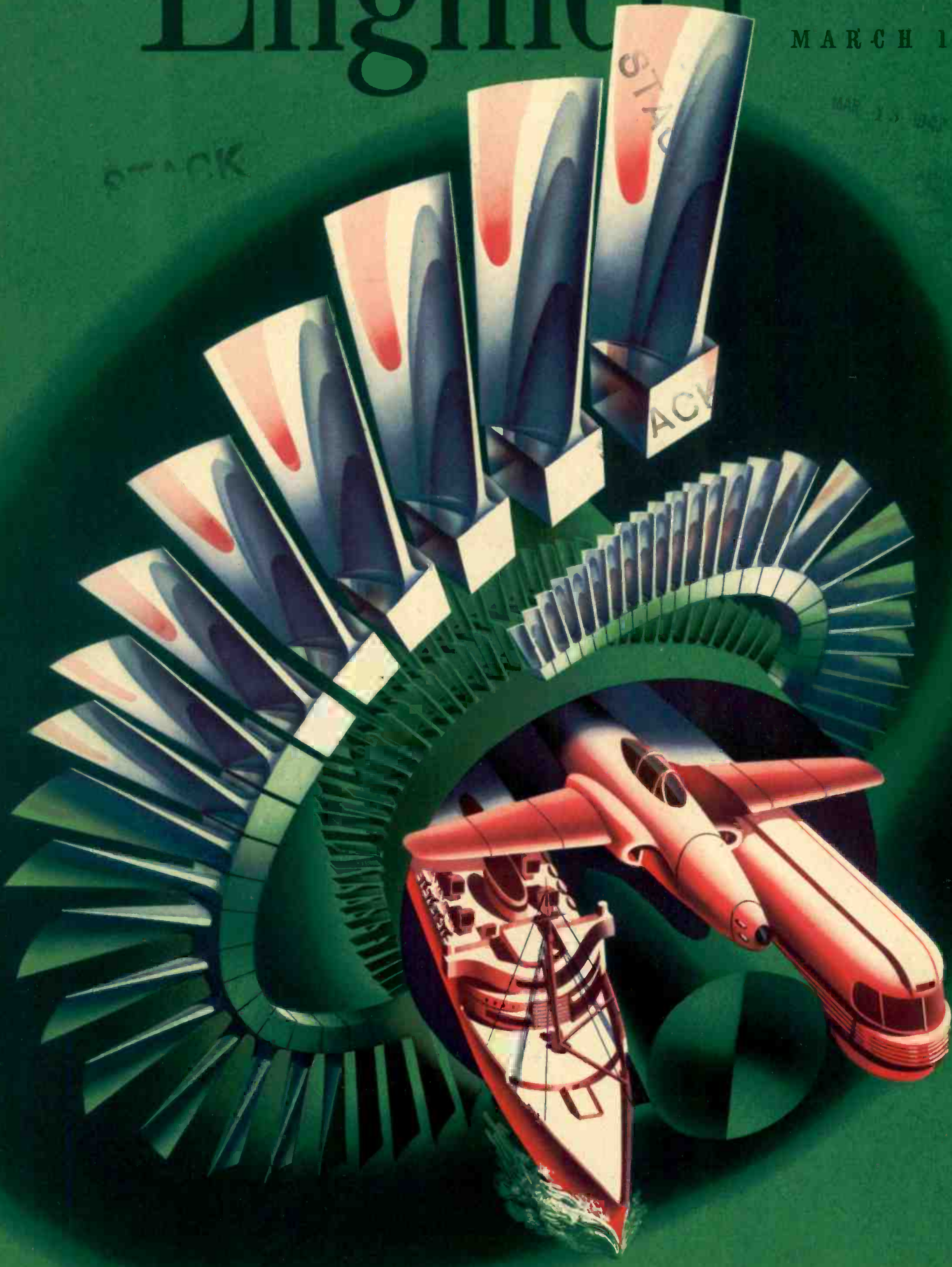
WESTINGHOUSE

Engineer

MARCH 1947



The Induction Motor—Its Origins and Growth

The induction motor, like some people and certain good ideas, was ahead of its time. It was invented before the development of the polyphase system on which it could be used. Indeed, one of the handicaps to its early development was the lack of polyphase generators to supply power for its testing. Development of the induction motor was actually shelved for about two years, until 1892 when successful polyphase generators began to appear.

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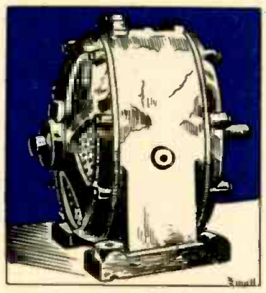

The tendency is always strong to assign credit for major discoveries to a single individual. More often than not this is impossible. This is true with the induction motor. The situation is neatly summed up by B. G. Lamme in his famous AIEE paper on the subject in 1921:

"The induction motor, in early days known as the Tesla motor, appeared in 1888, although it is difficult to say really when it was invented. Tesla invented it without question. But it may be said that Professor Ferraris also invented it, while Shallenberger was treading on his heels with an alternating-current motor-driven meter. Bradley was very close to the discovery with his polyphase synchronous converter. Thomson also was close to it with his three-coil arc machine. All these men worked independently of each other; therefore it can be seen that the induction motor was bound to be invented sooner or later. However, to Tesla belongs the true credit of independent invention and of bringing the matter before the public in such a way as to lead eventually to practical results."

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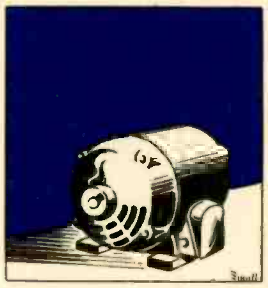
The first induction motors were not of the squirrel-cage variety. Early motor experimenters naturally followed direct-current motor practice, in having the field formed by windings on protruding or salient poles. This construction made a very poor motor. As Lamme tells the story: " . . . the motors were fundamentally handicapped in one feature, namely, the primary flux distribution. Distributed field or primary windings were unknown . . . The flux of the adjacent poles or phases did not overlap and uniform progression of the magnetic field was not possible . . . One of the greatest steps forward was the recognition of the advantages of distributed overlapping primary windings."



Lamme and his associates constructed a motor with distributed primary and secondary windings in 1892. The secondary winding (the stator) was short-circuited on itself at the polyphase terminals. On test, this motor gave very surprising results, compared with anything which had gone before. Its pullout torque was very large and its starting torque was very much better than expected. The current capacity of this motor proved to be materially larger than anticipated, probably because the distributed winding was considerably more effective in dissipating the heat.

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The squirrel-cage principle was the direct outgrowth of this 1892 motor. Lamme describes the course of events at Westinghouse: "An interesting test in connection with this motor was in determining the effect of short-circuiting the secondary winding from coil to coil, instead of the usual polyphase terminals. In the final test, the insulation was scraped or burned off the end windings of the secondary, exposing the bare copper, and the ends were then thoroughly soldered together, thus making a continuous ring of metal at each end. In other words, this was practically a modern type of cage winding. On test, this showed even better results and proved conclusively that short-circuiting of all the end windings together was, if anything, much better than simply short-circuiting the groups of windings on each other. In other words, this was an early proof that the cage-type secondary was a most effective type where the starting conditions would permit."

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These experiments led directly to the first commercial line of squirrel-cage motors, which Westinghouse presented to the market in 1897. This motor was immediately popular and extremely successful. For this there was good reason. It was essentially the same motor as is universally manufactured today; there has been no basic change in concept or principle in these intervening fifty years. Efficiencies, power-factors, and torques were not much different from those of modern motors. However, in physical size and appearance the induction motor has been vastly improved. The original Tesla motor developed about five hp. It weighed 1000 pounds; was about 30 inches in diameter. By the time the first commercial line of squirrel-cage motors appeared, a 5-hp, 4-pole motor weighed about 640 pounds and was considerably smaller (21-inch diameter). By 1905, improvements had brought the weight of the 5-hp motor down to 210 pounds and the size to 15 inches. The figures in 1930 stood at 147 pounds and 13 inches. The Lifeline motor (described on p. 50) of like rating weighs 137 pounds and is 11½ inches in diameter.

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The squirrel-cage induction motor has become the workhorse of industry. Three out of every four motors of one horsepower and larger are squirrel cage. In the last three years more than three million of these motors have been built in the United States, and the demand for more has never been as great. The induction motor—simplest of rotating electrical machines—is one of industry's foundations.

WESTINGHOUSE
Engineer

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On the Side

The Cover—The axial-flow compressor has become an industrial tool of important stature. While the engineering aspects of this matter are discussed at length in this issue, the artist, Richard Marsh, pictorially dramatizes it for our front cover. Marsh has made several of our most popular covers, but insists we have never given him an assignment as tough as drawing in true perspective the succession of turbine blades with their compound curved surfaces, figuratively spiralling out of a compressor rotor. Come to think of it, that wasn't easy.

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Applications for the Westinghouse Educational Foundation Fellowship in electric power-systems engineering, effective September 22, 1947, are being accepted at Illinois Institute of Technology through March 15, 1947. Established in 1945 to encourage graduate study in power-systems engineering, the fellowship provides free tuition for three semesters of study in addition to a grant of $500 each semester. The program consists of a prescribed course of study to include research and actual work in power systems now being made by the power and manufacturing companies cooperating on the a-c network calculator.

Selection is based on personal qualifications and interests, and on the scholastic ability of the candidates. All candidates must have a Bachelor of Science degree in Electrical Engineering from an accredited engineering college.

Application blanks and further information may be obtained from the Dean of the Graduate School of Illinois Institute of Technology, 3300 Federal Street, Chicago 16, Illinois.

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In This Issue

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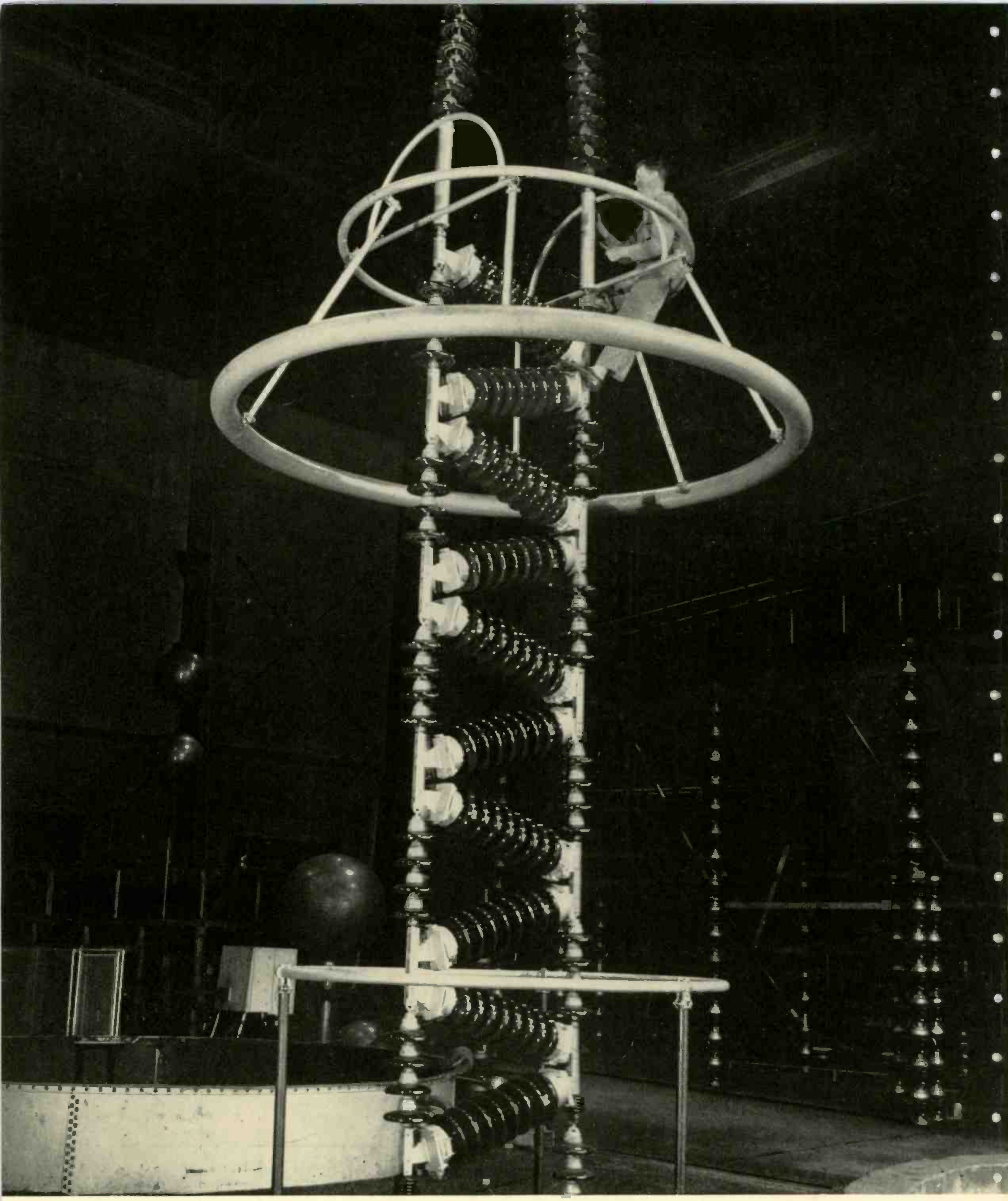


LIGHTNING LADDER

The experimental 500-kv transmission line will use two arresters of this flexible construction and one self-supporting unit. This arrester extends to higher voltages the articulated form that has proved advantageous in regions experiencing earth tremors.

A Compact Locomotive-Type Gas Turbine

Like the child of a great man, the gas turbine is in an uncomfortable spot—much is expected of it. This interim report on a 2000-hp unit, such as might be used for locomotives, indicates that those who expectantly have followed the progress of the gas turbine for non-aircraft applications will not be disappointed.

T. J. Putz, *Manager, Gas and Locomotive Turbine Section, Westinghouse Electric Corporation*

In considering power plants, particularly for locomotive, marine, or stand-by stationary service, the two features most eagerly sought, aside from ability to do the job, are simplicity and small weight and bulk. A new 2000-hp gas turbine possesses these qualities to a remarkable degree. It consists of a simple, straight-line arrangement of a gas turbine, combustor, air compressor, gear, and two d-c generators all mounted on a common bedplate. The total weight—machines and foundation—is 38 000 pounds. It is 26 feet long, 6 feet high, and 3½ feet wide. Two such units, for example, could go side by side lengthwise of a locomotive, giving 4000 hp in less than 30 feet of locomotive length. Thus a 4000-hp gas-turbine locomotive might be a single unit less than 60 feet long, whereas present Diesel-electrics of this power require two cabs, totaling 130 feet in length. This represents an output of 6 pounds per horsepower for the prime mover alone or 19 pounds per horsepower for the complete plant including generators, foundation, and auxiliaries.

By comparison Diesel engines develop one horsepower per 17 to 22 pounds bare weight or, including generators but not supporting frame or auxiliaries, from 23 to 28 pounds. The gas-turbine plant is physically much smaller and vastly simpler although direct comparisons of dimensions are impractical. The gas-turbine plant has but a few auxiliaries and they are small. In the limited space of a locomotive using a reciprocating-engine power plant, place must be found for a large lubricating oil supply, oil filters, oil pumps, oil coolers, radiators with their fans and motors, and recirculating water system. The gas turbine, by comparison, has a very small lubrication system and almost no cooling apparatus.

This 2000-hp gas turbine, still definitely in the experimental stage, burns bunker C fuel oil, which is less expensive than fuel presently required for piston engines. The extent of this advantage cost-wise varies widely with location, but extends generally over a range in favor of bunker C from about 1.2 to 2.0, with perhaps 1.5 being a national average.

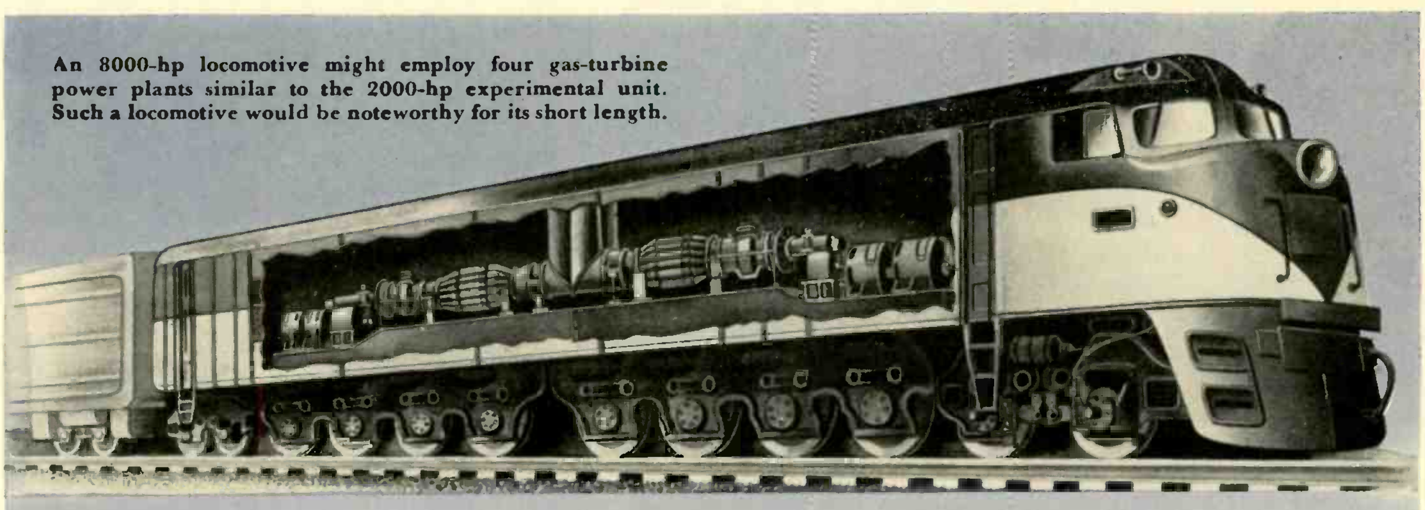
The efficiency of a gas-turbine power plant, being of the simple, open-cycle type is, it should be remarked, not the equal of the Diesel. A turbine inlet temperature of 1350 degrees F was selected for the experimental unit as the maximum practical when using the best available materials, but without resort to supplemental blade cooling. Under these conditions a thermal efficiency of 20 percent is anticipated. Comparable Diesel efficiencies range from 30 to 35 percent. Thus, as matters stand at present, fuel costs of the two types of power plants are about equal.

It should be borne in mind, however, that these are based on comparing the first experimental type of gas turbine with the already well-developed Diesel unit. If the customary apparatus-development pattern holds here—and there appears to be no contrary reason—the succeeding early editions of the gas-turbine unit will be markedly smaller, lighter, and more efficient. This, particularly, will be true if ways are found—and few doubt but that they will—for raising the turbine-inlet temperature. Raising the efficiency by ten points, and reducing the weight and bulk by a third are by no means too much to hope for, although these will require a period of extensive development.

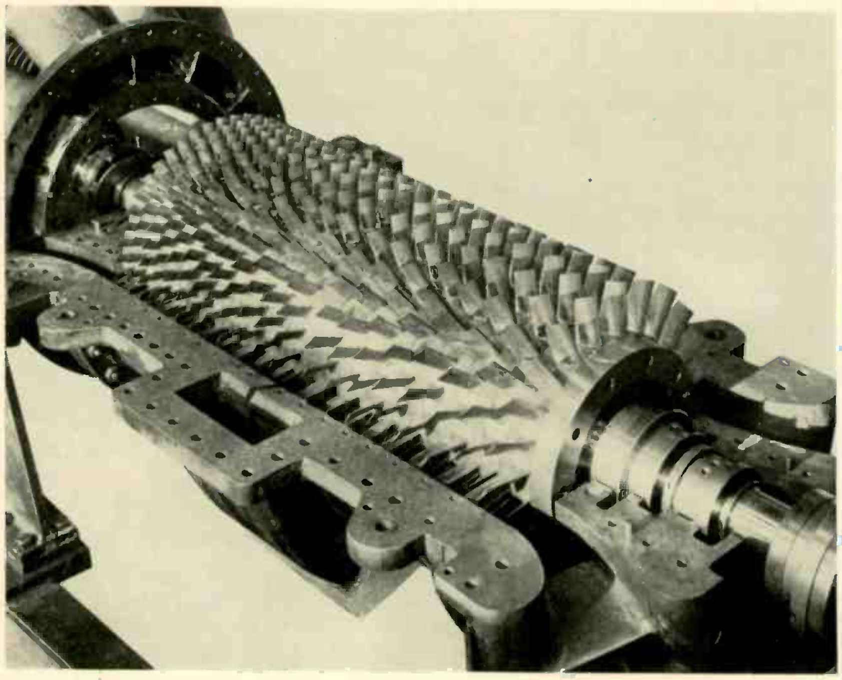
The general arrangement of the experimental unit is best shown by the illustrations.

The design features and the working function of the major components will be discussed in the order of their position in the cycle.

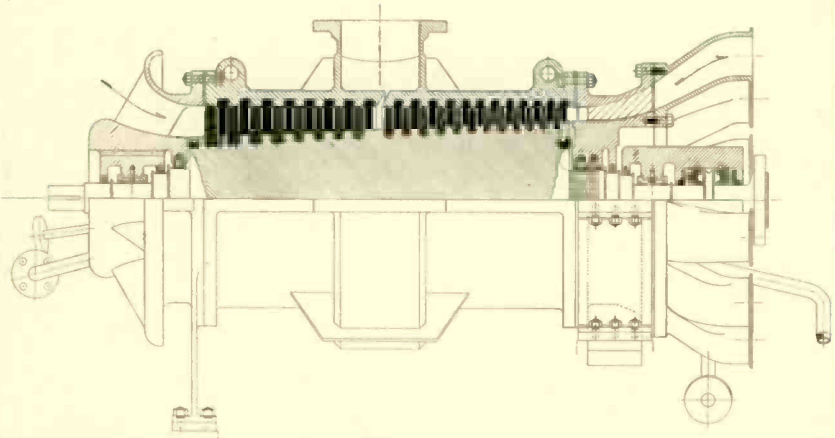
The *compressor* is of the axial-flow type, designed to pass



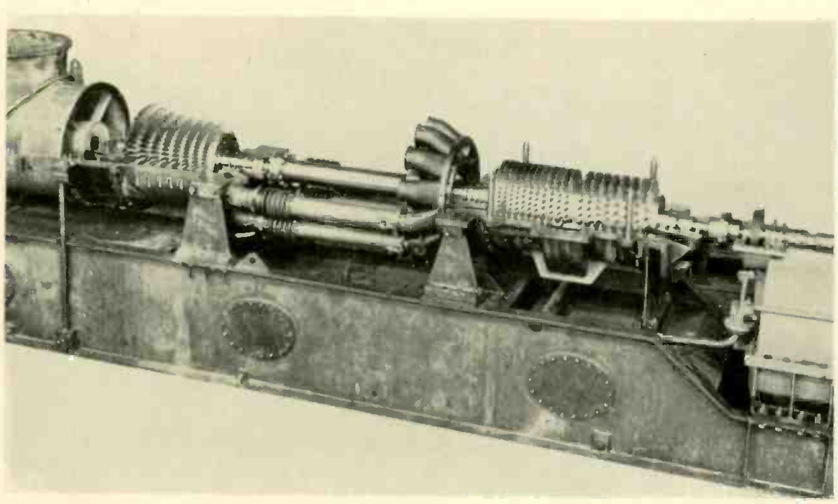
An 8000-hp locomotive might employ four gas-turbine power plants similar to the 2000-hp experimental unit. Such a locomotive would be noteworthy for its short length.



A large factor in the smallness of the unit is the compressor, which is of the axial-flow type. It absorbs 4000 of the 6000 hp developed by the turbine.



A partial cross-section through the axial-flow compressor. Air moves from left to right through the blading of constant tip diameter, to the multi-cell combustors.



Removal of several of the combustor elements and covers from the turbine and compressor shows the internal arrangement of the experimental power plant.

25 000 cfm of free air at a pressure ratio of 5 to 1. The pressure ratio and flow are varied by changing the speed. It contains twenty stages of non-symmetric blading* designed for the major pressure rise in the rotating blades. The rotating blades have a constant tip diameter of 18⅜ inches and vary in height from 3 inches at the inlet to 1½ inches at the discharge. The blades are unshrouded and profiled at the tip for mechanical clearance. They are forged from twelve-percent chromium steel stock similar to that used in turbine work, and the serrated root fastenings are machined in the base by using a formed milling cutter. The blades are caulked into serrated grooves cut in the rotor and are separated with spacer pieces to maintain the desired pitch.

Stationary blades are precision cast of 18-8 stainless steel and are caulked into grooves cut in the cylinder wall. They also are unshrouded and profiled at the tip.

The rotor is made of a solid carbon-steel forging and the cylinder of welded steel plate. Air seals at both ends are of the labyrinth type. The compressor, being solidly connected to the turbine, has the greater part of its thrust balanced by the turbine thrust, thus eliminating the need of a dummy. The small remaining thrust unbalance is taken by a standard segmental shoe-type bearing located on the discharge end of the compressor. The journal bearings are of the pressure-lubricated sleeve type.

On leaving the compressor the air flows through a diffuser in which the velocity is reduced and transition is made from an annular passage to twelve circular passages. This diffuser is made of steel castings welded to form a director to the combustor cells.

Combustors—Combustion is performed in twelve cell-type combustors, each 4½ inches in diameter and 3 feet long. The combustor casing is made of carbon-steel pipe with a bellows-type expansion joint welded to one end and tapered flanges welded to both ends. The flame tube is made of chromium-nickel alloy sheet rolled into circular sections and spot-welded together. Alternate sections are corrugated to provide sidewall cooling, which has proved extremely effective. Air-atomizing fuel nozzles are used to maintain high burner efficiency over a wide load range when burning number 6 (bunker C) fuel oil. These combustors have heat releases of about 1.2 million Btu per hour per cubic-foot per atmosphere.

The fuel oil is injected through the air atomizing spray nozzles, held in the end plate of the flame tube. These nozzles maintain good atomization at low fuel flows. After the oil is once ignited the flame is self-

*The various types of axial-flow compressors are described in a companion article by A. I. Ponomareff, on page 40 in this issue.

piloting, that is, there is a primary combustion zone within the flame tube to which only a part of the air is admitted and in which a flow reversal is created. To maintain satisfactory combustion and high efficiency over a wide range of air and fuel ratios, considerable experimentation was required to determine the proper location of air-entry holes. In the remainder of the combustor the secondary or dilutant air surrounding the flame tube is mixed with the hot gases from the primary combustion zone. The most effective way of mixing the cold and hot air streams is to have axial rows of holes in the flame tube. In this way the cold gases are able to penetrate effectively to the center of the flame tube, giving satisfactory temperature distribution at the discharge.

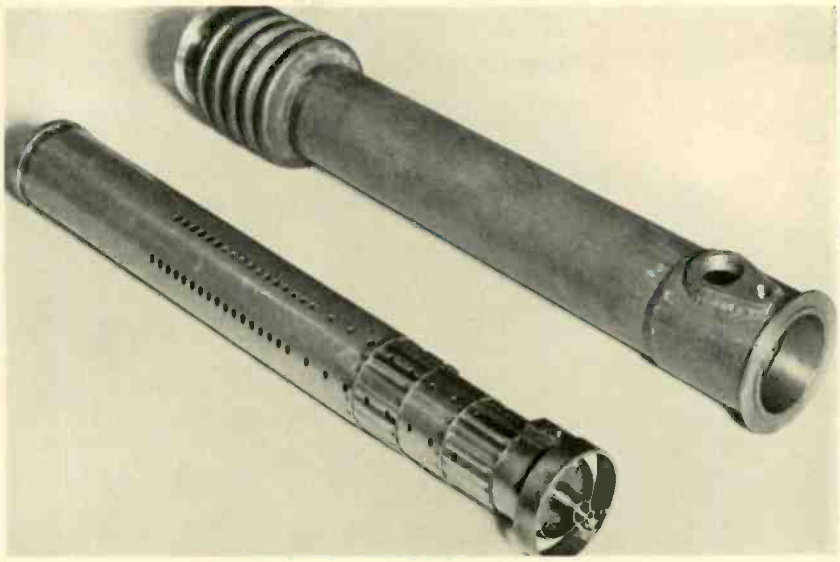
The igniters are constructed with an outer case and flame tube. The flame tube, containing the nozzle, extends through the combustor casing and the main flame tube into the primary combustion zone. Combustion is started by spark ignition of either an injection of acetylene gas or number three furnace oil.

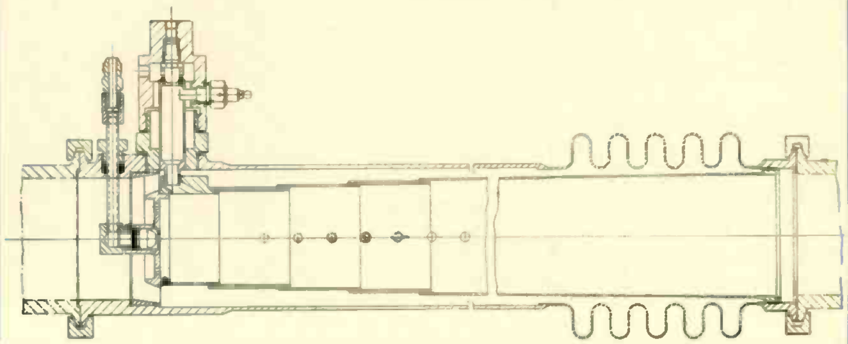
The *gas turbine* has eight stages designed for equal heat drop over the stationary and rotating blades at the mean diameter. All blades are made of cobalt-chromium-tungsten alloy. They are tapered and twisted and have a serrated root machined in the base. The stationary blades are also tapered and twisted and have a single T-type fastening, machined by a carbide tool. The blades are unshrouded and profiled at the tip.

The rotor is machined from a solid forging of stabilized 19-9 stainless steel, the main section being 14½ inches in diameter and 24 inches long. This was the largest forging ever made of this material at the time and a number were rejected before a sound forging was secured.

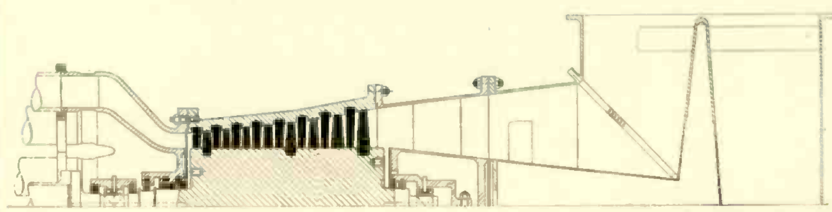
The cylinder is made of stabilized 19-9 stainless steel castings into which are cut grooves for holding the stationary blading. The design was made as nearly symmetrical as possible. The horizontal flanges have been eliminated and the vertical flanges on the inlet have been slotted to minimize the effect of thermal distortion on the cylinder walls while undergoing rapid temperature changes. In spite of the relatively simple casting involved, x-ray examination revealed several imperfections. The defective material was removed by machining and repaired by welding. The experience gained from this first cylinder indicates that in the future it may be more desirable to fabricate or forge the cylinder casing.

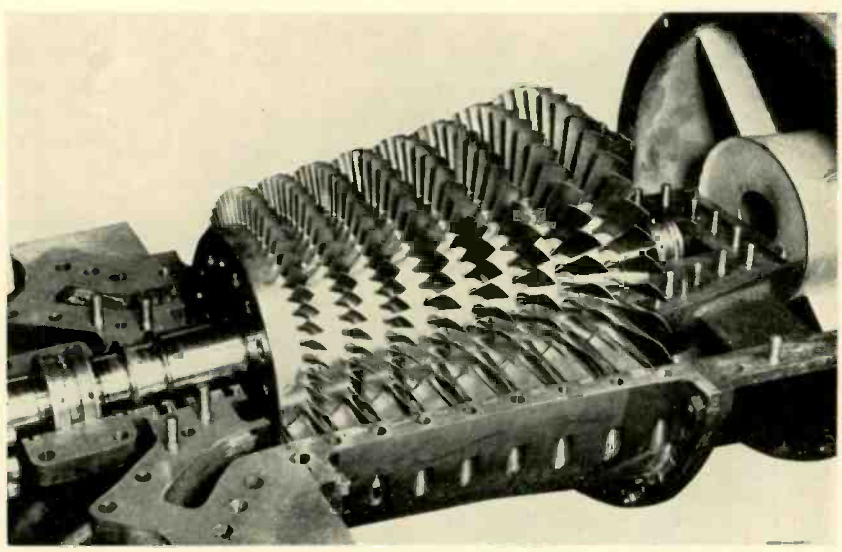
All bolting is made of Westinghouse K-42-B* material. For the horizontal bolt-





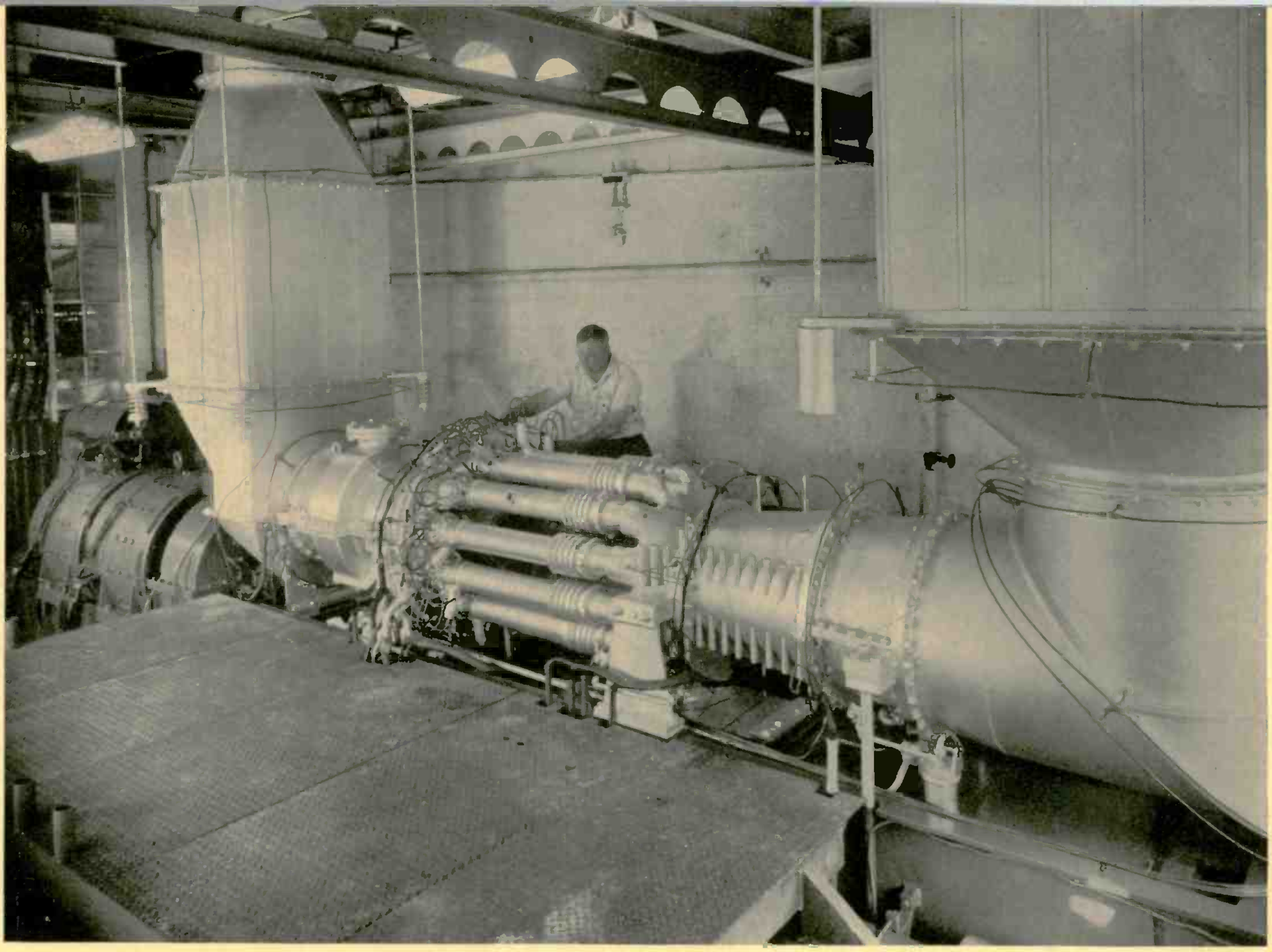
The photograph shows the flame tube, with its radial air-inlet hole, and the housing for one combustor element, while the drawing shows it in section.





Sectional and photographic views show the construction of the 6000-hp gas turbine and the exhaust arrangement. The bearings are pressure-lubricated.

*Paper presented by Mr. Howard Scott and Dr. R. B. Gordon before ASME annual meeting, New York, Dec. 6, 1946.



The experimental 2000-hp gas turbine as arranged in the laboratory for tests. Inlet and outlet are upward through the roof. Control and temperature-measuring leads extend to the instrument panel out of camera range to the left.

ing, sleeves are used to eliminate the need of a flange and to increase effective bolt length. The bolting problem is difficult since the gas turbine must operate over wide temperature ranges and must be capable of taking rapid temperature changes from 700 to 1350 degrees F in going from no load to full load. The bolting design used has proved entirely satisfactory up to the present.

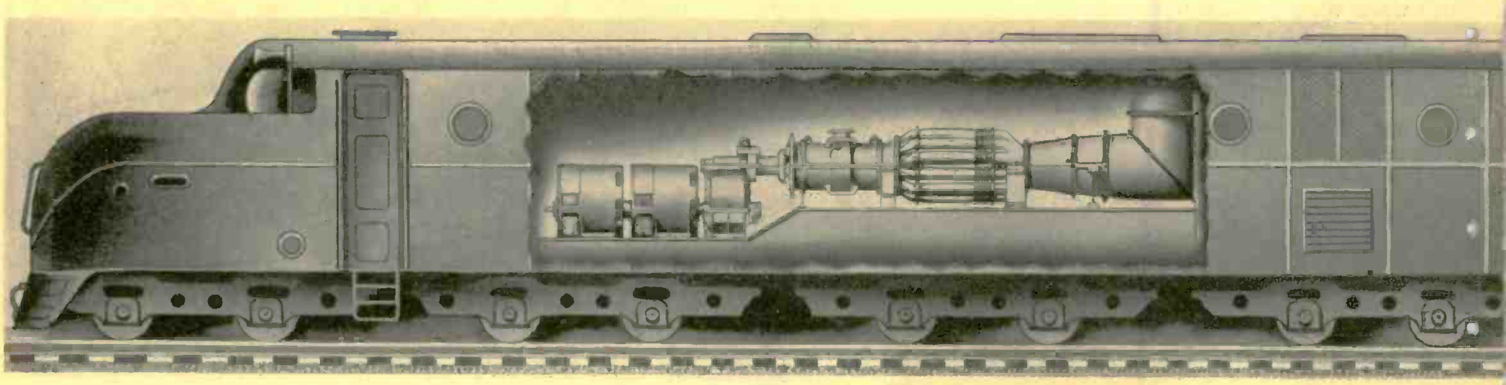
The turbine is positioned by using suitable mechanical hinges arranged to allow for rapid thermal changes while still maintaining proper alignment with the rest of the machinery.

A diffuser and elbow are used to recover a part of the leaving velocity energy and to turn the gases with a minimum of energy loss. At full load the exhaust velocity from the turbine is approximately 500 feet per second and a substantial portion of the leaving loss is recovered by the diffuser.

The gear is a single-reduction double-helical type. Of particular interest is the pinion which is made of an alloy steel and has twenty teeth that have been hobbed, flame hardened, and ground.** This type of gearing is similar to that employed on the Pennsylvania Railroad geared-turbine locomotive which has proved successful in actual road service. The experience gained from this gear design points the way to designs carrying twice the load without any appreciable change in weight or size. The gear has pressure-lubricated, sleeve-type bearings throughout.

Mounted on the reduction gear is a one-half horsepower turning gear motor which is connected by suitable gearing to the main pinion shaft through the spur gear. This rotates the set slowly and avoids thermal distortion of the rotating parts

**See "Gear Grinding, A New Method," by T. J. Putz and H. W. Semar, Westinghouse ENGINEER, July, 1946, p. 117.



at shutbown and enables quick starting whenever required.

A double-armature, d-c generator, operating at 1200 rpm, absorbs the useful power. The d-c generator provides loading facilities with a wide operating range, which offers an excellent means for making starting tests.

Applications

The possible applications for a simple open-cycle gas turbine unit are numerous. Its light weight, small space requirements, and extreme simplicity, combined with inherently low maintenance make it an attractive prime mover.

For locomotive applications large powers can be installed in a single cab and no cooling water would be required. Two of these 2 000-hp gas-turbine generator sets can be mounted side by side in a standard cab, which can accommodate four units total, or 8 000 installed horsepower. Compared to a Diesel locomotive, the gas-turbine locomotive of equal capacity will be less than one-half the length and approximately two-thirds the weight.

For main-propulsion ship drives, regenerators and intercoolers could be added to raise thermal efficiency. For large powers, the closed cycle can be adopted to reduce weight and space.

In the central-station field the simple open-cycle gas turbine is suitable for standby peak service particularly on the ends of transmission lines. The expense of banked boilers and spinning reserves required in central-station steam plants can be reduced by the substitution of low cost, quick starting gas-turbine generator sets. These could be strategically located to cover system peak loads.

In the industrial field, where, in addition to the need for power, there are pressurized air requirements, the gas turbine has already found a place.

Other applications such as portable power plants in the gas fields, power units for gas-transmission lines, and in plants near supplies of raw materials, but which locations are unsuited for steam power plants, are all attractive possibilities.

Operating Experience

While the testing of this unit is not yet completed, it appears that it will satisfactorily meet expected performance. To date the unit has operated approximately 60 hours, a good portion of this being at one-half load, and has been started 97 times.

Tests completed have indicated that compressor efficiencies of 85 percent and turbine efficiencies two or three points higher can readily be obtained. Combustion efficiencies of between 90 and 97 percent depending on the load carried are being realized.

The tests have not been of sufficiently long duration to establish the operating life of the materials subjected to high temperatures and to rapid temperature fluctuations. However, examination of these materials after this first period of operation has revealed no difficulties. The precision-cast blades used in the gas turbine have proved satisfactory. No measurable creep of the stressed, high-temperature parts has been observed. Fluorescent penetrant tests have given no evidence of heat checking or cracking, of the materials subject to rapid temperature changes from room temperature to 1 350 degrees F. The flame tubes of the combustors, which during the early combustor test work had short life, have shown no signs of distress. This is due, in great part, to the effective side-wall cooling that has been incorporated in this design.

The control of the gas-turbine unit is accomplished by manual regulation of a single fuel-control valve. The d-c generators use a suitable differential-field exciter designed to match the speed-load characteristics of the gas turbine. With this control the generator output and speed are unaffected by any change in locomotive speed. This is the simplest type of control and should be most suitable for railroad operation where simplicity and ruggedness is of prime importance. The differential field control to be used is a modification of that now being used on Diesel-electric transmission systems that has proved successful in daily commercial use on many switching and main-line locomotives.

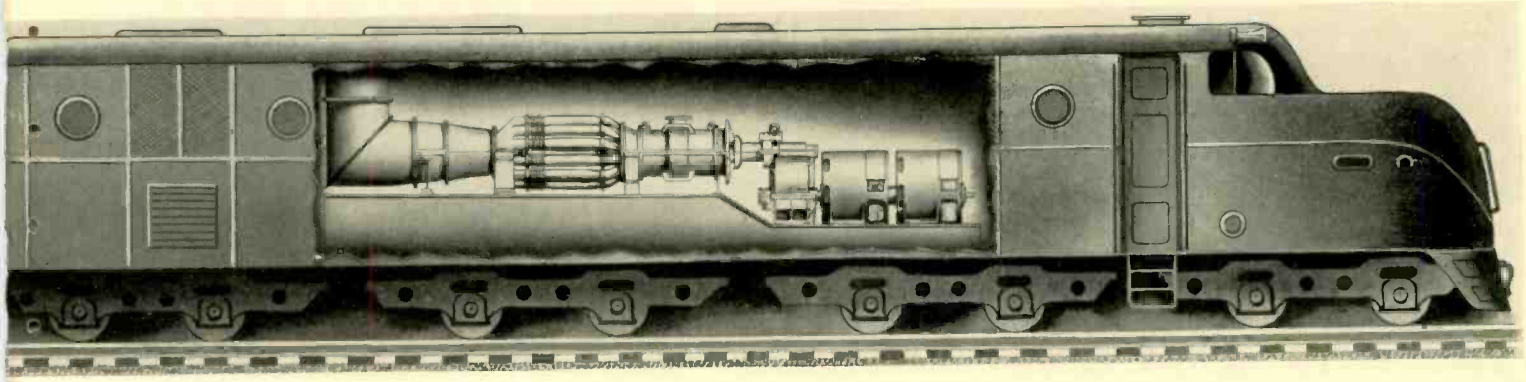
Starting tests have been completed which have shown that with 80-kw cranking power the unit can be brought from standstill to operating speed in one minute. If 50 kw is used, the time is increased to approximately 1½ minutes. The unit can be started from a standstill condition, when cranked to twenty percent of full-load speed.

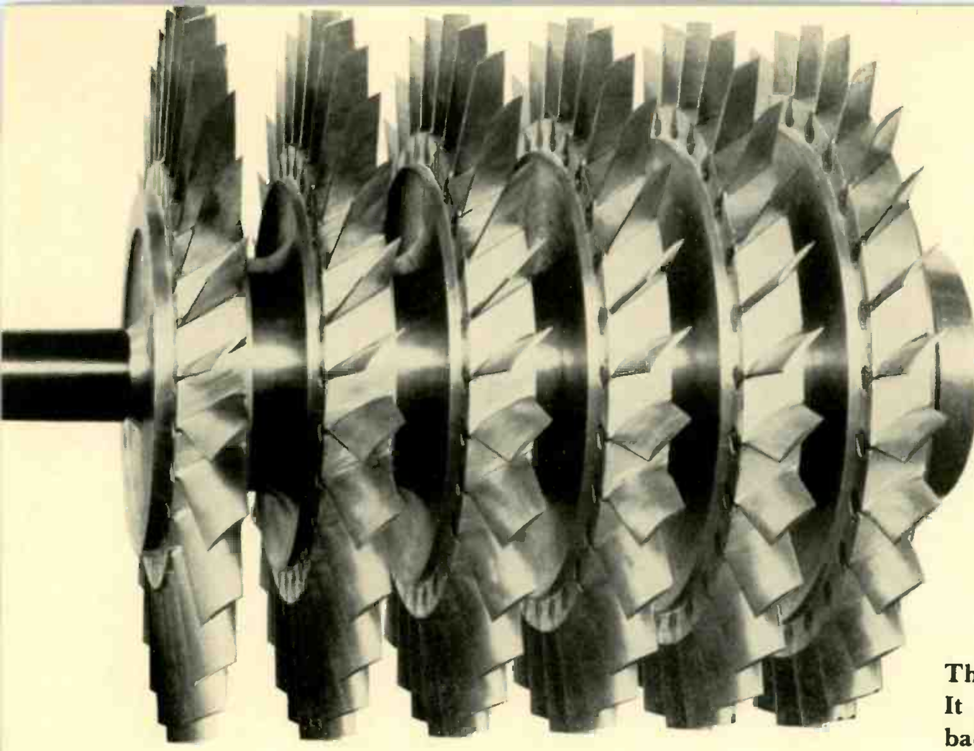
Conclusions

The concept behind this experimental locomotive-type gas turbine was maximum simplicity and economy of weight and dimensions, which factors are believed to be paramount in railroad service. Thus, for this first unit the open-cycle construction was adhered to. Higher efficiencies, which are desirable but not as commanding as factors effecting maintenance and size, can be secured. If this should become desirable the gas turbines of the closed-cycle type or those using heat-recovery auxiliaries, such as inter-coolers and regenerators, may be attempted.

While there still remains a large test program to be completed, the tests to date have been most encouraging. The operation of the unit has been excellent. Mechanically, the machinery runs very well, and has quick starting and loading response characteristics. Considerable optimism exists regarding the future of the gas turbine in this application, with confidence expressed that it will become the prototype of an established prime mover.

Artist's conception of the appearance and internal arrangement of a high-power gas-turbine freight locomotive. Here the short length stressed in the drawing on page 35 has given place to length and weight for maximum tractive effort.





Principles of the Axial-Flow Compressor

A. I. Ponomareff, *Manager,*
Pump and Blower Engineering Section,
Westinghouse Electric Corporation

The axial-flow compressor has been a slow starter. It appears to be simply a reaction turbine run backward. However, unlike some electrical machines that run equally well as generators or motors, a turbine operating as a compressor is hopelessly inefficient. For four decades the evolution of the axial-flow machine to its present commanding position of high efficiency has been a story of painstaking, step-by-step, unglamorous development. But, for many uses, it now leads the field.

Mention of the axial-flow compressor is almost daily occurring more frequently in engineering discussions. Old in idea, it has within the past few years become a practical machine. It has established itself in marine work and is now figuring in the success of land gas turbines and jet-propulsion units for aircraft.

An axial-flow compressor in construction resembles the familiar reaction steam turbine. The rotating member, supported by ball or sleeve bearings, consists of several rows of blades mounted on discs or drum-type spindle. A cylindrical compressor casing contains rows of stationary blades. As in a steam turbine, air or gas in an axial-flow compressor flows in an axial direction through the bladed annulus concentric with the axis of rotation. In contrast to a steam turbine, however, the flow path of an axial-flow compressor decreases in area in the direction of flow to accommodate the diminishing volume as the compression progresses from stage to stage. In entering a blade row the gas flowing in a generally axial direction is deflected through a small angle in the direction of rotation. This change in direction of flow is accompanied by a decrease in relative velocity with resultant pressure rise through diffusion. The change in the tangential component of air velocity, when multiplied by the blade velocity at the same point, represents the change in momentum and is proportional to the power input to the compressor.

In the mechanism of a pressure rise in an axial-flow compressor through diffusion unassisted by centrifugal force lies the principal difference between the axial-flow and centrifugal

The Background of the Axial-Flow Compressor

The idea of compressing gases in a machine similar in form to a reaction steam turbine, in which the flow is parallel to the axis of rotation, is very old. A patent by Parsons dated 1884 describes the use of a reversed turbine for an axial-flow compressor.[1] At that time the most fundamental difference between flow through the turbine and the compressor was not known, and use of turbine blading for a compressor produced very poor results. In a steam turbine the blading must be arranged for expanding or accelerating flow; in a compressor, for diffusing or retarding flow. In an expanding passage the pressure decreases in the direction of flow and the boundary layer is continuously supplied with pressure energy to accelerate the gas particles slowed down by friction with the confining walls, thus producing a stable flow. In a diffusing passage, on the other hand, the pressure forces are acting in a direction opposite to flow and tend to retard the boundary layer, producing eddying and back flow. The design of an expanding nozzle to produce 98 percent efficiency is not difficult, but to design a diffuser for 85 percent efficiency requires a strict adherence to certain rules as to rate of diffusion and change in direction of flow.

C. A. Parsons realized the fallacy of his reasoning; his patent dated 1910[2] describes an axial-flow compressor with blading that resembles in some respects that of present-day machines. A few Parsons' axial-flow compressors were built in England and one experimental unit by the Westinghouse Machine Company (1905–1906) in the United States. Because of the low level of efficiency obtained on test of the Westinghouse unit (50–55 percent), commercial promotion of this type of compressor was abandoned. In the ensuing decade and a half little was accomplished toward the development of an efficient axial-flow compressor. The demands for compressors were well covered by centrifugal and positive-displacement types which were then more efficient.

The rapid advance in the field of fluid dynamics in the years immediately after the first World War created considerable interest in applying airfoil theory to the design of an axial-flow blower. Several articles on design of axial-flow blowers appeared in technical publications. Some writers treated the performance of the axial-flow blowers from the standpoint of a propeller theory,[3] while others applied aerodynamic properties of an isolated airfoil in arriving at blower performance.[4,5]

In 1928 Westinghouse applied an axial-flow blower to the ventilation of a large turbine generator at the Hell Gate Station of the Consolidated Edison Company. This was followed by others, notably use of an axial-flow (propeller) forced-draft blower for U. S. Navy combat ships. The severe limitations in the space allocated for forced-draft blowers in Navy ships, as well as the heavy penalties on weight of machinery, are successfully met by the high-speed, light-weight and compact axial-flow blower. The steep pressure-capacity curve of the axial-flow blower particularly suited the Navy practice of operating two or three forced-draft blowers in parallel. The overloading characteristics of the axial-flow blower (high power consumption at shut-off or no delivery) contributed an added overspeed protection in case of a sudden closure of air ducts to or from the turbine-driven blower. These inherent features of an axial-flow blower verified during the severe operating conditions of World War II have resulted in a complete displacement of centrifugal blowers from the fire room of modern Navy ships.

The persistent effort of the Bureau of Ships, U. S. Navy, to reduce weight and bulk of apparatus in favor of speed, cruising radius, and militypes of compressors. The flow pattern in an axial-flow compressor, through a series of diffusing passages formed by a proper arrangement of blades in each row, differs radically from that found in the reaction steam turbine where the flow occurs in the direction of the pressure gradient, as explained below, "The Background of the Axial-Flow Compressor."

This fundamental difference in flow explains why the development of the axial-flow compressor did not parallel that of the steam turbine. During the last ten years most of the major steam-turbine manufacturers such as General Electric and Westinghouse here, Escher-Wyss and Brown Boveri in Switzerland, and Metropolitan Vickers in England, participated in the development of an axial-flow compressor, at least in connection with gas-turbine power plants. This indicates that problems encountered in the axial-flow compressor design are related to those of the steam turbine. Indeed, most of the mechanical problems of axial-flow compressors, such as the design of blades to withstand vibration under impact of air at high velocity, or of the design of a blade root to resist centrifugal forces of large magnitude, are common to both steam turbines and axial-flow compressors.

Turbine blades, being designed to accommodate steam expansion and large turning angles, are not suitable for use in axial-flow compressors requiring diffusing passages and small turning angles. Axial-flow compressor blades are usually subjected to high centrifugal forces. It is customary to employ a blade with the blade section area gradually tapered from the base to tip. The center of gravity of each section is usually disposed along a radial line to eliminate bending stresses resulting from centrifugal force. Although the blade section, shown in Fig. 1, is a typical airfoil wing section (NACA-4512), use of such sections is not essential in construction of an efficient axial-flow compressor. Compressor designers, however, prefer to use airfoil sections developed for aeronautics because complete information on the performance of these sections is available from either N.A.C.A.[14] or other agencies.

Performance of an axial-flow compressor is usually represented by curves of the pressure ratio and efficiency versus the flow in cubic feet per minute or pounds per second for different operating speeds. Aviation-gas-turbine compressors may operate over a wide range of pressures and temperatures because of changing elevation. It is customary, therefore, to represent compressor performance corrected to the standard sea-level conditions. The performance of a typical axial-flow compressor is shown in Fig. 2. To indicate the compressor operating range at various efficiency levels, the lines of constant efficiency can be superimposed as contour lines on the pressure-flow curves, as shown. The curves of pressure-ratio versus flow are relatively flat at low speeds, becoming steeper with increase in speed, and approaching the straight vertical line of a constant-flow machine.

The curves of pressure ratio versus flow for an axial-flow compressor are steeper than those exhibited by the centrifugal type, and represent a disadvantage for certain applications requiring wide variation in flow. This, of course, can be avoided by a variable-speed drive. With the reduction of operating speed the pressure ratio developed by the compressor decreases rapidly. At reduced speed the volumetric flow of air along the compressor axial length does not decrease as rapidly as the flow area proportioned for a higher compression ratio. This results in crowding of the last stages and a consequent marked reduction in efficiency at lower operating speeds.

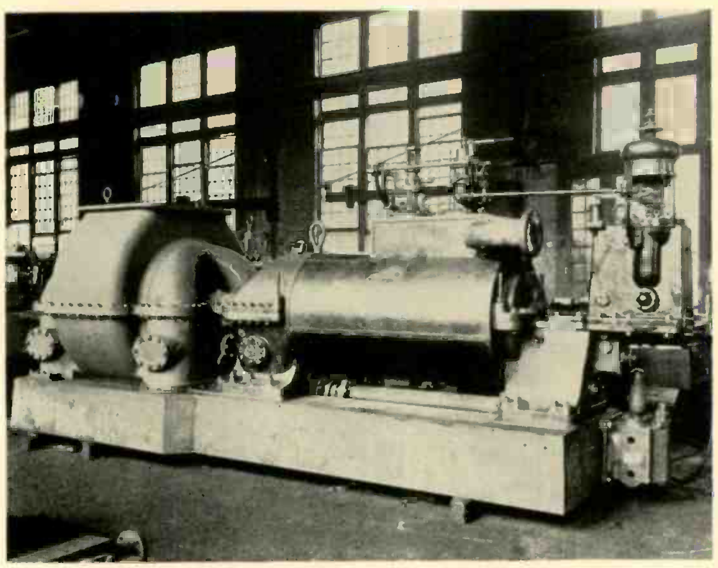
Neither centrifugal nor axial-flow compressors can operate over the entire capacity range from maximum flow to shut off or zero delivery. When the flow through a constant-speed, axial-flow compressor is reduced to between 75 and 85 percent of rating (corresponding to 50 to 60 percent load for the centrifugal type), surges in discharge pressure develop, accompanied by a large increase in noise and mechanical vibration. These pressure surges, mild at low speeds, sometimes reach violent proportions at high speeds, endangering the compressor. The points in the curves of pressure ratio versus flow at which surges of pressure begin to occur, form a limit of safe operation and are marked Limit of Stability on Fig. 2. This limit to stable operation sometimes is referred to as the surge line, stall line, or pumping limit. A laboratory study of the phenomenon indicates that surging is accompanied by flow separation from the blade at the base—strong radial flow

tary power has resulted in the development of boilers of high steaming rate. This has increased the forced-draft pressures well beyond the capability of a single-stage, axial-flow blower. Several two- and three-stage forced-draft blowers were installed for static pressures up to 105 inches of water.

Single-stage, axial-flow blowers for pressures up to 35 inches of water for air conditioning and industrial applications are generally accepted. Many manufacturers here and abroad have developed complete lines of such blowers for commercial application. In Germany many steam power plants are using axial-flow blowers for induced-draft application.

As the overall efficiency of the axial-flow blower continued to rise—reaching 90 percent for single-stage machines—it became more and more attractive as the compressor element of the gas turbines for aviation, marine, and land use. Because the compressor absorbs most of the power developed by the turbine a small percentage decrease in compressor losses means a large increase in net power output.

Some successful aviation gas turbines depend on a centrifugal compressor, such as the General Electric turbo-supercharger and Rolls-Royce jet engine in England. However, in general, the efficiency level obtainable in a centrifugal compressor is relatively low and does not compare favorably with that of the axial-flow type although considerably more time and effort have been spent on the development of the centrifugal type. The efficiency of the famed Whittle centrifugal compressor used in aviation gas turbines, for instance, is reported to be only 75 percent.[6] Multistage centrifugal compressors are somewhat more efficient. However, it is doubtful that they will approach the 85 or 86 percent already exhibited by axial-flow compressors for pressure ratios up to six.



A double-flow experimental compressor built by Westinghouse Machine Company in 1905 to Parsons' patent.

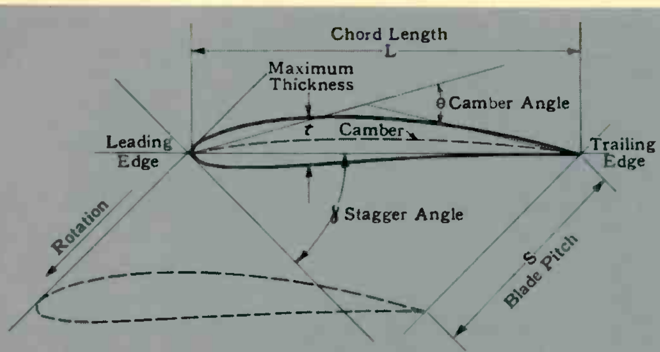


Fig. 1—A typical airfoil blade section such as used for axial-flow compressors, and the terminology used in connection with blading of axial-flow compressors.

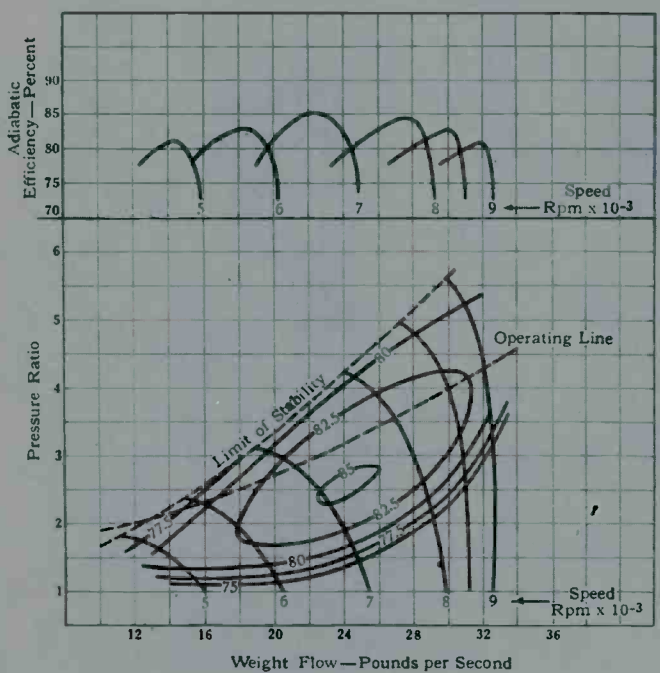


Fig. 2—Typical performance characteristic curves of an axial-flow compressor, indicating the limits of stable operation.

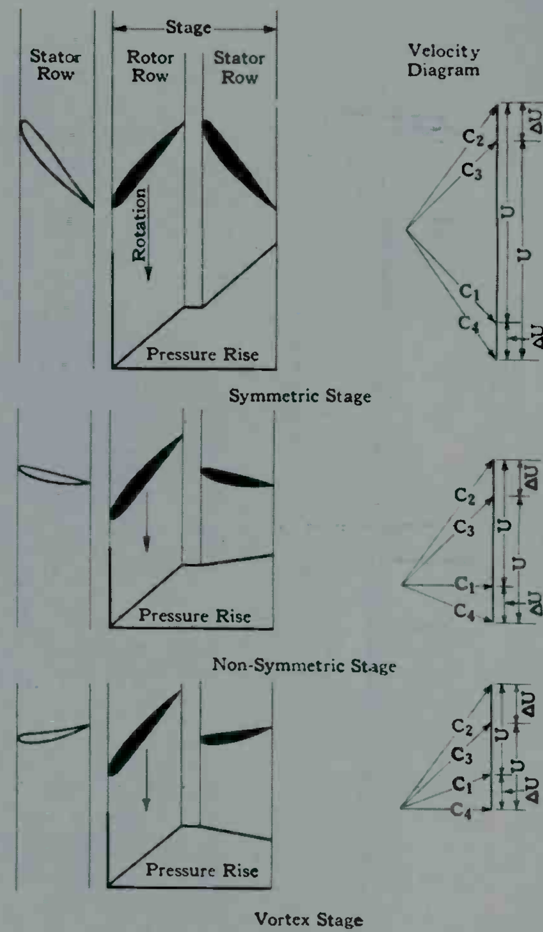


Fig. 3—Blading arrangement used on symmetric, nonsymmetric, and vortex types of compressors, showing pressure rise through a stage and velocity vector diagram, characteristic to these three principal types of axial-flow compressors.

outward—and a reversal of flow toward the leading edge of the blade. Although the limit of stability imposes definite restrictions as to the operating range of an axial-flow compressor, it does not exclude its use in a gas-turbine power plant or for some other applications. Usually it is possible to arrange a by-pass control on a compressor or a temperature control in the gas turbine to keep operating conditions within the limits of stability. Furthermore, compressor proportions can be selected so that the operating-system resistance line is always under the limit of stability line or crosses it at low speeds, where the pressure surges are mild and safe.

Types of Axial-Flow Compressors

Depending on the arrangement of blades, especially of those in a stationary row, axial-flow compressors are of three classifications: symmetric, non-symmetric, and vortex. The salient single-stage, pressure-rise characteristics of the three are shown in Fig. 3. For purposes of comparison the same blade form for the rotating rows and equal values of axial velocities are assumed for each type. Under these conditions an equal pressure rise is obtained in the rotating row of all three types and their performance can be compared on the basis of the blade speed, U, and the reaction of the stationary blades.

The Symmetric-Stage Compressor—In a symmetric, often referred to as 50-percent reaction stage, the stationary blades are constructed as a mirror image of the rotating blades. The velocity diagram, Fig. 3, shows that the absolute air velocities entering (C_4) and leaving (C_1), the stationary row, are symmetrical with the relative velocities C_2 and C_3. Inasmuch as these sets of vectors are equal

$$(C_4^2 - C_1^2) = (C_2^2 - C_3^2)$$

This indicates that the pressure rise in the stationary row is equal to that obtained in the rotating row. Equal pressure rise in the rotating and stationary rows of blades defines the symmetric type of compressor, while the symmetry of the velocity triangles leads to its name.

In this type of compressor a high axial velocity and blade tip speed can be used without producing high velocities relative to the blade. High relative velocities are detrimental to compressor efficiency because of compression shock when the localized velocities reach the velocity of sound (1150 feet per second at 85 degrees F). Blade tip speed exceeding the velocity of sound, and axial velocities up to 600 feet per second are common for the symmetric type of compressor.

The pressure rise in both rotating and stationary rows results in fewer stages for a given compression ratio. High axial

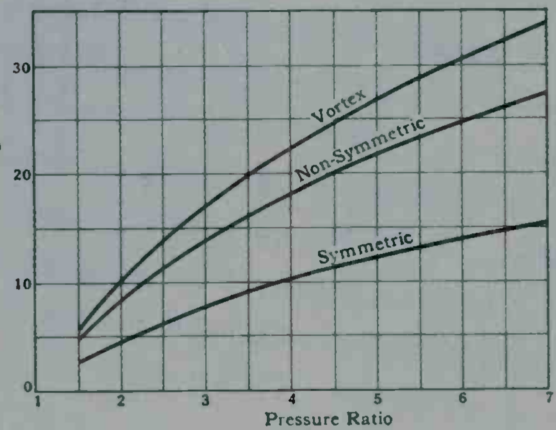


Fig. 4—Curves showing the number of stages required to develop various pressure ratios for symmetric, nonsymmetric, and vortex compressors.

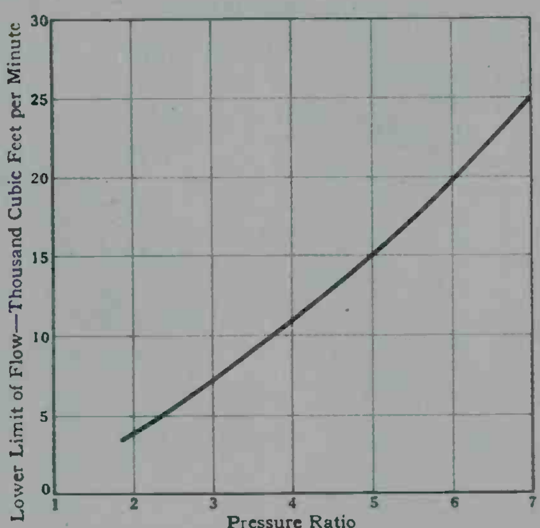


Fig. 5—These curves give the practical lower limits of flow for axial-flow compressors.

TABLE I—PERFORMANCE COMPARISON OF AXIAL-FLOW COMPRESSOR TYPES

(Flow=24 000 cfm or 30 pounds per second; compression ratio, 4:1; inlet pressure, 14.7 pounds per square inch absolute; inlet temperature, 70 degrees F; theoretical enthalpy rise, 61.5 Btu per pound; theoretical temperature rise, 256 degrees F.)

	Symmetric	Non-Symmetric	Vortex
Speed, rpm	15 750	8 750	5 000
No. of stages	10	18	22
Pressure Rise/Stage	1.149	1.08	1.062
Attainable Efficiency, percent	82	87	86
First Stage			
Tip Diameter, inches	16	19	24.5
Base Diameter, inches	10	11.5	15
Blade Height, inches	3.0	3.75	4.63
Tip Velocity, feet per second	1100	725	535
Axial Velocity, feet per second	525	335	200
Last Stage			
Tip Diameter, inches	16	19	24.5
Base Diameter, inches	14	16	21.25
Blade Height, inches	1.0	1.5	1.63
Tip Velocity, feet per second	1100	725	535
Axial Velocity, feet per second	475	275	195

An assortment of rotating and stationary blades used for axial-flow compressors built for aircraft and land purposes.

and blade velocities lead to small physical dimensions and high rotative speeds. The 9½-inch diameter, jet-propulsion compressor is designed for 5000 cfm of atmospheric air at a pressure ratio of three when operating at 34 000 rpm.

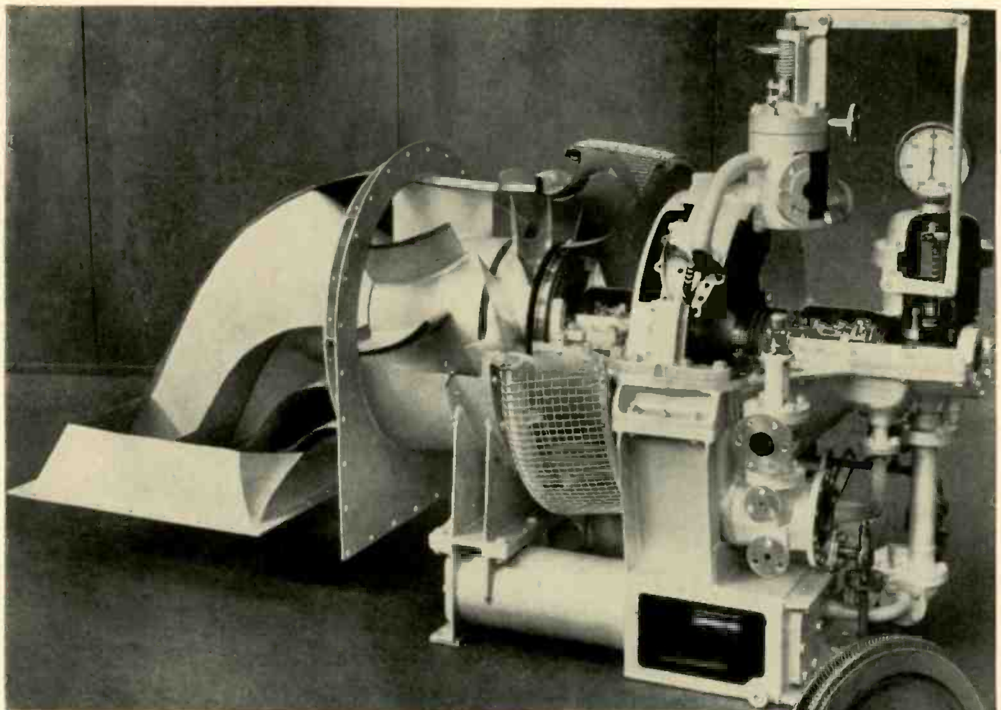
Many of the compressors used in connection with aviation gas turbines are of the symmetrical type. The weight of this compressor compares favorably with the weight of the centrifugal type, while the frontal area is only 40 to 50 percent as much. While efficiencies of the symmetric compressor above 85 percent have been reported, this type of compressor is probably inferior from the efficiency standpoint to the other two types because of the high leaving losses associated with high axial velocity.

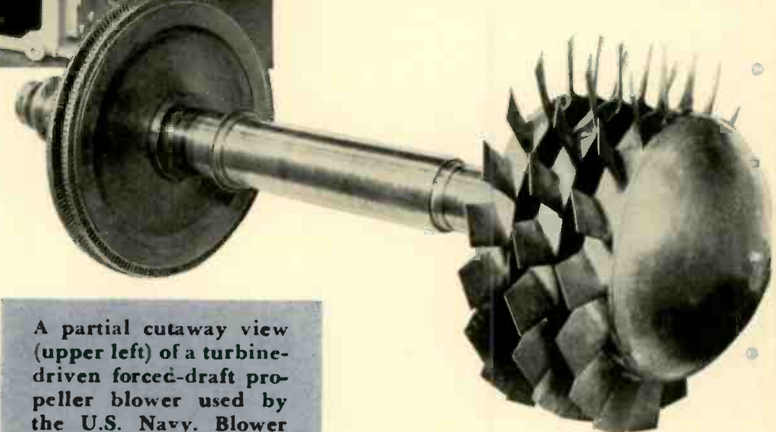
Non-Symmetric Stage Compressor—In a non-symmetric stage a lower blade speed is used so that the absolute velocity, C_4, entering the stationary row, after being turned in this row by the amount ΔU, emerges as pure axial velocity, C_1, Fig. 3. As all the rotating blades of the non-symmetric compressor are designed to accommodate axial flow at the inlet the first stationary row is usually omitted. The velocity diagram of the non-symmetric compressor stage shows that the pressure rise in the stationary row, obtained through removal of the swirling component ΔU, is very small. A non-symmetric compressor stage is at times referred to as a "ten-percent reaction" type of machine.

Blade tip speeds up to 750 feet per second and axial velocities up to 400 feet per second are used with this type of compressor. An efficiency of over 90 percent is realized on single-stage, non-symmetric compressors. A properly designed multistage compressor should give an efficiency of 88 percent under favorable conditions of flow and pressure ratio. The experimental 2000-hp gas turbine generator set* is served by the non-symmetric type compressor. Some compressors for aviation jet engines, such as Juno 004 and B.M.W. 003 in Germany, as well as Brown Boveri compressors used in oil refineries, are of the non-symmetric type.

Vortex Stage Compressor—The stationary blades of the vortex type of an axial-flow compressor are designed to produce a pure axial velocity leaving the rotating row of blades. To accomplish this the stationary blades are designed to give a swirling component ΔU in a direction opposite to the rotation of the rotor blades. This is accompanied by a small pressure drop in the stationary row as shown in Fig. 3. The vortex type of blading is designed to produce whirling velocity before the rotating blades. Such motion of fluid is known as vortex,

*Described by Mr. Putz on p. 35 of this issue.





A partial cutaway view (upper left) of a turbine-driven forced-draft propeller blower used by the U.S. Navy. Blower rotor (right) and steam-turbine wheel of a 30 000-cfm, 105-inch (water) pressure, forced-draft blower for marine service.

hence, the name of this type of compressor stage. The non-symmetric stage is, however, designed also for vortex flow at discharge from the rotating blades. Some designers of the axial-flow compressor refer to this type of compressor as non-symmetric, perhaps in contrast to the symmetric type not designed for vortex flow.

Low axial velocities and low blade tip speeds are features of the vortex type of compressor. Air velocities of about 200 feet per second and blade tip speeds as low as 450 feet per second are common for it. Low air and blade velocities result in relatively low operating speeds as well as in large physical dimensions. The small pressure rise per stage results in the necessity for more stages for a given compression ratio as compared with the other two types of axial-flow compressors. Escher-Wyss advocates the vortex type of compressor for a closed-cycle, gas-turbine power plant. In a closed gas cycle, air enters the compressor at some elevated pressure so that the volume to be handled by the compressor for a given generator output is small. Consequently low air velocities of the vortex compressor are desirable. It is doubtful if the high-velocity, symmetrical-type compressor would be suitable for a small closed-cycle gas-turbine power plant of, say, 2000 kw, because of the small volumetric flow through the compressor. The efficiency of the vortex-type compressor is comparable with that of the non-symmetric type, and, under some conditions, may be even better because of the small leaving losses with velocities below 200 feet per second.

The fundamental principles underlying design of the three types of axial-flow compressors, and the influence they exerted on design features, are shown in table I. It shows that a designer of an axial-flow compressor has a wide range of operating speeds and air velocities from which to choose a proper type of compressor. Although these three types of axial-flow compressors vary considerably in respect to speed, number of stages and stage diameters, the weight and the overall dimensions do not vary in the same proportions. When compared on the basis of the same stresses, reliability, and life, the apparent difference in the number of stages and stage diameters of the three types of axial-flow compressors is partially offset by the blade design. The blades of the vortex compressor designed for operation at 450 feet per second tip speed, for instance, need not be as wide as for the symmetric compressor operating at 1200 feet per second. The number of stages required to develop pressure ratios from 1.5:1 to 7:1 when using symmetrical, non-symmetrical, and vortex types of axial-flow compressors are shown in Fig. 4.

Conclusion

The axial-flow compressor is inherently a high-speed, high-capacity machine. The use of high air velocities coupled with high rotative speeds results in small physical dimensions. The fundamental problems associated with unstable fluid flow from the region of low pressure toward a higher pressure, impose definite limitations as to the pressure rise permissible in a single axial flow stage. Hence, multiple stages are required even for a moderate pressure ratio. In contrast to the multi-stage centrifugal unit, "staging" of the axial-flow compressor does not involve any appreciable losses. The efficiency of a multi-stage axial-flow compressor closely approaches that of a single axial-flow stage. Use of more stages for a given pressure ratio than are required with the centrifugal-type compressor partially offsets the weight advantages of the axial-flow compressor. Present development indicates, however, that it is possible to build an axial-flow compressor with weight-duty ratios that compare favorably with those of the centrifugal type. The advantages of a small frontal area, particularly important for aviation gas-turbine power plants, are distinctly in favor of the axial-flow compressor.

The axial-flow compressor fits exceptionally well as a component part of any gas-turbine power plant for aviation, marine, or land application. An efficient axial-flow compressor is the product of development of but a few recent years and its application to the other fields is not fully explored. There is no reason to believe that axial-flow compressors are limited to gas-turbine applications, although they have inherent charac-

A 30 000-cfm, 6:1 pressure ratio axial-flow compressor with cover removed.

teristics that may render their use less suitable for some other requirements. Among those are the steepness of the pressure-flow curve at the constant speed and the stalling characteristics of the blades. Both result in a narrow range of capacities at which a particular design of axial-flow compressor can operate.

As a high-speed machine, an axial-flow compressor has definite limitations as to the minimum flow for which it may be effectively used, as indicated in Fig. 5. These limitations are defined by the blade height of the last stage as well as by the proportions of the first-stage blade height to its diameter. Axial-flow compressors could be applied for the lower capacities at some sacrifice of efficiency and other advantages. However, the present state of development indicates that the range of capacities below that shown on the curve may be met more effectively by the centrifugal-type compressor. The field of capacities below, say 500 cubic feet per minute, especially at high-pressure ratio, rightfully belongs to the positive displacement (piston or rotary) compressor.

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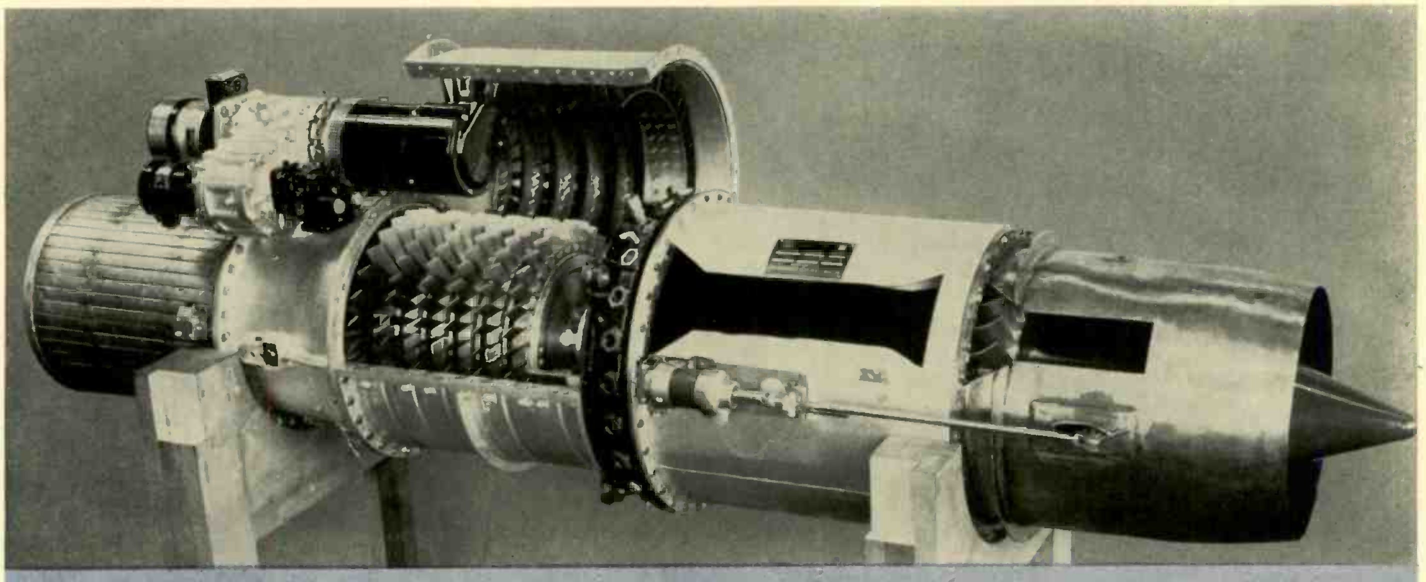

A 19-inch jet propulsion unit with the compressor cover removed to show details of the symmetrical type of aviation compressor.

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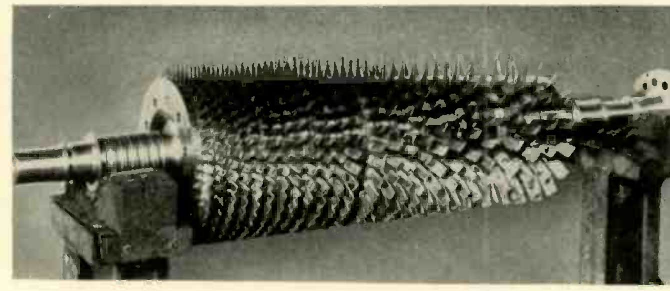


The bladed rotor of the 30 000-cfm compressor.

Factors Affecting Performance of Axial-Flow Compressor

Many variables affect the efficiency and the pressure generating capacity of an axial-flow compressor. The full extent of their influences on compressor performance is not yet known. Remarkable progress, however, has been achieved during the past five years in producing many practical curves and formulas showing the effect of such factors as form of blades, their orientation, and spacing. Among these factors the two most important and least understood are Mach and Reynolds' Numbers.

Mach Number—The distribution of air velocities along the blade passage of an axial-flow compressor is not uniform. The velocity near the convex side of the blade, for instance, is considerably higher than the mean flow velocity; while near the concave (pressure) side it is lower. When such localized air velocities reach those of sound, losses caused by the formation of shock waves ensue, and a complete change of flow pattern occurs. These effects, as well as their influence on compressor performance, are known as Mach-number effects. When applied to air flow through a compressor Mach number is the ratio of the mean air velocity relative to the blade to the velocity of sound in that air. Mach-number effects manifest themselves on compressor performance well below a Mach number of one because of localized velocities higher than the mean. The velocity of sound is known to be:

$$a=\sqrt{gkRT}. \quad \text{For air, } a \cong 49.2\sqrt{T}$$

where a is velocity of sound in feet per sec; g, acceleration due to gravity; k, ratio of specific heats; R, gas constant; and T, temperature degrees F absolute.

Reynolds' Number is a second dimensionless number associated with any problem of fluid flow that shows pronounced effect on compressor performance. The Reynolds' number, well known in fields of hydraulics and aerodynamics, is a scale effect. For a scale model and a prototype to have the same dynamic similarity of flow their Reynolds' numbers must be the same. Linear dimension is one element of Reynolds' numbers, hence in wind-tunnel testing work with models the other factors must be changed so as to keep the Reynolds' numbers for the models equal to that of the prototype.

An object moving with respect to a surrounding fluid is subject to two sets of forces. One is the viscous or fluid friction forces acting on the surfaces of the object, which roughly are proportional to velocity. The other is the inertia force, which increases about as the square of the velocity. In the physical sense the Reynolds' number is the ratio of these two forces. A small Reynolds' number, say 1000, for flow of oil in a pipe indicates viscous flow or a predominant effect of fluid viscosity on the flow pattern; while a high Reynolds' number, say 500 000, of air flow in a compressor indicates turbulent flow and the preponderance of inertia forces.

The mathematical expression for the Reynolds' number consists of three factors: (1) linear dimension of the object to which the flow is confined, (2) velocity at which the interaction of the first two takes place, and (3) a factor indicative of the fluid friction forces, which is called kinematic viscosity. It is the ratio of mass density to the viscosity. Mathematically the Reynolds' number is expressed as follows:

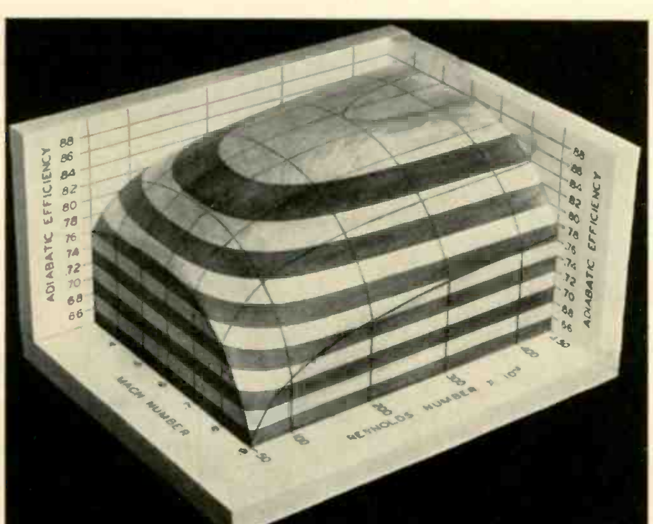
$$R_N=\frac{LV\rho}{\mu}=\frac{LV}{\nu}$$

Where L is linear dimension in feet; V, velocity in feet per second; ρ, mass-density in slugs per cubic feet; μ, viscosity, slug per second feet; and ν, kinematic viscosity, feet square per second. (A slug is mass in pounds divided by acceleration due to gravity).

In the three-dimensional diagram, derived from the Steam Division's variable-density, wind-tunnel tests, the levels of constant compressor efficiency are represented by layers of equal thickness (2 points in efficiency). For constant Reynolds' numbers compressor efficiency is highest at a Mach number of 0.6 level. With the increase of the Mach number from 0.6 to 0.8 compressor efficiency drops slowly, indicating that some localized velocities have approached the velocity of sound. After this point compressor efficiency declines rapidly.

The lines of the constant Mach number show the effect of Reynolds' number on compressor efficiency. The highest efficiency is realized at high Reynolds' numbers. The reduction in Reynolds' number to about 150 000 marks a small drop in compressor efficiency; while a further reduction down to 50 000 shows a pronounced decrease.

The above effect of the Reynolds' number on the compressor efficiency is very important in evaluating test results of small scale models of axial-flow compressor stages. A model of a compressor stage having 1-inch blade chord with relative velocity of 100 feet per second, for instance, operates at Reynolds' number of about 50 000, while the 1½ chord of the prototype stage with relative velocity of 700 feet per second operates at the Reynolds' number of 525 000.

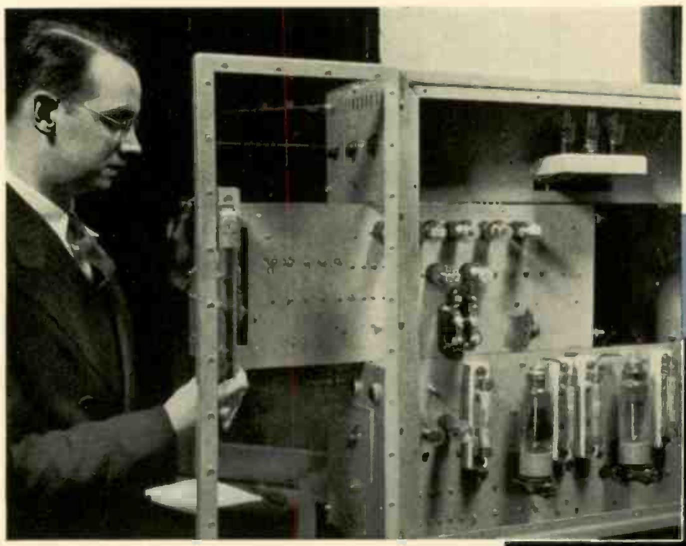


Isometric diagram of axial-flow compressor efficiency.

What's New!

Coordinated Resistance-Welding Controls

HAND in hand with the growing versatility of resistance welding has been the development of specialized electronic controls, most of them built around the ignitron. Now the physical form of these numerous controls has been coordinated into a family of related units called Synchrotrol. They are built as elements that fit into a standard frame, of which the base unit is the power unit or Weldotrol. Thus a standard synchronous-precision welding control—made up of units to serve the particular welding machine and function—forms a cabinet that can either be mounted on the side of the welder or placed conveniently near-by.



Several significant advantages accrue from this unified construction. Conspicuous among these are the greatly reduced installation, labor and wiring time, the reduction in floor space to about one half that required for unmatched units, the merits of factory wiring and testing, and the flexibility permitted in making changes in controls.

The controls are all mounted on the front panels of these units, which are 12 inches wide and 28 inches deep. Heights vary somewhat. Blank panels are included to maintain the uniform appearance of the assemblies where the desired units do not match the height of the framework. These panels also provide space for special controls and future additions.

The subassemblies are for both synchronous control, which opens and closes the power circuit at the same point on the voltage wave for every weld, and for nonsynchronous control. Voltage and current regulator units are included for the first time. The various unit panels are:

Synchronous Units: 1—Spot timer, 2—Heat control and firing mechanism, 3—Electro-mechanism seam timer, 4—Fully electronic seam timer, 5—Spot, pulsation, seam and timer, 6—Voltage regulator, 7—Current regulator, 8—Sequence timers (two types), 9—Blank panel, 10—Forge timing panel.

Nonsynchronous Units: 1—Heat control, 2—Sequence-weld timers (four types).

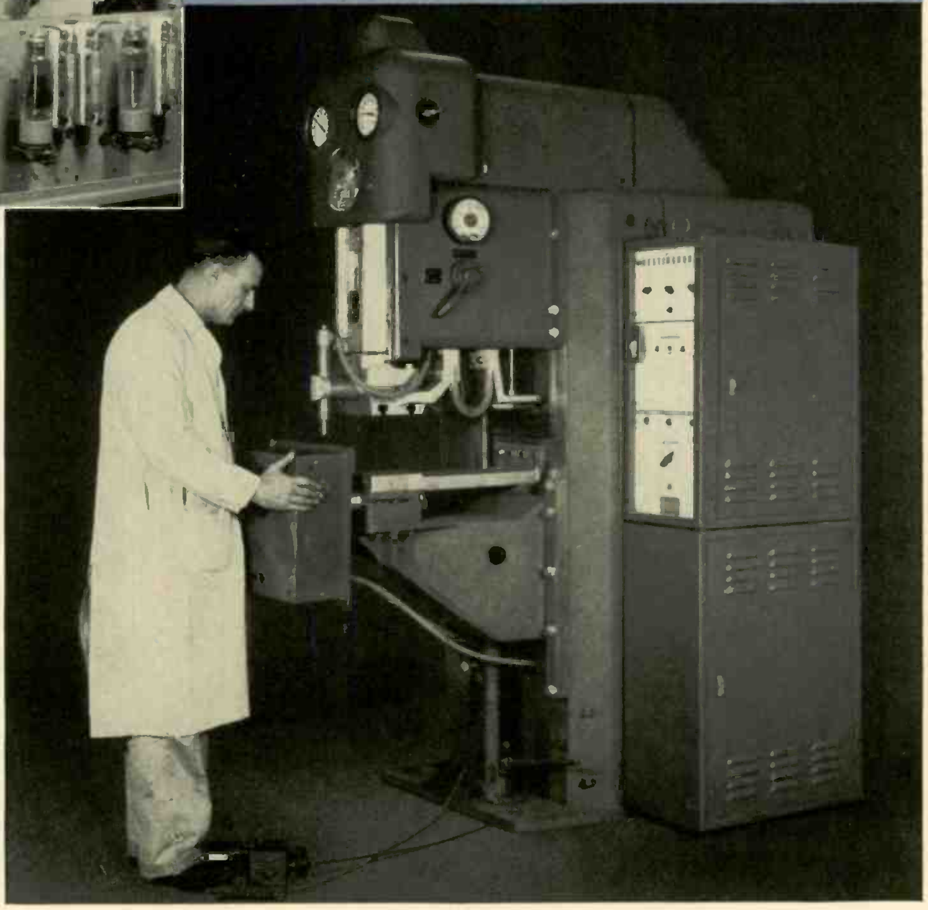
The completed assembly has a uniform appearance; within it are more than 160 possible combinations of welding control.

Operating circuits are improved and simplified, and where possible, common or like circuits are used. In some cases the number of tubes is reduced by the use of fewer, smaller, less expensive tubes so that the initial tube cost is only one third that of previous installations. The flexibility of the functions and combinations of these eliminate the need for many special control items.

Quick-Starting Fluorescent Lamp

FLIP the switch and the new 40-watt fluorescent lamp (T-12) starts instantly, just like an incandescent lamp. It is a hot-cathode lamp but is started by means of high voltage without any preheating of the cathodes. This is accomplished by applying approximately 450 volts to the lamp for starting and using a specially designed cathode that withstands the shock of the higher voltage. The two base pins on each end of the lamp are provided with an electrical bridging member inside the lamp base that short circuits and protects the lamp electrode. This prevents the primary current of the ballast from passing through the electrode filament with consequent damage to the lamp; but because of it the instant-start lamp will not operate satisfactorily on the starter type of circuit. The instant-start circuit is required for safety at this higher voltage. Regular type lampholders are used The instant-start lamp life is 2500 hours at three hours burning per start.

To meet the needs of a particular welding operation, standard Synchrotrol units are combined in a standard frame. Controls for normal varieties of welding are built in related physical forms.



CASTLE

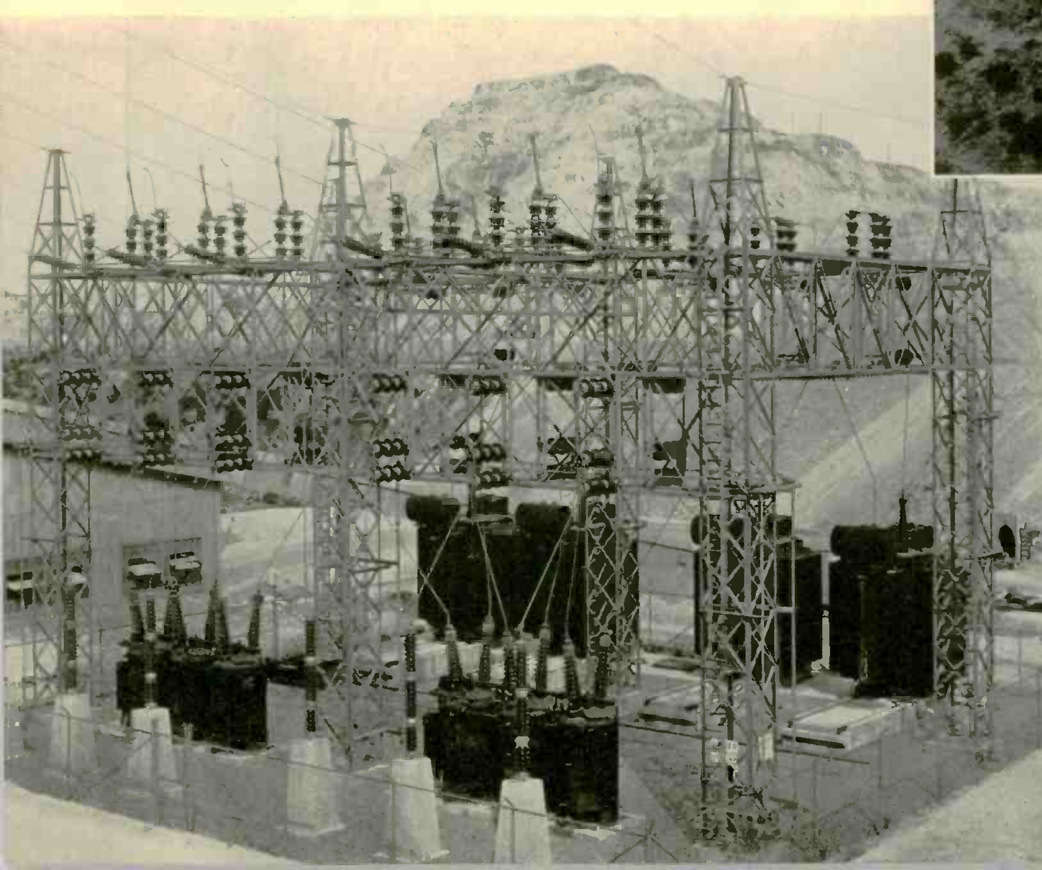
A Colossus o

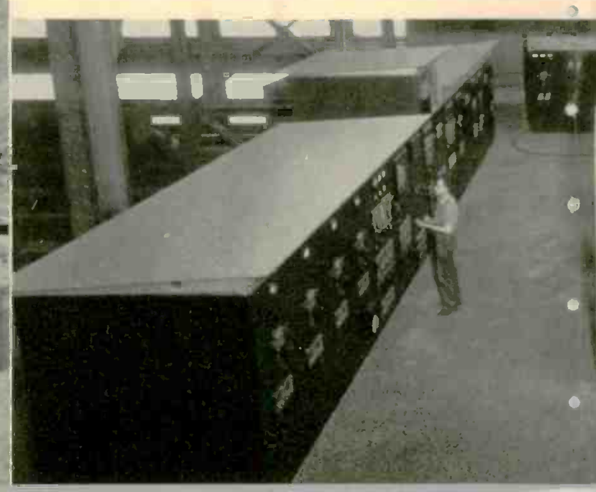
The open-pit mine of the Castle Dome Copper Company at Miami, Arizona, is a 4700-foot mountain of 19 000 000 tons of 0.74 percent copper with an additional 6 000 000 tons likely to prove in from exploration. This war-inspired colossus of mining is owned by Defense Plant Corporation—a subsidiary of RFC—and leased to Castle Dome Copper Company. The ore body is a blanket formation in quartz monzonite porphyry having its principal values in copper sulphide.

Water is piped eleven miles through a 16-inch steel and wood-stave line to a new 3½ million-gallon reservoir. Responsible for 59 percent of the total energy consumption, and a key commodity

A Marion electric shovel (above) bites off 5 cubic yards of copper-bearing ore. The truck is a Knuckey 30 tons, rear dump—one of 14 used. The substation (below) shows "The Dome" in the background. Power is supplied from a 110-kv loop circuit. De-ion-grid oil circuit breakers and arresters are in the foreground; in the background is a 10 000-kva transformer bank, with one spare unit.

Shown above is the open-pit mine of the Castle D
and center, with waste dumps at the right. Below
duty, metal-clad switchgear provides control o
mills, blowers, concentrator, primary and second



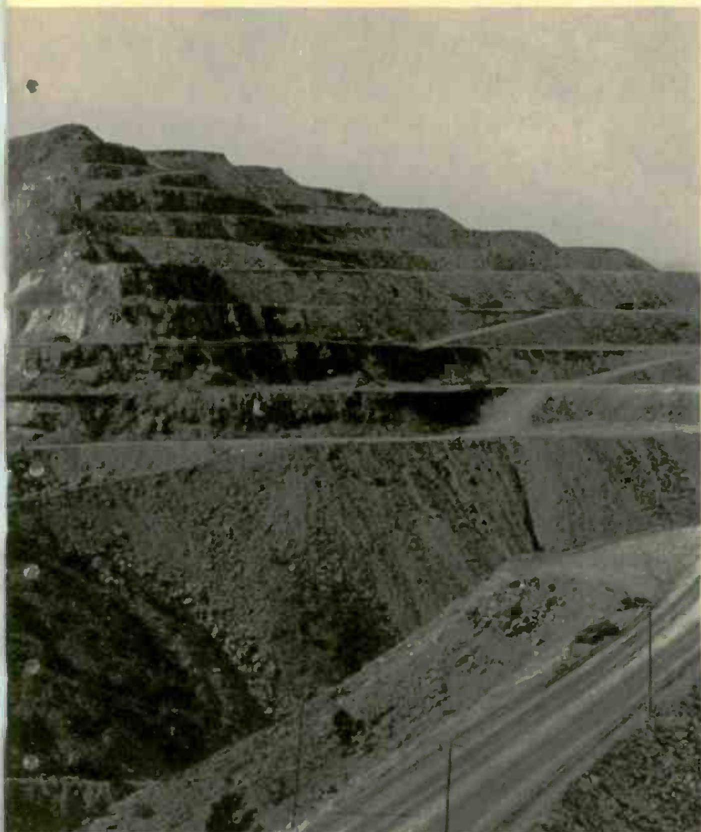


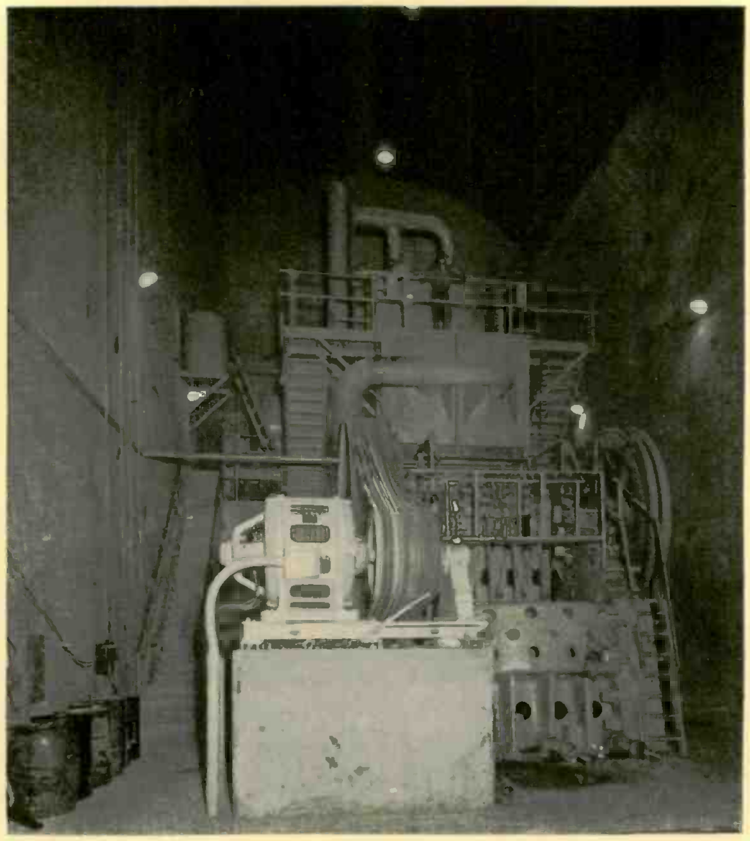
DOME—

Copper Mines

in this normally arid region, water is not wasted; 87 percent of it is reclaimed. A power line was constructed to connect with the Salt River Valley Water Users Association system. The primary supply is 110 000 volts at 25 cycles. The conveyor is a Goodrich, 48-inch belt, having a length of 2350 feet and a speed of 450 fpm. It is dual driven by a 200-hp motor at the head and a 100-hp unit at the tail. The lift is 190 feet at a 12-degree incline.

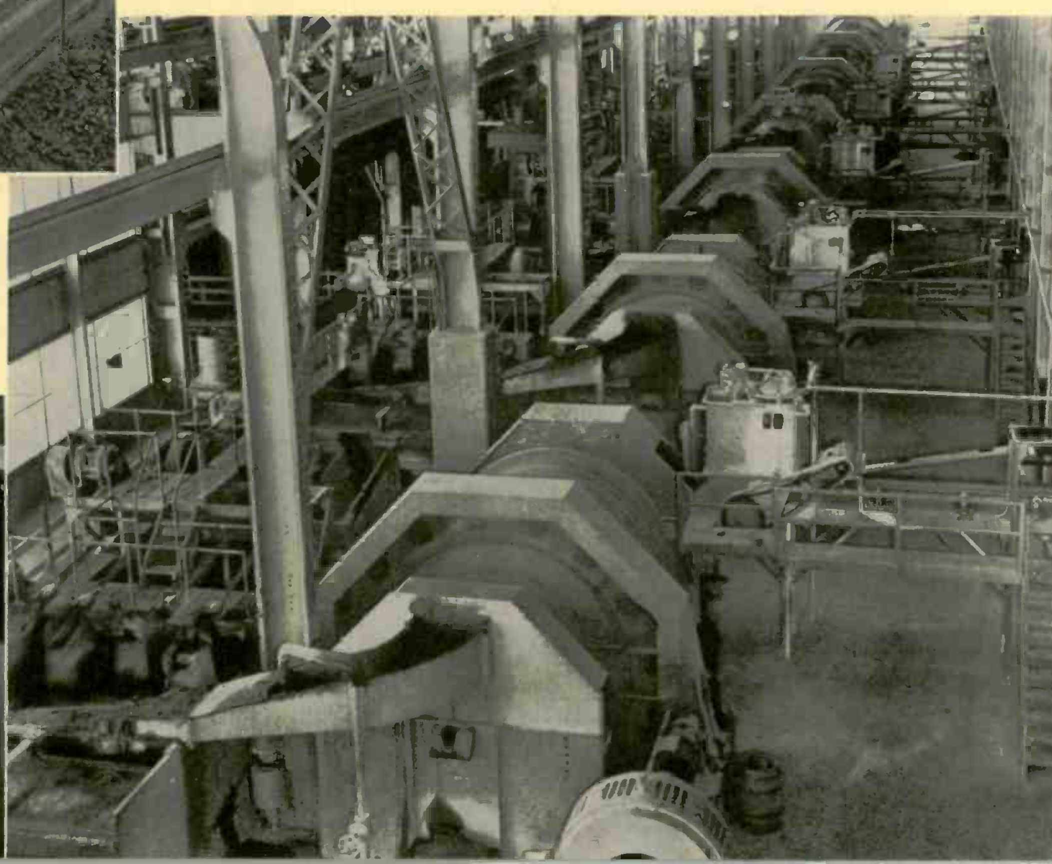
Initially, copper to be mined was set at 46 000 000 lb annually. During 1945, a recovery of 53 324 969 lb was obtained. All indications point to a belief that Castle Dome will be a producer for many years to come.

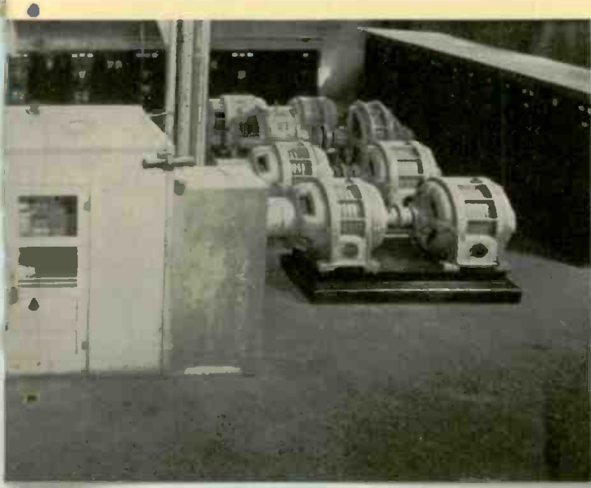


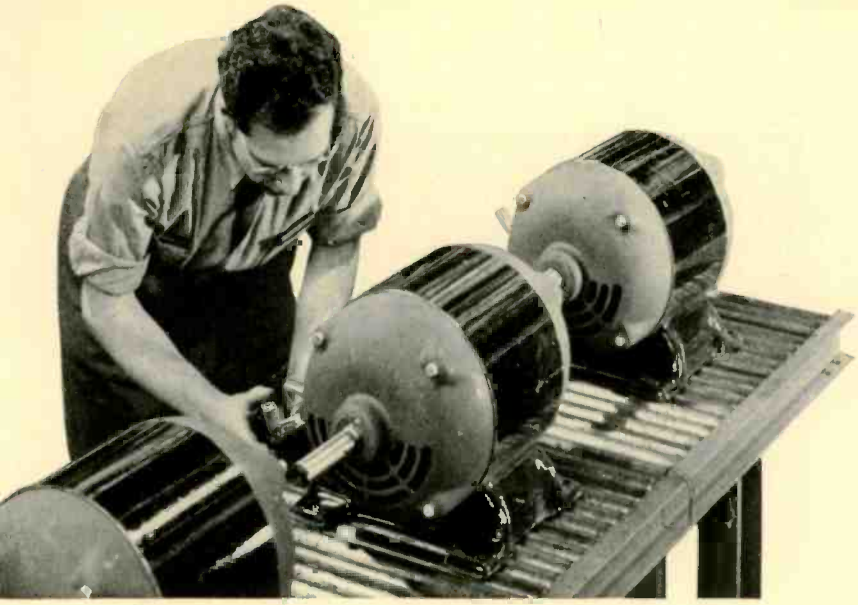


The primary crusher (above) is located underground. The huge jaws, size 66 by 84 in., are V-belt driven by a 300-hp, 25-cycle, 440-volt slip-ring motor. The concentrator ball mill (below) is seen in operation. Each of the seven sections is driven by a 600-hp, high-torque synchronous motor. Automatic feed maintains constant load control over varying ore hardness and grindability.

...e Copper Company. Ore benches are at the left ... the high-voltage indoor substation where heavy- ...ncoming circuits, synchronous condensers, ball ...y crushing plants, mine and tailings dam pumps.







New Induction Motor

The squirrel-cage induction motor has long been basic to industry, is the product of many years of development, and is the acme of simplicity. With this background one would expect it to have passed the knee of the improvement curve long ago. But it didn't, as the story of the newest version indicates. Smaller, lighter, better in many ways—it primarily is aimed at the most important factor in motor use—maintenance.

W. H. Formhals, *Head, A-C Industrial Motor Section,*
T. C. Fockler, *Manager, A-C Motor Engineering,*
Westinghouse Electric Corporation

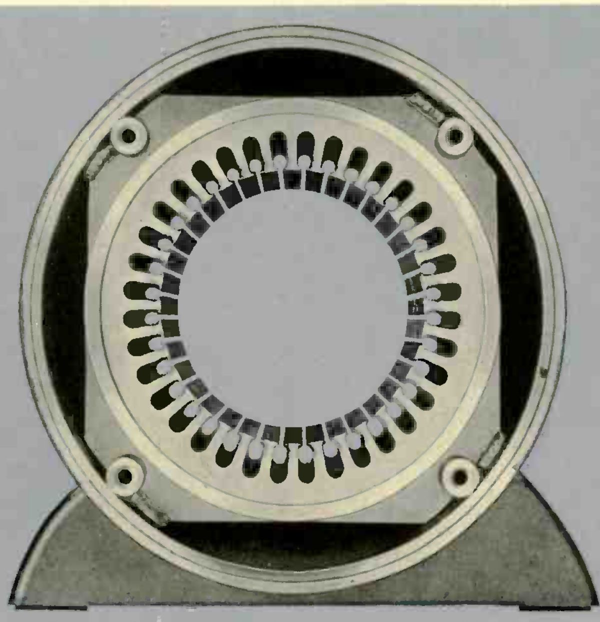
The squirrel-cage induction motor, although it is the oldest of all alternating-current devices, has been significantly improved. This newest of general-purpose induction motors, commonly referred to as the Lifeline motor, compared to its immediate predecessor, is much smaller. The 7½-hp, four-pole, open-type motor weighs only 85 percent as much as before, while the weight of the totally enclosed, fan-cooled motor has been cut in half. With less weight go the smaller overall dimensions, so important on machine tools and other places where space is an important factor. The mounting and shaft dimensions remain unchanged, in accordance with national standards.

Reduced maintenance was the first consideration in the conception and execution of the new motor; it was held even more important than economy of weight and bulk. Special attention was given to the two most common sources of trouble: bearings and stator windings. The bearings, for example, are sealed and require no lubrication for at least five years. The windings are of a new design and are inserted by novel methods established especially to eliminate previous causes of insulation weakness. Also the motor frame and exterior are such as to give it a much greater degree of mechanical protection from falling objects, dripping water, or from the bumps and shocks common in motor service. Vibration and noise have been reduced to new low limits because their causes have been eliminated to a large degree.

The Background for Improvement

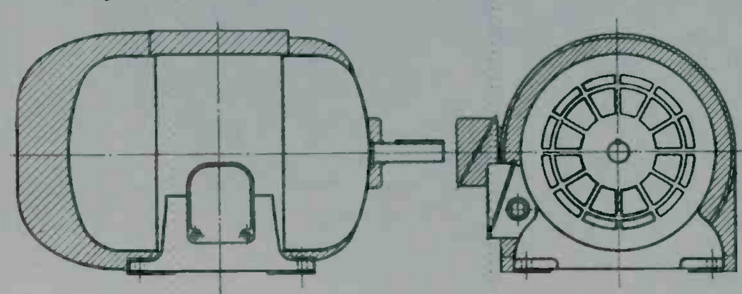
That such major steps in motor betterment are possible after 58 years of motor evolution is itself significant and surprising, the more so when one considers that the basic principle of the induction motor has not been altered since Tesla first developed the polyphase induction motor in 1888. Ordinarily, improvement of any machine of this age and importance relates to detail. Such extraordinary improvement can arise only out of extraordinary conditions; this has been the case with the new induction motor.

During the war it became evident that postwar conditions would demand an improved motor. As soon as consistent with the war program, a group of engineers were detached from regular design and production and posed the problem of creating a completely new motor, both as to design and manner of construction. Starting afresh, these men could capitalize on all worthwhile developments of recent years. Because of the anticipated large volume of motor business, new manufacturing setups and special-purpose, but expensive,



The core is formed by stacking punchings with notched corners on locking bars. The assembled core is pressed into the circular welded-steel frame and fastened by welding. The ends of the locking bars are tapped for the end-bell bolts. The punchings have slots with round bottoms and narrow necks.

Below is the outline of an open-protected Lifeline motor against the background of its predecessor, showing the reduction in size. Bolting and shaft dimensions necessarily remain the same. At the right is a similar comparison for new and old totally enclosed, fan-cooled motors.



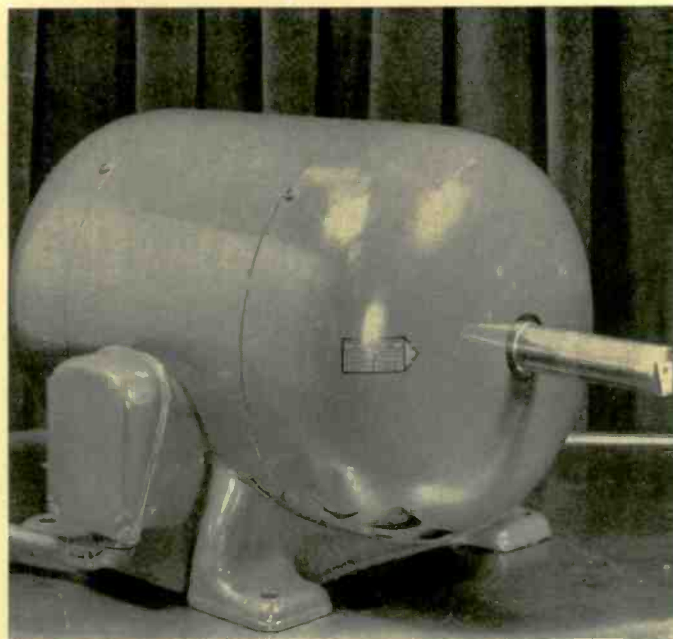
automatic machine tools could be justified. As important as anything, a whole new environment for motor production became available. An entirely new plant—built early in the war for aircraft manufacture—was turned over to motor manufacture. This permitted free adoption of new construction methods, assembly arrangements, and work-handling facilities, unfettered by the restrictions imposed by existing plant. Although the new plant required the training of personnel, some advantage accrued from the fact that these people could develop new habits unencumbered by habits engendered from working with motors of older design. In short, the new motor is the result of the rare combination of wholly new design, new methods, precision machines, processes, new materials, and new environment.

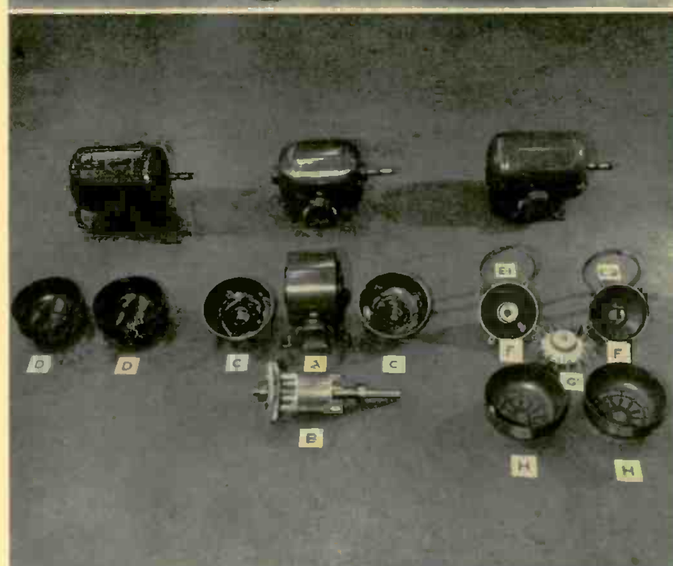
The outstanding construction change in the new motor is its use of fabricated steel throughout. No castings whatever are employed in the standard, general-purpose motor. Most of the improvements achieved in this motor stem from its fabrication from steel instead of castings.

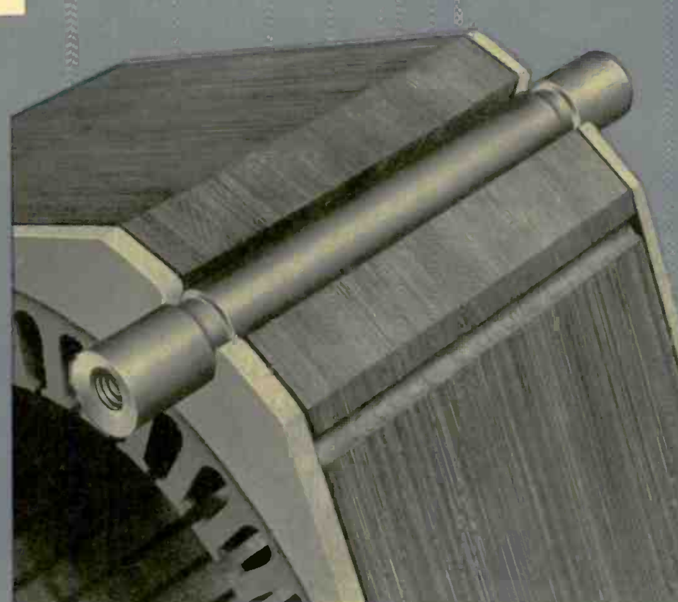
Several considerations lie behind the use of steel throughout the motor. Three are uppermost: (1) it permits a more precisely made machine, (2) it augments rigidity and shock strength, and (3) it provides a smoother exterior surface, which makes possible a more pleasing final finish.

As compared with motors employing castings for basic members the steel motor is a precision product. With steel it is not necessary to allow for the large dimensional variations common with parts of cast construction, hence the dimensions of the steel motor are smaller. The higher strength of steel also allows further reduction in size. The greater uniformity of quality possessed by steel permits a design that makes more effective use of the material. The steel-fabricated motor frame lends itself to precision manufacture, with assurance of greater uniformity between successive motors. These and other changes in design and materials conspire to reduce the weight and bulk of the motor.

While the amount of material in the mechanical structure of the motor has been significantly decreased the amount of active electrical and magnetic parts has not been reduced. Thus a large reduction of structural material is achieved without any sacrifice in the motor's ability to do its job. In fact, in some respects the performance has been improved, as

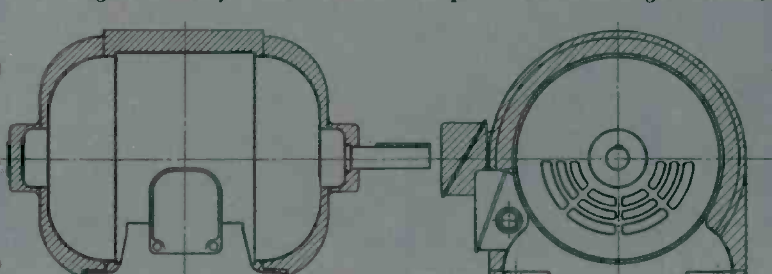


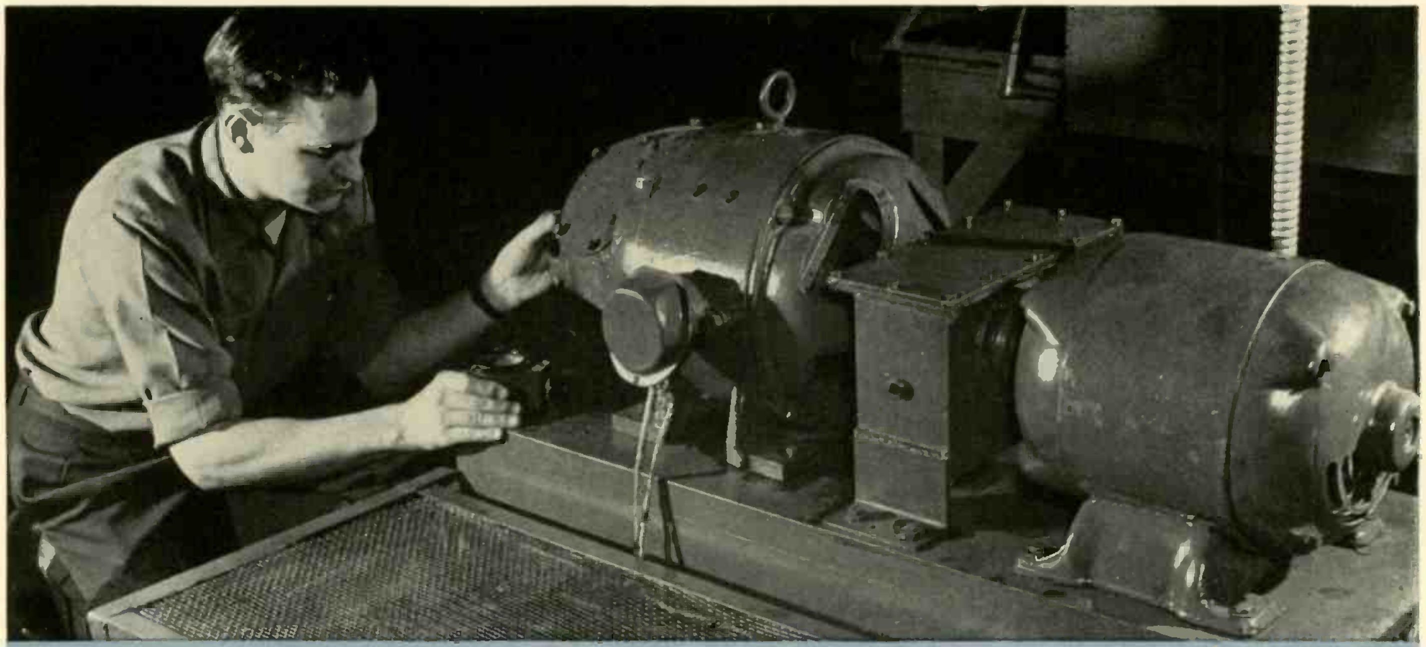




The new motor, top right, has pleasing lines, smooth contour, made possible by its smooth rolled or pressed steel parts. The basic subassemblies and parts for the three different motors, center, illustrate the interchangeability that has been designed into this motor. Stator *A* and rotor *B* are common to all three models. Add end bells *C* and an open-protected motor results. Reorient brackets, add hoods *D* to open-protected motor and splash-proof motor on the left results. The fan-cooled motor (right) has stator *A*, rotor *B* with blower *G* instead of the small one, adapter rings *E*-1, *E*-2, end bells *F* and hoods *H*.

The close-up of an assembled stator core shows how the punchings are firmly held between end plates with locking bars.





One of the Lifeline general-purpose motors is here a part of a motor-generator set, driving through a speed changer.

a result of better use of the electrical materials. Torques, both starting and maximum, have been increased by various amounts depending on the particular rating, but on an average approximating ten percent. Overload capacity is as good as before. Efficiency is somewhat improved.

Assisting in this enhanced operating performance is an improved stator-core construction. The laminations are, as before, of silicon steel. However, the magnetic material, after punching, is subjected to a carefully controlled annealing process, resulting in three desirable effects. The heat treatment relieves punching-induced strains, providing improved magnetic properties of the iron, reducing fundamental iron losses and stray load losses. The annealing operation burns off the burrs formed by the punch dies, thereby eliminating a troublesome source of iron losses, always a serious deterrent to motor efficiency.

Also, the heat treatment leaves an oxide film on all surfaces of the punchings. This oxide coating is an excellent insulator, hence eliminates the necessity for specially applied coatings such as water-glass or enamel. In other words the necessary lamination insulation becomes a part of the lamination itself and does not depend upon some added layer, which in itself may become a source of trouble in service.

Because appearance is an increasingly important consideration in all industrial machinery, this factor was held by the motor designers as a major objective. The use of a steel exterior helps achieve that goal inasmuch as a steel surface is smoother than cast metal and thus makes possible a smooth finish. The completely wound stator and frame of the motor are dipped in a varnish, which not only tends to seal the winding but also provides a primer coating on the exterior surface of the frame. A gray lacquer finish provides a second protective film. The result is a motor with a finish of enamel-like smoothness that discourages corrosion. Steel protected in this manner is as good if not better than cast iron, which has been traditionally assumed to be excellent from the standpoint of corrosion resistance.

How the Motor Is Built

Frame—By using steel the frame becomes remarkably simple. It is rolled from plate and is seam-welded by automatic submerged-arc machines. During welding the frame ring is wrapped around a mandrel and is thus accurately sized. The feet of deep-drawn steel are welded to the frame ring also by submerged-arc welding. Punchings, end plates, and lock bars are fitted together to form the stator core. In this operation the punchings are stacked on a mandrel, which is expanded after the required number of punchings are in place. Pressure is then applied to the stack to compress them to correct dimension. This mandrel insures that punchings are properly lined up and that the bore is accurate and smooth. While the core is still supported by the mandrel the frame is pushed over the core and the two welded together.

Machining is done in a double-ended lathe so that the ends of frame and core are finished simultaneously. The frame and core are machined from the stator bore. This assures concentricity of the two bracket fits relative to each other and to the bore, and parallelism of the fits.

Brackets are machined in special machines that rough and finish the rabbet fits and rough the hub for the bearing. The bracket is then put on a fit plate centering from the finished rabbet fit and the bearing bore is established, assuring concentricity with the rabbet fit. An important point is that the bore of the punchings provides the reference point for machining of the rabbet fits of the frame. This same reference is used for the rabbet fit of brackets so concentricity of bearing is guaranteed. Thus all possible has been done to assure that the bearings and bore are aligned for concentricity. This choice of machining practice assures alignment of parts with attendant smoother running and maintenance-free operation.

Stator Windings—With reduction in maintenance a major objective, every effort was made to design a winding and a means for its application that would remove all elements of weakness as much as possible.

One of these factors was the shape of the slot in the stator punching. Slots have customarily had flat bottoms with slightly rounded corners. To fit the insulation into such a slot satisfactorily, the *cell* had to be formed before insertion. This sharp bending of the slot insulation to form the corners sometimes resulted in a cracking of the varnish of the treated cambric and gave rise to the possibility of failure at this point. In addition the coils make a sharp bend in going from one slot to the next. With the slot of the square-bottom construction the individual wires of the coils all tend to crowd into the corner and increase the pressure there. Since this point has been weakened because of the cell crease, the possible sources of failure are doubled.

The new punchings have a semi-circular bottom, which allows the slot cell to be inserted by the winders without any bending of the material. In addition the wires are better distributed around the bottom of the slot because of the larger radius of curvature and thus the maximum pressure on the cell has been materially decreased.

The better distribution of the wires results in less tendency to turn at the cell ends where there is no support by the core.

The rounded bottom of the slots results in other advantages. One of the most important is that the die is easier to make and produces a better fitting of the two parts of the die, thus resulting in punchings freer of burrs than formerly. The decreased amount of burr means a better slot surface, another factor of importance in obtaining a trouble-free winding.

The necks on the punched slots have been made wider than before. This permits easier insertion of wires with less likelihood of scraping insulation from wire. Investigation in a winding laboratory led to coil shapes that permit coils to fit more readily one with the other, thus requiring no pounding or hard handling to shape them in place. More coils are connected in series, which, with a new stacking method, results in fewer brazed joints. Wood wedges are of such shape that when they are in place, the ends of the slot *cell* are folded over the top of wires in the slot, giving maximum creepage distance. All this tends to reduce inherent flaws being built into motors during the winding operation.

Wound stators are insulated with a thermosetting varnish that has better oil and water resistance than varnishes previously used. It dries with a hard, smooth surface, that is readily cleaned.

Bearings—The new motors use sealed ball bearings. These bearings are assembled, given a metered amount of oxidation-resistant lubricant, and sealed under ideal conditions before application to the motor. The grease used for the general-purpose motor is the result of a long series of competitive lubricant tests. For motors used in high-temperature ambients a silicone grease is used.

This bearing can be counted on for at least five years' normal service without relubrication. Test bearings of this type are still operating after nine years of service without relubrication, and no need for relubrication is apparent. This type of bearing has been used extensively for five years and records carefully kept indicate uniformly good service.

The use of sealed ball bearings is a large factor in the significant reduction of maintenance required by this motor. Aside from the fact that a program of frequent lubrication is not necessary, the construction avoids difficulties resulting from over-lubrication, the entrance of dirt along with the lubricant, or the use of improper lubricant.

Rotors—The rotors are of die-cast aluminum as before. However, improved dies and production methods result in rotors of more consistent quality.

Cooling—The motor is cooled by drawing air in at one end, passing it through the axial air ducts between core and frame, and expelling it at the other end. Effective cooling is achieved by the large volume of air thus moved by a blower at the intake end. All air openings are in the lower half of the end covers, reducing the likelihood of entrance of water.

Use of "straight-through" ventilation avoids all air openings in the motor frame, in keeping with the objective of avoiding any possibility for entrance of objects or moisture from above; this is a decided asset to appearance.

Interchangeability—The general trend in almost all apparatus is toward standardization and interchangeability of basic parts for different varieties of a given device. This idea is carried out to the full in this motor. The stator core and frame assembly is used regardless of whether the finished motor is to be drip-proof, splash-proof, totally enclosed fan-cooled, non-ventilated, horizontal, or vertical. Heretofore motors required a different frame casting for each of these types of enclosure.

By assembly of the basic core and frame with the particular end covers, the desired type of enclosure is obtained. The same holds true for vertical mounting. For ceiling mounting the end covers are simply rotated 180 degrees. Omission of the feet provides the footless type of motor sometimes required. The bearing housings have the same location in each type of bracket. This permits the use of a single set of shaft dimensions, simplifying manufacture and assuring uniformity.

The advantages of the interchangeability of parts is obvious as it results in material benefits both to the manufacturer and the user. Modifications can be made if necessary from one form of construction to another. Stocking of parts is reduced, and a general simplicity is attained.

The basic design concepts and construction methods that comprise the Lifeline motor are currently being applied to integral-horsepower motors of from 1 to 15 hp. The same basic construction may be extended to both squirrel-cage and wound-rotor motors in ratings up to 450 hp.

The new motor is the culmination of several fortunate circumstances. It is an addition to a distinguished line of the most common form of industrial motors—and a line that, with these manifest improvements, adds up to a major and significant milestone in motor evolution.

One of the important considerations in the design of the motor and the plant in which to build it was maximum utilization of production-line methods and their merits.

Radar Receivers and Crystal Rectifiers

Some devices, like ladies' fashions, experience a peak of popularity, followed by a period of obscurity, and a subsequent return to favor. Vividly associated with memories of the earliest days of ear-phone radio is the "cat-whisker" crystal detector. It was soon outmoded as a signal detector and seemed destined to have museum value only. Now it is back—in scientific, synthetic form without the aggravating temperamental characteristics of its progenitors. Radar receivers, with their special needs, brought about this rebirth of interest in crystals.

Dr. S. J. Angello, *Research Laboratories, Westinghouse Electric Corporation*

One of the earliest radio devices, the "cat whisker" and crystal rectifier, has returned to do an essential job in microwave radar. The crystal, now synthetic instead of natural galena or a casual product of the arc furnace, is as yet without competition because tubes to do the same work are not available at these frequencies.

In a broadcast radio receiver an electron tube is used as a mixer of signal frequency and locally produced intermediate frequency. At frequencies of 100 megacycles and above conventional electron tubes fall off in conversion efficiency. Special tubes have been constructed for frequencies up to 3000 megacycles, but above this the crystal detector is the only device that at present is suitable in this regard. Two factors affect conversion efficiency. These are (1) the interelectrode capacity, and (2) the time taken by an electron to move from cathode to plate, the "transit-time." The crystal rectifier has an extremely low capacitance, and transit-time effects are negligible.

The new synthetic crystal is a small wafer of especially prepared silicon mounted on a brass rod that slides in a brass end piece and is clamped with a set screw. The "cat whisker" is a five-mil tungsten wire bent to form a flat spring and is pointed at the end in contact with the crystal. A suitable pressure contact is made at the factory and is rendered permanent by a set screw and a wax filler in the ceramic cartridge. No searching of the crystal face is necessary, because research has provided a crystal face with nearly uniform sensitivity. In service it is necessary only to insert the crystal rectifier cartridge in the mixer unit of which it is a part. If the unit becomes damaged in some manner it can be removed and replaced with little delay.

The principle of the crystal rectifier dates back to F. Braun in 1874. He discovered that a metal-point contact on a crystalline substance, such as galena or silicon, has a resistance, dependent on voltage, as shown in Fig. 1. The impedance to a voltage in one direction is extremely high so that over a normal working range no current flows. To an applied potential of opposite polarity it presents a relatively low impedance, but in a nonlinear relation. The crystal, therefore, has the qualities of a rectifier.

The utility of this characteristic was recognized by the early pioneers in radio, and they used it to rectify high-

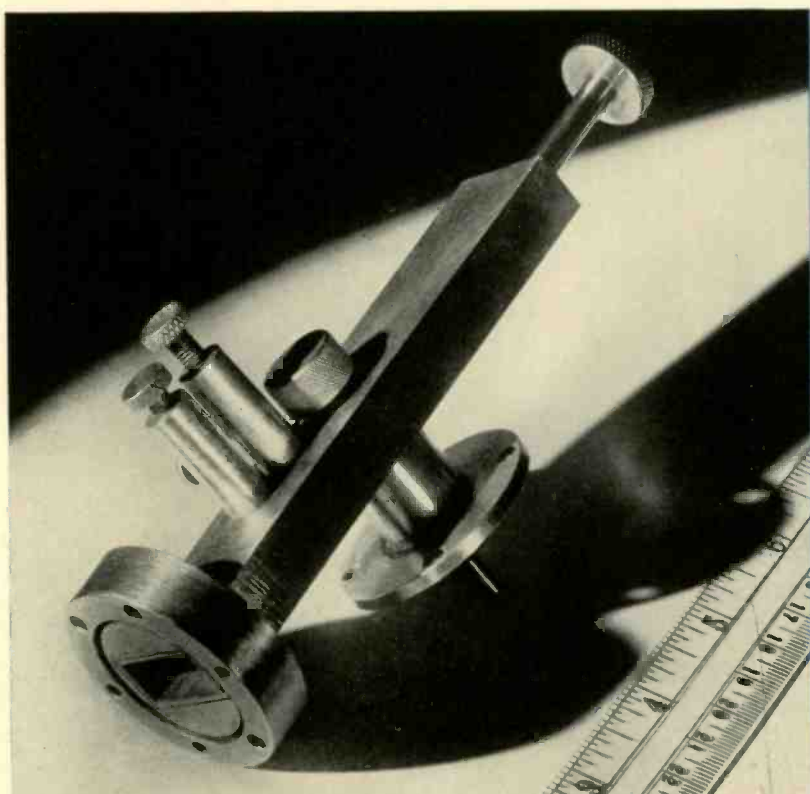
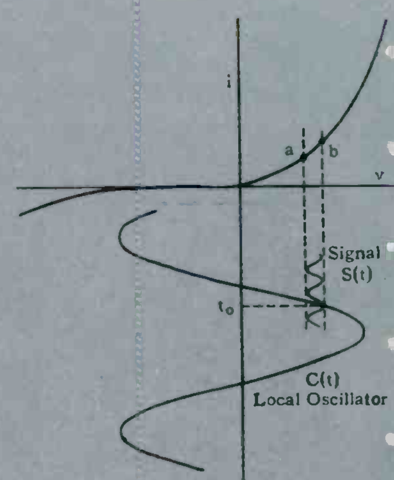


Fig. 1—Local oscillator and signal voltages when impressed on a nonlinear resistance. →



← **A 3-cm waveguide mixer, with crystal.**

Above 3000 mc, energy is propagated in waveguides. The mixer section of the waveguide contains the rectifier and is fitted with plunger and screws to match the rectifier to the guide. This matching is done to insure that all the incident energy is impressed on the rectifier and none is lost by reflection. Signal and local-oscillator energy go down the guide together. In the guide they merely *add* together because the system is linear. *Mixing* occurs in the rectifier, because its current-voltage characteristic is nonlinear. The intermediate frequency appears across the grid of the first i-f tube.

frequency voltages. The familiar "cat whisker" crystal detector had its shortcomings. It was necessary to probe the crystal face for a sensitive spot. This spot, once found, was easily lost.

Development of the superheterodyne receiver by E. H. Armstrong during World War I centered around the new, more stable audion tubes. Crystal rectifiers played an insignificant role, one which saw them finally relegated to the status of museum pieces. Rapid, war-spurred progress in the development of generators of microwave frequencies ran head-on into the seemingly insoluble problem of providing receivers for these frequencies. It quickly became evident that conventional tubes could not be used as mixers—and the humble, discarded crystal with its "cat whisker" contact was removed from the limbo of forgotten things, and made over for the vital task ahead of it.

For military radar, crystal rectifiers must be stable against severe shocks. From the manufacturer's point of view it is expedient to eliminate the necessity for seeking a sensitive spot. Crystal rectifiers in 1940 were essentially the same as the rectifiers of 1918 because the lack of demand had led to their neglect. Intensive research, started in 1940, had as its object the production of a stable, sensitive rectifier which could be manufactured in large quantities. This objective was quickly achieved by the cooperation of several companies and the National Defense Research Council Laboratories.

The metal-point crystal combination can be considered as a tiny cold cathode diode in which the crystal is the cathode and the metal point is the plate. Such an arrangement has a low capacity because of the small point area. Theory also indicates that the electrode spacing is about 250 millionths of an inch (10^{-5} cm) so that an electron can traverse such a space in negligible time. These circumstances help to sustain the conversion efficiency of crystal rectifiers—even at a frequency of 30 000 megacycles.

In spite of efforts to secure uniform crystal-rectifier performance, units coming from a production line show an undesirable spread in characteristics, and a means of selection must be employed to insure acceptable rectifiers. Electrical tests provide the criteria for selection.

The ultimate purpose of the receiver is to transform the pulse into a circuit impulse of *useful* intensity. It is clear that, if mixer conversion loss were the only factor involved in superheterodyne receiver performance, there would be no difficulty because the i-f amplifier could raise the mixer output to any desired power level. However, in a physical system there exist random voltage fluctuations called "noise" that establish a definite theoretical limit to receiver performance. Noise comes from the antenna, local oscillator tube, crystal rectifier, and i-f amplifiers. A signal coming into the mixer must compete on the output indicator with noise from the antenna and noise produced within the system.

The signal will not be intelligible at the indicator unless it is stronger than the noise. The signal power P_s necessary at the receiver input (now excluding antenna noise), so that the signal output will just equal the noise output, is a figure of merit for the receiver. This becomes the *noise factor* of the receiver if it is divided by kTB, where k is Boltzmann's constant, T is absolute temperature, and B is the receiver band-pass width. That is,

$$F = \frac{P_s}{kTB} = \text{noise factor.}$$

The number kTB is the noise power available from a pure resistance, and is commonly used as the noise reference level. The smaller that factor F becomes, the better the receiver performance. Of course, the lowest limit to F is unity. Insofar as the crystal rectifier is concerned, it contributes to increasing F by (1) its conversion loss and (2) the noise generated in the metal-crystal contact. Therefore, these two items are chosen as meaningful quantities to measure and use as a basis for electrical selection.

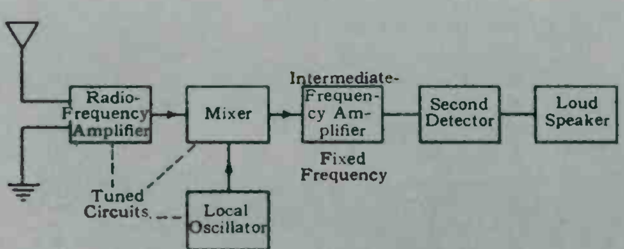


Fig. 2—A conventional superheterodyne receiver system.

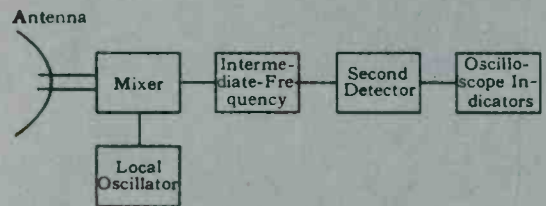


Fig. 3—Block diagram of a radar receiver.

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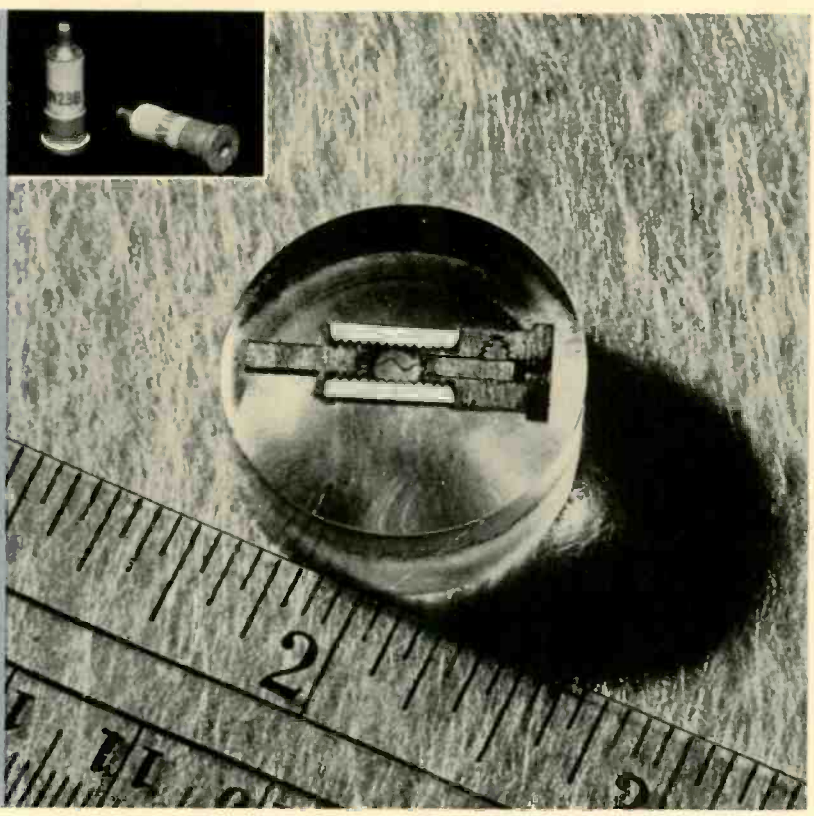
Cutaway view of crystal and holder showing positioning of five-mil tungsten contact wire. The insert is a view of two fully assembled crystal units, approximately full size.



The Function of a Crystal Rectifier

Both commercial broadcast radio and radar reception utilize the superheterodyne principle. A typical block diagram is shown in Fig. 2. The relatively high-frequency voltage from the antenna—in contrast to the low-frequency voltage desired at the speaker—is amplified in the radio-frequency amplifier. This selector circuit is tuned to respond to a definite narrow band of frequencies and rejecting all others, a process necessary for the selection of the desired broadcasting station. The amplified signal voltage is impressed on the mixer stage, to which, already, the local oscillator has applied a relatively strong r-f voltage of frequency several kilocycles higher or lower than the signal frequency. This difference between the signal and the oscillator frequencies is kept constant by ganged tuning of the two stages—a process called "tracking."

The mixer has the peculiar property of producing an output voltage with a frequency equal to the difference between the local oscillator and the signal. This is an extremely useful property, because a low-frequency voltage is much easier to amplify to a high level than one at a high frequency. Further, if the local oscillator tracks with the signal it is not necessary to provide tuning in the succeeding amplifier. Any intelligence superposed on the signal by some type of modulation is not modified in the frequency conversion. The second detector stage converts this modulation into a form suitable for actuating a loud speaker.

The block diagram for a radar receiver, Fig. 3, is slightly different than Fig. 2. Radio-frequency amplifiers are not available for frequencies higher than 3000 mc; therefore, the signal received by the antenna is fed directly to the mixer shown in the illustration and in which the crystal serves in place of the usual vacuum tube. The local-oscillator frequency must be supplied by a klystron[1]. Since the frequency of these tubes drifts, the difference or intermediate frequency must be chosen high enough to be large compared with local-oscillator and transmitter frequency drift, but must not be so high as to be extremely difficult to amplify. The commonly used intermediate frequencies for radar receivers are 30 and 60 mc.

The key to the operation of the mixer is to be found in the nonlinear volt-ampere characteristic pictured in Fig. 1[2]; for the present purposes it is not necessary to specify the properties of the device in addition to the volt-ampere characteristic. It will be seen that the local-oscillator voltage is large enough to traverse much of the characteristic curve shown in Fig. 1, and that it is much larger than the signal voltage.

The nonlinear characteristics of the crystal are such that the output current consists of several components at different frequencies. The only one of interest is the signal having a frequency equal to the difference of the signal and local-oscillator frequencies. Thus mixer circuits are arranged so that the voltage corresponding to the difference frequency is the only one to appear across the i-f (intermediate-frequency) amplifier input.

An important performance characteristic of a mixer is the ratio of intermediate frequency output power to signal input power, viz. $P_{\text{i-f}}/P_{\text{signal}}$

Expressed in percent, this is the *conversion efficiency*, and expressed as ten times the logarithm to the base ten, it is the conversion loss in decibels.

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[1] "The Klystron", by Dr. Sydney Krasik, *Westinghouse* ENGINEER, Vol. 6, Nov. 1946, p. 176.

[2] See L. C. Peterson, F. B. Llewellyn, *Proceedings Institute of Radio Engineers*, Vol. 33 (1945) p. 458.

Equipment was developed by the N. D. R. C. Laboratories to measure these quantities. Rectifiers accepted by the Army and Navy are tested by duplicates of their standards.

The exemplary performance of crystal rectifiers in radar systems during the war promises their continued use. Eventual development of electron-tube amplifiers and mixers will not displace the crystal rectifier entirely because it is light, small, and needs no auxiliary power source. Future development should provide even more sensitive and stable rectifiers.

• • •

The Crystal Accelerometer—A Shock Tester

A test pilot "peels off" and in the subsequent dive, plane and pilot may reach an acceleration of five times gravity, or as it is abbreviated—5 "g's." If 9 g's are reached while he is in a sitting position (not prone) the pilot will "black out" and crash - - - - - a turbine vibrates ominously at 15 g's. Thus, it can be seen that personnel and machinery are vitally affected by acceleration.

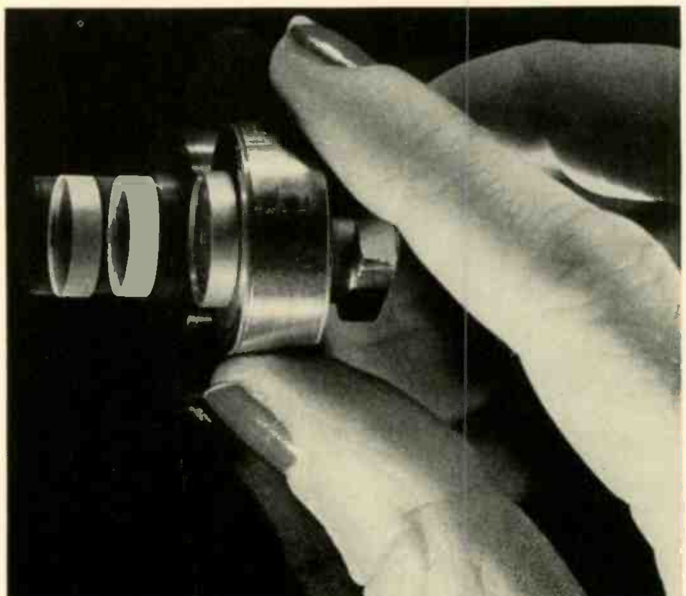
These acceleration rates of 5, 9 and 15 may be experienced for relatively long periods. However, the shock test engineer is concerned as well with ultra-high shock, split-second movements of the order of 5000 g's; in the measurement of these or lower values he uses a new tool—the crystal accelerometer.

This instrument measures the acceleration rate of the body being investigated because the acceleration is, in effect, proportional to the shock producing force. Piezoelectric crystal phenomena are made use of in the accelerometer. A change in force on the crystal causes an electrical charge to appear on the crystal surfaces. The amount of the charge is directly proportional to the change in force exerted, and therefore to the acceleration.

The crystal accelerometer is thoroughly portable, although its associated equipment may not be. Weighing only a half pound, it is small enough to be carried in a coat pocket. Two quartz crystal plates are clamped firmly in a steel housing. The minute charges generated on their surfaces are passed to a sensitive voltage-detector system, which is an inherent part of the instrument. An amplifier and oscillograph external to the accelerometer, connect to it by ordinary concentric shielded cable. A camera photographs the record on moving film with such speed that events of one thousandth of an inch cover an inch of film.

With the new instrument accelerations up to 8000 times gravity can be measured at a frequency limit of 10 000 cps.

The Crystal Accelerometer showing the quartz plates. Double exposure gives this photograph the appearance of an exploded view. The cover has been removed.



The Resnatron—A Generator of Microwaves

Linked to both radar and nuclear physics, the resnatron is one of the most significant of recent electronic developments. Attaining high power at ultra-high frequencies, the resnatron achieved fame as a jamming device against enemy radar. These same characteristics give it promise as a component for television, FM, and dielectric heating.

Dr. F. W. Boggs, *Westinghouse Research Laboratories*†

Development of practical high-frequency tubes, such as the magnetron* and klystron** was one of the most important contributions of radar to electronics. Yet these tubes usually are limited in power outputs or efficiency, or both. The powerful cavity magnetron, for example, is a pulsed tube, operating for only one microsecond with a repetition cycle of a thousand per second while the klystron is characterized by low output and low efficiency although possessing the important advantage of tunability. Out of the same program, however, came the resnatron, a tube capable of operating continuously at 50 kw or more in the ultra-high-frequency band.

The resnatron is thus patently significant in many industrial applications and represents an important addition to the family of electronic tubes, particularly now that television and FM are adopting the higher frequencies. In these applications and in the field of dielectric heating, the high power attainable by the resnatron at high frequencies is noteworthy.

Except for conditions imposed at high frequencies, chiefly the transit-time effect and the problem of heat dissipation, the resnatron differs little in principle from certain ordinary oscillator tubes. It consists of a cylindrical cathode having 24 emitting filaments, a control grid, an accelerating grid, and an anode. In addition, it has two resonant cavities, one between the cathode and control grid, the other between the accelerating grid and the anode, which behave much as the ordinary inductance-capacitance output, or tank circuit.

The principals on which the tube is based were investigated by Dr. David H. Sloan, and Dr. L. C. Marshall at the University of California, when seeking a high-power source of high frequency for electron acceleration. Their first successful resnatron was made in 1938. Later models, designed and developed for radar under a war-dictated stimulus, by Dr. Sloan and Dr. W. B. Fritter and their co-workers at Westinghouse Research Laboratories, were used to jam the operation of German radar systems searching for Allied planes. The tube itself was produced at the Sharon Works of the Westinghouse Electric Corporation.

Principles of Operation

The resnatron stems directly from the well-known class-C radio oscillator. When the principle of electrical oscillators was first discovered it was used primarily in class-A operation, which merely indicates that electrons pass from cathode to anode at all times even when the control grid is most negative. This process is now recognized as inefficient because substantial portions of the electrons arrive at the anode at improper phase. Later development showed that greater efficiency could be obtained if the current passed through the tube only during a short portion of the cycle. Such tubes are called class-C oscillators and are the ones commonly used in present-day radio practice.

Many types of circuits having different properties and adapted to different needs are used in conjunction with such tubes. One is the Hartley oscillator circuit, of which a typical example is shown in Fig. 1. When the grid is driven positive

*See "The Resonant-Cavity Magnetron," Dr. John W. Coltman, *Westinghouse* Engineer November, 1946, p. 172.

**See "The Klystron—Radar Receiver Oscillator," Dr. Sidney Krasik, *Westinghouse* Engineer, November, 1946, p. 176.

†Since preparing this manuscript, Dr. Boggs has joined the staff of U. S. Rubber Co. Laboratories at Passaic, N. J.

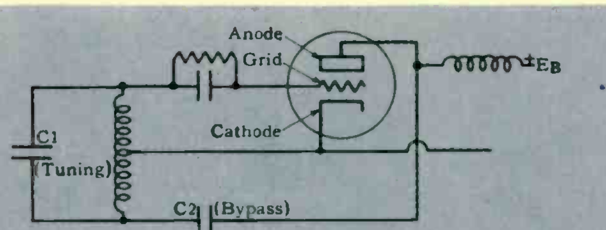
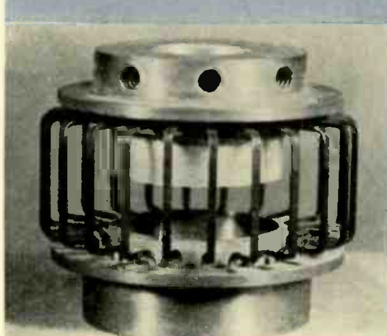
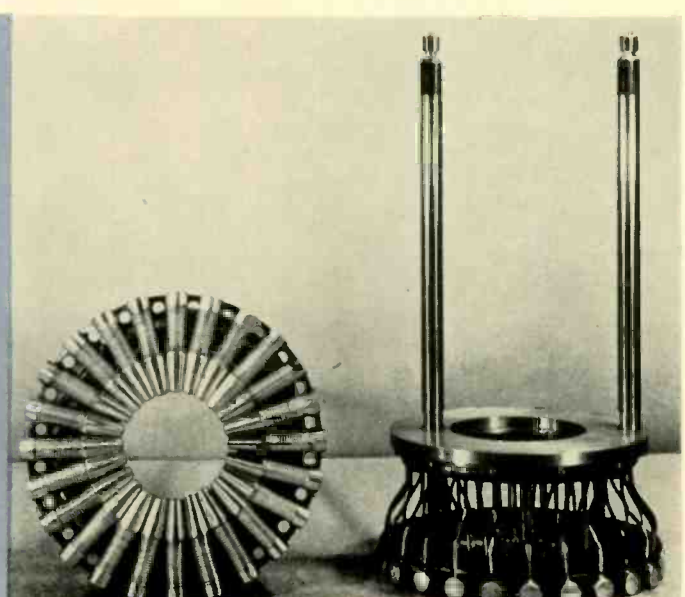


Fig. 1—Typical Hartley radio-oscillator circuit.

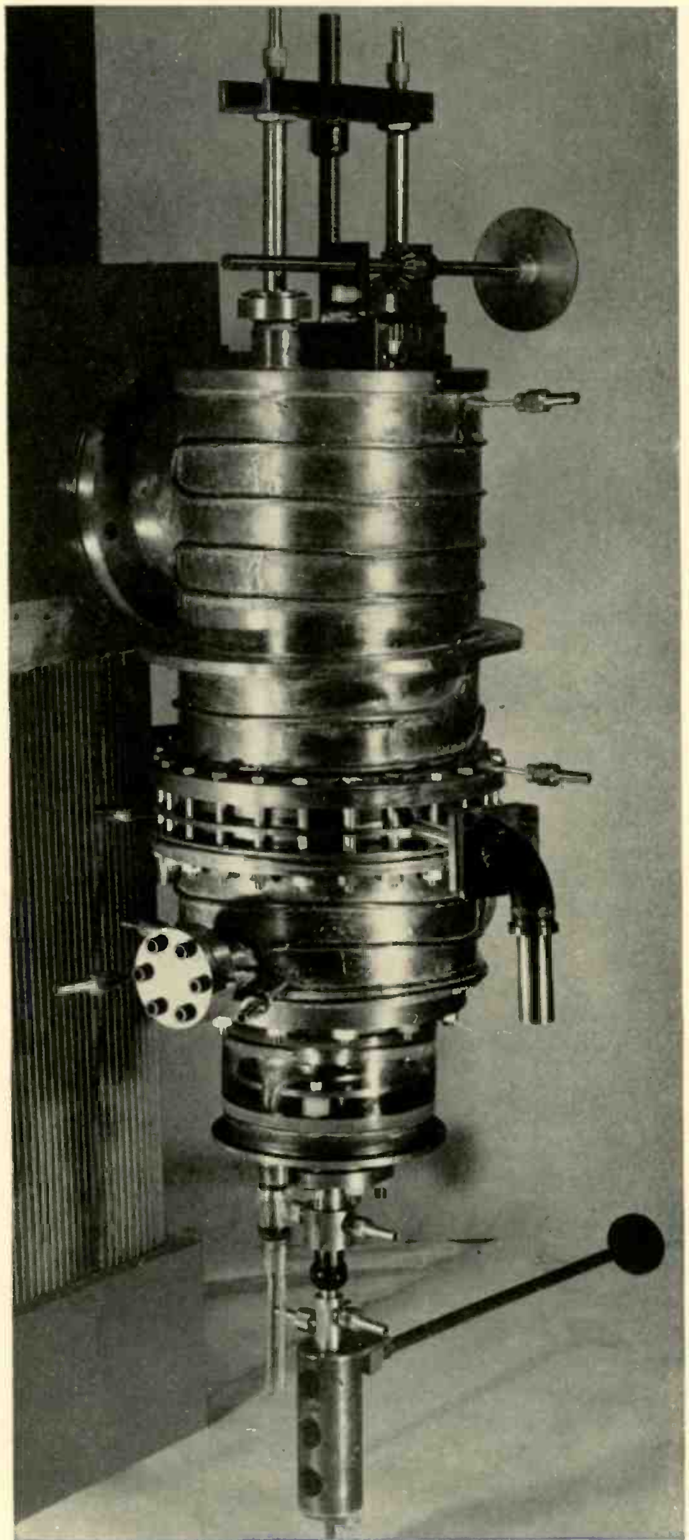


← The cathode consists of 24 tungsten strips, each size 50 mil—ground flat. The rating is 1800 amperes, 2.0 volts.



→ The "Daisy", an ingenious screen grid-anode tuning device. Twenty-four Sylphons maintain an equal pressure.

by an r-f voltage, electrons pass from the cathode to the anode, thus providing short bursts of current that excite oscillations in the resonant electric circuit, just as the short impulse in the escapement of a clock excites the oscillations of the pendulum. The condenser $C2$ serves to feed back some of the energy to the grid-cathode circuit, thus maintaining the oscillations. For this method of producing oscillations to be successful, it is necessary that the impulses be in the right phase, as in the case of the pendulum, otherwise they will retard the pendulum rather than drive it. The operation of the resnatron is entirely analogous.



The resnatron in detail. The lower horizontal rod is the cathode tuning drive; the upper is the "Daisy" tuning drive.

At very high frequencies, the time taken by the electrons to travel from the cathode to the anode and known as the transit time, becomes so great that the electrons are not moving in the right direction with respect to the field. Referring to the pendulum analogy again, this would be tantamount to continuing the pulse in one direction after the motion of the pendulum had already started in the other; obviously the efficiency of the tube would be decreased enormously. This difficulty can be overcome by decreasing the dimensions of the tube, but no matter how careful the design, some electrons inevitably will collide with the tube elements.

The kinetic energy of the electrons may be converted into heat if they strike an electrode, the heat generated by the impact on the electrode being of sufficient intensity to melt it. If the tube elements are reduced in size sufficient to lower the transit time, they will become too small for adequate cooling unless the current is likewise decreased. Thus, although tubes can be made to operate satisfactorily at higher frequencies their power output is inevitably small.

Transit-Time Effect

Inasmuch as the transit-time phenomenon cannot be avoided at the very high frequencies if appreciable power is to be attained, the tube construction must be such that transit time does not interfere with its operation. If the phase shift in the feedback line is properly chosen, electrons start from the grid sufficiently far in advance and are enabled to reach the anode before the field reverses itself; operation without too much loss of efficiency then becomes practical.

In standard tubes, the transit time is negligible compared with the period of oscillation, therefore it is unnecessary that all transit times be the same. As the frequency is increased the need of having all electrons pull together requires a structure in which they travel the same distance in passing between the electrodes. In a cylindrical tube such an optimum condition is possible only through radial or axial symmetry.

Electrons leaving the same portion of the grid at different times must act cooperatively to add energy to the r-f field, for electrons out of phase remove energy from the field. This is achieved by limiting the passage of electrons through the grid to that portion of the cycle during which they are in proper phase relation for maximum power conversion efficiency. However, a reduction in the average current passing through the tube results, with a consequent diminishment in power output.

Unlike the standard class-C oscillator the resnatron is not a triode, but a tetrode; there are not three but four different elements in the tube. The reason for including a fourth element, the accelerating grid, is to insure efficient operation. The extra electrode imparts a high velocity to the electrons after they leave the control grid. Since the electrons leave the grid not only at different times but also with different velocities, they tend to scatter as they pass through the space between the electrodes. If, however, they are accelerated by a high potential, their initial velocities are negligible compared to the velocities they attain when accelerated by the second grid. Moreover, if the field is the same for all electrons, all reach substantially the same velocity. Ideally, the accelerator should be at anode potential, a principle followed in the last tube constructed. However, it is much simpler to operate a tube in which the transit time can be adjusted by varying the accelerator voltage. If provision is made for this, the spacing between the electrodes can be made much more critical.

Cooling

Still another problem when operating tubes at high power is the removal of heat generated by electron collisions with the tube elements. The most serious cooling problem in any tetrode is presented by the control grid. As a result of the control grid's position in the tube and its small size, water cooling is difficult. If classical construction is retained and this grid is enlarged to allow for cooling, the amplification factor is reduced by the greater grid-to-cathode spacing which this entails. The design of the resnatron grid simultaneously overcomes many of these difficulties in an ingenious manner, contributing probably the most important single improvement Sloan has made.

A cut-away view and a cross-section of the electronic portion of the tube are shown in Fig. 2. The anode is formed of tubes through which cooling water is circulated. The tubes beyond the surface of the anode are placed so as to form an equipotential and at the same time allow space behind them. Electrons arriving from the screen are trapped in the space between this outer set of tubes and the anode proper and are thus prevented from remaining in the interaction space where they would interfere seriously with the efficiency of the tube. At the same time they form a negative space charge which suppresses secondary electrons resulting from anode bombardment by the primary electrons.

A calculation of the equipotentials and the stream lines on the grid of the resnatron are shown in Fig. 3. These lines show the effectiveness of the design in preventing the electrons from striking the grid. In establishing fields directing the electrons along paths through the electrode openings, the efficiency is increased by the smaller loss of electrons to the grids, and in addition the problem of cooling is minimized. The trajectories and equipotentials for the same grid for a much higher grid potential are shown in Fig. 4. Even at this very positive grid potential few electrons strike the grid. Actually electrons coming from the edge of the cathode are not taken into account, therefore the number colliding may be somewhat more than is indicated by these drawings.

The grid design increases the amplification factor without reducing the size of the grid, and without placing it close to the cathode. At the same time the electrons are focussed away from the grid and the other tube elements so that losses through collisions with the electrodes are reduced. Still another advantage accrues from this construction: the grid is sufficiently massive to facilitate cooling. These three characteristics of the grid design—directional fields, small grid-to-cathode spacings, and relative largeness for easy cooling—effectively solve the most serious problem faced when constructing high-power tubes. In all resnatrons the grid has been cooled by circulating water around its base; if necessary, water could be circulated directly through the electrode.

The focussing action of the grid on the beam from the cathode, to some extent is carried further by the screen. The overall effect has one result that is important and necessary in the cooling of the anode since certain portions of it are bombarded by particularly heavy streams of electrons: not only must water be circulated in these regions, but the circulation must be carefully planned to avoid cavitation or any formation of steam pockets that might lead to local heating and consequent leaks.

Cathode Limitation

For satisfactory power output and good modulation characteristics it is essential that sufficient current density be available. With existing cathodes this had been severely

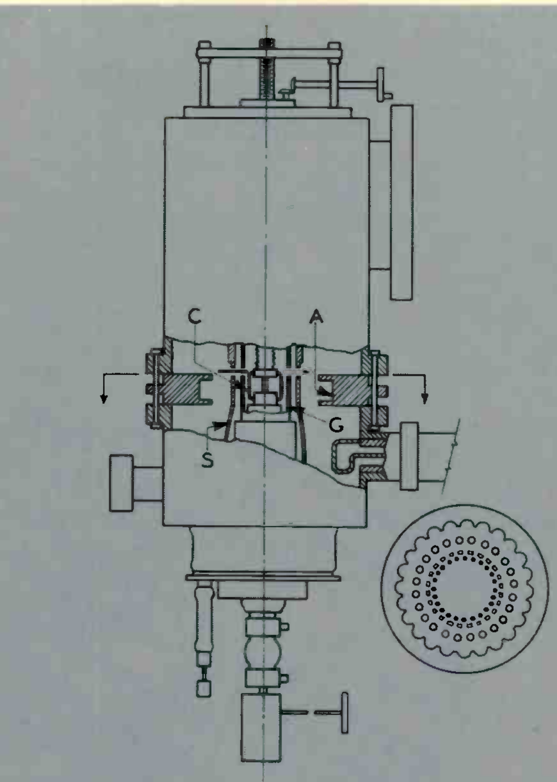


Fig. 2—Cut-away view of resnatron and cross-section (at arrows). *A* is the anode, *C* cathode, *G* grid, *S* the accelerator or screen. The close positioning of grid and cathode will be noted.

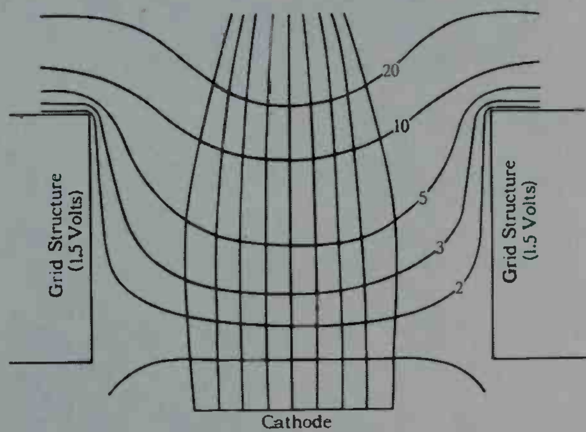


Fig. 3—Electron path based on a calculation of the equipotentials and stream lines on the grid. Design efficacy in minimizing electron-grid collisions is at once apparent.

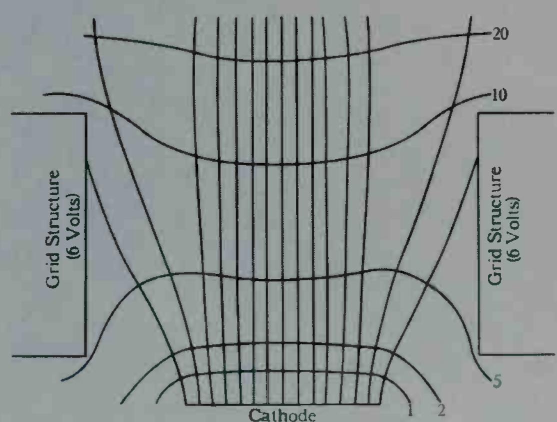


Fig. 4—Shown is the same grid structure as for Fig. 3, but with a much higher grid potential. Even with this increased voltage few electrons strike the grid.

limited. The current density for a unit area is a function of the cathode material and of its temperature, therefore the only practical means for increasing the power output is to increase the current per unit area from the cathode by increasing its temperature and consequently shortening its life. To obtain sufficient current in the resnatron, the cathodes have been run at such high temperatures that only one hundred hours of life can be expected. Cathodes therefore are designed for easy replacement.

Mechanical Aspects

Because the tube is entirely water cooled, copper tubing figures as one of the most important requirements in its construction. The accelerator is a grid made of copper tubes through which cooling water is circulated. The anode is a coil of copper tube in some of the designs. In others, dependent upon the frequency application, different arrangements are used. In general, however, the anode is cooled by a copious flow of water. The different portions of the tube are brazed together in a hydrogen furnace, or in some instances soft-soldered or torch-brazed. The few joints necessary for assembly of the tube are bolted with rubber or tin gaskets to assure a vacuum-tight joint.

The circuit elements of the tube are included in the vacuum envelope of the tube for two reasons: (1) to permit short leads to the circuit elements, and (2) to prevent dielectric heating losses at a glass-to-metal seal facing the tank circuit.

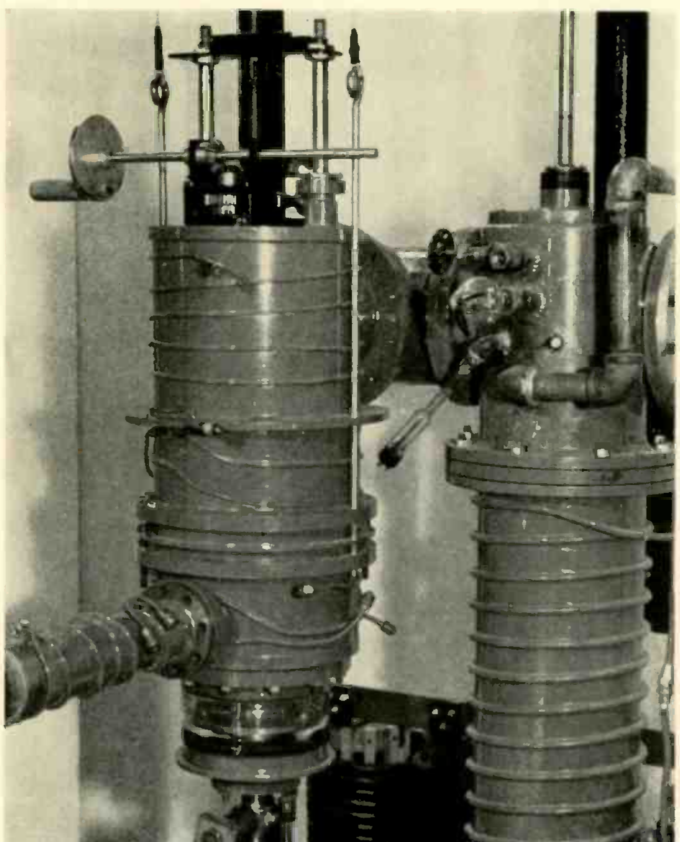
The first is obvious but the second is the important reason for the inclusion. If the circuit elements of the tube are external, inevitably there must be some tube envelope exposed to the high fields of the tank circuit. This follows from the fact that the high-voltage point of the tank circuit must be electrically joined to the anode. At resnatron operating frequencies this would cause considerable power loss in the glass, creating a violent temperature rise which would demolish the glass. For example, if the power output is 50 kw and the Q is 100, there will be 5000 kw in the tank circuit. The voltages are correspondingly great so that the dielectric-heating effect would be severe. By placing the circuit elements in the interior of the tube, it is possible to exclude the r-f from the insulating materials, thus removing a very serious obstacle to practical tube construction.

The circuit elements in the resnatron are sections of coaxial line. Two methods of tuning have been used. In the first, the lines are shorted at one end and terminate in a variable condenser at the other end. In the second, the line is shorted at both ends, the position of one short being variable. This end-plug is water-cooled, and the contacts placed at the ends of Sylphons or metal bellows which expand under cooling-water pressure. In this manner full electrical contact is assured at all times.

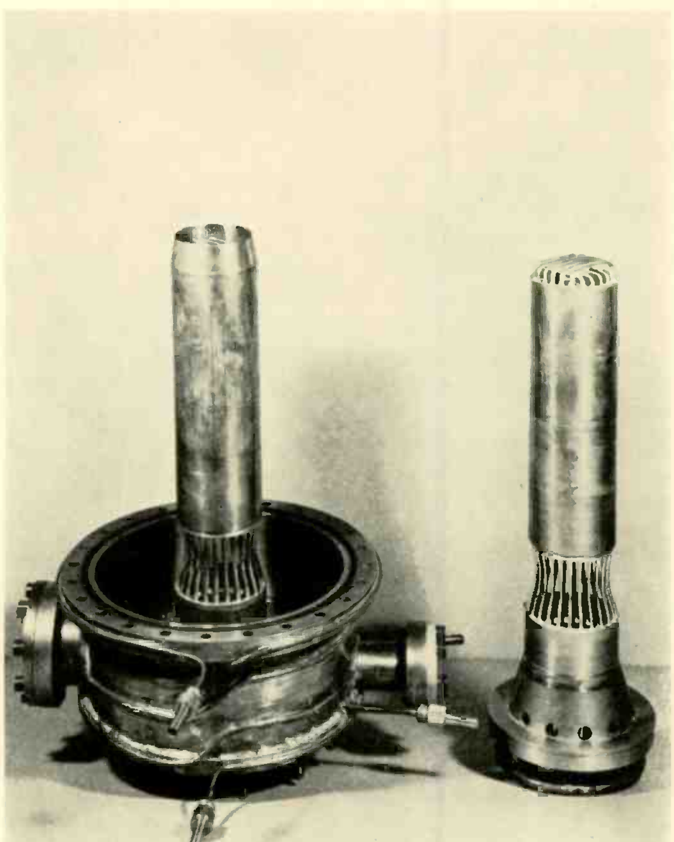
The resnatron is used principally as an oscillator, where feedback is obtained by means of a probe extending from the cathode into the anode cavity. For the resultant phase shift (90°) a suitable transit time is chosen.

It was as an oscillator that the resnatron gave such an outstanding performance in wartime jamming devices. It will function similarly in the field of high-frequency, high-power dielectric heating.

Intensive work continuing at research laboratories throughout the country promises to add the resnatron to the family of amplifier tubes. Undoubtedly it will be in this capacity that the tube will attain its maximum peacetime role as an amplifier in television and FM broadcasting.



The resnatron assembled for operation. Its associated diffusion pump is at the right.



The screen grid installed in its housing. Another type of grid structure is shown beside it.

A New Commutator-Bar Insulation

To produce, under war necessity, an acceptable substitute for mica was an achievement; to produce a superior one seemed the impossible. A new molded or laminated insulation, better than mica in some ways, is formed of two materials, one old, one new. It is composed of asbestos paper impregnated with Fosterite, the synthetic resin that spiraled to fame as a moistureproof insulation for radar and radio transformers used in tropical areas.

E. L. SCHULMAN, *Manager,*
Insulation Application Section,
Westinghouse Electric Corporation

THE Japanese, upon attacking Pearl Harbor, presented the electrical industry with many material procurement problems. If mica were one of the materials made unavailable, the industry would be faced with a staggering problem inasmuch as mica is the insulation backbone of its apparatus. Because no one knew how far the war would spread, it was necessary to prepare for any eventuality. Consequently, the war supplied the impetus for the development of a synthetic material that could replace mica in commutator-bar insulation, a development that has led to a new form of Micarta consisting of asbestos paper impregnated with a synthetic insulation.

A satisfactory commutator-bar insulation must have several different characteristics. Primarily, it must be physically stable at 100 degrees C in order that the commutator be kept tight and smooth. Commutator-bar insulation also must have good arc resistance, good dielectric strength, be non-tracking, have a "seasoning set" similar to shellac-bonded mica insulation, and be sandable and punchable. Any material possessing these characteristics would show promise as a substitute for shellac-bonded mica commutator insulation.

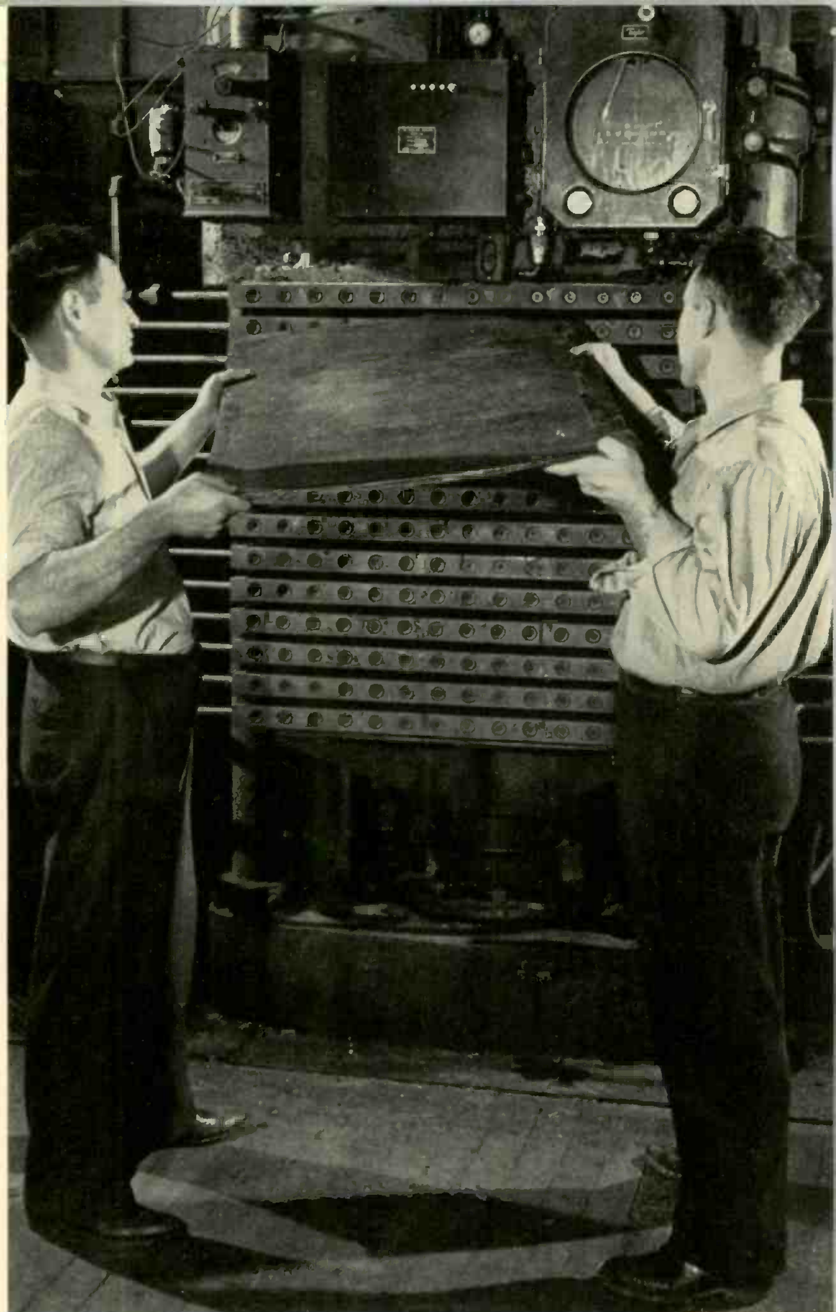
Many combinations of synthetic resins with paper or fabrics were made, examined, and discarded during the development program. Phenolic laminates were eliminated immediately because they track readily and lack arc resistance. Natural resins were not considered because they, too, might become unavailable. The material that proved most satisfactory was a combination of asbestos paper and a Fosterite resin.

Characteristics of Micarta 8564 Insulating Material (Fosterite-Asbestos)

Fosterite resins* are a group of alkyd-vinyl synthetics developed during the war years for moistureproofing electrical equipment. Fosterite resins are unusual in that they change from a liquid to a solid when heated. The particular Fosterite resin chosen for making commutator insulation has physical characteristics similar to those of shellac-bonded mica.

A finished sheet of Micarta 8564 insulating material, which will bear the name "Fosterite-asbestos" for descriptive purposes in this article, in appearance, is similar to a phenolic-bonded, asbestos-paper laminate except that its surface is not quite as glossy. The material is monolithic in character without any possibility of separating the plies. Unlike mica, it cannot delaminate. It punches readily, much better than an asbestos-paper phenolic laminate, which often has to be punched hot to prevent craze cracking. Fosterite resin-treated asbestos can be sawed but not as easily as the conventional type of asbestos-paper laminate. Saws must be sharpened more often when using this new material. However, it can be readily undercut on commutators although the cutting wheels have to be replaced oftener than when undercutting mica-insulated commutators. The material can be sanded and the tolerances held to ±0.0005 inch. In this respect, it is considerably better than mica sheets, which can be held to ±0.001 inch only with considerable difficulty.

Conventional resin-treated paper and Fosterite resin-treated asbestos differ in finished appearance. A phenolic-treated paper is merely coated and the product is quite stiff. The Fosterite resin solution is water-thin and actually impregnates the paper instead of coating it. A Fosterite resin solution which contains 60-percent solids has a viscosity of 25 centipoises, while a 50-percent solids solution of a phenolic resin has a



The laminated form of material made of Fosterite-impregnated asbestos paper is effected on ordinary presses.

*"Fosterite, A Moistureproof Insulation," *Westinghouse ENGINEER*, November, 1945, p. 184.

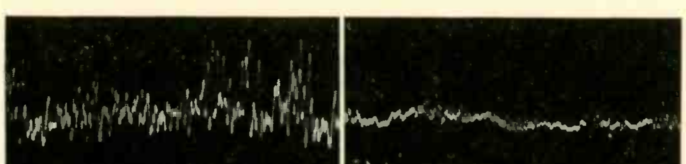
The Fosterite-asbestos material can be made in molded form of relatively complex shapes by building up suitable layers of the impregnated asbestos sheet in a mold and subsequently thermosetting the synthetic resin under heat and pressure.

viscosity of 200 cp., indicating its fluidity. Asbestos paper treated with Fosterite resin looks like blotting paper and has a leathery feel. The treated paper cannot be stored for more than three or four days and must be kept covered because one of the ingredients of the resin is slightly volatile. If the treated paper is stored too long, it will set and become unsuitable for laminated parts.

Method of Manufacture

Laminates—Sheets of asbestos, in the present batch process, are stacked in racks and lowered into the impregnating solution for approximately 30 minutes. The racks are then removed from the impregnant and allowed to drain for about one hour. The impregnated paper is placed in a 60-degree C oven for five minutes to remove the solvent, whereupon the paper is ready for laminating.

The equipment used for laminating Fosterite-asbestos is the same as for preparing conventional laminated materials, with one difference, however, in pressing the new material. When pressing phenolic-treated paper, the material is put into a hot press and steamed without pressure until the stack is hot. Pressure is then applied for a brief period, the duration being regulated by the thickness of the laminate. Fosterite-asbestos, on the other hand, is placed in a cold press and the pressure applied before the press is heated; otherwise, it reacts so quickly to temperature that the material would set before pressure could be applied. The laminating pressures range from 100 to 1500 psi, the higher pressures tending to make a better sheet.



Records made with an electrical smoothness tester of two identical railway motors, except one had a mica-insulated commutator (left) and one (right) was Micarta insulated.

Molded Shapes—Although Fosterite-asbestos was developed for use as commutator insulation, it soon became evident that the physical properties of the resin-treated paper were such that molded products could be fabricated easily. The treated paper is soft, pliable, and takes a deep draw.

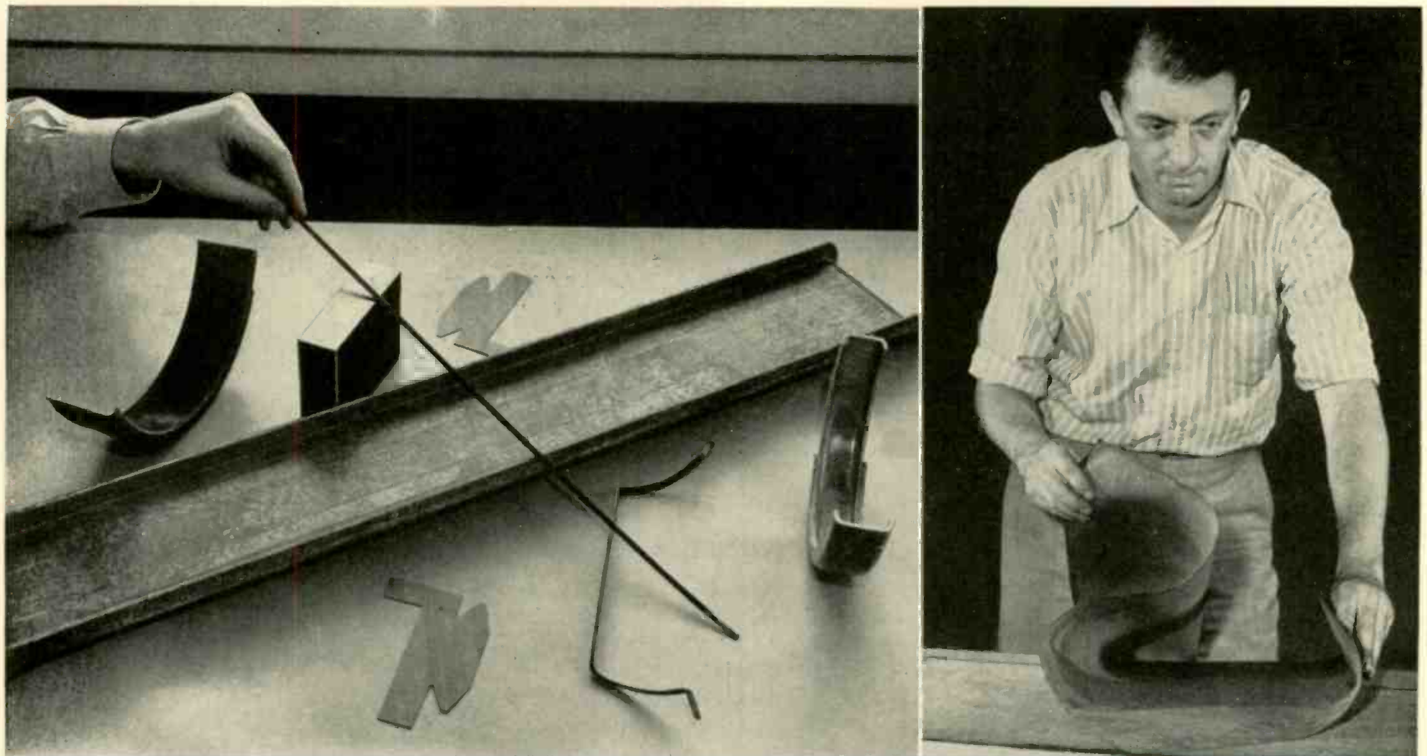
The process for molding is simple compared to molding mica. To mold mica, thin sheets must be fabricated, sanded to size, surface coated, cut into blanks, preformed, and finally molded. To mold Fosterite-asbestos, the paper is treated with the resin solution, cut into blanks, and then molded. Many operations are eliminated. The finished product is thermally set and does not resoften on heating as does mica.

To strengthen the molded product, Fosterite-asbestos is often used in combination with Fosterite-resin-treated cotton or asbestos cloth. Motors have been built with Fosterite-asbestos molded vee rings and commutator insulation. However, double-flanged vee rings are difficult to mold, although single-flange vee rings are easily formed in the proper molds.

Many sizes and shapes of coil-support channels are in production. Rectangular tubes are made simply by wrapping the treated paper around a rectangular mandrel and pressing.

Applications

The process used for building commutators with mica insulation can be followed quite closely when using Fosterite-asbestos insulation. The seasoning sets of mica and Fosterite-asbestos are quite similar, therefore the calculation for shrinkage need not be changed. The material seasons a little slower than mica. This necessitates about 25 percent longer time in the seasoning ovens. If the seasoning temperature is raised from 160 to 200 degrees C, it seasons as rapidly as mica.



The Fosterite-asbestos material is being made in a wide variety of forms and shapes, from simple flat sheets and rods to molded curved pieces. At right is one sheet of asbestos paper after impregnation with the Fosterite resin, ready for lamination and pressing.

Fosterite resin-paper asbestos laminate has been used successfully in punch-bar and machine-bar commutators, and plastic-molded commutators. However, it has one definite limitation, it cannot be used on flush commutators; because of its hardness, brushes would wear out quickly.

The insulation of rotating fields on a 6600-hp motor for an oil tanker required two to three hours by conventional means using mica tape and flexible mica. The time allotted to produce the motors necessitated a faster method. Molding was an obvious solution, but when an attempt was made to mold the pole insulation, Fosterite-asbestos was the only material found that would take the necessary deep draw. Thousands of the pole cells were made of this material. The time for insulating a pole was cut from two to three hours to less than thirty minutes.

Although coils have been insulated with Fosterite-asbestos the practice is not recommended if an alternate method is available. The insulation is quite brittle and does not withstand the rigors of winding as well as mica insulation. It should be considered only where the insulation wall is too thin to insulate with mica tape.

Service Experience

Many types of motors and several generators have been built using Fosterite-asbestos insulation. Some motors have operated satisfactorily for about four years. In addition four 12-inch fan motors with plastic-molded commutators were operated continuously for 5472 hours, all with entirely satisfactory commutation. They were then placed in 100 degrees F, 80-percent humidity for 3673 hours, and tested at 900 volts to ground for one second without failure. Commutation was satisfactory after shelf-life test. Brushes wore during the running tests $\frac{1}{32}$ inch, which is considerably less than with mica-insulated commutators.

After two and a half years service on a switching locomotive, a high-speed motor with a commutator insulated with Fosterite-asbestos was inspected. The commutator had a high glossy polish and no signs of etching, burning or pattern-marking caused by flashover or bad commutation. All parts were found tight, the commutator as well as the entire motor being clean and in perfect condition both electrically and mechanically.

The commutator of this motor was subsequently tested for smoothness and compared to a motor identical but for a mica-insulated commutator. The test was made on an electrical smoothness tester, and the resulting oscillogram indicated the relative smoothness of the commutators.

Fosterite-asbestos is superior to mica in some of its physical properties. However, its outstanding advantage is in cost. Accurate costs for producing it in a pilot plant are not available, but are known to be somewhat less than mica. A fully automatic plant is contemplated for treating the asbestos paper. In such a plant the cost should be considerably less than a corresponding mica part. The results on the use of the synthetic material have been so satisfactory thus far that a highly active future is predicted.

TABLE I—COMPARISON OF PHYSICAL AND ELECTRICAL PROPERTIES OF MICARTA 8564 INSULATION MATERIAL AND MICA

	8564 Insulation (Fosterite Resin Asbestos)	Commutator Mica
Shear strength, psi	393	204
Deflection at failure of shear test, mils	0.21	0.87
Tensile strength, psi	15 000	21 000
Charpy impact, pounds per inch	1.45	2.37
Elongation of 2-inch sample, inch	0.0085	0.0025
Oil absorption (25 degrees C, 24 hours), percent	0.14	159
Oil absorption (110 degrees C, 24 hours), percent	0.85	5.7
Moisture absorption (4 hours under 25 psi load), percent	1.71	2.39
Season set (1000 psi, 3 hours at 200 degrees C), percent	1.75	2.2
Short time dielectric, volts per mil	400	890
Power factor (800 volts, 25 degrees C), percent	15.9	1.8
Power factor (1500 volts, 25 degrees C), percent	19.7	1.8
Surface resistance (electrodes ½" apart), megohms per sq in.	30	2000
Arc resistance (ASTM), seconds	185	192
Temperature classification	B	B

STORIES OF RESEARCH

Taking the Measure of Metallic Grains

A most revealing clue in the search for better metals is the size of the structural grains. Relatively large grain size may produce superior rupture and creep strength. In the same metal, fine grain structure may give greater tensile strength, ductility, or endurance. Knowledge of controllable grain size is a vital tool in the metallurgist's kit.

An important contribution to this field of study has been made with development at the Westinghouse Research Laboratories of a new device for rapid and precise determination of metallic grain sizes. The grain-size comparator provides for counting the grains in a certain area or estimating their extent by comparison with a series of standard photographs. It is simply a small portable attachment for a standard metallograph and consists of a ground-glass screen hinged to an illuminating unit with a slotted wooden frame.

To determine the grain size of a particular specimen, a polished and etched sample is placed on the stage of the metallograph and projected in magnified form on the glass screen. Its granular boundaries can be seen in clear, map-like form. A transparent slide of a known, standard grain structure is slipped into the wooden frame and illuminated by incandescent light. The magnifying power of the metallograph is then changed by extending the bellows until the unknown image matches the grain size of the standard. The amount of adjustment needed is read from a scale on the metallograph, and grain size of the unknown specimen determined by reference to a standard graph.

A New Microwave Tool

Like most other performers in the electromagnetic spectrum, microwaves are beginning to demonstrate their versatility. Television appears to be one of the most promising fields of application, but research men are daily extending feelers to such "test cases" as microwave micrometers, specialized forms of induction heating, and atom-smashing machines.

To this growing list, Westinghouse research men have made an important contribution. It is the adaptation of microwave techniques to spectroscopy by Drs. W. E. Good, D. K. Coles, and T. W. Dakin, and based on the measurable absorption of microwave energy by gases and vapors. A microwave "spectroscope" has been developed that provides an insight into the vibrational behavior of molecules at frequencies not susceptible to other methods of spectroscopy.

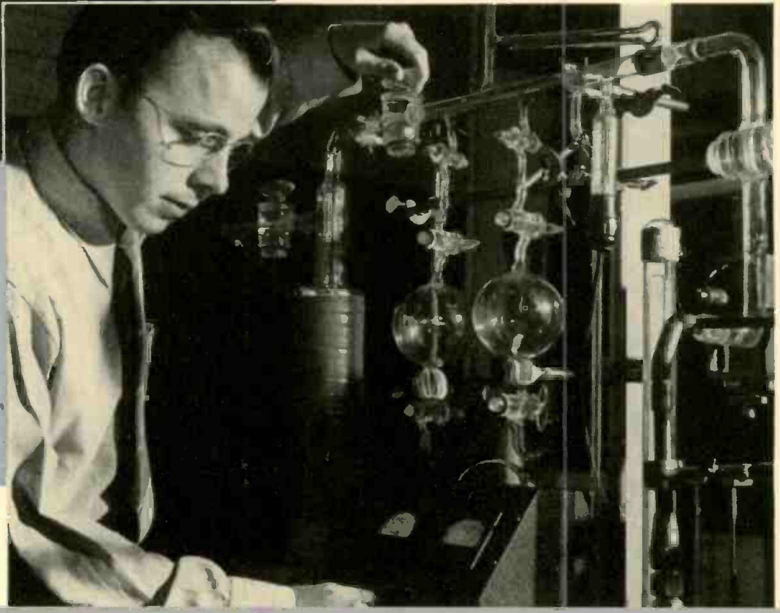
The apparatus resembles a radar set with the radiation taking place internally. The power source is a continuous-wave oscillator tube tuned over a frequency ranging between 20 000 and 25 000 megacycles. This energy is channeled down a 15-foot-long waveguide, into which gas can be pumped for analysis. A crystal rectifier at the end of the guide is used to detect the radio-frequency power.

Absorption takes place when the frequency of the generated power resonates with a particular rotational frequency of the molecules under study. The drop in energy as a result of absorption at this frequency is picked up by the crystal and measured in two ways: first, by direct reading from absorption indicating instruments; and second, by observation on an oscilloscope screen, which provides a picture of absorption versus frequency.

Thus far the spectroscope has been used to study water vapor, ammonia, carbon oxysulfide, acetone vapor, and several other simple compounds—all in the gaseous state. Numerous absorption lines have been observed and their frequencies and intensities measured. From these data, various characteristics of the molecular state have been calculated, such as interatomic distances, electrostatic force between atoms, and moment of inertia.

The new technique of spectroscopy has the advantage of much greater powers of resolution, chiefly because the spectrum can be swept and minutely studied over a selective band of frequencies. As a result the lines studied are much sharper, and the interference between spectra of different compounds, as experienced in infrared spectroscopy, is considerably less.

F. C. Hull of the Westinghouse Research Laboratories uses a grain-size comparator. Unknown specimen, left, is matched to standard in illuminated wooden frame. Calibration read from the metallograph gives grain size.



Dr. William E. Good of the Westinghouse Research Laboratories feeds ammonia gas into the test cell of a unique spectroscope. Valuable data on molecular behaviour at frequencies hitherto untouched by other types of spectroscopy have been obtained by this new technique.

PERSONALITY PROFILES

From co-polymers to high-power radar tubes just about sums up *F. W. Boggs'* experience after he came to Westinghouse in 1942. Primarily interested in molecular chemistry, Boggs was at work on a study of high-frequency dielectric constants when the call went out for aid on development of the Resnatron, the super-jamming device used during the war. He assisted D. H. Sloan, original designer of the tube, in bringing it to its wartime peak.

Boggs was born in Essex Falls, New York, but early in life went with his family to France, where he received his secondary education. He returned to America and Columbia University for his B.S. in 1938 and Cornell University for his Ph.D. in 1942. Evenings spent as research technician at the College of Physicians and Surgeons helped finance his way through Columbia. He is now at the research laboratories of the U. S. Rubber Company, Passaic, New Jersey.

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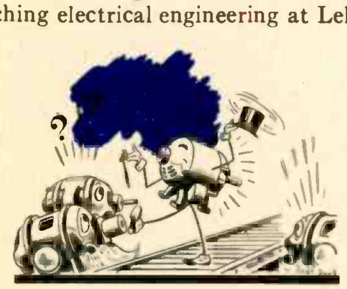
When *W. H. Formhals* last trod these pages—May, 1942—it was as an expert on Rototrols. Such he was, too, for he probably had more to do with the development of that remarkably versatile rotating regulator than any other man. Now, he is presented as an expert on squirrel-cage induction motors. That credit, too, is justified. During the days and many nights, six and often seven days each week, of the last year and a half Formhals has lived with the conception, design, and problems of manufacture of the new motor. Such constant attention to a problem should make one an expert. Formhals' background well qualified him to father the new motor. Before becoming an a-c motor designer Formhals had graduated from the University of Illinois in 1940, had spent some time on the Westinghouse graduate course, had received his Master's degree and had a turn of teaching electrical engineering at Lehigh.



Formhals' full attention is focused on the scores of problems attendant to establishing a new plant to build a new type of motor. But just the same we noticed when we made some reference to his earlier work on Rototrols that his eyes became reflective. After a moment of silence, he said: "Doggone it, and I have to leave Rototrols just when they are well on their feet and are 'going places'."

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In 1922 a young man still in his teens landed in San Francisco. By a devious route he had come from Russia, and was a veteran of the Russian war against Germany and of the more recent revolution. He spoke no English, had no money, knew no one. He got a job in the gold mines, then as a fruit picker and attended YMCA classes in English. In 1923 he entered the University of Utah and three and a half years later graduated with a B.S. in M.E., having provided, as he went along, the funds for his education.

Such is the early and hard background of *Alexander I. Ponomareff*, author of the piece on axial-flow compressors, and present head of the Pump and Blower Engineering Section of Westinghouse. Ponomareff came to Westinghouse in 1926, after college, and after the customary apprenticeship, spent three years in steam-turbine development and design. This was followed by a brief period with a firm of power-plant consultants and a year as an instructor in hydraulics and hydraulic machinery at the University of California. But he liked design best and in 1933 returned to Westinghouse to begin the work that has made him a recognized expert in turbine-type blowers and compressors. In this time he has led the long, painstaking development that brought the axial-flow blower into the realm of the practical. He personally has had much to do with the fact that the axial-flow blower is used on all fighting ships and it was from his section that the designs came for forced-draft blowers for over 1000 U. S. Navy fighting ships and several hundred merchant ships.

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Young electronics engineer *S. J. Angello* traveled the hard road to a doctorate from the University of Pennsylvania. Combining academic brilliance and stick-to-itiveness, he reached his goal in 1942 and immediately thereafter went to work at Westinghouse Research Laboratories. His highly successful synthetic crystal rectifier described in this issue has been hailed as an outstanding achievement in the realm of radar. Dr. Angello is now a professor at the Moore School, University of Pennsylvania.

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In an electrical-manufacturing company the mechanical engineers are often the unsung heroes. Although with electrical products the attention naturally focuses on the electrical problems, very often their design poses as many and as serious mechanical problems as electrical ones. Frequently much more. Hence the demand of electrical design companies for men of high mechanical skill. *T. C. Fockler* was one who helped meet that need at Westinghouse. A native of central Pennsylvania, Fockler received his mechanical-engineering training at Carnegie Tech. After a year with the McKinner Manufacturing Company of Pittsburgh working on machinery design, he joined Westinghouse in 1925 as a draftsman in the motor department. He became a designer in 1931 and for eight years was occupied with the mechanical problems attending the construction of high-speed d-c machines and motor-generator type arc welders. In 1939 he became chief of the motor-department drawing office, and recently when Westinghouse established its new motor manufacturing plant in Buffalo he was appointed Manager of A-C Motor Engineering. Fockler is widely recognized as an expert on the application of anti-friction bearings to rotating apparatus and to him goes much of the credit for the new sealed bearings that run for years without relubrication.

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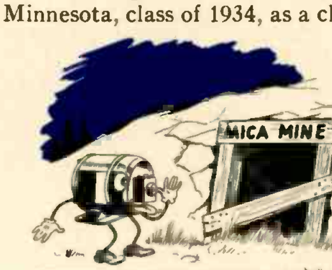
Two other of our authors are "repeaters." This is the third appearance within a year for *T. J. Putz*—all on different subjects. Last May he discussed the geared steam locomotive; last June, the new method of grinding pinions of super-hard steel; and now, the experimental gas turbine. Putz is manager of the engineering section at Westinghouse having to do with locomotive and gas turbines. Just 10 years ago this spring Putz graduated from the University of Illinois as a mechanical engineer. He has been active on various phases of turbine research and design.

E. L. Schulman, authority on plastic materials, is a graduate of the University of Minnesota, class of 1934, as a chemical



engineer. Since coming to Westinghouse in 1941 he has been associated with the development of various high-voltage insulations and mica substitutes. He has done much to make the Fosterite family of synthetics into usable materials.

Among mining locomotives, two speeds are better than one. This eight-ton unit has its controls arranged for slow-speed operation while gathering cars close to working faces and for a higher speed when hauling trains to and from main mine haulage ways.