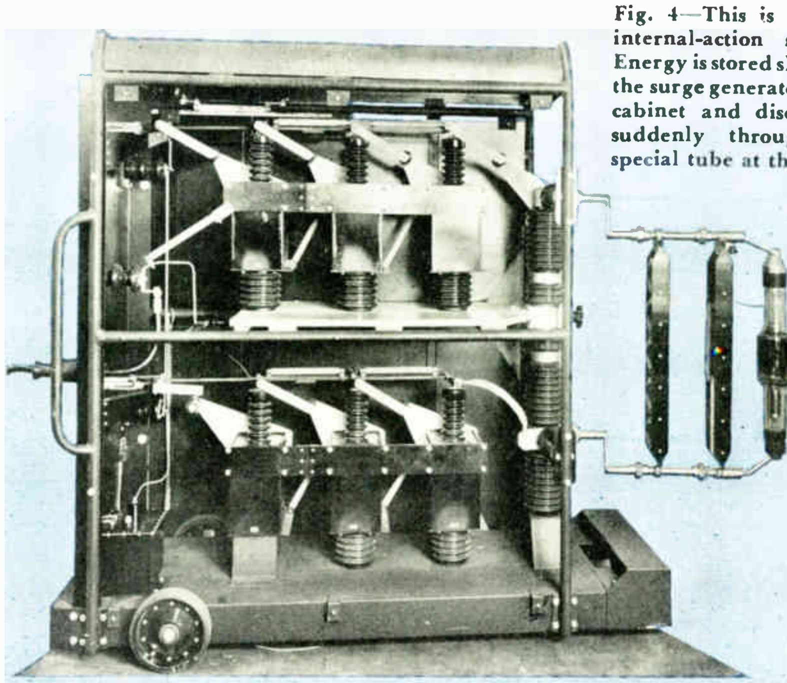

Fig. 4—This is a super internal-action stopper. Energy is stored slowly in the surge generator in the cabinet and discharged suddenly through the special tube at the right.

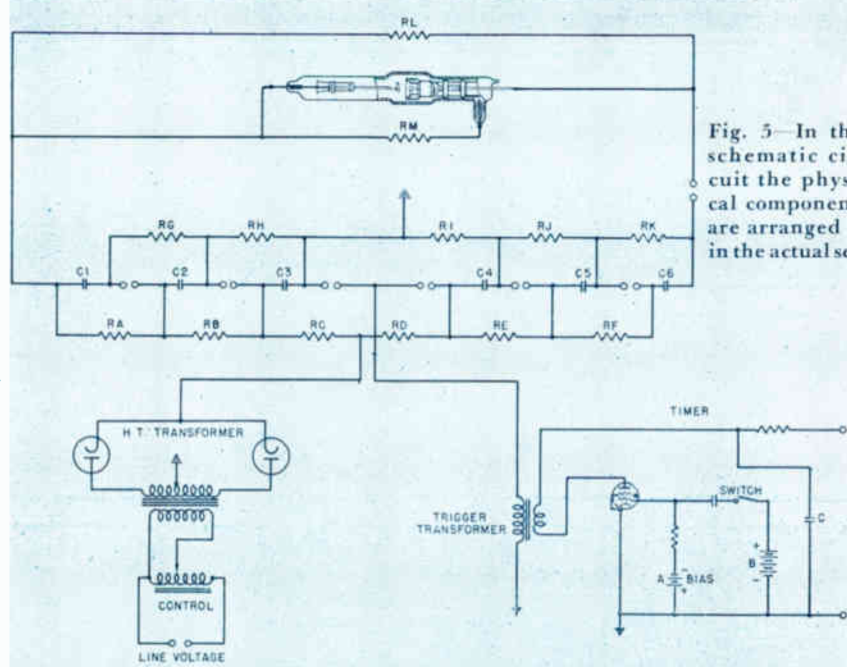

Fig. 5—In this schematic circuit the physical components are arranged as in the actual set.

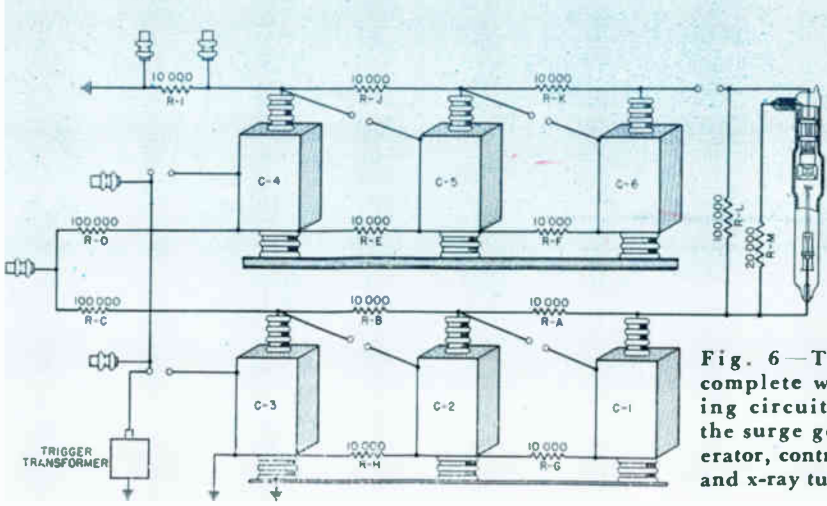

Fig. 6—The complete wiring circuit of the surge generator, control, and x-ray tube.

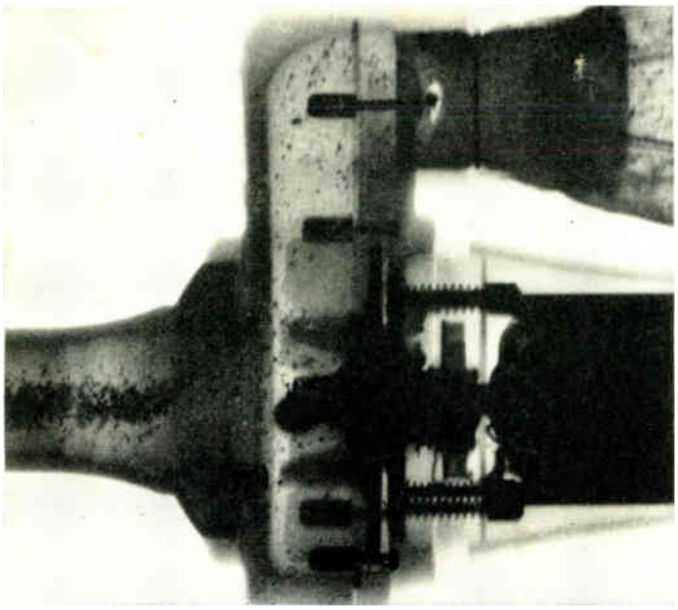

Fig. 7—The behavior of components on the interior of rapidly moving machinery can be studied as indicated by this high-speed shadowgraph of a vacuum cleaner and dirt particles.

nected between this gap and ground. The high-tension cable is connected to the upper lead of condenser C3 and to the case of condenser C4. The connections between the input potential and the case of C4 and the insulated lead of C3 are made through 100 000-ohm resistors.

When the condensers have been fully charged and the unit is ready to fire, an impulse is sent from the timing unit through the primary of the triggering transformer. This pulse is supplied by condenser C in the timing unit, which, at the appropriate instant, is caused to discharge by removing the negative bias on the grid of thyratron. This is done by closing the switch that connects battery *B* to the grid of the thyratron.

Several means have been used to accomplish this break, such as a bullet cutting a wire and setting off the machine to radiograph itself, or a golf club breaking a swinging contact. In the timing unit furnished with the surge generator the triggering can be done by either breaking or making a contact and the unit is provided with several resistances and capacities so that the time interval between actuating the contact and firing the x-ray tube can be chosen to catch the desired phase of the action cycle.

The pulse delivered to the circuit by the secondary of the triggering transformer causes the gap between ground and condenser C3 to break down. When this gap breaks down, the voltage between the gap of condenser C4 and ground rises until the gap on condenser C4 breaks down. This results in immediate discharge of all condensers. The voltage applied across the x-ray tube is then equal to six times the charging voltage on the condensers. This high voltage is applied directly across the closely spaced cathode and auxiliary electrode. Electrons are drawn from the cathode and this initial discharge evolves into a metallic arc between the cathode and auxiliary electrodes that spreads out into the focusing cup and becomes a virtual cathode of apparently unlimited current-carrying capacity. Due to the action of resistance *R-M*, the discharge transfers to the anode with consequent production of x-rays.

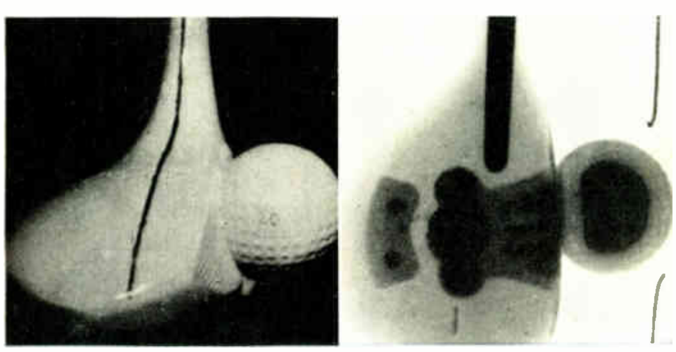

Fig. 8—While a high-speed light-camera shows what the outside of a golf ball and club look like during impact, the high-speed x-ray picture shows the interior of ball and club.

Applications of High-Speed Radiography

The usefulness of the high-speed x-ray in ballistic studies is conspicuous. The engineers at the Frankford Arsenal Laboratory were quick to so use it. The equipment has been used by them to study what happens to a bullet when it strikes a piece of armor, and also what happens to the armor during penetration. Ordinary photographic methods, including high-speed photography, are handicapped because the actual penetration is obscured by luminous fragments thrown back at the time of impact. This difficulty is, of course, avoided in radiography.

High-speed x-ray pictures have been taken of armor-piercing bullets during the actual penetration. Two mutually perpendicular high-speed x-ray pictures, taken in sequence of a .30-caliber armor-piercing bullet penetrating a small two-by-two-inch piece of ½-inch thick armor, are shown in Fig. 9. The first of the high-speed x-ray pictures was taken when the core of the bullet had penetrated ⅜ inch into the yielding armor plate. The jacket, which cannot penetrate the armor, has telescoped forward on itself and exposed the base to the core. The second high-speed x-ray picture was taken of this same bullet approximately 20 microseconds after the first picture. The core of the bullet has penetrated the armor and its tip is projecting through the back. Part of the armor pushed out by the penetration can be seen. The jacket of the bullet has continued to telescope on itself and even more of the base of the core is in evidence. Other high-speed x-ray pictures taken during this study showed the flow of the jacket material and the breaking up of the core as the bullets penetrated the armor.

The high-speed x-ray equipment is pre-eminently fitted to study the bullet motion and behavior inside a gun barrel. No other means is available for taking a picture of a bullet as it passes down the bore of the gun. When a bullet is fired in a gun barrel, the blast that accompanies each shot reaches the muzzle before the bullet does. A spark shadowgraph of the blast which precedes the bullet exit is shown in Fig. 10. This spark shadowgraph was taken at the instant the silvered glass rod placed at the muzzle of the gun was broken. The location of the bullet, still several inches from the muzzle, was determined by means of a simultaneous high-speed x-ray picture shown. Previous methods of determining the location of the bullet at any instant in the gun barrel, such as by strain gauges, have proved to be inaccurate.

The high-speed x-ray equipment has been used to observe the realignment of component parts inside the bullet when it is fired. A stationary x-ray picture was taken of the bullet in question. The bullet is then fired and a high-speed x-ray picture is taken of this same bullet in flight. A comparison of the

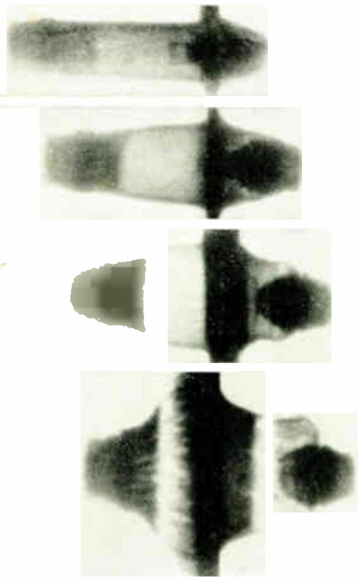

Fig. 9—From high-speed x-ray pictures like these taken under the direction of E. R. Thilo of Frankford Arsenal, ballistics experts learn many things about projectiles and armor plate.

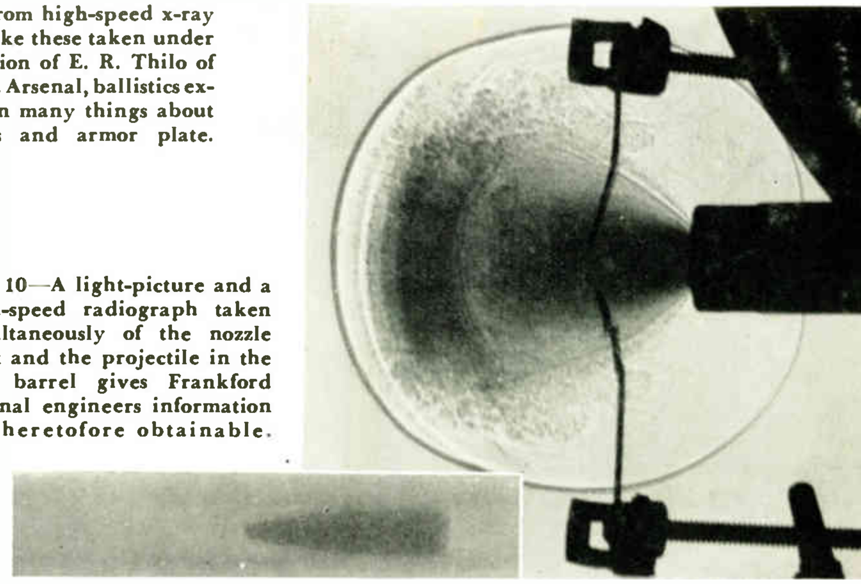

Fig. 10—A light-picture and a high-speed radiograph taken simultaneously of the nozzle blast and the projectile in the gun barrel gives Frankford Arsenal engineers information not heretofore obtainable.

two x-ray pictures reveals any shift of the component parts that has taken place. This procedure can be used, for example, to study the motion of the component parts of valves during their operation.

A series of high-speed x-ray pictures has been taken of a 20-mm, high-explosive shell passing through steel plate. It was necessary to place a steel plate ¼-inch thick over the x-ray filmholder in order to protect it from the force of the explosion and the flying fragments. A new protection plate was required after every shot. Despite the fact that all the pictures were taken through ¼ inch of steel, the details of the explosion are clearly evident. One of the amazing things revealed by this study is the immense swelling of the shell to almost twice normal diameter before it finally bursts open.

The high-speed x-ray equipment has one use for which it was not designed. It can be readily adapted to serve as the light source for high-speed "flash" photography. A wire spark gap is substituted for the x-ray tube on the surge generator. The short-duration, high-intensity spark resulting from the discharge of the surge generator can be used to take a millionth of a second photograph of any moving object. A picture of a .50-caliber bullet in free flight taken in a millionth of a second is shown in Fig. 11. The light from the spark discharge of the surge generator was used as illumination.

The applications of this equipment have primarily been confined to the field of ballistics, simply because of the tremendous interest in this subject during the war and the high speed is so well adapted to this purpose. Many applications exist in other mechanical-engineering fields. The requirements for a suitable application are: (1) a desire to study parts in motion, (2) a condition where high-speed light photography is not adequate, either because the parts to be studied are not visible, or because of the danger of mechanical damage to an unprotected camera.

Consider the severe problem of the blades in both steam and gas turbines. Under the stresses imposed by the high speed and thrust of the expanding vapors, the condition under rotation may be very different from that existing at rest. Further, the blades are necessarily enclosed in a heavy metal case. The operation of turbine blading becomes a problem susceptible to study by the high-speed x-ray unit.

Valve action for reciprocating engines, compressors, and similar machines can be observed in normal operation by this x-ray unit. Deformation in butterfly valves in one case caused a shift in the timing of one machine that impaired the operation. Just how the valves were acting could be determined by the x-ray.

Extension of the applications of this unit must come in the postwar period when more of these units become available. This extension will be in those applications that satisfy the two fundamental requirements.

The new uses will be in those fields of engineering when parts are moving rapidly and cannot be "seen" by the conventional camera using a light source.

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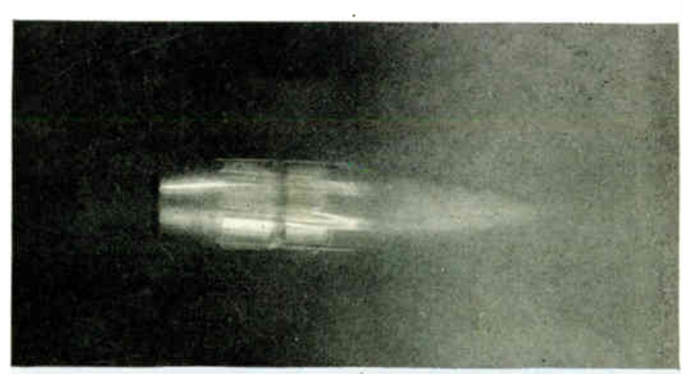

Fig. 11—To take this light-picture of a bullet in flight the x-ray tube was removed and the surge generator discharged across a gap to give an intense but extremely brief light.

Electronic Load Control of Machine Tools

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"Don't work too hard" is the trite and meaningless statement often heard. But it can have real meaning when applied to an electric motor. A motor may, under some circumstances, exert too much force, injuring itself or the mechanism it drives. However, the motor can be provided with "judgment" by which its output is automatically modified by change of demands on the machine tool.

Automatic motor load control can be used effectively to increase production and, at the same time, minimize cutter damage. A milling machine provides an excellent example. If a milling machine is making a roughing cut on a casting, milling a slot in an irregular-shaped piece, or performing a similar operation, the rate of removing metal varies. The load on the cutter and cutter motor varies approximately in proportion to the amount of metal removed. Differences in the metal itself, such as hard spots, cause additional variations in the load. If the rate of metal removal becomes too great, either the cutter will break or the motor will be overloaded. Therefore, the operator adjusts the depth of cut and rate of feed for the worst possible combination of conditions to be met in the machining cycle.

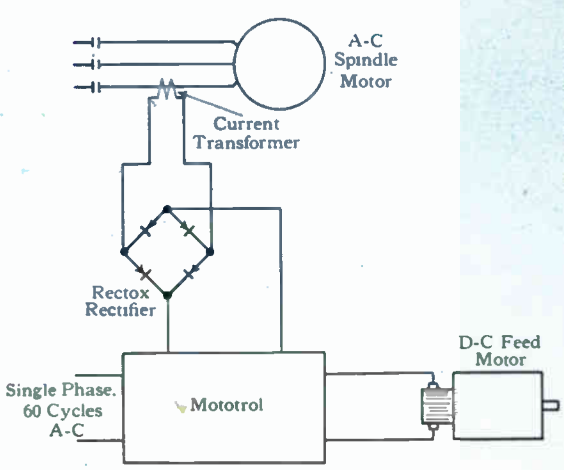
Quite often, this maximum loading lasts for a small portion of the total cycle, so that the cutter is working at its peak loading but a small part of the total time, and, as a result, the overall rate of metal removal is low.

If the tool feed of the milling machine is equipped with a wide-speed-range, adjustable-voltage drive, the load on the cutter can be maintained nearly constant by automatically adjusting the feed speed to compensate for the varying depth of cut or hardness of the material. By one simple arrangement, the load on the spindle motor is measured and the feed speed automatically adjusted to maintain the load on this motor to some predetermined value. The scheme is applicable for either a-c or d-c motors on the spindle. Adjustments can be made easily by the operator for controlling the load on the spindle motor and also for limiting the maximum feed speed, if desirable.

Maximum benefit from this system requires the use of an adjustable-voltage drive, which can be either of the m-g set or the electronic type. The basic scheme when using an a-c spindle motor and electronic adjustable-voltage feed drive is shown in Fig. 1. On the assumption that the load on the a-c motor is roughly proportional to the line current, a current transformer is connected in one phase of the a-c motor and fed into a Rectox unit, which rectifies the current from the current transformer. This current is proportional to load and can be used to control the adjustable-voltage system of the feed motor to vary the feed speed.

If the a-c motor is of a special design so that the current is not proportional to load, or if it is desired to adjust the load over a fairly wide range, a slight variation in the circuit can be used. The output current obtained is actually proportional to the kw input of the motors instead of the current input, and is a more exact measurement of cutter load.

This arrangement is satisfactory for the simpler forms of milling machines that have only one milling cutter. Many milling machines have more than one spindle, four being used on many machines. In Fig. 2, a circuit similar to the one shown in Fig. 1 has been modified so that it can be used for any number of milling cutters. The output circuits of the Rectox units are all connected in series. The current flowing



Load Control for Spindle Motor

Fig. 1—The basic scheme of controlling the feed of a machine-tool cutter as a function of the spindle-motor load.

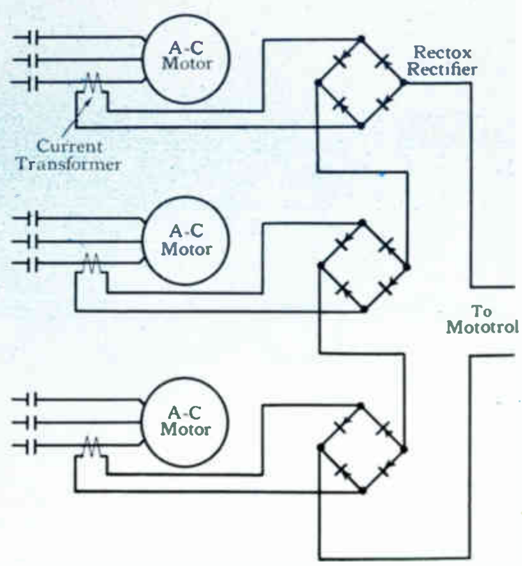
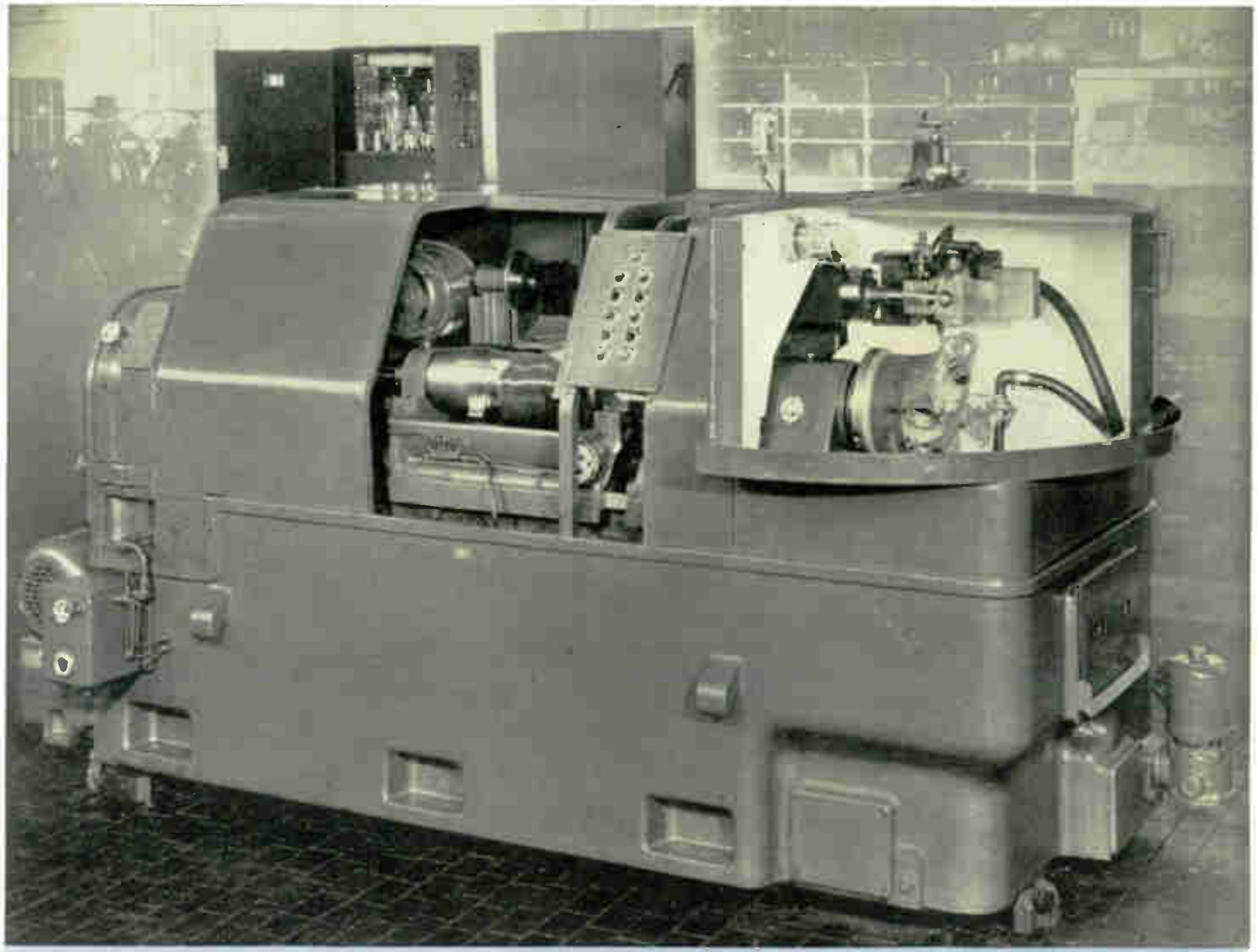


Fig. 2—The basic scheme of Fig. 1 is here modified for use with a number of milling cutters.

Load Control for Multi-Spindle Drive



This fin miller, designed by the Sundstrand Machine Tool Company to take advantage of the load-control feature of the Mototrol, machines cooling fins on the cylinder heads of aviation engines. It is evident that the load on the cutter will vary widely and in some places there will be no load. By speeding up the feed speed over the no-load section and electronically reducing the speed of the feed to the proper value when the milling tool engages metal, the use factor of the fin-milling machine is increased as much as 30 percent.

in the output circuit is always proportional to the maximum load on any one of the motors. On most circuits this output is either the sum or difference of the current, but this particular arrangement selects the maximum current of any one of the motors. With this connection, the feed motor is regulated to maintain automatically the desired load on at least one of the cutter motors at all times, while the remaining cutters are carrying any loads from no load up to full load.

ENGINEERING PROFILES

Steel is being rolled in strips as thin as 0.0015 inch and brass as thin as 0.004 inch. To avoid breaks, the metal must be threaded through the mill at low speed and the tension carefully controlled. An electronic control adjusts the field of the reel motors to compensate for the build-up or lessening of the coil of strip on the reel. A light source looks over the top of the coil to a movable photoelectric cell. As the coil increases in diameter, it tends to block the light beam and the photoelectric cell automatically moves up to keep in the light beam. This movement, a measure of the change in coil diameter, is translated into a change in field current that keeps the tension exactly at the preset level, regardless of the size of the coil of strip on the reel. In a cold-strip mill, a 0.0015-inch strip can be controlled down to a strip speed of but eight inches per minute.

• • •

Machines that are marvels of ingenuity turn out 50 molded glass bottles each minute. Molten glass is deposited mechanically in a mold near the outer circumference of a circular table. As the table revolves, the glass is pressed, blown, cooled, etc., at succeeding points until it is removed as a completed bottle. The bottles are lined up and pushed into a leer (annealing oven). Mechanical linkages also are used to synchronize the leer loading with the master table. Elimination of these long horizontal shafts, gears, couplings and the vertical jack shaft of the feeder has been accomplished electrically. Wound-rotor motors with rotors connected in parallel (called a synchro-tie system) behave as though the rotors are connected by a flexible shaft. Synchro-tie units applied to the molten-glass flow gate and to the leer loaders are operated by a driving motor at the master table. Positive action at these points insures the admission of molten glass into the mold as it swings into position, at the same time removing the completed bottle from the succeeding mold and placing the bottle in position for admission to the leer. Complicated mechanical linkages are replaced by trouble-free electrical connections.

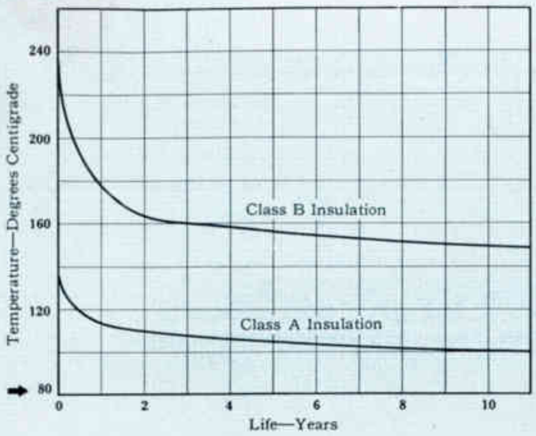


Fig. 1—Class-A and class-B insulation time-temperature characteristics (Lamme and Steinmetz).

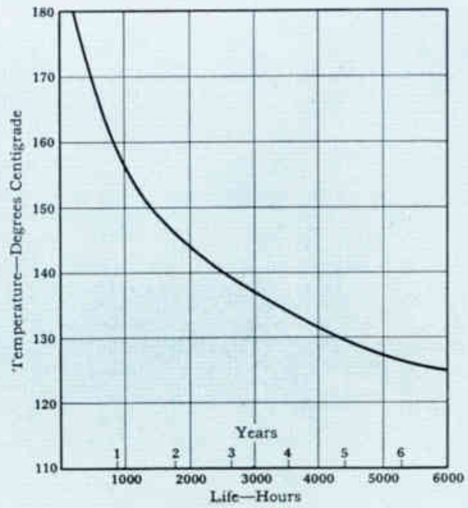


Fig. 2 — Hypothetical life temperature for insulation (Hobart).

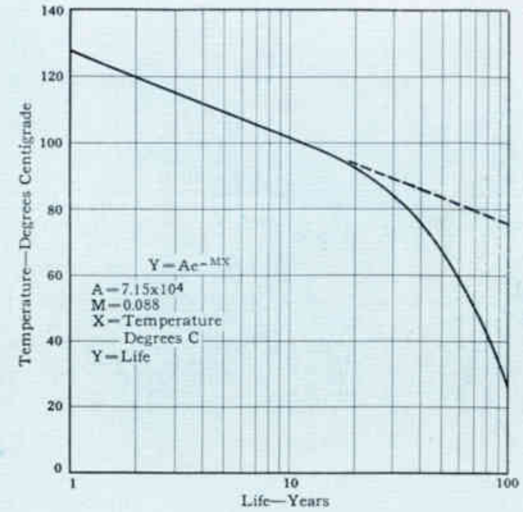


Fig. 3—Life-temperature curve of class-A insulation in oil (Montsinger).

Synthetic Insulation and the 10-Degree Rule

Rules of thumb are such useful things. But, because they are so handy, we may fall into the easy error of using them without the necessary occasional check to determine if they are still applicable to present conditions. The new synthetic insulations require a reexamination of the effect of temperature on insulation life.

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Engineers have frequently used a "rule of thumb" for interpreting accelerated thermal-aging tests on insulation. This rule states that the thermal life of insulation is halved for each 10-degree C increase in temperature, or doubled for each 10-degree C decrease. This has been very useful and sufficiently accurate within reasonable limits of temperature spread. However, the advent of numerous new types of insulation has raised the question as to the soundness of the rule. A review of recent studies of insulation life indicates that the basic rule is adequate for reasonable approximation.

The general practice in making accelerated life tests is to study the effects at several temperatures and to determine the actual slope of the life curve for that particular combination of insulation. Then extrapolation to operating temperatures is more reliable.

A review of the historical background of this rule provides a better understanding of it and helps in evaluating its applicability to new insulations. Men engaged in early development of electrical machinery recognized that a relationship between the life of machine insulation and the operating temperature existed. In 1898 discussions of this relation occurred in meetings of the AIEE.[1] In 1905, laboratory tests were undertaken by Rayner at the National Physical Laboratory in London,[2] to study the effects of temperature and time on dielectric and mechanical properties of insulation that demonstrated this correlation. In 1913 Lamme and Steinmetz said: "The problem of permissible temperature limits in electric apparatus is largely that of durability of the insulation."[3] At that time, Lamme proposed the idea of a curve expressing the life of insulation for a machine.[4] The difference in the rate of thermal aging of class-A and class-B was recognized in the variations in the life expectation for these two classes of insulation as shown in Fig. 1. Lamme's conception of the shape of these curves was a well-defined asymptote, parallel to the axis of time. Hobart proposed the use of equivalent aging tests in 1923, which consisted of "a higher temperature applied for a shorter time."[5] He presented a hypothetical curve for typical insulation, shown as Fig. 2, which he believed would permit extrapolation of accelerated test results.

In 1930 Montsinger suggested a general law for insulation aging that plots a straight line on semi-log curve paper, with time as the logarithmic co-ordinate, as shown in Fig. 3.[6] This takes the form that for a specific increment in temperature, the life decreases by half for each such increment, and is expressed by the equation given in Fig. 3. Curiously, Hobart's data from Fig. 2 also plots a straight line on semi-log paper.

In 1940 the author pointed out that there is a range of time during which insulation may fail instead of an absolute end point.[7] This is illustrated in Fig. 4, where life is indicated as a variable thing with a range of normal expectancy. During this period between minimum and maximum life, other factors than temperature are the actual causes of failure. The spread of this range may be quite wide as indicated in Fig. 4.

Scott and Thompson reported in 1942 that tests on many small motors with class-A insulation have confirmed the belief that insulation ages according to the general law suggested by Montsinger.[8] They introduced statistical methods of analyzing their results and plotted the 90-percent failure zone as well as average life as a function of temperature. Some of their typical data is shown in Fig. 5.

In recent years a tremendous amount of data has been collected on numerous types of varnishes tested by various methods at different temperatures. These tests confirm the basic premise that the life of varnish-treated insulations follows the straight-line curve on semi-log paper, as Fig. 6 shows. All conform to the general pattern within the range explored.

The curve of Fig. 7 compares the life curves that have been used by the authorities referred to with the addition of a few points that have frequently been mentioned as typical life values. These curves indicate some variation in concepts of actual life of insulation but in general agree that life is a function of temperature where other factors do not predomi-

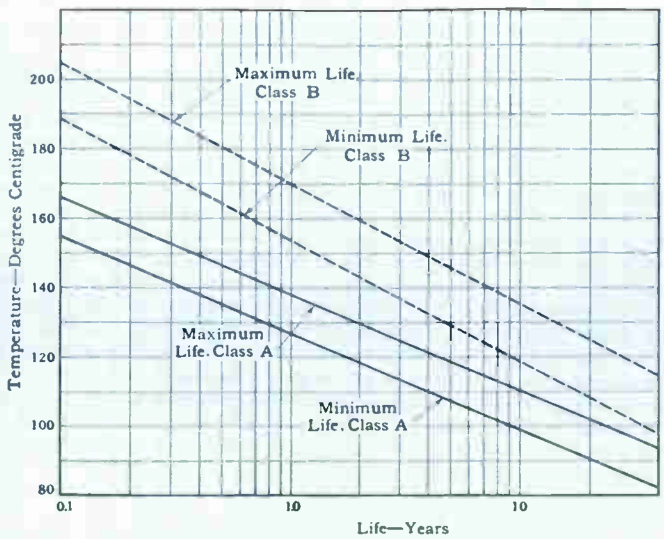

Fig. 4—Temperature effect on insulation life (Moses).

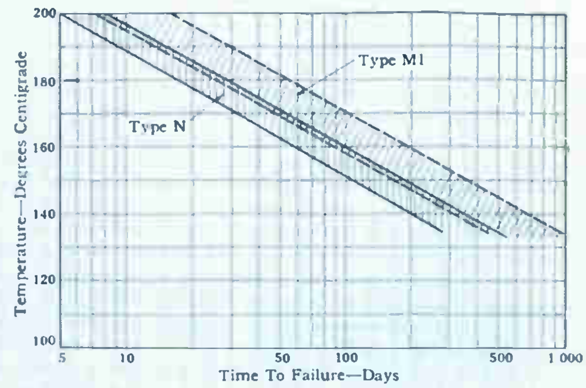

Fig. 5—Temperature-aging characteristics of class-A stator-coil insulation according to Scott & Thompson.

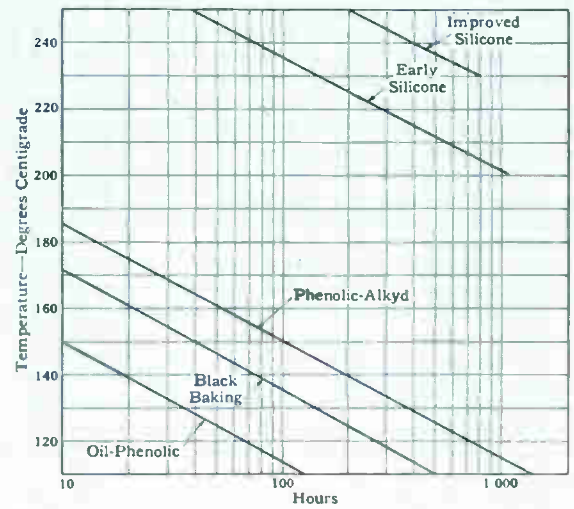

Fig. 6—Varnish heat-endurance tests determine the life span under various temperatures. The terminal point in the life test is shown when the varnish cracks when the material is wrapped about a mandrel of specific diameter.

nate. Wide differences exist in the actual values assigned to insulation life because classes of insulation (such as AIEE classes A and B) are not completely descriptive. Different insulations within a class may vary widely in life because of variations in materials, and technique of fabricating and processing.

The general agreement of various investigators that insulation life is approximately a logarithmic function of temperature affords a useful method for estimating insulation life from accelerated aging tests at elevated temperatures. Obviously it is not possible to demonstrate completely the adequacy of new developments in insulation by life tests at normal operating temperature. Some accelerated method of evaluating life is therefore necessary to permit taking advantage of new developments in the art within a reasonable time. Accelerated aging tests, carefully evaluated and extrapolated, are a useful tool in establishing the approximate operating temperature level of a new insulation and for weeding out materials that show no promise. In such a test program, it is important to make tests at several elevated temperatures. Sufficient specimens should be tested at each temperature to insure that a reasonable average is obtained. In extrapolating from a high-temperature test, the slope of the curve should be drawn on the pessimistic side.

It is essential in considering insulation life to remember that the effect of temperature is not the sole factor. The data given in this article relates to accelerated aging tests on samples of insulating materials. Other factors, sometimes even more important than temperature are: (a) Expansion and contraction stresses caused by relative movement of the windings and the surrounding structure lead to deterioration of the winding and reduction in life. In general, the larger the machine the more important is this factor in determining winding life. (b) Mechanical vibration may cause winding failures. (c) Deterioration from exposure to air, moisture, and chemical contamination. (d) Electrical stress, particularly corona. (e) Miscellaneous occurrences.

When accelerated tests are available at only one temperature and the slope of the life curve is unknown, it is difficult to extrapolate to lower temperatures. However, the available test data indicates that the slope of most explored ranges is eight to twelve degrees C for half life. In such cases, a general idea of the order of magnitude of life can be obtained by using the old "rule of thumb" with a ten-degree C increment for half life.

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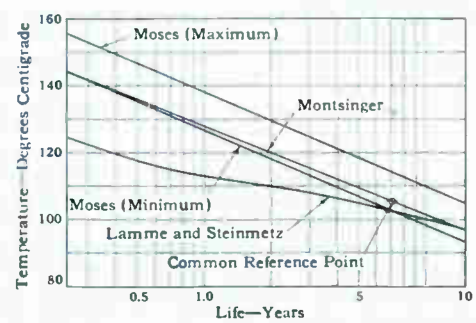


Fig. 7—Composite curve for thermal aging of class-A insulation (factors of insulation life other than temperature not predominating).

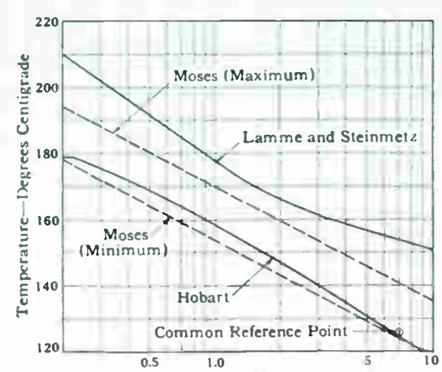


Fig. 8—Composite curve for thermal aging of class-B insulation (factors of insulation life other than temperature not predominating).

STORIES OF RESEARCH

The Tympanometer—A Swallow Counter

As for aviators, obviously the eyes have it. But the requirements of high-altitude flying demand that the ears have it too. A definite relationship has been found between the ease or difficulty of compensation of the flier for changes in altitude and his ability as an air fighter at high altitudes. This altitude accommodation is made by swallowing, which equalizes the pressure on both sides of the ear drum or tympanum. Recording the accommodations as a function of the rate of change of pressure is the chore of the electronic tympanometer.

Heretofore, physicians have had to enter a high-altitude chamber with the prospective flier and count the swallows, and relate them to the rate of change of pressure, i.e., altitude. To make the examination more accurate and obviate the necessity of the physician remaining in the high-altitude chamber during the test, instruments that appear to be oversize earphones with "horns" have been developed at the Westinghouse Research Laboratories. Clamped on the head of the flier, an earpiece over each ear, the swallows are automatically registered by the instruments and recorded on a chart outside the chamber.

Against each ear of the subject are placed fluid-filled chambers. The fluid rests against the ear drum on one side, and on the other against a diaphragm in the "earphone." The "earphone" is a microwave transmitter—the "horn" its antenna. The diaphragm, coupled by the liquid to the eardrum, with each swallow moves a pin within the instrument. This movement of the pin causes a peak in the transmitted wave. Thus, the record of a compensation appears as a peak in an otherwise smooth graph.

The problem of transmitting the impulses to the recorder outside the high-altitude chamber is essentially one of telemetering. Because the chamber is a metal enclosure, the receiving antenna is strung inside, emerging by means of a coaxial cable. Accurately plotted graphs of swallows versus altitude (or pressure) are made without the doctor being required to undergo the discomfort of the high-altitude cycle.

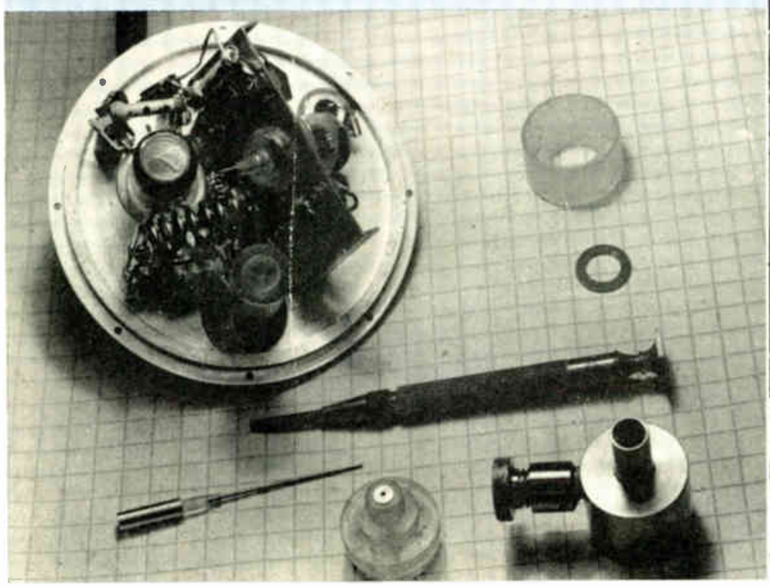
Swallowing is a voluntary accommodation for differences in altitude. There are other entirely involuntary compensations of great importance in determining the fitness of an individual for high altitude. The end result of these involuntary accommodations also is equalization of pressure on both sides of the tympanum and the rate of response of these to outside pressure variations is also shown by the tympanometer.

An Adjustable-Range Force-Measuring Spring

In most testing machines it is necessary to change the force-measuring system when testing materials requiring widely varying loads. If the usual force-measuring spring is made with sufficient strength and stiffness to withstand maximum loads of perhaps 40 000 to 50 000 pounds, it is so designed that the deflection under such loads is substantial and easily measured with a suitable extensometer. For light loads the deflection of such a spring is obviously smaller. For a 4000-pound load, the ratio of movement to that of maximum loading is as high as 12.5 to 1 with corresponding decrease in measurement accuracy. A new type force-measuring beam has been developed by Mr. M. J. Manjoine of the Westinghouse Research Laboratories. The stiffness of this beam can be varied to provide comparable deflections under such widely divergent load ranges as 0 to 4000 pounds, 0 to 20 000 pounds, and the maximum, 0 to 100 000.

One type of equipment used in testing materials in tension is shown in Fig. 1. The screw-jack exerts a force on the bottom of the slotted force-measuring bar. An extensometer is mounted on the top of the bar. The extensometer probe extends down through a vertical hole drilled in the bar and rests against the top of the lower

Into each oversize "earphone" Mr. R. T. Gabler has compressed the essentials of a microwave transmitter, complete means of varying the output wave in response to both voluntary and involuntary accommodations to varying atmospheric pressures as indicated by movement of the tympanum (ear drum). The inset shows the size of the acorn-type tubes and the completely shielded circuit components.



section. Any change in the force exerted against this lower section by the screw-jack moves this probe and the change is registered on the extensometer.

When the necessary force is applied by the motor-driven screw-jack, the force-measuring spring is deflected a certain distance. Contacts in the extensometer, through electrical controls, limit this deflection (hence the applied force) by stopping the drive motor. When the material under test elongates to such an extent that the deflection of the weighing bar drops below a preset figure, electrical contacts again activate the motor-starter control and re-establish the original force on the bar. Thus a constant force is maintained on the beam and a constant load on the specimen material. This force-measuring spring or weighing bar is shown in Fig. 2 in more detail.

The spring with easily varied stiffness is shown in Fig. 3. It is made similar to the one shown in Fig. 2, except that there are three slots instead of one. In the center of two slots transverse holes have been drilled. The lower slot is long and relatively close to the bottom of the beam. This is the most easily deflected portion of the bar. Should the force involved exceed the resistance of this section, short steel pins can be inserted into the drilled-out places in the center of the slot. (Because the extensometer probe extends from the top of the spring through a vertical hole in the center, the steel pins cannot extend entirely through the thickness of the spring. A short pin is placed in the drilled-out portion of the slot from each side, thus avoiding interference with the extensometer probe.) Thus the lower section is firmly coupled to the middle section and utilizes the stiffness of both. Should additional stiffness be required, pins inserted in the hole in the second slot cause the force to be opposed by three sections of the beam, thus providing maximum stiffness.

With the new weighing bar it is possible to run tests on such widely dissimilar materials as steel, copper, porcelain, and plastics and secure in each class the same degree of accuracy in measuring the stresses involved. By matching the stiffness of the beam to the forces required by the different tests, approximately the same degree of deflection is secured in each case and the accuracy of the results is comparable. With the usual single-slot bar, the disparity in deflection under loads of 4000 and 100 000 pounds per square inch is a measure of the difference in accuracy and ease of control.

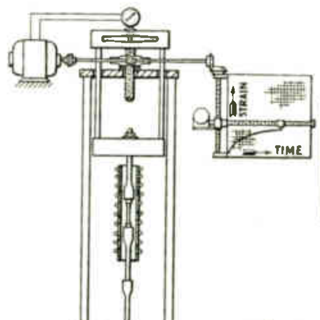


Fig. 1

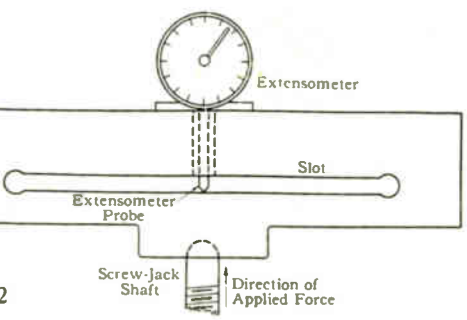


Fig. 2

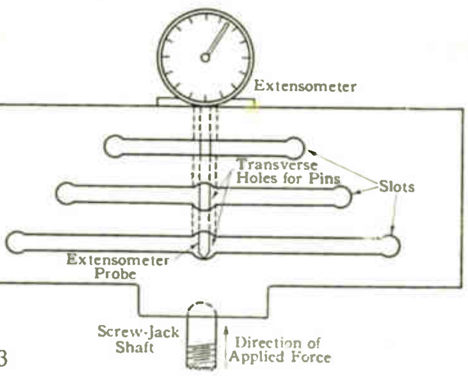
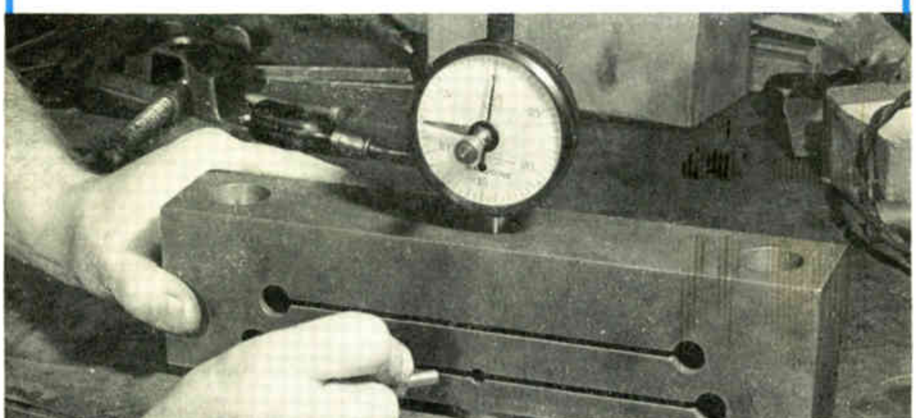


Fig. 3

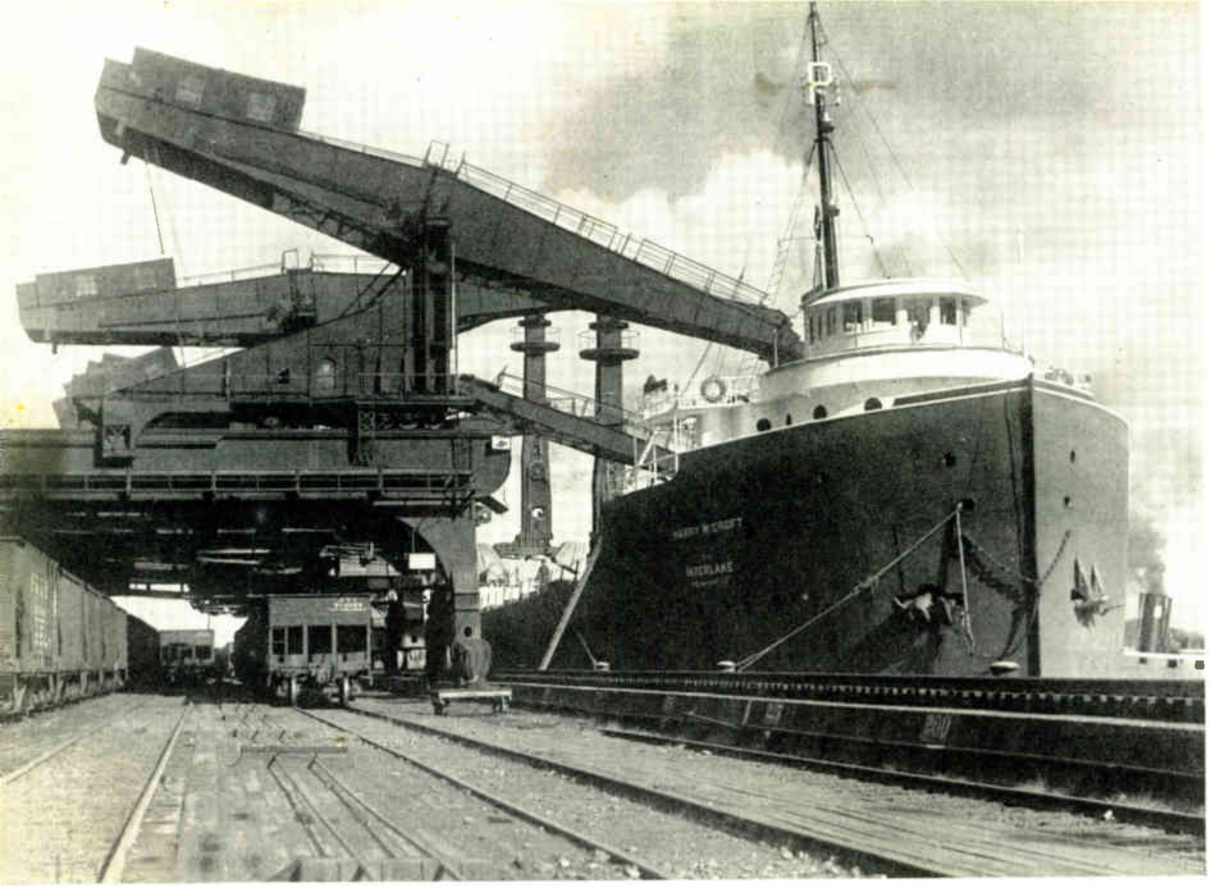
Fig. 1—Diagrammatic layout of an automatic machine for recording creep-to-rupture data.

Fig. 2—A sketch of the usual force-measuring bar.

Fig. 3—The transverse holes in the center of the slots permit the use of this weighing spring over a number of ranges.



A force-measuring bar with two ranges is shown in the picture above. Pins such as shown in the foreground are placed in the holes in the slots, both in front and back of the bar. In the lower photograph, Mr. M. J. Manjoine is changing the range of a weighing bar on an automatic creep-testing machine.



At a Lake Erie port Hewlett unloaders quickly empty a boat of its iron ore. (Photo by Carl McDow)

Iron Ore—

A shortage of iron ore would be a major national calamity. Fortunately nature was kind to the United States in the aggregate. But, characteristically, we have been using the best, easiest-to-get ore first and —during the war—at a furious pace. The end of this high-grade ore is not as distant as we should like. We must be prepared to meet the demands for iron from ore of lower grade but of enormous extent.

The United States has sufficient unmined iron ore to last several hundred years. But, the present commercial sources are such that if we have to fight another war like this one we will be faced by an appalling shortage. We are not even now able to supply the needs of all the furnaces with ore that can be used without treatment to increase the iron content or otherwise improve its grade. These seemingly contradictory statements take a deal of explaining.

Scattered throughout nearly all states are many iron-bearing ores that, counting all grades, comprise a gigantic tonnage total. Just how large is the total, as with any underground resource, is not known with finality, although present estimates are probably reasonably close. Only minor discoveries of ore bodies have been made in the last two decades. The quoted figures of economically workable iron-ore reserves differ widely because many factors, some intangible, bear on their compilation.

Iron-bearing formations of such low grade or location that they cannot today be considered workable ore may, through improvements in mining and steel-mill practices, be classed tomorrow as available. Then the estimates are subject to divergent opinion, some pessimistic, others optimistic. The expression in print of these contrary views, often with some heat, has shocked the American public into the realization that what was once thought to be an unlimited source of rich, easy-to-get directly usable ore is not inexhaustible. According to some, it has a brief life of 10 years, or of 20 to 40 years according to others. Even the longer estimate of the life of the rich deposits is something of a shock.

What Constitutes Iron Ore

Making pig iron is a gigantic, multi-step refining operation. The start is made with iron-bearing formation, which may vary in iron content from 35 to 70 percent, and differ widely in amount and kind of impurities, in physical form, mineral and chemical composition. The ores as mined or concentrated are fed to blast furnaces that reduce the iron minerals to metallic iron and eliminate nearly all the remaining impurities. How much of the concentrating is done on the ore and how much is left for the smelting furnace to do is not rigidly fixed, but is a matter of design and relative economics. The blast furnaces between the Great Lakes and the Ohio River—where three-fourths of the steel in this country is produced—have been built to use ores from Minnesota, Michigan, and Wisconsin, referred to as lake ores. These ores, as sent to the furnaces, have for years consistently run about 51.5 percent natural iron or better. Some of them as mined can be used directly, but others are of poorer quality and must be mixed with ore of higher iron content or treated to raise the iron content. This process of improving the chemical composition or the physical structure of the ore is termed iron-ore beneficiation, a jaw-breaking term but meaning precisely what it says.

Whether a given deposit can be classed as iron ore depends not only on its iron content but on many other factors as well. Some of these are fixed by nature and others shift in response to changes in technology, and to economics, tax laws, and even to the policies of nations. Among the more important factors is the quality of the ore, that is, the proportion of the iron oxide, the kind of and amounts of accompanying impurities, and the hardness, porosity, and other physical properties. Others are cost of production and whether the ore can be mined from the surface or must be removed by more expensive underground methods. Geography, too, is important. Nearness of the ore body to sources of other essential raw materials—coal and limestone—and to the consuming markets for the product, pig iron, obviously is significant; and transportation facilities play a vital role.

Iron appears in ores predominantly as an oxide, of which one—rust—is familiar. Virtually all our iron is produced from three of the several oxide ores. These are hematite,

Prepared by Charles A. Scarlott from published material and from information provided by executives and technical experts of several organizations. Of especial help were members of the Lake Superior Iron Ore Association, the U. S. Bureau of Mines (Washington and Minneapolis), the University of Minnesota Mines Experiment Station, the Michigan Department of Conservation, and the Pickands, Mather and Company of Cleveland.

The "range" is a narrow band varying one to three miles in width. Actually it is the beveled, eroded edge of a thick iron-bearing rock formation—a series of sedimentary beds formed like many other sedimentary rocks on an ancient ocean floor. This old ocean bed has been tilted to the southeast at an angle of five to fifteen degrees.

The iron is thought to have been originally deposited mainly as carbonate.* In the millenniums that followed, when erosion was active, the oxygen-bearing surface waters, percolating through the rocks, attacked the iron formation, breaking up the iron carbonate, producing iron oxide and carbonic acid. Water has solvent power for crystalline silica or quartz, which, although small, is promoted markedly by carbonic acid. In this slow but inexorable fashion, especially in the areas where earth movements had shattered the rocks more or less so that waters could move through them, much of silica was dissolved and carried away leaving the insoluble iron oxides behind. Nature, in short, did a part of the iron concentration job (beneficiation) for us. As a result of this leaching action, pockets of iron ore of various sizes and degree of concentration developed along the outcropping edge of the iron formation until the glaciers came along relatively recently and dumped their geologic debris over the surface, effectively halting the concentration process.

Some of these pockets of naturally concentrated iron ore are our great mines on the Mesabi range today. The ore, once the glacial overburden has been stripped off, is exposed as a soft, reddish to brownish rock, readily dug with power shovels after a minimum of blasting to loosen the ore banks.

The pits throughout the 100-mile range differ greatly in size. The natural-iron content of the ore as mined varies from about 40 to 60 percent. The pits vary from a few hundred yards to a mile or more in width and greater in length. The depths are as much as several hundred feet. The largest is the famous Hull-Rust-Mahoning pit at Hibbing, Minn., operated by the Oliver Iron Mining Company for the U. S. Steel Corporation and by Pickands, Mather & Company. In 1944 it produced about 21 million tons of ore. The total produced by that one pit since it was first operated in 1896 is approximately 375 million tons. It is three miles long, from one half to one mile wide, and about 450 feet deep in places.

The average content of iron in the Mesabi ores as shipped runs pretty close to 52.0 percent (natural, or undried). The free moisture averages about 11 percent; the silica nearly 8; phosphorus, 0.062; manganese, 0.68. It does not contain serious amounts of titanium, sulphur or phosphorus. It is loaded by mechanical shovels onto trucks or dump cars, and moved out of the pits by trucks, locomotives, or by belt conveyors, depending on circumstances of the particular pit, to central points where it is loaded into 50- or 70-ton ore cars. Trains of these loaded cars are then hauled by steam locomotives to the ore docks on Lake Superior. About four fifths of this ore has come from open pits and the remainder from underground operations.

How much remains is uncertain and is a matter of controversy. The Minnesota tax commission in 1943 estimated that 647 million tons of open-pit ore and 413 million of underground ore of present commercial grades is still available in the Mesabi. Of this total of 1060 million gross tons, 902 million is indicated as direct-shipping ore and 158 million tons as concentrate that can be processed by present commercial methods. More than this may exist, but the possibility of there being a great deal more, particularly of open-pit ore,

*See "Geology of the Iron Ranges" by Stephen Royce, Chapter II of "Lake Superior Iron Ores" published by Lake Superior Iron Ore Association

This map gives an idea of the principal areas now producing iron ore, the coking-coal regions, and the concentrations of blast-furnace capacity as percentages of the U. S. total. Circles indicate quantities by regions of mined and unmined ore now considered commercial and rough estimates of marginal ore (data by E. W. Pehrson, U. S. Bureau of Mines). The amount of marginal ore in the Central and Western regions is thought to be small.

is generally conceded by experts not to be great. According to Minnesota laws, taxation on an ore body begins as soon as it is proved to have value. This obviously tends to discourage exploration. On the basis of the taxable reserves of 1060 million gross tons of ore that can be shipped direct or beneficiated by comparatively simple means, the ore of the Mesabi range is a little more than half gone—including the best and most easily mined portion—and it is far more than half gone in years of life because of the present high depletion rate.

If the war rate of production were continued, the known open-pit direct-shipping Mesabi ore would be gone in about ten years. But no one believes the recent depletion rate will continue. The average annual tonnage taken from the Mesabi over the ten-year period 1930–1939 was 21.6 million gross tons. The average over the twenty-year period, 1920–1939 was nearly 27.7 million tons. If mining continues uniformly on the Mesabi at the rate of 30 million tons, the life of the presently known reserve will be about thirty five years.

That end, however, will not necessarily usher in a day of iron-ore famine. Not even on the Mesabi. It does mean that the cream—the easy-to-get, low-cost ore—will be gone. However, other and still larger reserves of lower grade ore exist on the Mesabi. As has been shown, Mother Nature never completed her task of beneficiation of the Mesabi iron-bearing rock, for only a small fraction of the total was leached of its silica and thus concentrated.

A rough classification divides Mesabi ore into three groups. The first comprises the ore bodies previously discussed. These total about a billion tons now classed as commercial and thus is taxable. Second is an intermediate grade ore, possibly a billion tons in total, in which the natural leaching process is only partly completed. This ore varies in iron content from about 35 to 50 percent. Almost all of it will require extensive beneficiation before it can be used in the present blast furnaces. It usually, but not always, occurs below the high-grade ore but sometimes around the borders or even above it, and much of it can still be mined by open-pit methods. It is a harder rock and requires blasting and subsequent crushing for the necessary concentration to increase the iron content.

Although this intermediate grade of ore clearly costs more to mine and to handle, the work of beneficiation has been partially done—sufficiently so that the process can be completed by known methods without excessive difficulty or expense. Economics, not technology, becomes the ruling factor. Where such intermediate-grade ore appeared on top of the high-grade ore being mined, it had to be removed anyway in order to reach the better ores. In some cases it was processed and shipped, and in others stockpiled.

The amount of ore from the Mesabi region subjected to all kinds of beneficiation before shipment is steadily mounting. It has increased from about 10 000 tons in 1907 to about 14 million tons in 1944, and undoubtedly this growth will continue. Concentrated ore now accounts for about 22 percent of the ore shipped from Minnesota and 18 percent of that from the outer Lake Superior district.

The third class of ore (really only potential or marginal ore) is the original, unweathered rock, locally called taconite. The volume of this is so large that one can think of it as practically inexhaustible. Less definitely charted than the other two grades of ore, it is estimated at many billions of tons.

Taconite is low-grade ore, varying in natural-iron content from about 25 to 35 percent, with 30 percent being an acceptable average. In some of the taconite areas the iron occurs as magnetite, although more extensively hematite predominates. Occasionally siderite occurs. The silica content is high, about 40 percent. This potential ore is in the form of hard rock in which the iron-oxide particles are small and intimately mixed with and attached to the particles of fine-ground silica, known as chert. These conditions necessitate drilling, blasting, crushing, and extensive subsequent treatment, all of which raise hob with costs.

The locations of the taconite and other marginal reserves are indicated approximately on the accompanying map. The location of these secondary reserves is significant. Because they coincide with the present high-grade ores and because of the locations of big beds of coking coal it would not seem likely that the physical locations of the steel-making industry are to be soon disturbed, even as the supply of high-grade iron ore runs low. Competition from imported ores would seem to have more effect on our future steel industry than any change in center of gravity of our own iron mining.

Although Mesabi ore by its immensity, quality, and accessibility overshadows all other iron-ore deposits in the United States, it is by no means the only one. The Lake Superior district, which comprises Minnesota, Wisconsin, and Michigan, has five currently worked major iron ranges in addition to the Mesabi. The Cuyuna, also in Minnesota, is thirty miles southwest of Mesabi, and is the only other range of this group in which the tonnage of ore from surface operations exceeds that obtained from underground. The Cuyuna mines have produced about 53 million gross tons of ore that runs about 42 percent natural iron and ten percent silica. The ore is rather high in manganese, averaging 6.5 percent. About sixty five million tons of commercial-grade ore is the Tax Commission estimate of remaining reserves in the range. Production in recent years is about two million tons annually.

The Vermilion range, a few miles north of the Mesabi, and the Gogebic, Marquette, and Menominee ranges of upper Wisconsin and Michigan comprise the remaining four of the Lake Superior group. Although overshadowed by Mesabi, they are sizable and extremely important sources of high-grade iron ore. The three of the Michigan-Wisconsin group have produced to date about 650 million tons and currently are providing about one fifth of the Lake Superior total. The Vermilion and the three Michigan-Wisconsin iron ranges are primarily or entirely underground operations, although all of them have had and some still do have a few surface pits. Although mining underground is necessarily more expensive than from open pits, these mines can continue operation throughout the year, stockpiling their output during the winter months when the Lakes are frozen.

The combined average annual output of all the Lake Superior mines, except those on the Mesabi, in the ten-year prewar

TABLE I—PRODUCTION AND ESTIMATED RESERVES IRON ORE IN UNITED STATES

	Open Pit or U.G.[1]	Iron %	Production—Million Tons: Annual Average 1930 to 1939	% of U. S. Total	1942 1943 1944	% of U. S. Total	Total Mined to Date	Estimated Reserves Millions of Tons: Commercial Direct Open Pit	Direct U.G.	Concentrate	Total	Marginal
Mesabi	O.P.	51.8	21.63	56.8	65.90	65.8	1316.0	536.0	365.0	158.0	1060.0	
Vermilion	U.G.	57.7	1.05	2.8	1.75	1.7	74.0	....	13.5	....	13.5	....
Cuyuna	O.P.	42.1	0.96	2.5	2.88	2.9	50.0	12.1	36.1	15.7	63.9	....
Gogebic	U.G.	53.0	3.43	9.0	5.78	5.8	240.0	....	38.8	....	38.8	....
Marquette	U.G.	51.1	3.11	8.2	5.64	5.6	225.0	....	49.7	....	49.7	....
Menominee	U.G.	51.6	1.78	4.7	4.90	4.9	203.0	....	54.0	....	54.0	35% Fe
Lake Superior—Total	....	51.7	31.96	84.0	86.85	86.7	2108.0	....	....	....	1280.0	60 000
Alabama	U.G.	36.2	3.92	10.3	8.02	8.0	....	....	....	....	....	....
Other	U.G.	45.3	0.03	0.1	0.25	0.3	....	....	....	....	....	....
Southeastern—Total	....	36.5	3.95	10.4	8.27	8.3	324.9	....	....	....	2110.0	3 000
New York & Pa.	U.G.	60.5	1.32	3.5	2.95	3.0	....	....	....	....	....	....
New Jersey	U.G.	62.7	0.23	0.6	0.54	0.5	....	....	....	....	....	....
Eastern—Total	....	60.8	1.55	4.1	3.49	3.5	167.0	....	....	....	920.0	3 000
Central & Gulf—Total	U.G.	52.6	0.04	0.1	0.04	0.1	11.4	....	....	....	216.0	....
Western—Total	U.G.	53.8	0.57	1.4	1.40	1.4	41.0	....	....	....	378.0	....
United States—Total	....		38.07	100.0	100.05	100	2652.3	....	....	....	4904.0	66 000

[1]Predominant operation.
*Sources: Lake Superior Iron Ore Association; "Mining Directory of Minnesota"; U. S. Bureau of Mines.

period, is about ten million gross tons. In the ninety years since its opening, the Lake Superior district has shipped about 2100 million tons of iron ore. Ore still available in the entire district, judged by present commercial standards of workable ore, is about one and one quarter billion tons, according to State Tax Commission estimates. About 175 million tons of this is from material that requires beneficiation before it can be utilized. How much ultimately will be added to this known reserve by future discoveries and economic and technologic changes is a matter of opinion. Some competent observers indicate expected additions of 25 percent to 50 percent or more, most or all of which will probably require beneficiation. Whatever this added tonnage may be, it does not increase the ability of the district long to continue its recent high rates of output.

Other U.S. Iron-Ore Resources

Next in importance to the Lake Superior district as producers of iron ore are the mines in the Birmingham region, and those of the northeastern district, which comprises New York, Pennsylvania and New Jersey. Normally the mines in Alabama account for 8 to 12 percent of the national total; the northeastern region, about four percent. All the other mines in the United States have accounted for less than two percent of the annual total.

The city of Birmingham, Alabama, is built on top of an underground body of iron-bearing rock which, in tonnage, is enormous. It is poor in quality as compared to Lake Superior ore. A total reserve of one and a half to two billion tons (including the high-silica ore) is believed to remain in the Birmingham district. Production has been reasonably stable, with output in recent years reaching about nine million tons annually. The Birmingham mines have a long time to go although they also have the problem of beneficiation to remove silica from the ores, in order to use much of the known reserve.

The Birmingham deposit illustrates beautifully the fact that something more than iron content is required for a deposit to be counted as ore. If located in the Lake Superior district, Alabama ores probably would not be classed as present workable ores, as the iron content is too low—only about 36 percent. But, unlike Lake Superior ores, a substantial part of these ores contain a large proportion of highly important lime (about 15.6 percent), which makes the ores to an appreciable extent self-fluxing.

The Birmingham ores are underground, although initially they were mined in open cuts along the outcrop. The Red Mountain ores occur in several sedimentary beds of which two have been important sources, the larger bed or seam varying from 15 to 30 feet thick, and the smaller from 4 to 6 feet. About 7 to 12 feet of the larger bed have been good enough to mine. These ores occur along a belt of outcrop that extends over 20 miles running generally northeast and southwest, and tilted eastward at angles of 15 degrees to 30 degrees. Similar ore outcrops in thin seams continue far to the northeast, across Tennessee and beyond.

Nature was generous to the Birmingham region. Although

TABLE II—WORLD IRON-ORE PRODUCTION AND RESERVES

	Actual Reserves[1]: Million metric tons	Approx. % Fe	Potential Reserves[1]: Million metric tons	Approx. % Fe	Production Annual Average Million Gross Tons (1927–1936)[2]
North America					
Canada	100	50	10 000	35	....
Cuba	3000	40	12 000	....	0.30
Mexico	100	60	100	....	0.01
Newfoundland	1250	40	2 000	40	0.90
United States	3800	45	67 000	35	42.0
Total	8250	....	91 100	....	....
Europe					
France	4500	35	6 000	35	38.0
Germany	800	32	2 000	30	4.69
Austria	200	35	200	....	0.97
Great Britain	3100	30	7 000	30	10.2
Greece	100	50	50	45	0.1
Norway	300	35	1 000	30	0.6
Poland	140	30	200	25	0.4
Luxemburg	....	....	....	....	5.20
Spain	800	45	1 000	35	3.40
Sweden	1250	62	1 250	60	7.35
U.S.S.R. (Europe)	3100	45	15 000	35	14.0*
Other	370	....	340	....	....
Total	14660	....	34 040	....	....
Asia					
China	500	40	700	35	1.77
India	3600	60	10 000	....	1.97
Dutch E. Indies	100	....	1 500	....	....
Philippines	500	47	500	....	....
U.S.S.R. (Asia)	1400	45	2 400	....	....
Total	6100	....	15 100	....	....
Australia	400	60	....	....	1.0
South America					
Brazil	4000	60	11 000	40	0.03
Chile	120	60	....	....	1.1
Peru	100	60	....	....	....
Venezuela	100	60	1 000	45	....
Total	4320	....	12 000	....	....
Africa					
Algeria	160	50	....	....	1.52
Union of So. Africa	1000	55	7 000	....	....
Rhodesia	....	....	Very Large	....	....
Sierra Leone	....	....	Large	....	....
WORLD TOTAL	34 890	....	159 240	....	135.51

[1]"World Iron Ore Map," Harry M. Mikami, Economic Geology, January-February, 1944, p. 22.
[2]"Lake Superior Iron Ore," 1938, p. 342.
*Total for Europe and Asia.

What It Is, Where It Comes From, How Much Is Left

magnetite, and limonite. Mother Nature was lavish as to the amounts she bequeathed to us but not too thoughtful as to where and with what she placed them.

Most iron occurs in ore as hematite (Fe_2O_3), which in pure form is 70 percent iron. Unfortunately it is non-magnetic and can't be concentrated by magnetic means. Ninety percent of total iron ore mined in the United States is hematite. Smaller quantities occur as magnetite (Fe_3O_4), which is being mined extensively. Magnetite contains 72.4 percent iron. Limonite ($2Fe_2O_3 \cdot 3H_2O$), which can be considered as hematite combined with water, is a valuable iron ore and is mined in considerable volume. In pure form limonite contains 59.8 percent iron. Other oxides less completely hydrated than limonite also occur. Iron carbonate ($FeCO_3$), called siderite, can be used but it does not count for much among the totals of iron-ore reserves in this country or abroad. Also pyrite (iron sulphide, FeS_2) may be a source of by-product iron ore after roasting to recover the sulphur.

The iron-ore minerals occur in nature mixed in almost every conceivable proportion and degree of intimacy with other materials. The most abundant impurity, but not always the most objectionable, is silica, usually in the fine crystalline form, known as chert. In the modern blast furnace, silica acts as an acid, and must be fluxed with approximately as much base (by weight) such as limestone or dolomite to produce the desired slag. Thus, in general, an ore low in silica is desirable. Conversely one of high lime content, making the ore all or partially self-fluxing, is highly desirable and may command a premium.

Where and How Much

By a historical fluke the great Mesabi iron range belongs to the United States and not to Canada. The dividing line between Ontario and Minnesota was first set by the Treaty of Paris in 1783 but was so obscure and the maps so inaccurate it could not be located on the ground. John Jay, as Secretary of State, in 1794 proposed that the boundary line run from the mouth of the St. Louis river, at Duluth, to Red Lake, which would place both the Mesabi and Vermilion iron ranges in Canada. Fortunately the British rejected the proposal. After several abortive attempts to set the line it was finally fixed as it now stands by the Webster-Ashburton Treaty of 1842.

The benefit of this accident of blind bargaining to the industrial economy of the United States is incalculable. Mesabi ore is of good quality and easy to smelt; it lies close to the surface so that most of it is mineable in open pits. It is soft. It is enormous in volume. It carried the load of the emergency demand in the last war, and it is carrying the load in this war. However, the fabulous Mesabi pits cannot stand this accelerated rate of depletion forever.

Normal annual consumption of iron ore in the United States is about 50 million gross tons* (1921–1940 average = 49.3 million tons). Of this, the Mesabi range alone contributed about 57 percent of the total. The demands of war have driven iron-ore production to an average peak of 100 million tons per year, of which the Mesabi produced 65 million tons. Its nearest competitors are the combined Michigan-Wisconsin area and the Birmingham districts, which produce only one fourth and one eighth as much, respectively. The Mesabi exceeds all other iron-producing districts combined, in tonnage produced to date, in tonnage of known reserves of both high and low grades, and in current rate of production.

The Mesabi range is one of those rare miracles of geology. It is flanked on the northwest by a low range of hills of granite and extends for about a 100-mile northeast and southwest direction, from a point 60 miles northwest of Duluth, at its nearest point. It takes its name from this range of hills—which the Chippewa Indians called Mesabi, meaning "giant." Thus the largest of all iron-producing ranges is appropriately named.

*2240 pounds each. All figures in this discussion refer to gross tons.

Iron ore starts on its journey from mine face to blast furnace in this mine of the Tennessee Coal and Iron Company near Birmingham.

she could have provided an iron ore of higher grade and more accessible, she did place beside it vast coal beds. The coal, too, is inferior in quality to the Pittsburgh seam, but it and the iron ore make up their quality deficiencies by their physical intimacy. On this fact rests the iron industry of Birmingham, which in prewar years produced about one twelfth of the pig iron in the United States.

Iron was taken from New York and Pennsylvania mines as early as 1710. These mines are still going strong. Although they have long been surpassed by the mines of the Lake region, they have continued year in and year out to contribute from 2.5 to 4.5 percent of the total. The ores, mainly underground, are of good quality, mostly magnetite, which can be magnetically concentrated to provide a very high-grade charge for the furnaces. Those mined in New York and New Jersey range from 30 to 50 percent iron, and the Cornwall ores, near Lebanon, Pennsylvania, nearly 45 percent iron. Most of these ores are easily concentrated to about 60 percent iron. They move mostly to furnaces in eastern Pennsylvania and New York, and also to the Buffalo and Pittsburgh districts, where they supplement the lake ore supply at some of these plants.

Great as is the concentration of the steel-making business in the North and East and in the Birmingham district, other producers about the country, although small by comparison, play increasingly important roles in our industrial economy and clearly must have sources of iron ore not too distant. Witness the blast furnace plants in Colorado, Utah, California and Texas, all supplying iron to steel plants in those areas. Many states have deposits of iron-bearing rock, but few have achieved commercial importance because of low grade, difficult mining, inadequate size, remoteness from other raw materials, or from markets. Forty-two states have, at one time or another, produced iron ore.

Aside from the Birmingham district, the southern states have probably several hundred million tons of hematite, limonite and carbonate ores, which are not likely to be considered workable for a long time to come. Limonite deposits scattered over northeastern Texas have been variously estimated up to 200 million tons. A new blast furnace at Houston and another at Daingerfield, Texas, have been constructed during the war to use local ores, but the Daingerfield furnace has never operated. Colorado and New Mexico have small iron-ore deposits of fifteen million tons or less, total. Eastern Wyoming—which supplies the Pueblo, Colorado, furnaces, has substantial reserves probably adequate for the plant for a long time. Reserves of all grades in Utah are estimated at upwards of 40 to 50 million tons available to the three blast furnaces at the new steel plant at Geneva, Utah, and to the two older furnaces at Provo. Some Utah ore moves also to Pueblo and some will be shipped to the new Kaiser furnace at Fontana—near Los Angeles, California. The Kaiser plant has been supplied heretofore with ore from a mine near Kelso, California. Arizona, Nevada, Oregon, Washington, and California have scattered small deposits. Under the pressure of war the output of the western mines has increased. In 1942 they produced 1.48 million tons; in 1943, 2.45 million tons, and last year 2.8 million tons (of which Utah supplied 1.5 million tons). Percentage-wise, the increase has been from less than one percent to nearly three percent of the U. S. total.

Ores in Other Parts of the World

Foreign ores have never been a large factor of competition to U. S. ores, but might be some time. There are several sources of such ore, some whopping big ones. The blast furnaces of Sparrows Point, Maryland, were built primarily to feed on Chilean ore, of which about 1½ million tons was imported annually. This, incidentally, comprised more than half of the total U. S. iron imports.

Chile has important deposits, mainly of hematite, about 60 percent natural iron. But the Chilean deposits are relatively small compared to those in Brazil, in the vicinity of Itabira and the highlands about 350 miles from the Atlantic coast. Inadequate transportation is a principal obstacle to the large-scale development of these ores. The Itabira deposits are thought to contain several billion tons of hard hematite ore that is low in phosphorus. They average about 65 percent natural iron. They can be surface-mined or quarried the year around. The amount of overburden is small. Other important but less extensive deposits occur in Brazil southwest of Itabira—at Bello Horizonte—which are being developed to supply


A portion of the Oliver Iron Mining Co. operation in the big pit near Hibbing, Minn.

the new Brazilian steel plant at Volta Redonda. Venezuela has important deposits of high-grade iron ore, which are now being developed for use on our eastern seaboard.

Cuba's iron deposits are extensive, being estimated at over three billion tons, largely of earthy brown ore high in alumina and moisture (both combined and absorbed water), and containing appreciable proportions of chromium and nickel. After drying, these ores run about 46 percent iron. They are low in phosphorus. Other important sources and possible amounts in the western hemisphere include: Newfoundland, four billion tons; and Canada, at least 100 million tons of ore that can be produced competitively and a great deal more not workable according to present standards. The famed Steep Rock Lake deposit recently opened in Canada, just above the Minnesota border (where a lake was drained to give access to an iron-ore body), is more spectacular than significant in the world's totals. The tonnage of ore, running high in iron and low in silica and phosphorus, is now estimated to be of the order of 50 million tons.

Widespread iron-ore deposits in northwest Labrador have been under exploration in the past few years. They are remote from transportation, in an area of rigorous climate, but these are not insuperable obstacles to their development.

Various foreign ores, mainly those in South America, are potential competitors to our mines in the United States. The extent of the competition depends on the various economic factors at home and abroad, and upon public policies affecting trade, and construction of the St. Lawrence river waterway.

The Growing Importance of Beneficiation

That the United States cannot allow itself to be dependent on foreign sources of raw materials has been a recent painful lesson. The need for new or better methods of beneficiating low-grade iron ore is a national must. The need is here now and the urgency increases daily. We cannot wait until the good ore is gone before developing applicable methods. The need for low-cost beneficiation methods is sharply accentuated by the fact that the shortage of commercial grade ore reserves is so much more imminent for some producers than for others. A few companies, mostly the largest ones, have reserves ample perhaps for two or three decades, but the supplies available to other important, but smaller, companies are woefully short right now.

Fortunately the industry is not idle. Large sums have been spent and are being spent on beneficiation research. Twelve producers have for some time been supporting an extensive research program at Battelle Institute at Columbus, Ohio. The U. S. Bureau of Mines, the Mines Experiment Station at the University of Minnesota, and other public agencies have been hard at work on the problem for some years.

There is no single preferred method of beneficiation, not even for a single body of ore. For most, some relatively simple mechanical separation of the iron-bearing particles from the silica or sand grains, by washing, is adequate. By far most of the beneficiation now practiced in the Lake Superior District (all in Minnesota) is by such washing. Other methods make use also of the differences in relative densities of iron minerals and waste material and include crushing and grinding followed by heavy-medium separation or by jigging and hydraulic separation. Flotation methods, applicable to finely pulverized material, by which either the desirable or the undesirable components are floated off by use of chemical reagents are generally more expensive, and are not as yet applicable.

Magnetite ores can be concentrated by crushing and magnetic separation of the iron oxide from the silica. Hematite can be converted to magnetite for concentration by roasting. Much experimentation has been done in this direction, and one commercial plant is operated on the Cuyema Range, but the process is not yet considered generally competitive. Absence of low-cost fuel in the Lake Superior district hampers the roasting process there.

There is likely to be more extensive application of heavy-medium separation, sometimes called the "sink and float" process, such as is now practiced at several plants in Minnesota. The roughly crushed ore is fed into a cone in which is maintained a liquid consisting of a finely powdered ferro-silicon alloy and water, and the resulting mixture agitated. The density of the ferro-silicon liquid is intermediate to that of the iron ore and the silica, so that the silica rises to the top of the cone and overflows while the iron ore is drawn off below. The ferro-silicon is recovered for reuse magnetically.

The enormous taconite reserves in Minnesota are bound to be important in the long-range picture. This iron-bearing rock is hard, low in iron and high in silica. Concentration is difficult, but the research on the problem is expected to develop processes adequate to the requirements when needed. The magnetic taconite is amenable, of course, to well known methods of magnetic separation, but the fine-grained concentrate must be sintered or otherwise prepared for furnace use.

As the need for beneficiation increases, as its techniques improve, more and more will it become a large industry itself, added to the already complex chain of activities from mines to mills in the making of steel. It is inevitable that this incipient industry will rely to a great extent for necessary low costs on electrical machines.

Citizens of the United States still have iron in the bank. But it cannot all be cashed with equal ease. Having it as mineable ore, rich in quality and near the surface, is one thing. Having it in low grade hard rock, or deep in the earth is another. Inevitably, as the good ore tapers to exhaustion—within a relatively few years as we reckon the life of our nation—we must and will learn how to work and beneficiate these lean, hard ores, and do it cheaply. That calls for the thing we have in abundance—ingenuity and technical skill.

On the Mesabi, much of the ore is scooped up by electric shovels and loaded directly into cars for haulage to Duluth.

Kovar, an Alloy That Seals Metal to Glass

Among men or materials there are many roads to fame. An alloy called Kovar has achieved deserved distinction because it expands with heat at the same rate as hard glass. This fortunate fact enables permanent, glass-to-metal joints to be made or remade easily, quickly, with average skills. The importance of this means of joining glass and metal in the high-quantity production of radio, radar, and other military electronic tubes has been incalculable.

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Among the thousands of metals, the alloy Kovar occupies a unique position in that it was developed specifically to join to glass. It serves as a connecting link between metallic and non-metallic materials and thereby extends considerably the useful field of applications of each.

Many modern electrical devices operate within airtight enclosures. In some cases the enclosure is evacuated, in others it contains a special gas or vapor. Often it has the sole purpose of protecting vital elements against the damaging effects of moisture and dirt. Lamps, radio tubes, ignitron tubes, x-ray tubes, refrigerators, transformers, and meters are equipments in which a sealed enclosure is an essential part. Even small transformers and combat equipment function better when in vacuum-tight cans. All of these enclosures have one feature in common. Current must be carried into and out of the enclosure and the electrical leads must be insulated. This must be done without sacrifice of tightness. Glass at once suggests itself as the insulating material because it is gas-tight, but to be usefully applied, it must make a vacuum-tight seal with metal. For lamps, photoelectric cells, and observation windows, glass is particularly useful for its satisfactory characteristics of visible light transmission.

Fig. 1—An idea of the range of seals possible with Kovar is given by these typical metal-to-glass seals now in regular production.

In sealing glass to metal, the most important factor is the match in expansion of the two materials. Glass, being brittle, cracks if unduly stressed. The range of expansion coefficients among both metals and glasses is great although there is a considerable amount of overlap. Certain glasses have a rather low coefficient of expansion. This is matched closely only in unalloyed metals, by the expensive molybdenum and tungsten. These two metals seal into hard glass (resistant to thermal shock) but offer manufacturing difficulties in machining and fabrication, and their cost is excessive.

Prior to the advent of Kovar, seals of glass to metal were limited to small areas, or to soft glass, and often had questionable mechanical properties. Usually these seals were made of "feather-edged" copper in which the metal is made to absorb all the stresses arising from difference in expansion. Because copper amalgamates with mercury, the copper in seals exposed to mercury vapor (as in rectifier tubes) must be plated with a mercury-resistant metal. This introduces additional expense and offers questionable protection. Other disadvan-

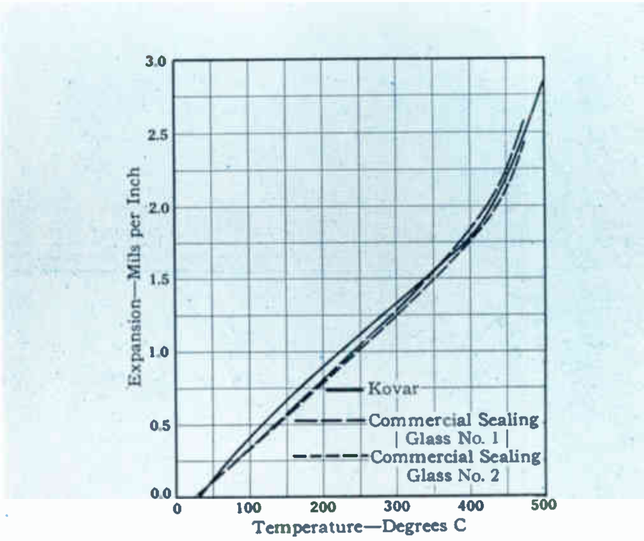

Fig. 2—A comparison of the thermal expansion of Kovar with two commercial glasses.

tages of copper were the high degree of skill and tedious low-temperature baking or degassing of the seals required by the Housekeeper (feather edge) technique. High-chromium-iron alloys seal only into soft glass. This combination offers inadequate resistance to thermal shock and such alloys are difficult to fabricate.

An alloy for sealing to low-expansion hard glass must embody the following properties:

1—Must seal readily into hard glass, which is highly resistant to thermal shock.

2—Must have substantially the same expansion from low temperature to the annealing temperature of the glass.

3—Must produce a permanent and gas-tight seal.

4—Must be easily machined or fabricated to permit the use of small and intricate shapes.

5—Composition must be controllable to permit duplication of results.

6—Must resist mercury attack.

7—Must be usable without need for feather edge on tubular or intricate shapes.

8—Must be relatively inexpensive, eliminating restraints on size.

9—Must be weldable, solderable, or brazeable to other metals.

Kovar supplies all these needs. It is an alloy of 29 percent nickel, 17 percent cobalt, and 54 percent iron produced in the induction furnace. By careful control of composition, the expansion of a hard glass is matched with precision. The two Kovar seals in Fig. 1 show the approximate commercial size range now practicable. The match in expansion of Kovar with two sealing glasses is shown by curves in Fig. 2.

In mechanical properties and in working and fabricating characteristics, Kovar is quite typical of the nickel alloys. Annealed, its tensile strength is about 70 000 pounds per square inch, with a hardness range of 160 to 180 Brinell. It can be forged, rolled, drawn, and machined and therefore is available in sheet, wire, tubing, cups, eyelets, and other miscellaneous shapes.

Kovar has a high electrical resistivity (45 microhms per cm) and is ferromagnetic, having approximately the same magnetic properties as annealed low-carbon steel. It is more resistant to corrosion than ordinary steel but is inferior to stainless steel in this respect. A high degree of resistance to scaling or to corrosion is not required by present Kovar applications. However, there have been no cases in which the usefulness of Kovar has been limited by corrosion. It can be joined to other metals by brazing, soldering, or welding.

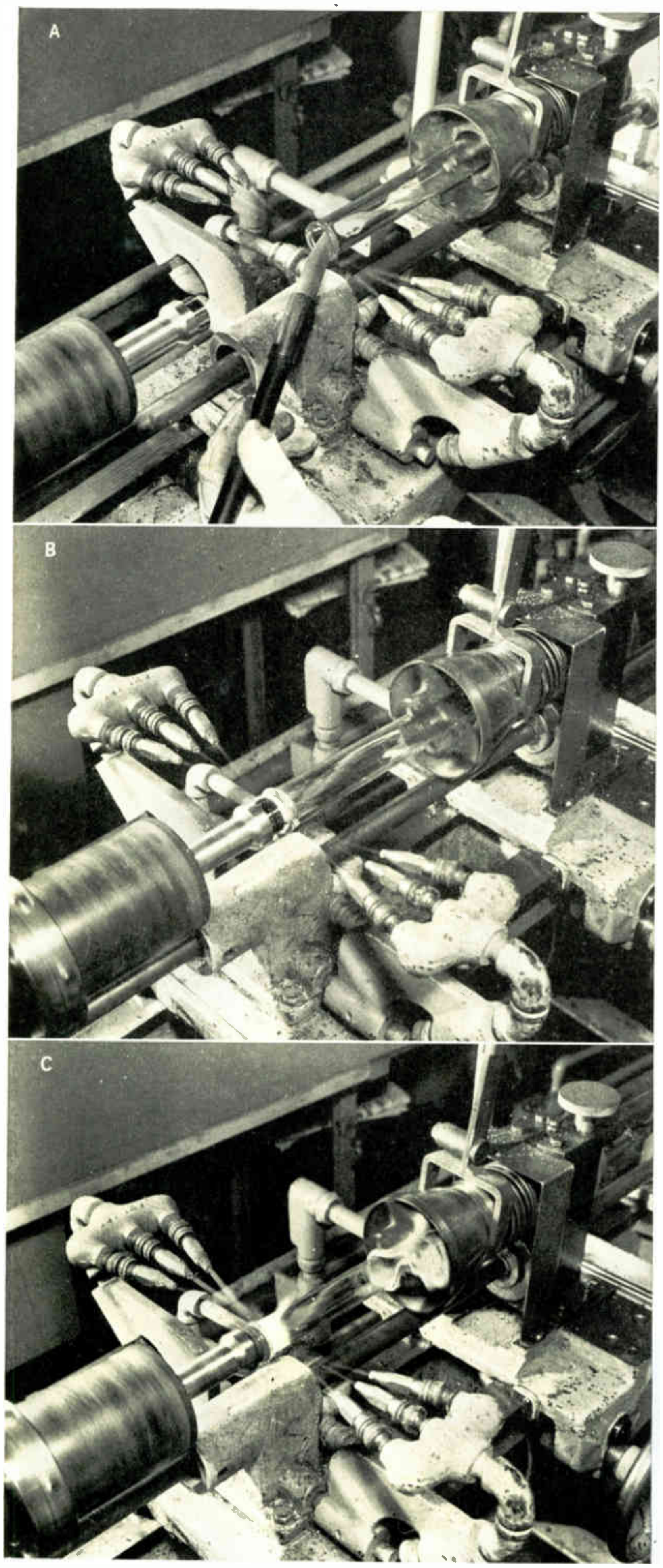

Fig. 3—Sealing Kovar to glass is a simple operation lending itself to high-speed production methods and requiring no unusual skills. In (A) the glass tubing is formed under heat to mate with the Kovar part. The Kovar and glass, both spinning in the flames of the glass jets, are brought together in (B). The seal between Kovar and glass remains in the flames until the glass flows sufficiently to insure complete joining and dissolving of the oxide coating of the metal into the glass making a mechanically strong bond as in (C).

Brazing is commonly used because brazed joints are reliably vacuum-tight and can withstand the moderately high temperatures encountered in sealing Kovar to glass.

The seal between Kovar and glass is a chemical bond. The seal is heated and the surface oxide that has been formed on the Kovar part is dissolved into the glass at the glass-Kovar interface. This forms a perfect hermetic seal, permanently vacuum and pressure tight under all climatic conditions. The process is basically quite simple. The part to be sealed is designed to prevent sharp corners at points to be sealed. The Kovar part is annealed in a decarburizing atmosphere to remove the effects of cold work and to eliminate residual carbon at and near the surface. The part is then brought to a dull-red heat in an oxidizing atmosphere until a thin adherent oxide film is obtained. Molten glass may then be applied immediately or it may be reheated for sealing in a separate operation. A final sealing operation is shown in Fig. 3.

A feature unique in the Kovar-to-glass seal is the ease with which such a seal can be repaired should it be damaged. To demonstrate this facility, the seal in an electronic tube was broken, not once, but six times. After each rupture, the seal was quickly re-established by the same methods used in making the original seal. No new oxide coating was needed as heating the Kovar to bring it to the sealing temperature recoated the metal with the oxide film which was absorbed in the usual way, resulting in a vacuum-tight seal every whit as good as the original seal. After six deliberate fractures and resealing, it could not be shown by any test that this tube was different in any way from a perfect, unimpaired standard tube.

One of the outstanding features of the Kovar-to-glass seal is the ease of manufacture. When suitable processes have been established, only a moderate amount of skill is required on the part of the operator. In many cases it is possible to train an operator to make Kovar seals in a single day. This has been a very important factor in the tremendous expansion of tube manufacture occasioned by the war. This results in low scrap loss and a more satisfactory product. Unlike the feather-edge seal, should the operator fail to make a good Kovar seal, it can easily and quickly be remade without loss of the materials. Another feature of the seal is sturdiness. Because the match between the coefficients of expansion of glass and Kovar is accurate, the parts can be designed for rigidity and strength. An electronic tube, for example, does not deform under atmospheric pressure when pumped out and stands relatively great abuse without mechanical failure. The experience of Kovar seals in combat equipment where ruggedness is at a premium has been excellent. These features can be used by the design engineer in many ways, to increase useful life, to improve appearance, to increase rating, to decrease weight, etc. An x-ray tube, for example, in which a feather edge of copper was sealed into the glass, was redesigned to use a Kovar seal. This conversion resulted in a saving of ten percent factory scrap and eliminated ten percent of field failures. To these savings must be added the savings of the extra costs of making field replacements.

In military operations, equipment must function under adverse conditions. Temperatures range from sub-zero to tropical heat. High humidity, insects and fungi contribute to rapid deterioration of such equipment as communication and range-finding apparatus. To shield against these deteriorating influences, total enclosures using Kovar-glass seals for leads were applied to transformers, resistors, capacitors, condensers, vibrators, switches, receivers, transmitters, and various other electrical components. Adequate protection was given to sensitive instruments and their performance improved. The small seal shown in Fig. 1 is a type of terminal used in such an enclosure. It must be able to withstand the heat shock of soldering or immersion in cold sea water without failure at the other extreme. The seals must remain rugged and permanently pressure and vacuum tight.

A temperature-compensated tuning fork (the basis for electronic frequency standards of high precision —one part per million per degree) is hermetically sealed with Kovar-glass terminals. The instrument is incorporated in equipment used in actual combat and is also used in testing instruments where this exceptional precision must be maintained. Kovar-glass terminals contribute to the maintenance of the vacuum required in the container. The use of these terminal seals enables the manufacturer to reduce the size and weight of the container and facilitates easier, more dependable and economical unit assembly.

In the instrument and gauge field, the use of Kovar-glass sight tubes and index glasses proves ideal for sealing mechanisms under pressure and where visual means for reading operational data must be provided. In other cases, manufacturing costs are reduced through the elimination of soldered seams with a resultant saving in labor and material. A typical example of this is the gas-tight construction of a meter where the use of a Kovar-glass seal in the glass window of the index box eliminates the need for a protective covering and reduces the length of soldered seam by 12 inches, with consequent elimination of possible leakage or breakage. The seal protects the meter against moisture, dirt, and corrosion, and results in improved accuracy and longer life.

Thousands of experiments now being conducted in laboratories throughout the country are contributing new applications and uses for Kovar. The ease of rolling, forging and spinning Kovar into many forms and shapes, some of which are shown in Fig. 4, enhances its use in a number of diversified fields of application that are continually expanding. Kovar-glass seals in particular materially contribute to the successful operation and long life of equipment in the fields of television, electrically operated and controlled appliances, private and public communication systems, production machinery and other electronic applications. The experience gained in the war use of Kovar together with its sturdy simplicity will make for superior peace-time products where glass-to-metal seals are required.

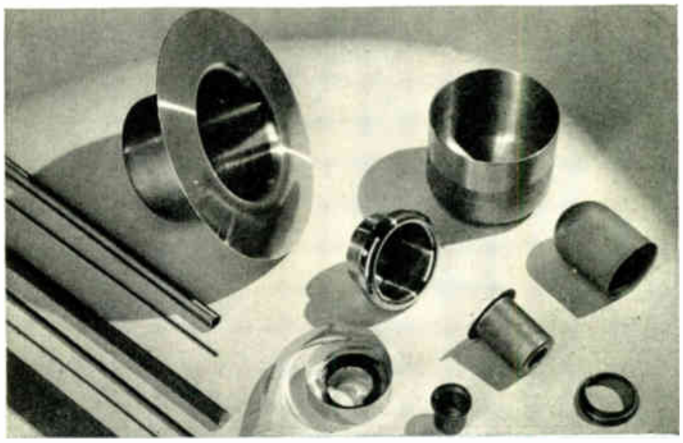

Fig. 4—Kovar lends itself readily to manufacturing processes, including drawing, rolling, spinning, and punching.

Welding Haze Eliminated

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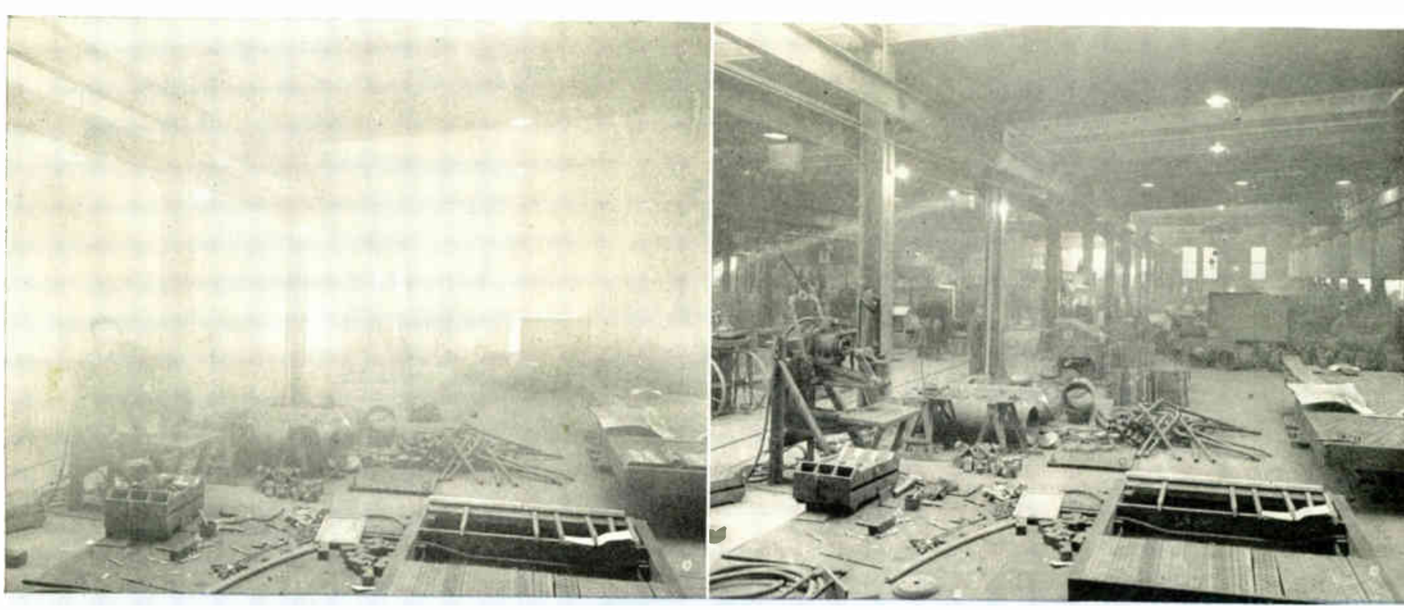
The sudden rise of arc welding to its present stature has not been an unmixed blessing. A concomitant of industrial welding has been the generation of clouds of welding smokes. Because welding smokes are comprised of minute particles of matter—both metallic and non-metallic—that are suspended in air, they lend themselves readily to removal by electrostatic precipitation.

Where there is a great concentration of arc welding the welding smokes may be sufficiently dense to obscure the lighting system and make even nearby objects difficult to see. The smokes deposit layers of dirt on the plant walls, electrical equipment, and machinery. Under such conditions, employes feel a sense of insecurity and are exposed to increased hazards of accidents with a resulting loss of efficiency. Because of the deposition of fine gritty dusts, maintenance costs are increased. Canadian manufacturers are faced with a costly problem of ventilation in the winter months. In winter, a large portion of the plant-operating overhead is the cost of maintaining a comfortable working temperature in the shop when the outside temperature hovers below zero (Fahrenheit). Even on the coldest days, the windows are left open to dilute the smoke-laden air with a resultant increase in heating costs.

Modern fabrication practices greatly increased the welding done in the large shops of the Dominion Bridge Company at Lachine, near Montreal, Canada. The acuteness of their welding-smoke problem caused a study of installations in plants in the United States where the Precipitron is used to remove dusts, smokes, lints and even oil mists from the air. The practicality of the scheme was easily determined. Economic justification of such an installation was established by a survey of the plant heating and ventilating requirements.

The survey showed that a heating and ventilating system using about 80 percent recirculated air and 20 percent fresh make-up air, with a Precipitron to remove the smokes from the recirculated air, had an initial cost substantially below that of a system using a boiler of adequate capacity to heat a continuous 100-percent supply of fresh air that was exhausted to the outside with no recirculation. The operating cost of the system recirculating cleaned air also was shown to be much less than that of the alternative scheme because the energy expended in heating the recirculated air would not be entirely lost. A trial installation was authorized and a large section of the welding shop was isolated from the rest of the plant and fitted with proper intake and discharge ducts. In a penthouse were installed the Precipitron for cleaning the recirculated air, the necessary heating coils, the blower fan and suitable water and compressed-air outlets for washing down and re-oiling the precipitator plates. The system provides 30 000 cubic feet of recirculated air per minute.

The experience of the past winter has proved the worth of this system using electrostatic precipitation of welding smokes from the shop air and recirculating it, together with adequate amounts of fresh make-up air. The Precipitron, whose power requirements are but 380 watts, removes from the air more than 90 percent of all air-borne particles, even those measuring but one two-hundred-fifty-thousandths of an inch—the smallest particles comprising welding smoke. The efficacy of the system in removal of welding smokes is demonstrated dramatically in two ways. The quantity of solids removed from the recirculated air is such that weekly washing of the plates in the Precipitron is necessary. Also, the pictures of the plant proper shown below, taken within one half hour of each other under supervision of the plant management to prevent any interruption of war-essential work, indicate the vast improvement achieved by this installation.



The atmospheric conditions that existed in the Lachine plant of the Dominion Bridge Company, Ltd., are shown in the photograph above. Next to it is shown a picture taken one half hour later after the air in the shop had been recirculated through a Precipitron.

The Place of the Gas Turbine in Aviation

The reciprocating engine no longer holds undisputed sway in the field of aircraft propulsion. The war has greatly hastened the developments of two new types of aerial power plants: the turbine-jet engine and the gas-turbine, geared-propeller drive. Analysis indicates the newcomers should be viewed not so much as competitors of the piston engine but as serving to extend the present limits of aircraft to larger or faster ships or both.

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The constant trend in aviation has been toward bigger and faster airplanes, predicated on more powerful engines. Until recently, airplanes were driven only by reciprocating internal-combustion engines. Radically different power plants have appeared; of them, two will undoubtedly figure largely in aviation of the near future. One is the jet-propulsion engine; the other is the gas-turbine, geared-propeller drive. Both will use continuous-combustion gas turbines as the prime mover.

The reciprocating engine will undoubtedly continue to hold its present position in the field of low power and for planes of low speed. However, the gas turbine will come into its own both as a jet engine and as a propeller drive for high-powered planes and for high-speed flight.

Of the three types of power plants, the turbine-propeller drive is superior to the reciprocating engine in all speed ranges and over the jet engine in low and intermediate speeds. The jet is pre-eminent in the highest speed range. The probable fields of use of the three types are indicated in Fig. 1.

Comparisons of the turbine power plants with conventional engines should properly be made on the basis of finished airplanes designed to fit best the characteristics of their particular power plants. Test-stand fuel-consumption rates are a good measuring stick between engines of similar types, but should not be used as a primary figure of merit in comparing different engine types. The size, weight, and cooling requirements of an engine, together with its efficiency in converting fuel energy into thrust horsepower and the ease with which it is installed in clean, low-drag airframes, give the full measure of its overall economy.

The Reciprocating Engine

The modern reciprocating aircraft engine is a marvel of engineering. Inspired to no small degree by military requirements, it has been developed to a high peak of efficiency, lightness of weight, and reliability. However, power ratings have reached a point where further major increases can probably be attained only by improvements in fuels or the addition of cylinders. The diameter or frontal area of engines is already limited by allowable piston speeds (i.e., lubrication limits). Hence, larger engines must be longer engines, and the specific weight is likely to increase instead of decrease as engine outputs become larger. Unfortunately, reciprocating engines capable of delivering several thousand horsepower require controls, accessories, and exhaust-disposal systems that complicate installation and create maintenance problems to an extent that limits further large increases in power rating, somewhat as indicated by the curve in Fig. 2 suggested by one authority.

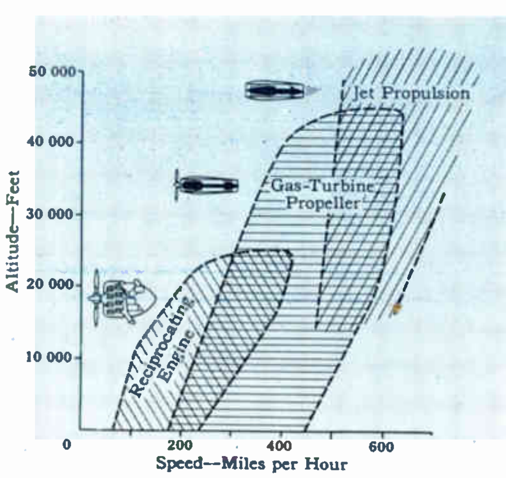


Fig. 1—Probable fields of use of the three types of aircraft power plants of the near future.

The reciprocating engine is by nature adapted to cruising flight rather than sustained high-speed flight. Its highest efficiency and greatest reliability are achieved only when the engine is operated below 60 percent of rated power. An underpowered airplane is constantly plagued by power-plant troubles of a mechanical nature. Typical fuel rates at various operating conditions are shown in Fig. 3.

The Gas-Turbine Jet Engine

In the enormously publicized jet-propulsion engines, all the power output is used to accelerate the air taken into the engine to a jet of approximately acoustic velocity, which is expelled through an exhaust nozzle. The resultant thrust felt by the engine housing is the reaction to the force required to accelerate the intake air to its exhaust velocity. (Rockets also work by accelerating their internal charge to a high velocity, but they carry their oxygen as well as fuel, which makes them independent of the atmosphere.) The gas turbine inducts air, compresses it, adds heat at high pressure, and expands the high-temperature combustion products. Most of the energy is recovered in expansion through the turbine blading and must be used to supply energy required for compression. The remainder of the expansion occurs through a nozzle, where the energy appears as kinetic energy of the exhaust gases.

The gas turbine can be easily adapted to jet propulsion, but the conventional engine cannot. This is, primarily, because the gas turbine handles a much greater mass of air (four to eight times more than the reciprocating engine for each pound of fuel burned), which leads to a more efficient jet reaction. The difference here is that the reciprocating engine requires a large mass flow of air for cooling external to the combustion space,

*Discussions of the combustion gas turbine and the principles of jet propulsion are given in the Westinghouse ENGINEER for May, 1944, and March, 1945, respectively.

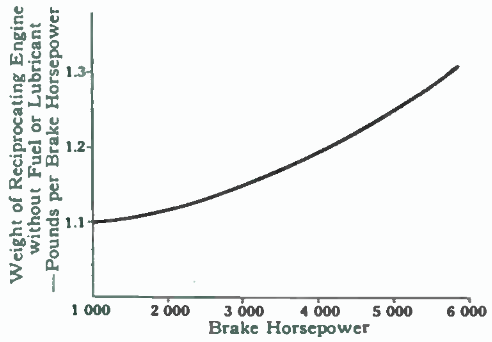


Fig. 2—Predicted specific weights of conventional engines. (From "Aircraft Power Plant—Past and Future" by Sir A. H. Roy Fedden.)

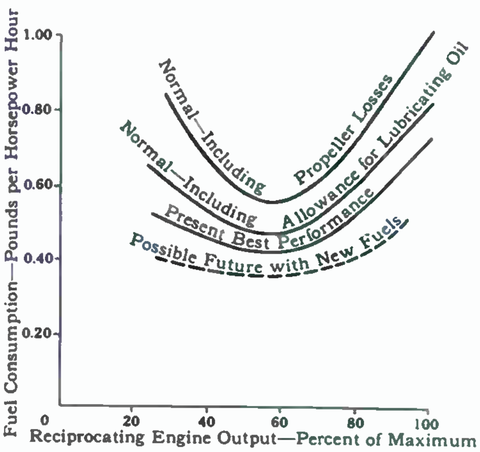


Fig. 3—Typical fuel-consumption rates for a large reciprocating aircraft engine under different operating conditions at various loads.

while the gas turbine swallows its own cooling air and subjects it to the same thermodynamic cycle as the air needed just to burn the fuel. The relatively high combustion temperatures of the reciprocating engine result in high-speed exhaust gases with highly unfavorable velocity ratios for use in jet flight at subsonic speeds.

An axial-flow jet engine, in which the compressor, combustion chamber, and turbine are arranged in line so as to present the minimum frontal area, is shown in Fig. 4. Some jet engines have been built using centrifugal compressors, which result in a machine of larger diameter, not so well suited aerodynamically for installation in a high-speed airplane.

Principal advantages of the jet engine are its simplicity and light weight. The installed weight of the jet-propulsion engine is but little higher than the bare engine, because only a small amount of oil is required for lubrication, and the engine itself requires no external cooling provisions.

The jet-engine thrust is relatively constant over the normal speed range of airplanes. Therefore, the rating of a jet engine is usually given in terms of thrust instead of horsepower and means nothing from a power standpoint until the speed is also given. A thrust of one pound at a speed of 375 miles per hour is equivalent to one horsepower; at lower speeds the power rating decreases. Accordingly, at higher speeds, it increases in direct proportion.

An adjustable-pitch propeller is capable of converting shaft power into thrust horsepower rather efficiently over a wide range of airplane speeds, but the jet's efficiency is quite low at low speeds. As shown in Fig. 5, present jet efficiency does not equal propeller efficiency until flight speeds of about 500 mph are attained. Below this speed the jet efficiency, consequently its fuel economy, is inferior. The fuel efficiency of a jet engine is low, principally because of the poor jet-efficiency characteristic, secondly because the gas turbine itself operates at a low compression ratio, which signifies low efficiency. At 375 mph, the apparent or test-stand propulsive efficiency of a jet engine is less than half that of the conventional power plant. Its take-off thrust is one fourth that of a propeller with the same power rating at 375 mph, Fig. 6. Jet propulsion performance is excellent at high speed, at the expense of range and low-speed performances. Jet efficiency overtakes propeller efficiency in a speed range in which compressibility effects impose critical aircraft design limitations. Much aerodynamic research must be carried out before jet propulsion can be utilized to its best advantage.

The Turbine-Propeller Drive

A simple open-cycle gas turbine can be built today to work at a peak temperature (temperature of gases entering the turbine) of 1500 degrees F. With further metallurgical progress, the life of highly stressed turbine parts operating at high temperature will be increased so that this limit can be raised. With a compression ratio of ten to one, and with compressor and turbine efficiencies of 85 percent, a fuel efficiency of 26 percent is possible. By increasing the efficiencies of the compressor and turbine to 87 and 89 percent, respectively, the overall efficiency rises to 28 percent at sea-level conditions. At 15 000 feet, where ambient temperature is low, the cycle efficiency rises to 31.5 percent.

The axial-flow gas turbine for propeller drive will be a symmetrical machine, its reduction gear concentric with its rotor, as indicated in the schematic illustration, Fig. 7. Its diameter will be less than half that of a conventional engine of comparable power, permitting it to be easily buried within

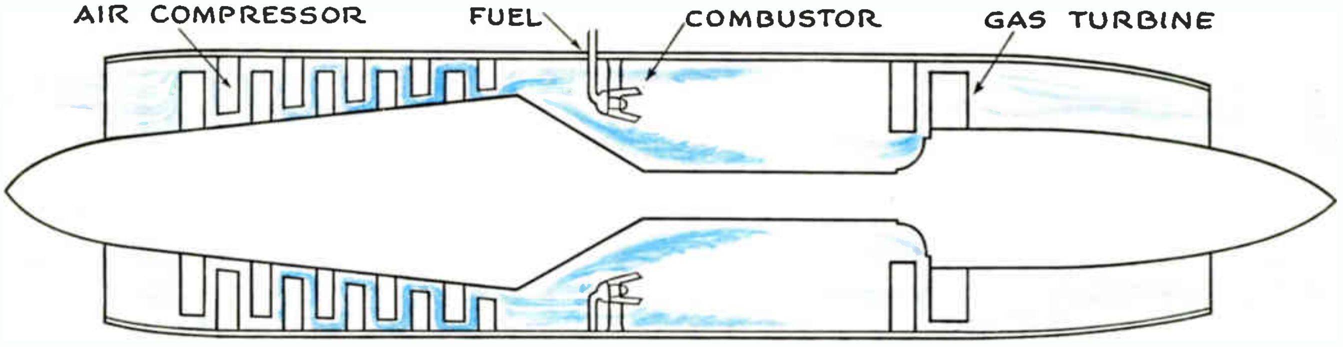


Fig. 4—Schematic illustration of an aircraft jet-propulsion engine with axial-flow compressor and in-line combustor and turbine.

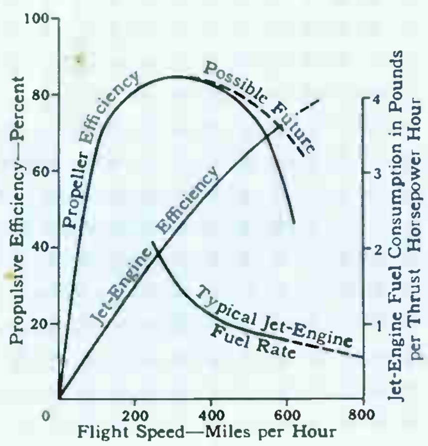
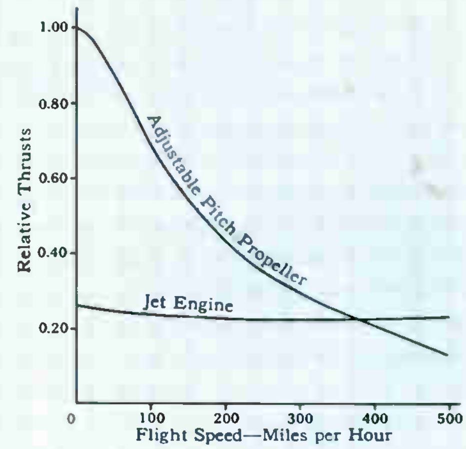


Fig. 5—Propulsive efficiencies of propellers and jets of jet engines.

Fig. 6—Relative propeller and jet-engine thrusts with equal thrust power at 375 mph, versus speed.



a fuselage or wing. The gas turbine presents little frontal area and requires no external cooling air for itself, and hence offers little drag at high speeds. This, in addition to the fact that the gas-turbine efficiency is best at its peak load, points to the adaptability of this type of power plant to high-speed flight.

The efficiency of a gas turbine is highest at its rated load and rated speed. As turbine speed decreases, the efficiencies of compression and expansion decline and the compression ratio also decreases rapidly. Because the useful power output of the machine is the relatively small difference between the power developed by the turbine and power absorbed by the compressor, any change in compressor or turbine efficiency is magnified in its effect on power output. In fact it is doubtful if the turbine output will be sufficient to drive the compressor below half speed—much less supply power to the propeller. Idling speed for a gas-turbine propeller drive will be between one half and two thirds rated speed.

The gas turbine for propeller drive operates on four to eight times the quantity of air used by a reciprocating engine of comparable power. A large exhaust-jet thrust is available to supplement the propeller, because normally about 20 percent of the useful power remains in the exhaust gases as kinetic energy. The proportion of useful power remaining in the exhaust to power delivered to the propeller can be controlled by the designer.

The gas turbine permits a much lighter power-plant installation than does the reciprocating engine. The installed weight of the geared-gas-turbine engine should be less than three fourths the weight of a reciprocating engine installation of equivalent output.

In general, operations at normal-flight altitudes are favorable to economical turbine performance. Fuel rates are indicated in Fig. 8. As a rough approximation, the exhaust-jet thrust just about compensates for propeller losses and nacelle and cooling drag. Hence, the shaft power output of the turbine is approximately equal to the net thrust horsepower available. This is quite different from the case with the reciprocating engine, as will be shown later.

The gas turbine is not a supercharged engine. Therefore, the selection of power rating must be based on altitude requirements. For sea-level operation, considerable excess power will usually be available. Typical power availability curves for various types of power plants are shown in Fig. 9.

The Airplane and the Reciprocating Engine

The reciprocating engine, in its normal cruising power range, is an efficient means of converting fuel energy into shaft power. However, its application to aircraft is complicated by many difficult problems, among which are the necessity for supercharging at high altitudes, severe vibration, excessive weight installed as compared with bare engine weight, and high nacelle-drag and engine-cooling power losses.

For medium- and long-range aircraft, the most important problems are probably the reduction of nacelle-drag and engine-cooling losses. Airplanes designed for low-speed operations can afford to have a large part of the plane's parasitic drag absorbed in engine nacelle and engine-cooling losses, because induced drag may be a large portion of the total flight power requirement, while engine losses are a relatively minor factor. This is definitely not the case with long-range and high-speed aircraft where induced drag is relatively small and parasitic drag all important.

The reciprocating engine presents a dismayingly large frontal area when placed in a wing nacelle; the total profile area of power plant frequently exceeds that of the fuselage. Similarly, the reciprocating engine requires large volumes of cooling air that must be forced around the cylinders of air-

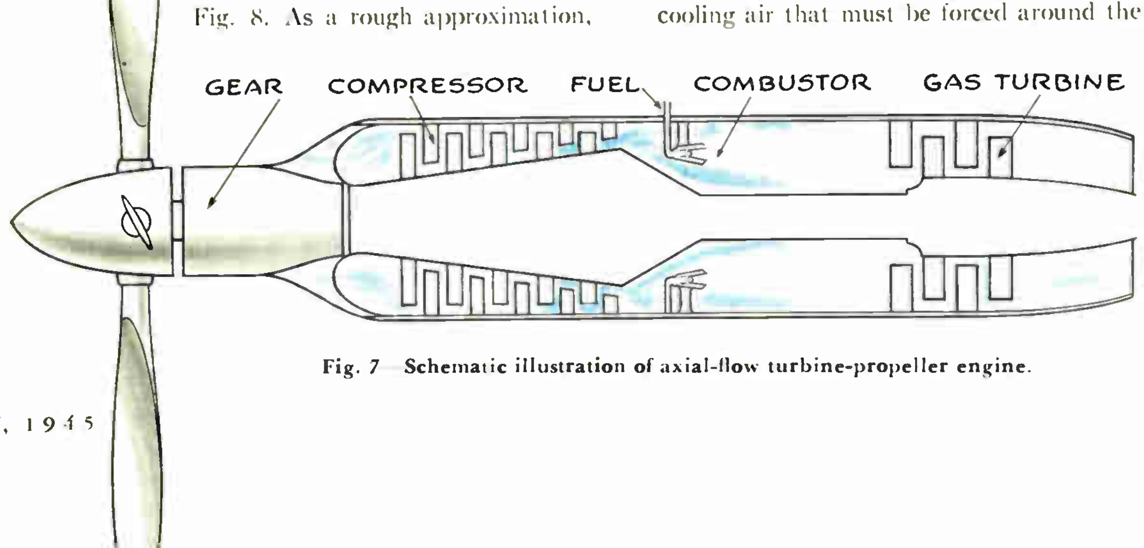


Fig. 7—Schematic illustration of axial-flow turbine-propeller engine.

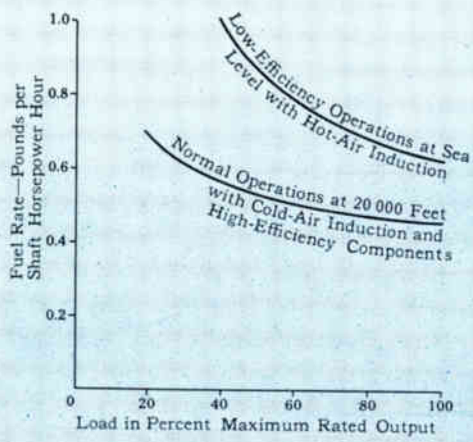


Fig. 8—Range of fuel-consumption rates for aircraft gas turbines with reduction gear output to propeller shaft; rates have not been adjusted for inclusion of exhaust-jet thrust effects.

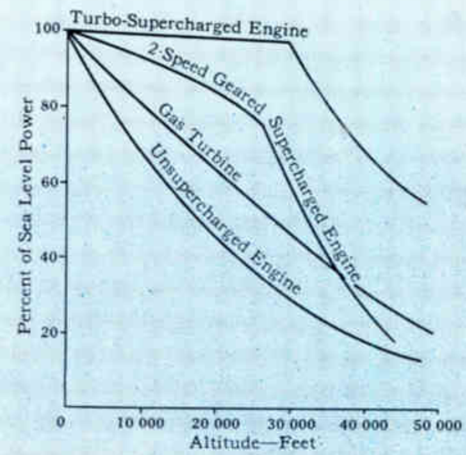


Fig. 9—Effect of altitude operations on power availability of various typical aircraft power plants.

cooled engines or through the radiators of liquid-cooled engines as well as through numerous accessories and oil coolers. The power losses at different airplane speeds for a typical 2000-hp engine installation complete with propeller and installed in a wing nacelle are shown in Figs. 10 and 11. The remaining available power under any but low-speed flight conditions is greatly reduced by these losses. Typical losses for maximum engine power at all speeds are shown in Fig. 10. The average losses for the same engine under flight conditions in a large airplane with a maximum speed of 400 mph are given in Fig. 11; higher speeds would still further accentuate the losses. Also shown on Fig. 11 is a fuel-rate curve based upon the net thrust horsepower of the power plant after all power-plant losses have been accounted for; this should be compared with the excellent performance of similar engines on the basis of shaft horsepower output indicated in Fig. 3.

Large reductions have been made in propeller losses, also in nacelle and cooling drags, as a result, principally, of nacelle design improvements and the use of cooling fans on radial engines. Further reductions can be expected in the future, particularly for specialized applications such as high-altitude, high-speed flight. Until such improvements are made, high-speed operations will be limited by power plant rather than airframe whenever reciprocating engines are used.

Jet Propulsion of Aircraft

The axial-flow jet engine of Fig. 4 is a slender package capable of delivering almost constant thrust at all speeds from take-off to dive maximum. Throughout this speed range, fuel is burned at practically a constant rate, and changes in speed have but little effect on thrust or fuel consumption. Further, the jet-propulsive efficiency is approximately proportional to speed, as shown in Fig. 5. These factors recommend jet engines for high-speed aircraft. At low air speeds, fuel-consumption rates are exorbitant when compared with propeller-driven aircraft.

To offset the disadvantage of low efficiency at low speeds, the jet engine delivers a lot of power for very low weight of installed power plant in its proper range of flight speed. Cycle efficiency, while not as good as that of the piston engine, is fair, which means low fuel cost per thrust horsepower at high speeds. The engine is small enough in diameter for it to be buried in the wings of all but the smallest planes.

Apart from booster applications in aircraft that are underpowered with reciprocating engines, jet engines should not be installed in any but the cleanest of low-drag airplanes. The most suitable applications for jet propulsion appear to lie in speed ranges where compressibility effects are the principal unknowns. Supersonic problems are fairly well known from ballistics, and low-speed flight has been well explored. This leaves the natural range of flight speed of the jet engine a large blank. Jet propulsion probably will serve as the tool and incentive to fill this gap in our knowledge.

To project our present designs somewhat into the future and estimate possible trends, Fig. 12 has been prepared. The solid curves represent the power-required and power-available characteristics of an extremely fast high-altitude single seater of present reciprocating-engine design. The dotted curves are for a jet-propelled plane of equal gross weight and wing area but in which it is assumed that the drag has been reduced by one half through refinements made possible by a jet engine instead of the reciprocating engine. This, it should be remembered,

Significant Facts of Aircraft Propulsion

The three types of drive are: reciprocating engines; gas-turbine, geared-propeller; gas-turbine jet.

The piston engine, while efficient and reliable, appears to be approaching the practical limit of power output and mechanical complication.

The conventional piston engine with variable-pitch propeller will probably remain unequalled for small aircraft and low flight speeds.

The axial-flow geared gas turbine will match best fuel efficiency of present piston engine at high outputs.

The gas turbine must operate at or near full load and at or near full speed.

As compared to the piston engine, the axial-flow gas turbine has low frontal area, has lower installed weight per horsepower, and inherently has few lubrication and cooling problems.

A gas turbine geared to a propeller will have good overall operating characteristics at both low and high flight speeds.

The jet engine at low flight speeds has poor fuel consumption characteristics.

The jet engine, for low specific fuel rates, must fly at speeds of over 500 mph.

Compressibility effects at very high flight speeds demand radically new aerodynamic designs before aircraft can capitalize on jet propulsion.

is a rather optimistic assumption that cannot at present be realized.

The maximum speed at 20 000 feet altitude increases from 460 mph for the conventional plane to approximately 600 mph for the jet-powered machine, assuming that compressibility effects are absent. The speed increase, however, does not bring with it a better cruising radius even when proper allowance is made for the larger fuel tanks that are permitted by the lighter weight jet engine. The lowest fuel rate in pounds per mile at this altitude for the jet plane is almost double that of the conventional aircraft.

By increasing the flight altitude of the low-drag jet plane of Fig. 12 to 30 000 feet, the maximum speed may decrease slightly because of compressibility effects, but the best cruising speed is increased by about 50 mph with a fuel consumption per mile about 40 percent greater than the conventional airplane. The conventional aircraft with a high maximum speed is able to throttle back to a 270-mph cruise for maximum range. The jet plane will have to fly at over 500 mph for maximum range; and high speed always means large power expenditures, a point often overlooked by rocket and jet enthusiasts. However, this jet plane would fly the same course in half the time that the conventional aircraft would take, and in military service could therefore afford a reduction in range for interceptor service and related missions.

The relative merits of a jet fighter and a conventional fighter with regard to take-off run, rate of climb, and extreme range are compared in Fig. 13. The jet-propelled aircraft is superior to that powered in the conventional manner, in all particulars except take-off, climb, and range. By using a jet engine of 50 to 70 percent more thrust than in this example, the take-off run would be reduced to about the same as the conventional fighter, the climb and ceiling would be greatly increased, and the cruising speed and maximum speed would be increased slightly, all at the expense of a heavier power plant and a further serious reduction in range.

These comparisons also hold for large aircraft, such as transports and bombers, although in the case of the bomber particularly it is even more difficult to achieve really large reductions in drag because of the constant large increments of drag imposed by armament and navigational devices. Substantial reductions in drag can be effected, but not enough to result in jet- and piston-engine fuel rates indicated in Fig. 12.

The Turbine-Propeller Airplane

The gas turbine geared to a propeller, shown in Fig. 7 with typical fuel-consumption rates shown in Fig. 8, has the advantages of the jet engine with respect to drag reduction and ease of installation. At the same time it retains the high propulsive efficiency of the propeller at low speeds. The present limit of usefulness of the geared-turbine propeller at high flight speeds is set by the characteristics of available propellers, which lose out quite rapidly in efficiency above 500 mph. Research on propellers is necessary for several reasons, however, and propeller manufacturers are hopeful that the good efficiency range can be extended to considerably higher speeds. Something must also be done to reduce the necessity for large spinner diameters on present propellers in order to take full advantage of the small diameter of the gas turbine. Some weight reductions may be possible because of the absence of torsional vibration in the turbine-propeller shaft. Estimates of possible reductions in propeller weight vary from zero to one fourth. The advantages and disadvantages of shrouded propellers (i.e., within enclosures) have been much studied and discussed, but at the speeds now contemplated, the extra complication does not yet appear profitable.

The principal and immediate advantage of the geared-propeller, gas-turbine drive is a large reduction in airplane drag. Two large airplanes, one with conventional engines installed and the other with turbines are shown in Fig. 14. The contrast is striking, both in appearance and drag. Overall power-plant performance for the gas turbine with geared propeller is shown in Figs. 15 and 16, which should be contrasted with Figs. 10 and 11 for the piston-engine power plant. The thrust power obtained from the turbine exhaust is approximately large enough to offset engine nacelle drag and ordinary propeller losses under normal flight conditions. Therefore, as an approximation, the shaft power output of a geared turbine of this type is roughly equivalent to its net thrust horsepower as a complete power plant under flight conditions. For a direct comparison of total power-plant losses of conventional engine power

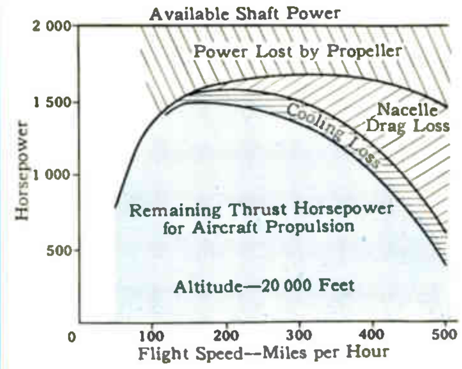


Fig. 10—Typical losses associated with a large reciprocating engine in a wing nacelle and operated at full power output.

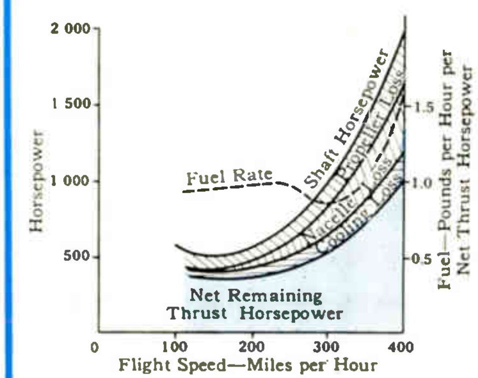


Fig. 11—Typical flight losses of the power plant of Fig. 10 when operated on the power-required curve of an airplane designed primarily for long-range operations.

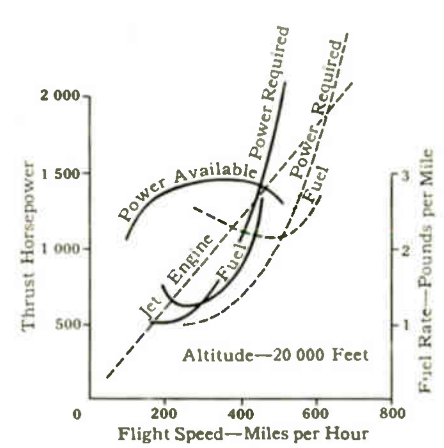


Fig. 12—Power-required and power-available curves for single-engine airplane with reciprocating engine (solid lines) and jet engine (dotted lines).

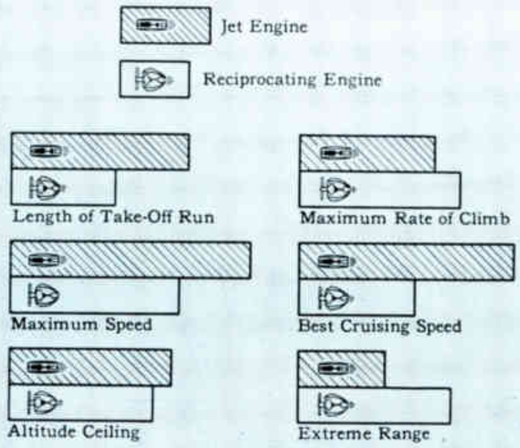


Fig. 13—General performance comparisons for the two airplanes under the conditions of Fig. 12.

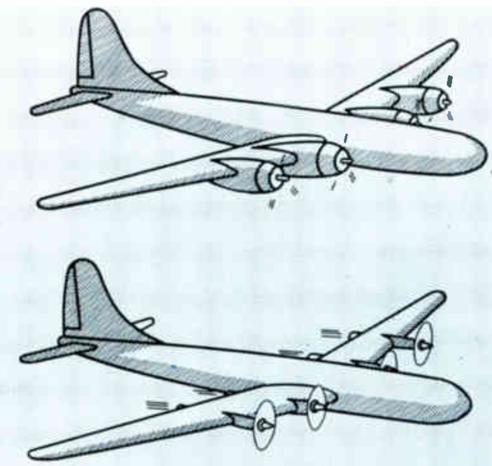


Fig. 14—Appearance comparisons of two large aircraft, the upper one with reciprocating engines, and the lower one with gas turbines geared to propellers. (Power-plant horsepower outputs are assumed to be equal at 20 000 feet.)

plants and geared turbines with propellers, see Figs. 11 and 16.

It is possible to make a choice of the division of power outputs of a turbine-propeller unit between jet-exhaust thrust and the propeller shaft. For example, for a high-speed airplane that must still have a good take-off characteristic, 50 percent of the power might be used in jet thrust and the remainder in the propeller. For ordinary applications, however, between 20 and 25 per cent of the available energy should remain in the exhaust jet, the turbine shaft recovering the remainder. Thus, for the example chosen here, most of the energy is absorbed by the propeller with excellent overall power-plant performance at low flight speeds, and with fuel economy at high power levels that is quite superior to the conventional power plant.

This type of power plant is equally adaptable to fighters or large airplanes. The improvement in fuel efficiency with increasing air speed and power results in somewhat higher cruising speeds than for aircraft with reciprocating-engine power plants. The decrease in available power at higher altitudes makes it necessary to install gas-turbine power plants that may have considerably more power at sea level and for

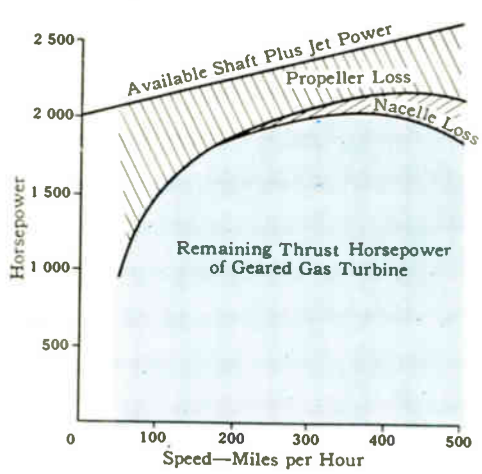


Fig. 15—Typical flight losses estimated for a gas-turbine engine with geared propeller. Jet thrust almost offsets the propeller and nacelle losses developed through most speeds.

low-altitude climb than is now considered normal in airplane design. This is an advantage instead of a disadvantage, however; a propeller able to absorb the turbine's shaft output at 20 000 or 30 000 feet can efficiently handle the greatly increased output of the same turbine at sea level, because of the denser air at low altitudes. Thus a turbine power plant with a rating equal to that of a supercharged conventional engine at 20 000 feet altitude might have a take-off thrust at sea level 60 percent greater than that of the conventional engine. A much shorter take-off run than normal is therefore possible, and rate of climb is greatly superior to that possible with the conventional aircraft.

The field of usefulness of the gas turbine with propeller, then, extends to all aircraft requiring engines of greater than perhaps about 2000 hp, and designed for all speeds up to and in excess of 500 mph.

The total thrust horsepower requirements of a typical four-engine airplane at 20 000 feet altitude are shown in Fig. 17. The curve for the plane with reciprocating engines includes all power-plant drag losses but does not include propeller efficiency. The gross weight in each instance is assumed to be 120 000 pounds and power plant plus fuel weights are held constant. The conventional engine installation is four engines supercharged to 2000 hp each at 20 000 feet. In the jet-propelled version, four engines each developing 6000 pounds static thrust are used. This gives 24 000 pounds take-off thrust, approximately equal to the take-off thrust of the plane with reciprocating engines. Once in flight, two of the jet engines can be shut off for cruising under 25 000 feet altitude. In the gas-turbine, geared-propeller airplane, four engines capable of delivering 2000 shaft hp each at 20 000 feet are used. At take-off these engines will deliver 3200 hp each. A propeller designed to absorb 2000 hp in the low-density air of 20 000 feet altitude can handle 3800 hp at sea level with the same level of propulsive efficiency. At take-off the three types of aircraft drive compare as indicated in table I.

Cruising conditions are compared in table II. The jet-propelled plane cruises on four engines at 35 000 feet and on only two engines at 20 000 feet. Fuel consumption with four jet engines operating is prohibitive for any operations other than at take-off or high altitudes. Included in table II is the cruising fuel consumption when four gas-turbine-driven propellers are used and also when two turbine propellers are used and two feathered. A suitable drag allowance has been made for the feathered propellers.

The sensitivity of the gas-turbine-driven propeller to partial load operation is seen in table II. An 18-percent increase in range is obtained by operating two engines close to full load and maximum efficiency instead of operating four engines at less than half load. This is a fundamental difference that exists between turbines and reciprocating engines, and it makes necessary a careful selection of turbine ratings for any given application if maximum fuel economy is to be gained. The same conditions are true of jet-propulsion engines, and it is profitable to operate close to 80 percent of full rating of the turbines either by shutting down excess power units or going to a sufficiently high altitude to decrease the maximum rated output to a value near the required flight power. In the case of the jet-propelled plane, because high speed and high propulsive efficiency go together, high-altitude operation is essential to maximum flight economy.

The general characteristics of the three airplanes described in tables I and II are compared in Fig. 18. In this figure the maximum-speed comparison is based on an altitude of 35 000 feet for the jet engine and 20 000 feet for the gas-turbine propeller drive and reciprocating engine. The comparison of the best cruising speeds is predicated, in the case of the jet engine, on four jets at 35 000 feet and an altitude of 20 000 feet for the other two power plants. The gas-turbine, propeller-drive airplane is superior to the conventional aircraft on every count with the exception of altitude ceiling, where it and supercharged reciprocating engines are about equal. Because turbine-propeller fuel economy and installed power-plant weights are both superior to those of the conventional engine, the long- and short-range load-carrying abilities of the turbine-propeller aircraft are superior to the conventional one. On the other hand, the jet-propelled aircraft has a light power-plant installation and can get off the ground for short flights with about five tons more payload than the conventional aircraft, and about three tons more than the turbine-propeller version. However, jet propulsion requires so much more fuel than other types of power plant that at about 2000 miles extreme range the jet plane loses out to the reciprocating engine and is far behind the geared turbine in payload.

As in the case of the jet-propelled fighter, the jet bomber or cargo plane must be limited in use to relatively short-range, very high-speed, high-altitude operations that can accept the expense of high fuel costs, until we have learned more about the aerodynamics of flight at speeds over 500 mph. The gas turbine with a geared propeller, however, has immediate applications in all classes of service where requirements are much above 1000 hp at usual flight altitudes, and should be ready for use when aircraft designs require 10 000 hp or more in a single power-plant unit.

TABLE I—COMPARISON OF THREE TYPES OF DRIVES FOR A LARGE AIRPLANE AT TAKE-OFF

Type of Power Plant	Gross Weight, Lb	Installed Power Plant Wt., Lb	Fuel Weight, Lb	Take-Off Thrust, Lb
Piston Engine	120 000	20 800	40 000	28 000
Turbine Propeller	120 000	15 200	45 600	44 000
Jet Propelled	120 000	8 000	52 800	24 000

TABLE II—COMPARISON OF LARGE AIRPLANES CRUISING AT 20 000 FEET

Type of Power Plant	Best Cruising Speed Mph	Miles per Lb Fuel	Extreme Range Miles
Piston Engine	250	0.120	4800
Turbine Propeller (4 engines)	300	0.125	5700
Turbine Propeller (2 engines)	280	0.145	6600
Jet Propelled (2 engines)	350	0.050	2650
Jet Propelled (4 engines 35 000 feet alt.)	460	0.066	3500

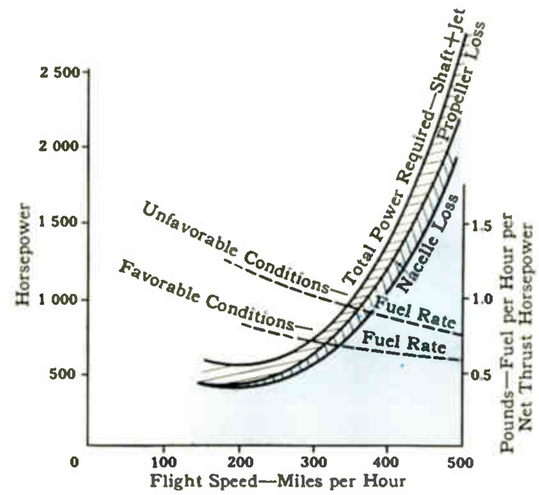


Fig. 16—Typical flight losses of the geared gas-turbine power plant of Fig. 15 when operated on the power-required curve of a high-speed aircraft at 20 000 feet altitude.

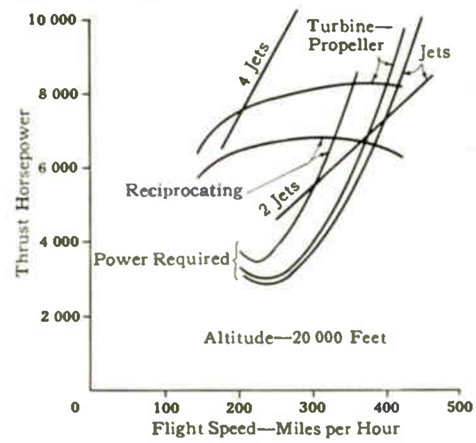


Fig. 17—Power-available and power-required curves of a large (120 000-lb) airplane equipped with four engines.

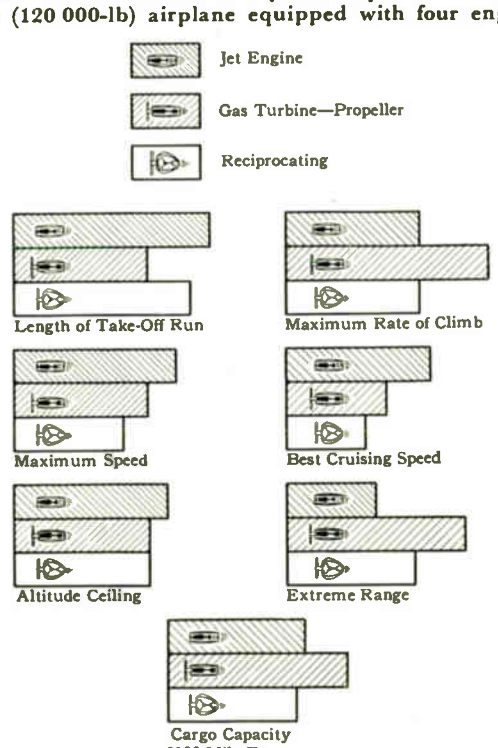


Fig. 18—General comparisons of the characteristics of the three types of airplanes shown in Fig. 17 and tables I and II.

What's New!

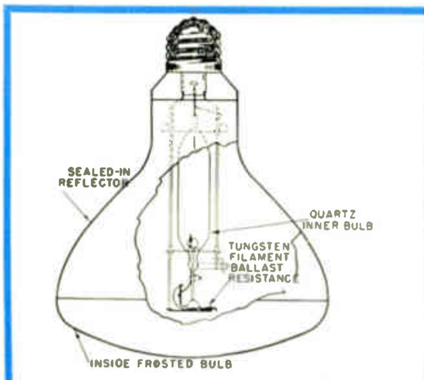
Shades of Florida Sun Tan—at Home

The annual treks to shore resorts to acquire the fashionable and healthful sun tan may be out this year. In effect the shore is brought to the home by the Westinghouse RS sunlight lamp that provides the desired tan-promoting rays simply and quickly. Closely resembling a reflector-type spot lamp or photoflood lamp, the sun lamp is as easy to use as an ordinary lamp bulb. Merely screw the lamp into a convenient socket in the a-c home-lighting system and snap the switch. After a one-minute initial heating period, the lamp produces a beam of ultraviolet rays of constant intensity that, at a distance of two feet, is three times as potent as that of the sun at the seashore.

This mercury-vapor lamp achieves the unusual engineering distinction among sunlamps in that it is entirely self-contained, can be used in any position, and requires no outside ballast, starter, or external reflector. As shown in the sketch, the RS lamp is really a lamp within a lamp. The exterior globe is made of a special ultraviolet-transmitting glass. It is flattened at the end and is frosted inside to provide a smooth beam pattern.

Within this outer glass envelope is a sealed quartz tube that contains mercury and a pair of electrodes, one of which is a heater-type. A tungsten filament serves as a ballast resistance. When, in starting, voltage is impressed across the terminals of the lamp, the bimetal switch is closed. This shunts the gap between the electrodes of the ultraviolet generator so that current flows through the heater electrode. At this period in the starting cycle the tungsten filament and the heater electrode are in series. The heated electrode is a good emitter of electrons and helps to increase the mercury vapor. The heat from the tungsten filament in a short time causes the bimetal switch to open, thus removing the shunt from across the electrodes. This places the line voltage across the arc electrodes, which are in series with the tungsten filament. The arc is struck between the electrodes in the mercury vapor where the resistance drop is about 15 volts. The tungsten filament in series with the electrodes acts as a stabilizing ballast to control the current drawn by the lamp.

With the ultraviolet rays from the quartz mercury-vapor lamp is mixed infrared rays that provide a comfortable warmth in the beam. The erythemal action (reddening of the skin) varies inversely as the square of the distance between the lamp and the skin. At a distance of 24 inches the rays cover a circle 20 inches in diameter with practically iform distribution of ultraviolet emanations. On the average untanned skin this normally produces a mild reddening in five minutes equivalent to that achieved in 15 minutes at the seashore. At a distance of 12 inches the time is reduced to one-fourth normal and at 48 inches, the time can be increased four times. The life of the RS lamp is about 400 applications.



The components of the RS sunlamp are shown in this sketch.

Five leisurely minutes daily under the sun lamp builds a healthful and becoming tan.

Maintenance and Inspection of Transformer Diaphragm Relief Devices

If dangerous pressures develop within the tank of an oil-cooled apparatus, a diaphragm designed to fracture at a predetermined pressure breaks and relieves the pressure. The diaphragm must remain intact during normal operation of the equipment. Certain procedures of inspection and maintenance have been established to insure its protection and proper functioning.

The relief diaphragm is an integral portion of the top of the tank. Over the relief diaphragm is placed a protective cover, or weather hood, that rests on the gasketed top rim of the relief device. The overhanging rim of the hood protects this gasketed joint from the weather

However, certain conditions of wind and rain or ice and melting snow have resulted in water getting past the weather-hood gasket into the chamber above the diaphragm, particularly in equipment built before 1935. Neoprene gaskets, set with special cement, are now recommended for use in the weather-hood joint. Also suggested for equipment built before 1935 is the provision of two holes in the weather hood for visual inspection of the diaphragm each year. One hole permits light to be projected into the space above the diaphragm and the other hole is for viewing the lighted assembly. These holes are threaded and fitted with brass plugs.

New weather-hood gaskets are available for the relief devices using diaphragms of glass or Micarta. These gaskets maintain a better seal and are not as subject to deterioration as cork gaskets.

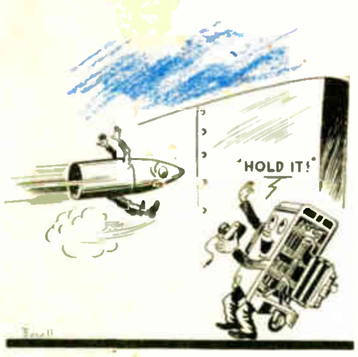
P E R S O N A L I T Y   P R O F I L E S

In 1940 *Dr. Charles Slack* and *Louis Ehrke* were studying the vagaries of an x-ray tube. They were disturbed by the occasional extremely large bursts of emission from the cathode, something that seemingly should be quelled. But with the characteristic research point of view that every phenomenon is significant, these two physicists sought to capitalize on this foible. Why not encourage it and make it the basis for intense x-ray beams. Pursuing this reasoning the ultra-high-speed x-ray was born.

Slack arrived at the research department of the Westinghouse Lamp Division by a devious route. Born in Ohio, he got his primary school training in Georgia, his bachelor of science degree from the University of Georgia (1922) and his master and doctor degrees from Columbia (1923 and 1926). Since he became a Westinghouse research physicist—he is now Assistant Director of Research, Lamp Division—Slack has conducted a wide variety of research programs.

Ehrke is a graduate mechanical engineer of Stevens Institute of Technology, class of 1924. Almost continuously since graduation he has been occupied with research problems as an associate of Dr. Slack. Ehrke is noted for unusual manual dexterity and ingenuity in solving the mechanical aspects of research problems.

The third member of the high-speed x-ray trio, *Charles T. Zavales*, found his engineering studies at City College of New York much interrupted. Being both ingenious and handy with tools, he was given the task of animating the science



exhibits in the Junior Science Hall for the New York World's Fair and was then placed in charge of operating them during the two Fair seasons. That might seem quite enough extracurricular activity for one student. But not for Zavales. He found time to assist a professor at Columbia in some research on the elasticity of wires, and was busy with another professor and inventor in the development and application of classroom hearing aids for children with defective hearing. When these chores and his studies in electrical engineering didn't keep him busy he worked in a laboratory across the Hudson River where Westinghouse makes meters and instruments. Since 1941 he has been engaged in x-ray engineering for Westinghouse at Baltimore.

• • •

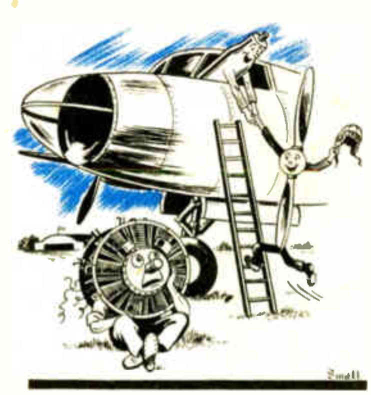
W. H. Brandt early in his career found his forte, physics, and hewed to that line throughout his college and university work. He received his B.A. in Physics

from North Central College in 1931. In 1933 the University of Illinois granted him the degree of M.S. in Physics and he immediately entered upon an original work in spectroscopy at the same institution, which earned him a doctor's degree. October, 1934, found him doing fundamental work in magnetic materials at the Cold Metal Process Company of Youngstown, Ohio. Brandt came with Westinghouse in 1936 and was active in the field of high-temperature and magnetic alloys. He became section engineer of the magnetics and development section of the group now known as the Materials Engineering Department. Now Dr. Brandt's activities are more diversified as Assistant Manager of the Division. His contributions in the materials field were quickly recognized and in 1940, he was awarded the Silver "W" for development work of exceptional merit. A self-styled duffer at golf, the only divots he has been taking lately are with a hoe. It could be that much searching of soul stuffs would be necessary to tell which pleased him more: Winning against a large field the prize for "Best Sample of Any Vegetable" (a cantaloupe in Western Pennsylvania, of all things!) or the publishing in the March 1945 issue of "The Journal of Applied Physics" an article entitled "Solution of the Diffusion Equation Applicable to Edgewise Growth of Pearlite."

Coming with Westinghouse in 1940, *Frank W. Godsey, Jr.* was eminently fitted by training and experience for his work in the New Products Division at East Pittsburgh. Graduating with the degree of B.S. in E.E. from Rice Institute in 1927, he furthered his education at Yale University and received his M.S. in E.E. in 1929. Godsey was with the Safety Car Heating and Lighting Company from 1928 to 1934 and while there received in absentia the Professional Degree in E.E. from Yale University ('33). He was with Sprague Specialties from 1934 to 1940. Godsey entered upon his work with Westinghouse as an advisory engineer. Recently he has been made manager of the New Products Division. Godsey is active in the professional associations, being a member of the AIEE, SAE, Institute of Aeronautical Sciences, and Sigma Xi. A prolific inventor, many developments of real merit have resulted from this flair. Many of his tales of duck and pheasant hunting seem to take on a flavor of this same inventiveness, but mostly he has meat on the table to confound disbelievers.

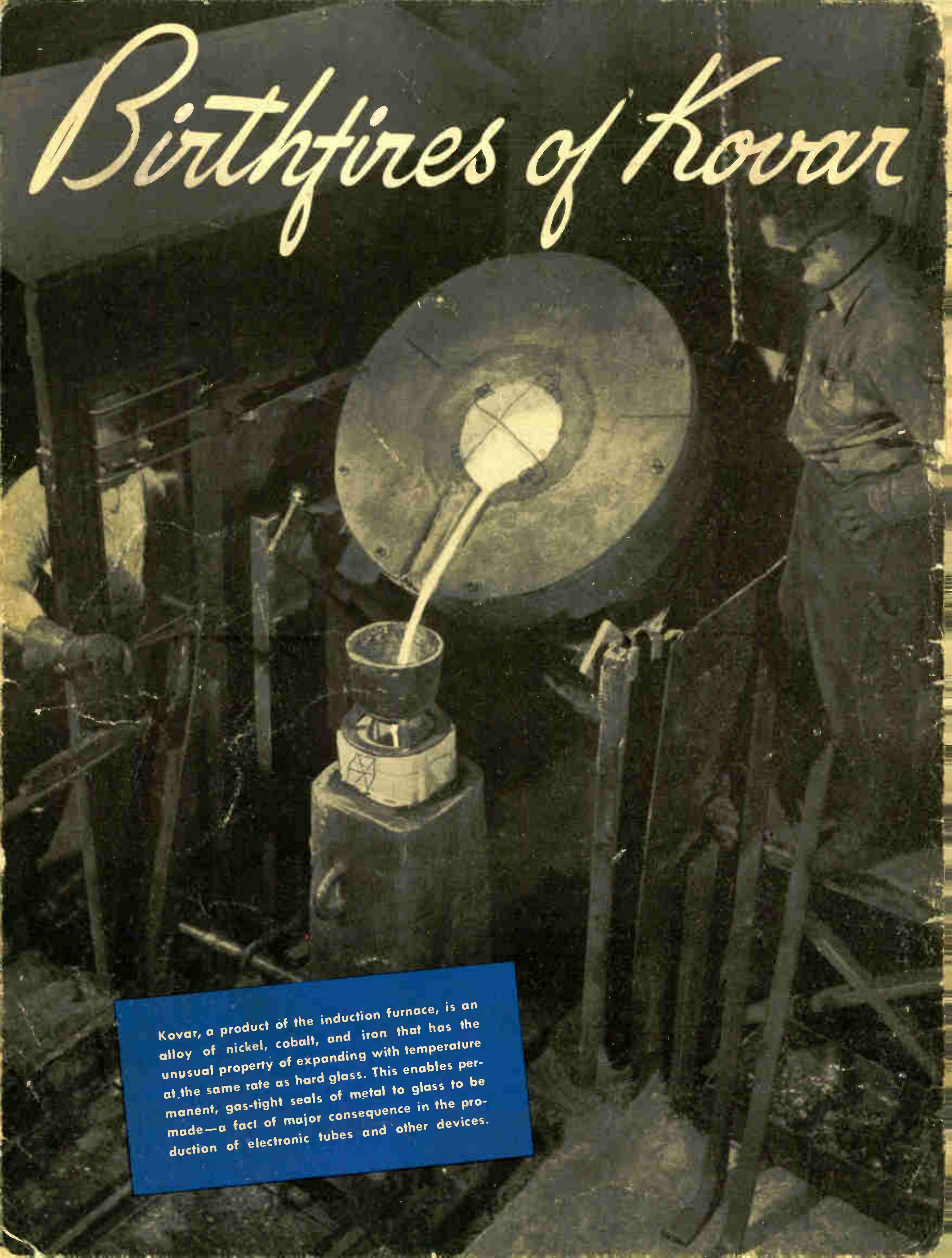
• • •

Charles D. Flagle received his Bachelor of Engineering from Johns Hopkins in 1940, coming with Westinghouse the same year. His work centered in the Development Engineering Department of the Steam Division. The experience here gained in apparatus design and solving problems of steam-turbine development paved the way for his entrance into the gas-turbine field in 1942. Since September of that year he has been identified with the engineering and construction of the



Company's first jet-propulsion engine for aircraft. Aside from the gratification of being in a field of direct military significance, there lurks the possibility of an actual test flight. To preserve a balanced outlook, Flagle is pursuing academic courses at the University of Pennsylvania.

Birthfires of Kovar



Kovar, a product of the induction furnace, is an alloy of nickel, cobalt, and iron that has the unusual property of expanding with temperature at the same rate as hard glass. This enables permanent, gas-tight seals of metal to glass to be made—a fact of major consequence in the production of electronic tubes and other devices.