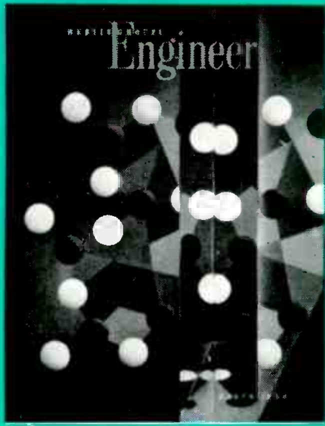
WESTINGHOUSE

Engineer

MARCH 1960

FUEL ELEMENT FOR YANKEE ATOMIC ELECTRIC PLANT

This is one of the first fuel element assemblies for the Yankee Atomic Electric Company's power plant at Rowe, Massachusetts. When completed late this year, the 134 000-kw plant will have 76 of these units within its pressurized water reactor. Each assembly, which is about eight feet long and approximately eight inches square, is comprised of 304 stainless steel tubes, each of which contains 150 pellets of slightly enriched uranium oxide. Yankee Atomic is a Massachusetts electric company formed by ten New England utilities in 1954 to undertake construction and operation of a nuclear power plant, the first commercial one in New England.



COVER DESIGN: To symbolize glass on this month's cover, artist Dick Marsh has viewed his rendition of the atomic structure of glass through refracting surfaces of plate glass—physically impossible, but imaginatively beautiful.

RICHARD W. DODGE, *editor*
MATT MATTHEWS, *managing editor*
EDWARD X. REDINGS, *design and production*
J. A. HUTCHESON, J. H. JEWELL, DALE MCFEATTERS, *editorial advisors*

Published bimonthly (January, March, May, July, September, and November) by Westinghouse Electric Corporation, Pittsburgh, Pa.

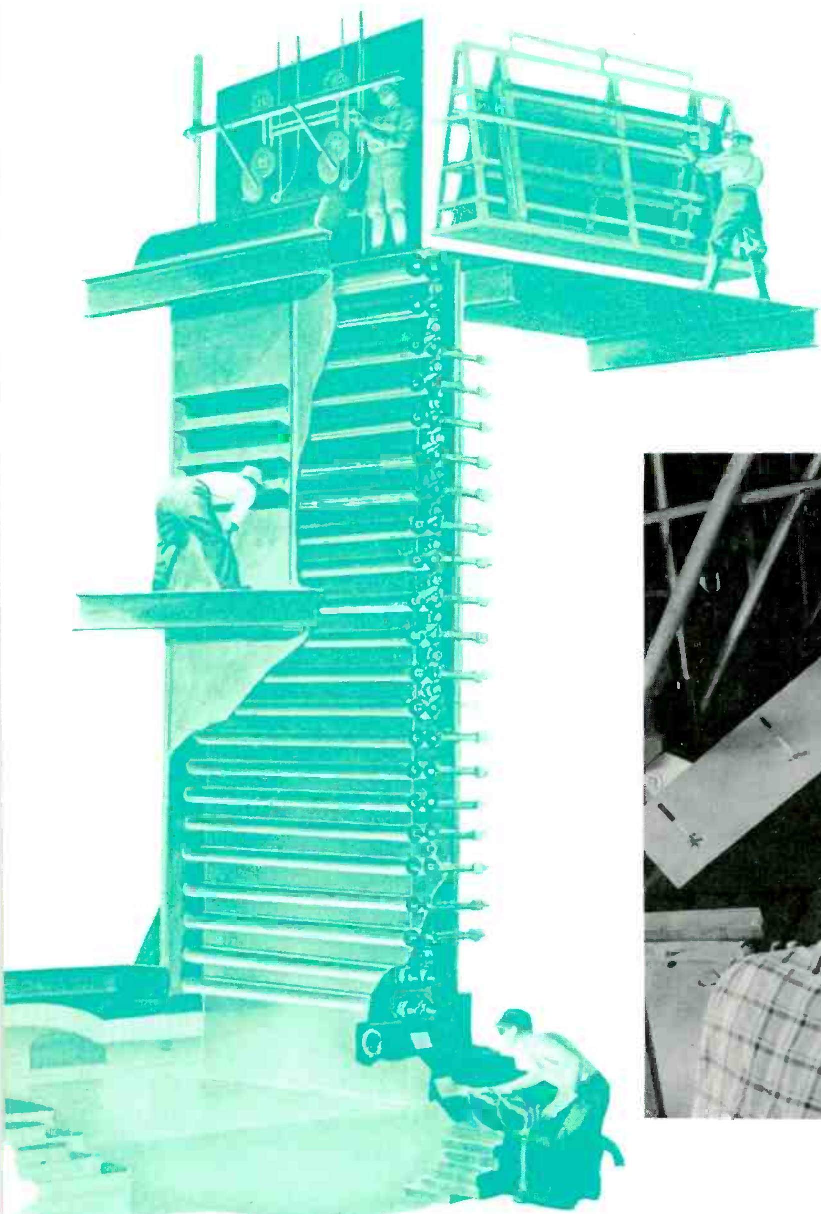
SUBSCRIPTIONS: Annual subscription price in the United States and possessions is $2.50; in Canada, $3.00; other countries, $3.00. Single copy, 50¢. Address all communications to *Westinghouse* ENGINEER, P.O. Box 2278, 3 Gateway Center, Pittsburgh 30, Pa.

INDEXING AND MICROFILM: *Westinghouse* ENGINEER contents are regularly indexed in Industrial Arts Index. Reproductions of the magazine by years are available on positive microfilm from University Microfilms, 313 N. First Street, Ann Arbor, Michigan.

THE WESTINGHOUSE ENGINEER IS PRINTED IN THE UNITED STATES BY THE LAKESIDE PRESS, CHICAGO, ILLINOIS

TABLE OF CONTENTS

GLASS . . . A COMMON AND UNCOMMON MATERIAL



Though glass as a material is taken completely for granted, the substance itself is both confusing and complex. Even today no agreement has been reached as to the definition of glass. Americans regard glass as an inorganic mixture of fused ingredients existing as a supercooled liquid, whereas Europeans prefer to broaden the definition to include organic materials as well.

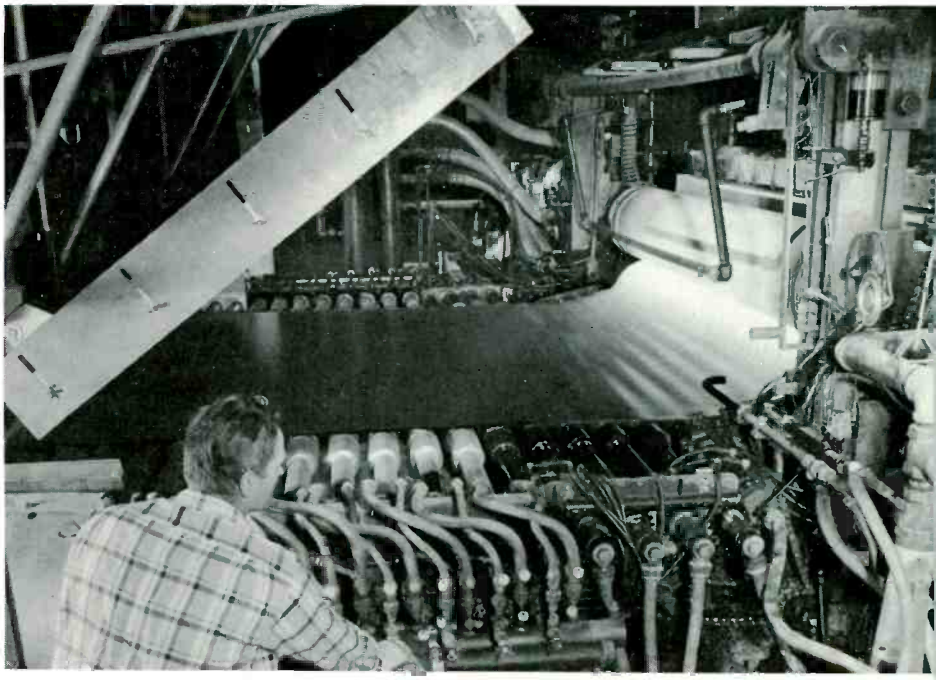
Glass is, however, more a state of matter than a particular mix of ingredients. Paradoxically, glass behaves more as a solid than most solids, in that it is elastic, but when the elastic limit is exceeded it fractures instead of deforming.

Fortunately, its amorphousness permits it to be blown, drawn, pressed, or cast. A comparison of glass, which has no melting point, with steel shows the characteristic advantages of this material. Glass can be drawn from furnaces and continuously worked. Steel or iron, on the other hand, turns immediately into a liquid at its melting point, and consequently must be solidified in molds, reheated, and then worked.

Generally considered a fragile material, glass is potentially very strong, but its strength is critically dependent upon its surface condition. Any flaws take a drastic toll on its strength. Interestingly, a small diameter glass rod is proportionately stronger than a larger one simply because there is less possibility of surface flaws. Unfortunately, when glass cools many surface flaws appear. But strength tests show that before the flaws set in, certain types of glass can withstand pressures of one million pounds per square inch.

The reasons behind its most used characteristic—transparency—are responsible for other properties of glass. For example, glass is transparent because it has no free electrons, and therefore is an insulator as well. With free elec-

This article is based on information and references furnished by Pittsburgh Plate Glass Company, Libbey Owens Ford Glass Company, and Corning Glass Works, and was written by D. E. Udell.



trons the magnetic component of the electromagnetic radiation would force the electrons to move, thus cancelling out the electric component of the electromagnetic radiation. With either the electric or magnetic field eliminated, light would cease to exist. This situation is analogous to the cancellation of radio waves by bridges or other metallic structures with "free" electrons.

Though a good insulator at room temperatures, glass becomes a good electrical conductor at elevated temperatures. This is due to the fact that glass can be considered as an ionic liquid. Because of the high viscosity at room temperature, the ions are not easily moved; however, as temperature increases, ions are permitted to flow, and will sustain an electric current.

history

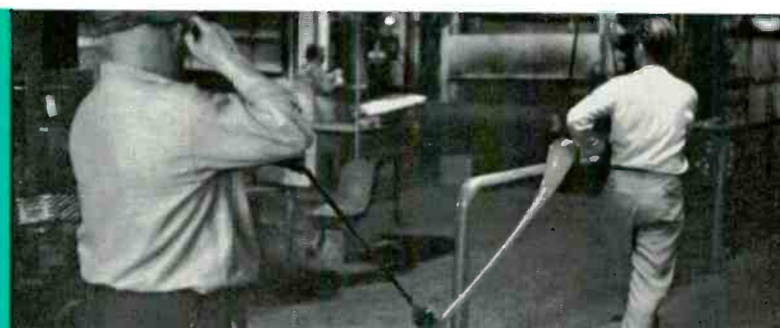
Because it could be easily worked, glass became an art medium for the Egyptians several thousand years before the Christian era. They fabricated pitchers, jugs, and other containers from colored glass, which they adorned with gems and thin strands of glass. Interestingly, early Egyptians did not know of glass blowing. Instead they wrapped molten rods of glass around a solid mold. A subsequent heat cycle fused the spirally wound container into solid form.

The discovery and development of glass blowing in about 100 BC was a significant manufacturing change in the glass industry. Manufacturing methods for glass tubing, window glass, and all containers were up to this century merely variants of this basic process. At the time, however, glass blowing brought about a shift in artistry, from the glass engraver to the glass blower, so the shape of the container became the major medium of artistic expression. Not until about 100 AD was colorless transparent glass developed. Its perfection by the Romans opened up a new use for this material—windows. The Romans are credited with the first use of windows, and also developed manufacturing techniques for making flat glass that were used until this century. The first window, found in the ruins of a Roman bath house, supposedly was made by dropping a piece of molten glass on a rock and pulling at it from all sides until it had taken on a sheet-like form.

Crown glass was also developed by the Romans. This flat glass was made first by blowing a hollow sphere of glass, to which was attached a rod or "punty." The blowpipe was then ripped off, leaving a hole in one end of the sphere. By whirling the sphere around on the punty and simultaneously heating it, the centrifugal force flattened the glass into a sheet. The center portion attached to the rod—called the crown—was too thick to be used, and as a result the sheet had to be cut into small pieces. Following the crown glass method was the hand cylinder method. Instead of a sphere, a long cylinder was blown, which was cut down the center and heated until it flattened out into a sheet. Early in this century this general method was still used, except it was a mechanized instead of a manual operation. A blowpipe was lowered into a pot of molten glass and raised vertically with an electric drive to a height of about 40 feet. A diameter of nearly 30 inches was maintained with pressurized air. This increased production, but it was still a discontinuous operation and could not compare with the relatively simple but high-production methods used today.

Even today, glass blowing is truly an art demanding much patience and instinct. Anyone attempting to blow glass bubbles in a laboratory soon finds out the bubble fractures shortly after forming. The glass blower, however, takes the molten glob of glass and rolls or "marvers" it on a cold steel table to shape the "gather" and harden the outer surface. With the hardened surface, the bubble will withstand the pressure of the air inside. In addition, the air being blown inside cools the inner surface, leaving a low

Facing Page—In the manufacture of plate glass, molten glass from the furnace flows over a lip into the forming rolls shown here. A continuous ribbon of glass about 11 feet wide is formed. (*photo courtesy Pittsburgh Plate Glass Company*)
Left—Hand blowing of glass products begins with gathering a blob of molten glass on the end of an iron blowpipe. As shown here a hot bulb of glass can be placed in a mold, and the bulb blown out against the wall of the mold.
Top right—Molten glass can be drawn into rod or tubing by hand. A large gather of glass is made on a blowing iron, and a small bubble of air is forced into the gather. Another iron is then attached to the end of the glass by a helper, and the "gaffer," keeping the bore open by occasional puffs of air, stretches the glass by walking backward away from his helper.
Bottom right—Glass is drawn automatically at speeds approaching 40 miles an hour to form tubing and rod. (*photos on this page courtesy of Corning Glass Works*)



viscous glass fluid between a hardened inner and outer wall. By holding the ware in different positions, the blower can make the inside fluid layer flow, thus obtaining different wall thicknesses for decorative purposes.

methods and techniques

Manufacturing techniques today capitalize upon the unique properties of glass. For example, one method of making window glass is to draw it vertically from a molten pool of glass, through a slit in a block of refractory material. In another method, the glass is drawn vertically, then horizontally over a roller. The thickness can be regulated in either process by the temperature and the rate at which the glass is pulled.

Plate glass, on the other hand, is rolled after being drawn from the furnace. However it is subsequently ground and polished to produce a sheet free of waviness.

Another large departure from methods that imitated the glass blower is in the manufacture of electric light bulb envelopes. Because of the tremendous productivity required, glass blowers obviously could not meet the demand, nor could machines that imitated the steps used by the blower, namely attaching a glob of glass to a blowpipe, marvering it, blowing a ball, and inserting it in a mold and giving it a final puff of air.

Present machines can deliver about 2000 bulbs per minute. One machine performs all forming operations on a continuous basis. A continuous stream of glass passes between two rolls, one of which has equally spaced recessions so that a ribbon of glass is produced with equally spaced biscuits of glass. The ribbon is deposited on a conveyor and the biscuits matched with holes in the conveyor belt. The glass then sags through the belt, producing pear-shaped globs, which closely resemble the finished products. Two half-section rotating molds then enclose the glob. Simultaneously an air hose is lowered from above and compressed air forces the glass to conform to the contour of the mold. The mold then opens, and an arm breaks the finished light bulb envelope from the ribbon.

Old methods are still used on many items where the demand does not warrant high-production machinery. Some tubing, for example, is sometimes hand drawn. A glass worker forms a glob of molten glass on a blowpipe, marvers it, and his helper attaches a punty to the other end. The helper pulls the glass into tubing by walking away from the blower. An occasional puff of air maintains the opening.

Most tubing today, however, is made by either the Danner or Vello process. In the Danner process, a molten stream of glass is poured onto a horizontal revolving hollow mandrel, through which is blown compressed air. Continuous tubing is simply drawn from the mandrel; the temperature of the glass, the amount of glass poured on the mandrel and the rate at which the tubing is pulled determine the diameter of the tube. The Vello process is quite similar. In this case, the mandrel protrudes from the bottom of a molten tank of glass. The glass flows along and off the rotating mandrel and again is drawn off as tubing.

Glass is capable of being worked in many ways. It can be drawn, pressed, blown, but strangely it is difficult to cast in large pieces. The primary reflective mirror for the Mt. Palomar telescope is a notable example of a glass casting, and the utmost care was required in its annealing. The blank for the 200-inch diameter mirror was cooled down to room temperature at the almost inconceivable rate of 0.8 degree F per day—a feat which required almost a year to accomplish.

Though glass brings to mind a material that is transparent and brittle, surprising changes can be made without altering its chemical structure. The two most extreme variants are foam glass and fiber glass.

Foam glass, produced since 1940, has achieved a reputation as an excellent heat insulator. Made into rectangular blocks, this material will float on water, can be cut like wood, is rigid and fireproof. Foam glass is made by mixing finely ground glass and carbon. When the mixture is melted, it expands into a black foam. The result is a glass material containing more than 10 million inert air cells per cubic foot.

Fiber glass is another product which appears to have discarded some of the properties of glass. Like other glass products, it is fireproof and does not absorb water. However, it is flexible, and soft to the touch. Inspection shows, however, that fiber glass is composed of minute glass rods, each one with characteristics identical to those of the parent material.

Fiber glass can be made in either staple form, resembling wool, or in continuous strands, resembling silk.

To produce staple fibers, molten glass is forced through tiny orifices and is whisked away by a blast of steam or air, producing fibers about 9 inches long and about 0.00027 inch in diameter. The fibers can be used either in bulk form, as insulation, or they can be made into strands, much like wool or cotton.

Continuous fibers are also forced through small orifices. But instead of being blown into short fibers, they are drawn off continuously and wound on spindles.

An infinite number of different characteristics can be achieved with chemical additives. Basically, glass can be considered as a structure of silicon and oxygen atoms. The resulting bonds between the silicon and oxygen atoms is such that no repeatable structure is created.

The structure created, however, has "holes" in which different chemical additives, such as sodium, can exist as ions. Common glassware, such as window glass, light bulb envelopes, and tableware contain large amounts of sodium ions. By varying the amount of entrapped sodium ions, the electrical conductivity can be greatly changed.

To good crystalware and lenses are added lead, which increases the index of refraction. The high index gives lead glass its luster and sparkle. Large amounts of lead, up to 60 percent, are also added for radioactive shielding glass.

Different chemicals can also be added to produce coloring effects. Most glass has small amounts of iron oxide, which produces a greenish color. Though not evident when looking through a single thickness of window glass, when viewed lengthwise, a greenish color is definitely apparent.

By removing all additives and leaving a structure composed almost exclusively of silicon and oxygen atoms, excellent heat-resistant glass can be produced.

Though used for thousands of years, glass is just beginning to be understood. Further investigation will undoubtedly disclose even more unusual characteristics, which in turn will increase the utility of this complex and unique material. ■

ELECTRIC POWER FOR THE FLAT GLASS INDUSTRY

From conventional window glass to accurately ground plate glass, electric drives and controls play a vital part in the manufacture of flat glass products.

E. C. FOX
Industrial Engineering Department
Westinghouse Electric Corporation
East Pittsburgh, Pennsylvania

The major developments in the manufacture of flat glass have been from semi-continuous to continuous processing and from manual to machine handling. Electric drives and controls have made this possible, coincident, of course, with the development of new manufacturing methods.

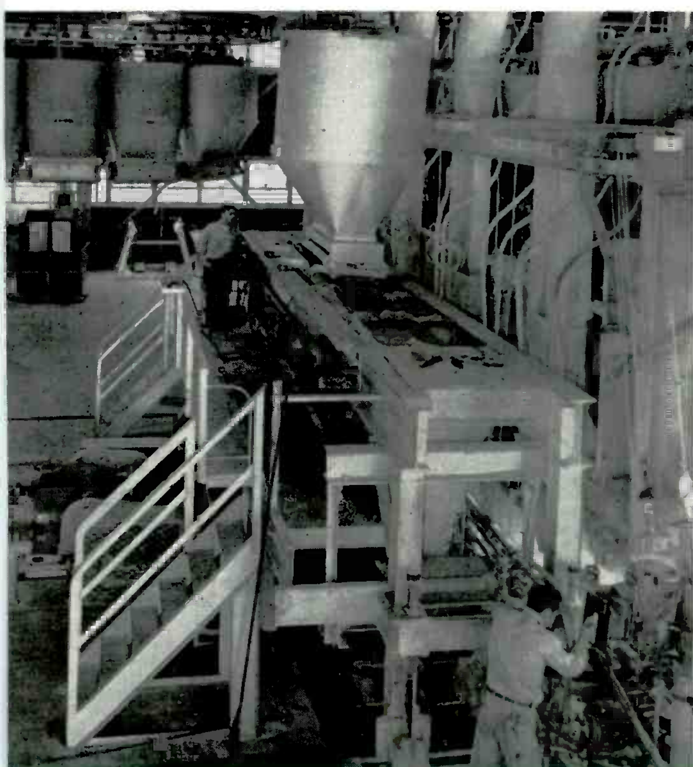
For example, today electric power is used to weigh the raw materials and convey them to the melting furnace, heat the furnace, regulate and power the rolls that pull the glass from the furnace, and run the grinding and polishing lines. In the future, in-line computers might help to increase the usable glass from a line by optimizing the final cutting operation.

preparation of raw materials

The basic raw materials used in the production of flat glass are sand, sodium oxide and calcium oxide. Small amounts of other materials are added to produce different characteristics. At most plants, the raw materials are delivered by rail; the materials are then carried to the storage bins by conveyors. Broken pieces of scrap glass called cullet also are stored in bins.

The electrical equipment used to drive and control the raw material handling equipment is similar to bulk handling equipment used in other industries. Squirrel-cage induction motors drive the conveyor systems. The starting characteristics of these motors are chosen to meet the requirements of the conveyors. In many cases, NEMA-C motors are required to obtain additional starting torque. Some of the motors are mounted outside or in dust-contaminated atmospheres and the enclosure must be chosen to meet these conditions.

The raw materials, including cullet, are accurately weighed, mixed, and conveyed to the glass furnace. This is accomplished by means of batch control. Raw materials are normally removed from the storage bins with vibrators, which transfer the materials to a weighing bin. When the desired weight is obtained, the materials are dumped from the weighing bins onto a conveyor belt that transports the raw materials to the mixing operation. The raw materials then proceed to the glass furnace. A complex relay sequenc-



Charging end of melting tank.

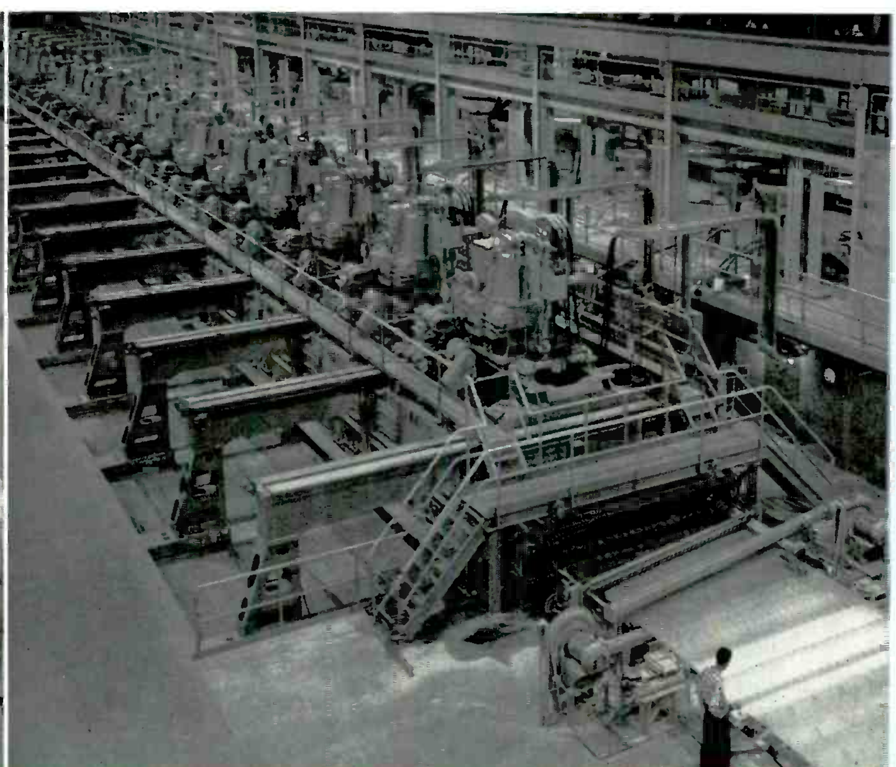


Plate glass manufacture. (*Photos courtesy Pittsburgh Plate Glass Company*) ing control is required to synchronize the weighing and mixing process. In future installations, static logic controls could replace the relay system for an increase in reliability. Data logging could be included with static controls to register the weight and other raw material information in each batch.

The rate at which the raw materials are fed into the glass furnace is controlled to maintain a constant level of molten glass in the furnace. Some furnaces are equipped with a regulator system to control this rate. The system uses a tungsten or platinum probe to determine the level inside the furnace. The probe is slowly driven down by a small ac or dc motor. When the probe touches the surface, the passage of electric current from the probe into the molten glass automatically stops the probe. After determining the position of the probe, the feed of raw material is then either increased or decreased.

flat glass furnaces

The operation of the glass furnace is basically the same for both window and plate glass. A mixture of gas and air is burned over the molten glass within the furnace. The raw materials are placed in one end of the furnace and molten glass is pulled from the other end. The temperature of the glass within the furnace varies from 1500 to 3000 degrees F, at which temperature glass is a good electrical conductor.

Some furnaces use electric heating as a form of booster heat by placing electrodes in the bottom and sides of the furnace and passing alternating current between them. The electrodes are usually composed of molybdenum, one of the few metals that will not react with molten glass.

Electric booster heating has two advantages. First, electric heating causes a mixing action in the molten glass, allowing an increase in the productive capacity of the furnace. Secondly, the temperature of the glass at critical locations can be accurately controlled. However, because the conductivity of glass increases with temperature, a current regulator is required in most cases.

The electrodes receive power either directly from the plant power system, or through transformers to provide isolation and a voltage change. The regulating system senses the current value with current transformers. The output of the current transformer is rectified and compared with a reference voltage. The difference between the two signals is amplified in a magnetic amplifier. The magnetic amplifier controls saturable reactors in the power leads of the electrodes.

production of plate glass

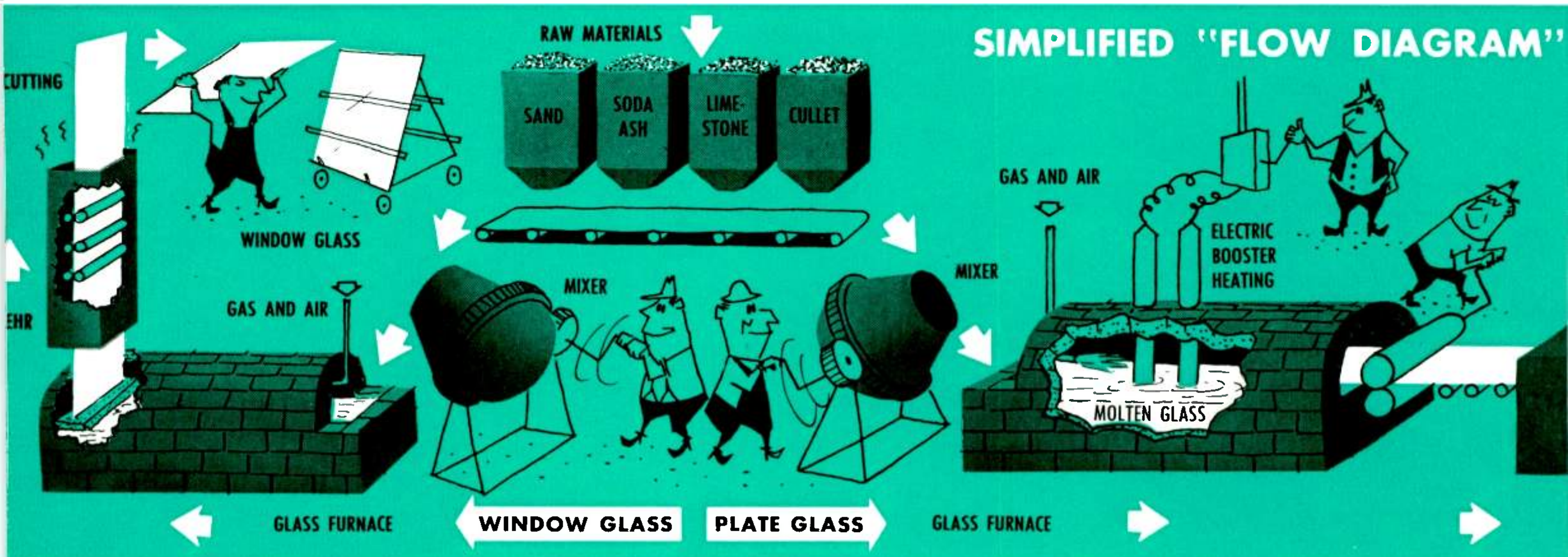
Chemists define glass as a super-cooled liquid. Because glass does not have a definite melting point, it gradually becomes softer as the temperature increases. When glass is pulled from the furnace it has about the same consistency as cold molasses. With this consistency, glass can be drawn from the furnace in a sheet by a pair of pull rolls.

After leaving the pull rolls, the glass enters the lehr, which cools the glass slowly to prevent thermal stresses. The lehr consists of a furnace-enclosed live-roll conveyor several hundred feet long.

The speed between the pull rolls and the lehr must be accurately maintained. Also, the reliability of the lehr and pull roll drives is very important. If the lehr drive should stop, the rolls in the lehr and the pull rolls would warp due to the heat of the glass. Maximum reliability of the drive is often obtained by using a dual drive system, which consists of two separate drive systems with both systems driving through an over-running clutch. The system that runs faster drives the load. Should the faster system stop, the speed of the lehr and pull roll will drop to the speed of the other system.

The drive systems normally used for the lehr and pull rolls are of the direct-current adjustable-voltage type. Tachometer feedback regulators accurately control speed.

The dc motors must be designed to operate in high ambient temperatures found near the lehrs and pull rolls. These motors are generally built with class B insulation, rated to operate on the class A insulation temperature rise of 40 degrees C.



The lehr is heated by either gas or electricity. When electrically heated, resistance heaters are controlled by saturable reactors used in conjunction with magnetic amplifiers to maintain the proper lehr temperatures.

grinding and polishing plate glass

Glass leaving the lehr is cut into large sheets preparatory to grinding and polishing. The sheets are first cemented to the top of large steel tables with plaster of paris. The tables, mounted on slides or wheels, are pushed underneath the grinding and polishing wheels. The grinding wheels are of greater diameter than the table width and have cast iron heads that ride on the surface of the glass and act as a grinding agent.

After the glass has passed under the grinding heads the surface is cleaned. The glass then passes under felt-covered polishing wheels. Rouge suspended in water is pumped between the felt and glass, thus polishing the surface to obtain clearness. The glass passes under several of these polishing heads. The entire grinding and polishing operation is repeated for the opposite side.

Grinding and polishing operations require the largest amount of electric power in glass manufacture. The motors that turn the grinding and polishing wheels are from 40 to 75 horsepower. As many as 100 grinding and polishing wheels are used. Both ac induction motors and dc motors are used for the grinding and polishing wheel drives. When dc motors are used, all the motors are driven from a dc bus. Resistance starters are used to start each motor. In older plants, motor-generator sets generate direct current while newer plants use ignitron rectifiers. Today silicon rectifiers could be used to provide direct current.

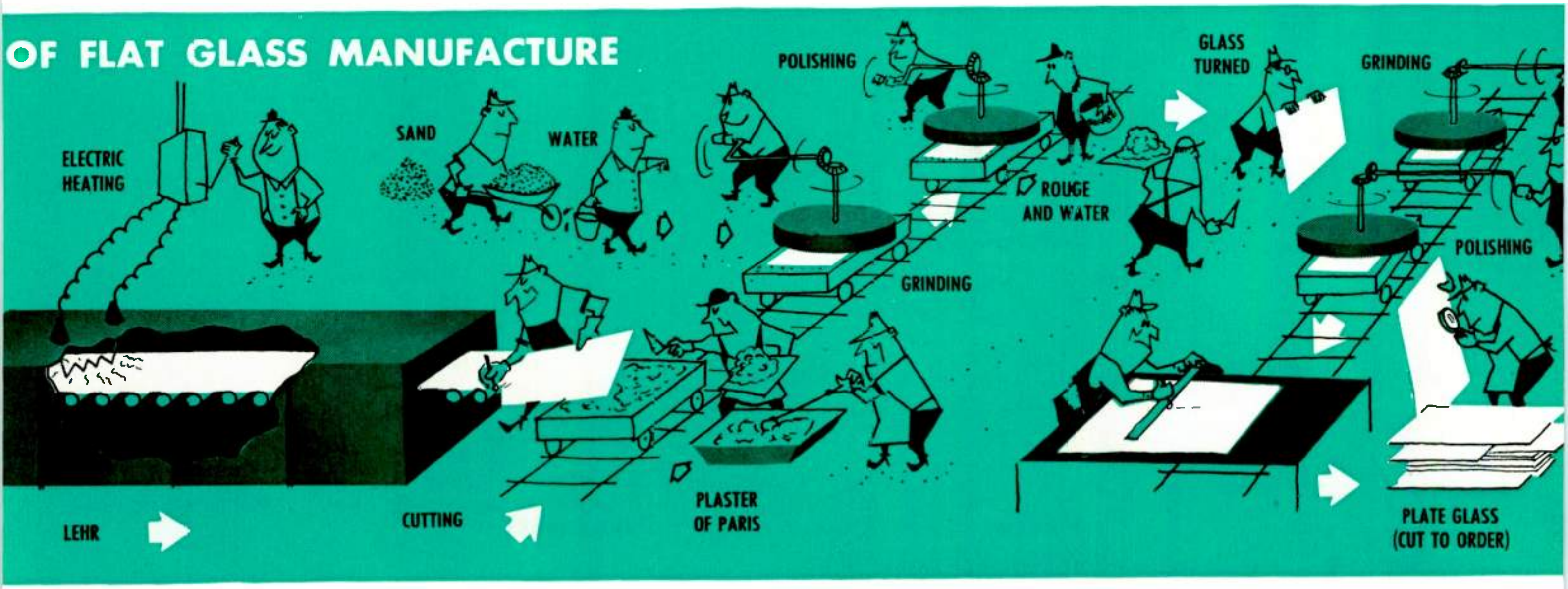
A pusher drive moves the tables along the grinding and polishing line. The drive consists of a pinion mounted at the beginning of the line, which engages a rack mounted underneath the tables. Since there is no spacing between tables at this point, the pinion is always engaged with the rack. The pinion is driven by an adjustable-voltage dc drive. A high starting torque is required to overcome the static friction that exists if the tables are not moving. The rate of acceleration should be smooth; a 5-to-1 speed adjustment is normally required with a maximum line speed of not over 500 inches per minute. The horsepower required for the pusher drive depends on the number of grinding and polishing wheels and whether the tables have wheels or slides. Wheeled tables require less horsepower.

Many other electrical drive and control systems are required on a grinding and polishing line. One of the most critical drives is the sand pump drive, which pumps a sand and water mixture to the grinding heads. If these pumps should fail, the sand would settle in the piping. The pumps are driven by an ac constant-speed motor, or a variable-speed motor when the flow is adjusted by changing the speed of the pump. Variable speed is obtained with either dc motors or other types of variable-speed drives, such as a Rectiflow drive.

A recent development in the grinding and polishing of glass is the double grinding and polishing line. This process was first developed and used in Europe. In the double system, the glass is ground and polished on both sides simultaneously. The advantages are that the glass is ground and polished only once, and more uniform thickness can be maintained. The glass is not cut into pieces after leaving the lehr, but goes directly into the grinding and polishing process as a continuous strip. The glass rides on driven rolls, which are placed between grinding and polishing heads. The grinding heads are driven by individual adjustable-speed drives.

production of window glass

The production of window glass is less complicated than plate glass. The glass is pulled from the furnace in the form of a sheet. In many cases, the glass is pulled vertically through a slit in a clay block, which is at the surface of the molten glass. The shape of the slit, the speed at which the glass is pulled, and the temperature of the glass determine the thickness of the glass sheet. A continuous sheet is pulled from the furnace with a set of driven rolls. These



rolls are several feet above the furnace so that the surface of glass is hard enough to prevent the rolls from marking it during the process.

The glass moving vertically from the furnace is enclosed and the temperature is regulated to prevent thermal stresses resulting from rapid cooling. After the glass has moved several feet vertically, it is cut into large sheets. Several sheets of window glass generally are pulled from a single furnace, whereas in the production of plate glass only one sheet is pulled from a furnace.

A dc or some other form of adjustable-speed drive powers the rolls that pull the glass from the furnace. By adjusting the speed of the drive, the overall thickness of the glass can be changed. In recent years, the trend has been to use speed regulation to insure constant speed. The speed-regulated drive is similar to that used on the plate glass lehrs, but dual drives are not normally used.

glass cutting

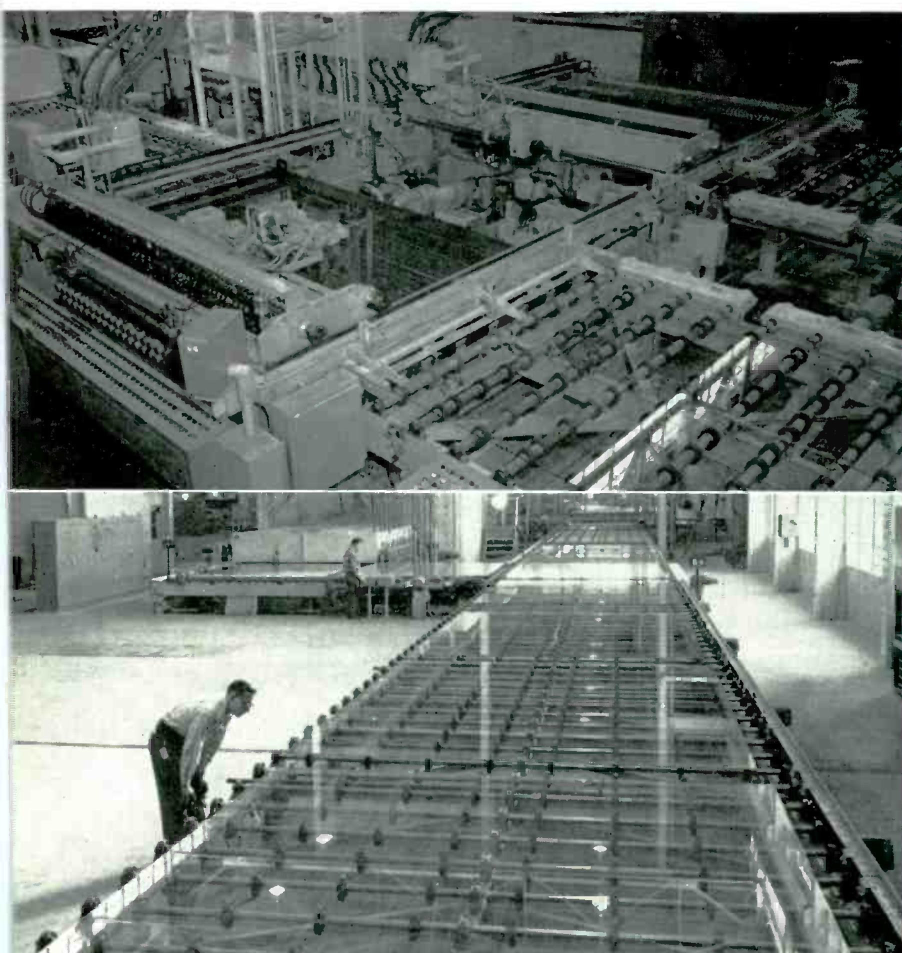
The next step in the process for both window and plate glass is to cut the large sheets to final size. In the case of window glass, the glass is cut to standard sizes and shipped. If sizes other than standard are required, the glass is recut by the local supplier. Plate glass is generally cut to its final size and shape at the factory.

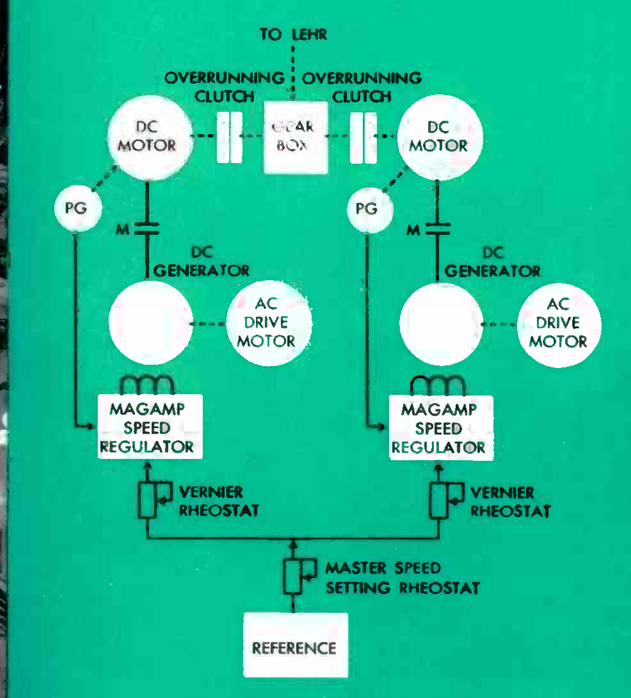
Most glass is cut by hand, in such a way as to obtain the minimum waste. In addition, imperfections in the sheet, caused by air bubbles or stones within the glass, must be cut out.

Some automatic machinery is used for cutting glass. These machines generally can be used best when the incoming glass is composed of equal-size sheets and standard-size pieces are to be cut. Plate glass generally is not cut by machines because of the wide variety of sizes required. One exception is automobile plate glass. However, because machines cannot spot flaws, imperfect pieces must be recut or destroyed.

Plate glass cutting looks attractive as an application for on-line computers. The number and size of pieces on order could be fed to an industrial on-line computer. As each sheet enters the cutting machine, the size of the sheet could be automatically measured and the size and position of any imperfections in the glass fed into the computer. With this information, the computer could set the cutting heads to have minimum waste and yet obtain the desired size pieces to fill orders. However, one of the major problems yet to be solved is the automatic determination of glass imperfections.

Through the application of new electrical drives and controls, coupled with new manufacturing techniques, flat glass can continue to be one of the cheapest, most versatile, and readily available construction materials. ■





Schematic diagram of regulator system used for speed control of lehr.

Top photo—Automatic cutting line. Bottom photo—Polished plates entering cleaning equipment. *(photos courtesy Pittsburgh Plate Glass Company)*

ACCELERATION CHARACTERISTICS OF SQUIRREL-CAGE MOTORS

The starting of an induction motor is a critical period in the motor's life. Proper consideration of the conditions that occur during starting lead to correct application.

R. L. NAILEN

Motor Engineering Section
Westinghouse Electric Corporation
Sunnyvale, California

One of the most important considerations in applying induction motors is the way a motor behaves while starting its load and bringing it up to speed. Lack of understanding of this behavior has led to many burnouts and breakdowns.

The characteristic of the motor that distinguishes it from other types of prime movers is that it instantly develops large starting torque when energized. No driven machine, or for that matter the rotating part of the motor itself, is capable of coming up to full speed as fast as that torque is applied. The results are thermal strain in the motor, and mechanical strain on the motor shaft, coupling, and load.

Whereas overloading of the motor while it is running primarily causes overheating of the stator winding, starting duty often causes unsafe temperature rise in the rotor.

Physically, the basis for this lies in the equivalent circuit of the motor. The electrical power P_G transferred (via magnetic field) across the air gap into the motor rotor splits—part of it goes out the shaft and into stored energy in the rotating system (P_S), and the remainder goes into rotor heating ($I_2^2R_2$). At the moment of starting (RPM = 0, S = 1.0), all that power goes into rotor heating. When full speed is reached, most of this power is going out the shaft. The power "split" when load torque is negligible is shown in Fig. 1b.

However, when the load torque requirement during starting is not negligible, the motor takes longer to accelerate the load. The longer it takes to reach full speed, the more the rotor losses (heating) will increase (Fig. 1c).

The stator, as well as the rotor, is heated. Ratio of stator heating to rotor heating depends upon the ratio of stator resistance (R_1) to rotor resistance (R_2). This again is consistent with the equivalent circuit of the motor.

High load torque, then, is one source of overheating during starting. A second source is high load inertia. This likewise has the effect of "drag" on the motor as it is brought up to speed, increasing starting time and losses.

These two conditions—high load torque and high load inertia—do not necessarily occur together. For example, fan loads usually have low torque requirements during acceleration. With small standard motors that have starting torques of 150 percent or more, the load torque on start may be negligible in comparison. However, fan inertia is often quite high, as much as 20 times that of the

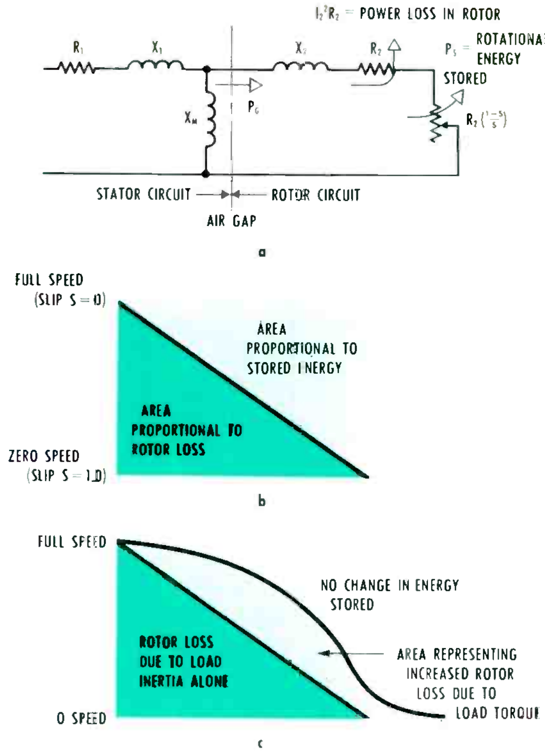


Fig. 1—Equivalent circuit of induction motor and graphical representation of rotor heating losses during the starting period.

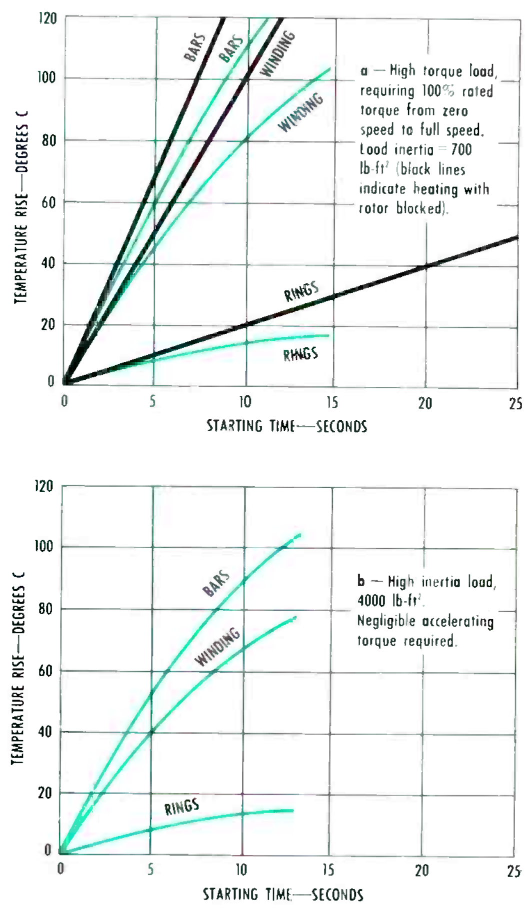


Fig. 2—Curves showing heating in stator winding, rotor bars, and rotor end rings of 200-hp, 1200-rpm induction motor starting (a) high torque and (b) high inertia loads. Motor data: starting torque 120 percent, breakdown torque 240 percent, inertia of motor alone equals 200 lb-ft².

motor alone. On the other hand, belt conveyors, some types of ore mills, etc., may require at least 100 percent rated torque throughout the starting period. Yet load inertia may only be 5 to 10 times motor inertia—which is seldom excessive. Most industrial loads fall somewhere between these two extremes.

From motor equivalent circuit theory and design constants, the distribution and rate of motor heating during starting can be determined for any given motor and load. This is normally a job for the motor designer. However, it should be emphasized that in order to do that job the designer needs both the load inertia and the load speed-torque characteristic. Heating calculations are based on the assumption that all stored energy in any part of the motor remains there and causes temperature rise. Although slight heat losses do occur through radiation, etc., they are difficult to account for and are ignored.

The curves of Fig. 2 show the temperature build-up in a typical 200-hp, 1200-rpm motor starting the two types of loads—one of high torque but low inertia, and the other of high inertia but negligible torque during starting. Note that the total accelerating times for both loads are almost the same, but starting the high torque load overheats the stator winding.

While the high inertia drive is still safe from a temperature standpoint, it is close to safety limits. Although load torque was considered negligible for that example, a relatively small amount of such torque would cause overheating. This example indicates that the effect of load torque at start should not be neglected in heating calculations—particularly for larger motors.

What is "safe" depends first upon rotor size and structure. Small motors in the NEMA frame sizes customarily have rotor bars and end rings integrally die cast, either in aluminum or copper. This makes a very rugged structure (Fig. 3) that can stand heat. A calculated temperature rise of 200 degrees C during the starting period is not excessive.

However, larger rotors use separate bars and end rings brazed together, which form an inherently weaker structure. (The motor in the example was of this type, Fig. 4.)

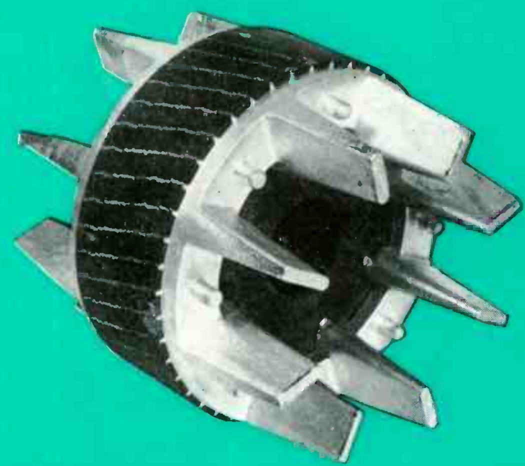


Fig. 3—Small die cast (aluminum) rotor assembly, for 1½-hp motor.

Fig. 4—Large brazed rotor, showing bar and end ring arrangement (400-hp double cage motor).

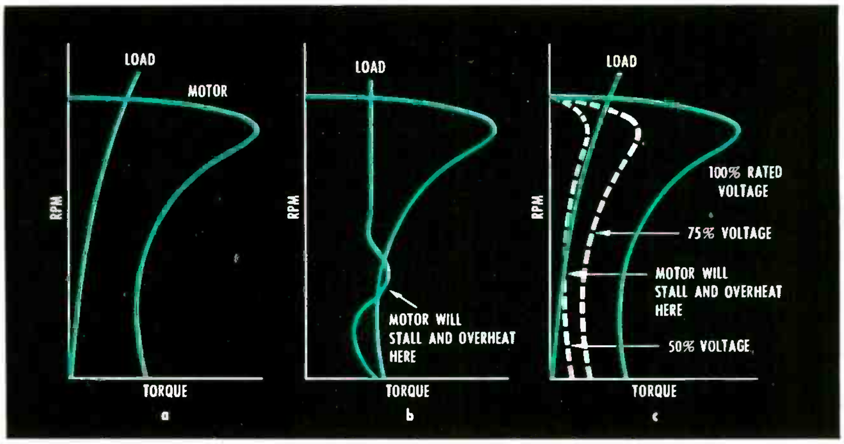


Fig. 5—Speed-torque curves for normal motor design (such as NEMA B) showing: (a) normal operation with low load torque on start; (b) high load torque during starting period; and (c) reduced voltage starting.

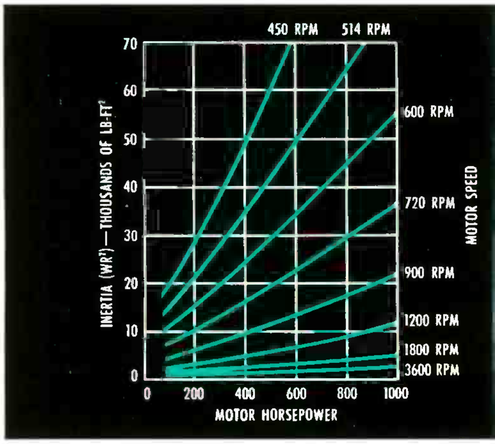


Fig. 6—Maximum load inertia that can normally be handled by squirrel-cage induction motors of various speeds.

In particular, radial expansion of the heated rings flexes the bar ends and can cause fatigue failure. Axial expansion of the heated bars causes no such trouble. Therefore, allowable bar temperature rise can be much higher than allowable ring temperature. Common safe limits are 200 degrees C rise in the bars and 40 to 60 degrees C rise in the rings. On an actual start, the relative bar and ring temperatures reached depend upon the relative volume, resistivity, and specific heat of the bar and ring materials.

What is "safe" temperature rise in the stator depends upon the R_1/R_2 ratio, as stated above, as well as upon the volume of copper in the stator winding. Since this ratio is widely variable with motor design (usually ranging from 0.5 to 2.0), there are times when the stator winding reaches its safe temperature limit before the rotor does. This happens to be true in the example. With Class A insulation, a short time winding rise of 70 to 125 degrees C is about maximum. (The higher limits apply to small NEMA frame size motors where heating calculations are conservative due to relatively rapid conduction of heat out of the winding.) With Class B or Class H insulation, these values could be increased.

How often the motor must start a load also has a bearing on choosing safe limits. "Borderline" conditions acceptable for a drive that need start only once a day would probably not be satisfactory for one that starts at least several times per hour.

The first conclusion to be drawn is that it is not possible, with all motors, to protect the motor from damaging temperatures during starting by protecting the stator winding alone.

But the only practicable way to protect the rotor is to be able to predict its time rate of heating, and from this to know the length of its safe accelerating time. Therefore, it is not possible to assign a fixed value of safe accelerating time for a complete design line of motors, or for a particular type of motor. When load torque can be neglected, then for a given motor design there is one inertia load that will bring the motor to its maximum safe temperature. To this load there corresponds one and only one starting time. But when load torque must be considered, then there is no such simple answer.

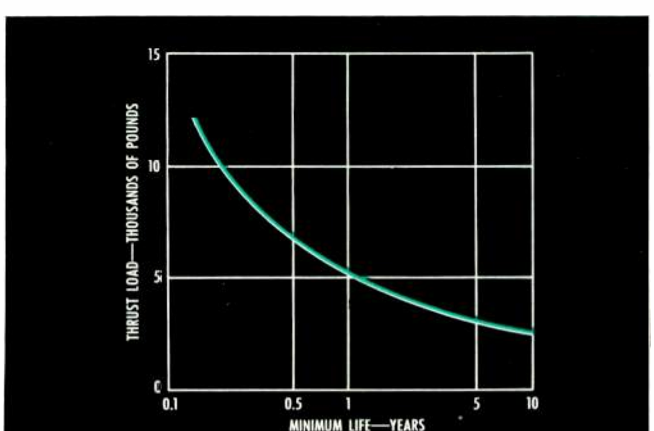


Fig. 7—This shows thrust bearing life as function of thrust load for a 6320 bearing.

For example, the safe starting time for the motor illustrated, with low inertia load, is about 9 seconds. Yet with the high inertia, low torque load, the motor is quite safe after accelerating for 14 seconds. Therefore, it would not be true to state flatly that the starting time for this motor design must always be limited to 10 or even 15 seconds regardless of the nature of the load. Actual starting times encountered in practice may range from 1 to 30 seconds or even more without damage to the motor.

This re-emphasizes the fact that the detailed solution of the problem of safe motor acceleration is best left up to the motor designer. To solve it he must know the load characteristics. Data can then be furnished to the system designer or application engineer to enable him to properly set up relay or fuse coordination to take the motor off the line if it is somehow unable to get up to speed within the safe time for the particular drive; and to allow in the power system for the effects of voltage dip during motor starting. The motor will draw almost full locked current until it reaches 60 or 70 percent speed, and for some drives this may take an appreciable time without harm to the motor.

Once the time-temperature relationships in the motor have been calculated, the next step, if heating is excessive, is to make some change in the drive. Assuming the load cannot be changed, possibly motor speed may be reduced. This will have the two-fold effect of increasing motor size for a given horsepower rating, thus increasing thermal capacity, and also of decreasing heat input, due to the drop in full-load speed. Use of one of many available types of fluid or magnetic couplings also may help.

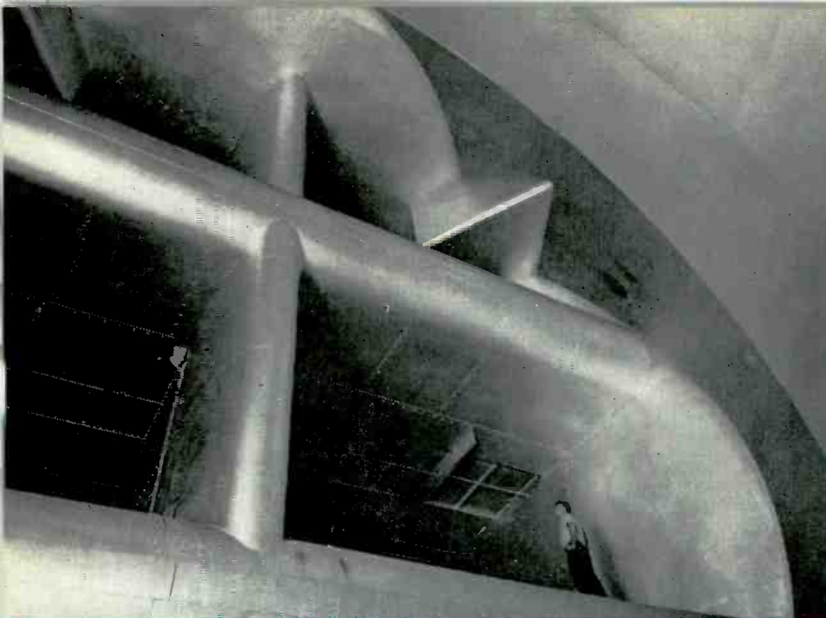
The second major problem encountered in motor starting is the mechanical shock to the rotating system caused by the instantaneous application of starting torque when the motor is energized.

This is particularly troublesome for small motors driving high inertia loads. Shafts or couplings may fail due to repeated torsional impact. The problem is a major one on large belt conveyor drives, common in the mining industry. Excessive accelerating torque causes the belts to stretch, with serious reduction in conveyor life.

An often-used solution is to request that the motor be supplied with lower than normal torques, particularly starting torque. This is the so-called "soft start" design. However, such a design may merely substitute one problem for another unless adequate thermal capacity exists in the motor to take care of the increased heating that may accompany the decrease in motor torque.

While reduced-voltage starting is used primarily to reduce starting current to meet power system requirements, it may also be employed to reduce accelerating torque of a standard design motor to mechanically safe values. Here too, motor heating should be checked. Reduction in applied voltage decreases torque directly as the square of the voltage reduction, and the end result may be unsafe motor temperatures.

Other solutions to both thermal and mechanical problems include the use of wound-rotor motors (with the increased cost of more complex control plus some increase in motor price and size), or the use of special types of couplings or clutches to drive the load, as mentioned above. ■



This "grille" in the supersonic tunnel consists of coolers for the high speed air flow. More than 65 000 gallons of water per minute are pumped through baffles to absorb heat.

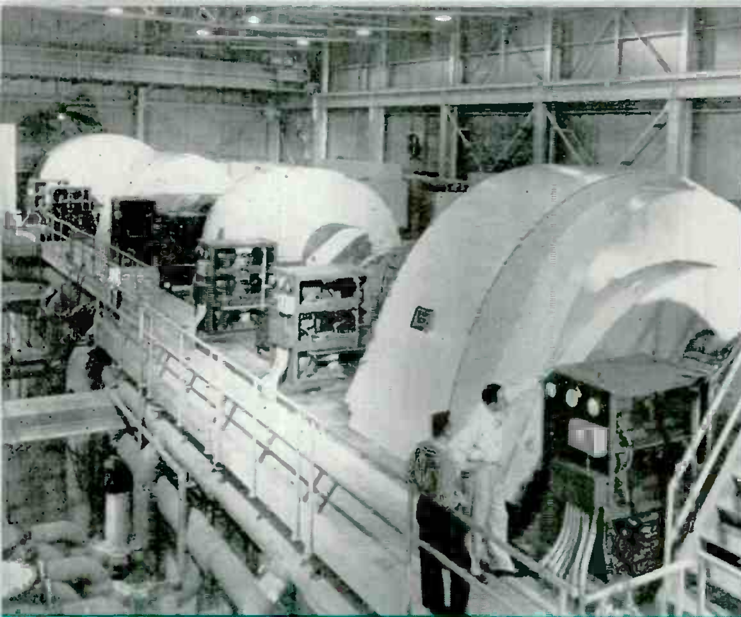
With these instruments in the main control room, flight conditions are simulated in the tunnel. In the supersonic portion, speeds of about 3000 mph at 100 000 feet can be simulated.

SUPERSONIC TUNNEL NEARS COMPLETION

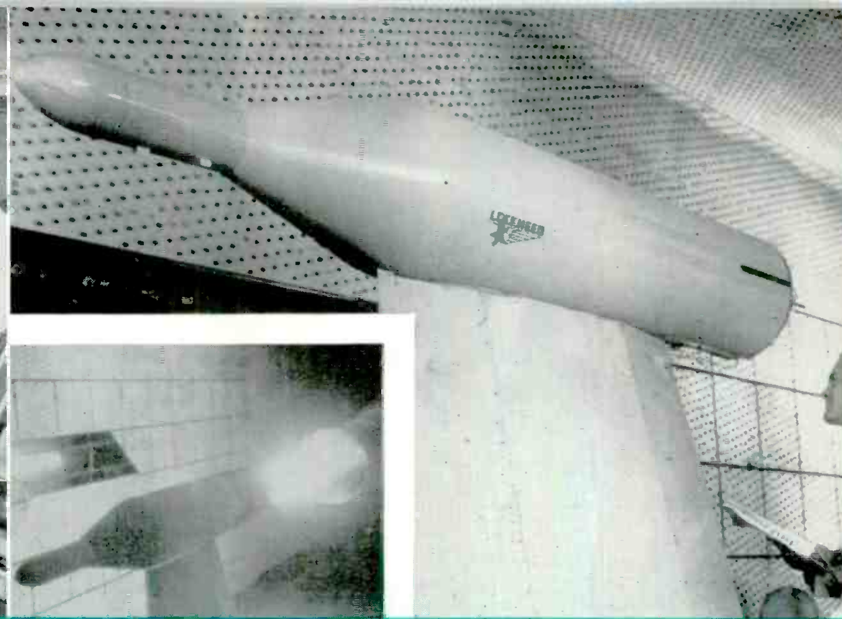
Some of the toughest problems of space travel, those encountered by a rocket as it leaves or re-enters the earth's atmosphere, are being attacked on a realistic scale in huge, unique wind tunnels, part of the U. S. Air Force's Arnold Engineering Development Center.

In two tunnels—one a transonic unit now in operation, and the other a supersonic circuit nearing completion—man now is able, without endangering his life and with loss of valuable equipment greatly minimized, to achieve conditions simulating what may be expected when rocketing from sea level to altitudes of more than 100 000 feet—the "edge of outer space."

This array of controls is located in the motor drive control room, and is used to operate the four huge motors shown above.



This four-motor drive system built by Westinghouse develops 216 000 hp. Two of the motors are rated at 83 000 hp each, and the other two at 25 000 hp each.



This is a one-fifth scale model of the Navy's *Polaris* missile installed for test in the 16-foot transonic section; the insert, taken from movie film, shows the missile under test.

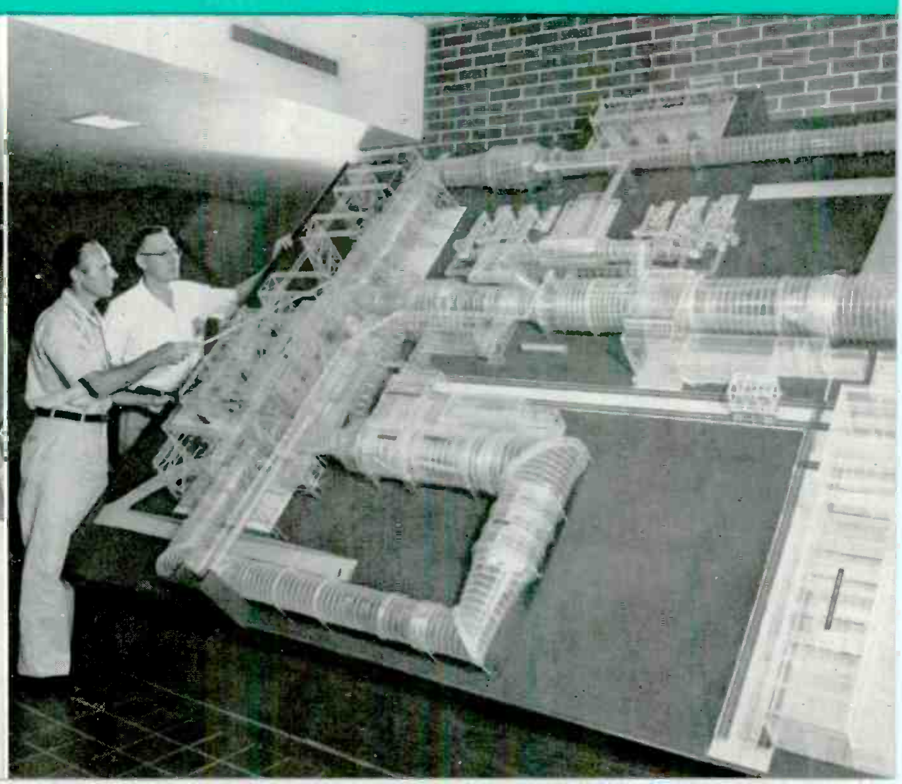
Largest of the 22 wind tunnels and test cells at the site is the propulsion wind tunnel, comprised of the transonic and supersonic circuits, which is one of the three major laboratories at the Center. The world's largest rotating machine supplies the power for these two record-breaking tunnels. It includes the world's two most powerful synchronous motors, each developing 83 000 horsepower, and two smaller motors of 25 000 horsepower each. The four motors are connected in tandem fashion to two huge compressors—one three-stage unit for the transonic circuit, the other an 18-stage unit for the supersonic circuit; both the motors and the compressors were built by Westinghouse.

The Center's transonic circuit has been conducting aerodynamic and propulsion tests for nearly three years, and it soon will be joined by its associated supersonic tunnel. Tests have been conducted on more than 30 of the major weapon system projects of the United States government, including the USAF *Titan*, *Snark*, GAM-72 and *Bomarc* missiles, nose cones for all intercontinental ballistic missiles, the Navy's *Polaris*, the Army's *Jupiter* and the National Aeronautics and Space Administration's *Mercury* "man-in-space" project.

The accompanying photographs show sections of the nearly completed supersonic circuit. ■

This is a portion of the giant 287-foot long supersonic compressor unit. Four compressors, with a total of 21 separate stages, comprise this entire rotating mass.

This plastic model shows the general layout of the propulsion wind tunnel. The lower loop is the transonic circuit, the upper loop, the supersonic circuit. Drive motors are at left.



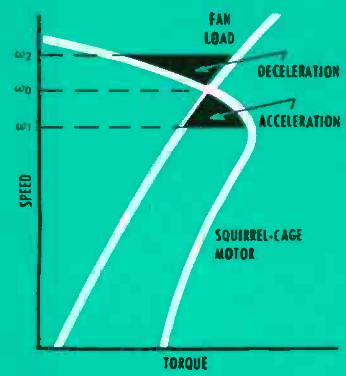


Fig. 1—Curves show stable equilibrium of motor and load.

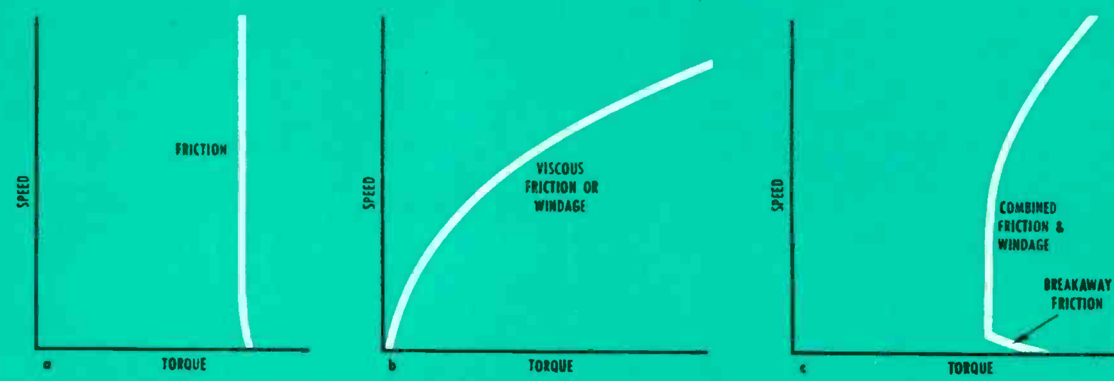


Fig. 2—Speed-torque curves of typical passive loads: (a) Friction; (b) Viscous friction or windage; (c) Combined friction and windage.

MATCHING LOAD AND DRIVE CHARACTERISTICS

The proper application of adjustable-speed drives to the loads of today's high speed, high quality machinery is one of the most important engineering problems facing the electrical engineer.

C. G. HELMICK
Industrial Engineering Department
Westinghouse Electric Corporation
East Pittsburgh, Pennsylvania

The success of a manufacturing operation is becoming increasingly dependent on the electrical drive equipment used. Better process and quality control at higher speeds is a common requirement. Better continuity and reliability is demanded of continuous processes. Minimum capital, maintenance and operating costs are necessary from an economic standpoint. All of these points figure into the selection of drive equipment.

Undoubtedly the most important aspect of drive selection is performance. And the key to performance is proper matching of drive characteristics to load requirements.

the matching problem

The basic matching problem hinges on one factor—*equilibrium*. Load-torque requirements must be balanced by drive-torque availability under all operating conditions or equilibrium is upset. Upset can result in a stalled ma-

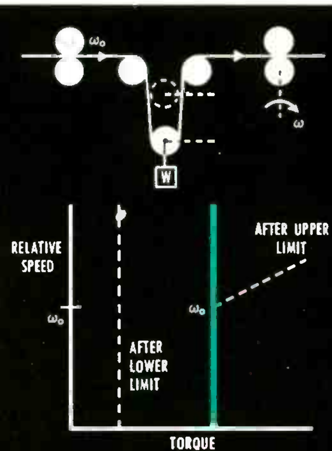


Fig. 5—Characteristic curve of pulling tension against dancer mechanism.

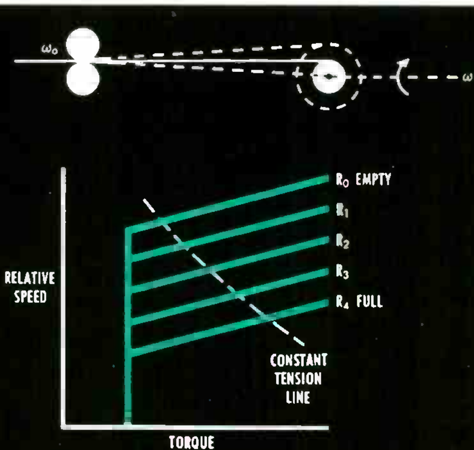
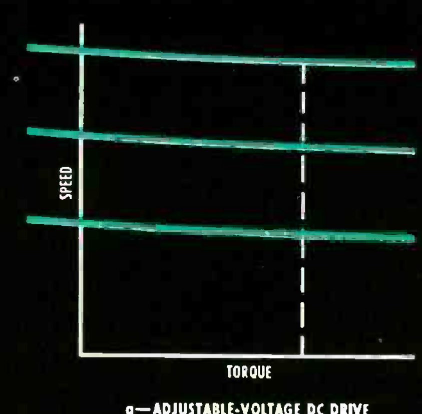
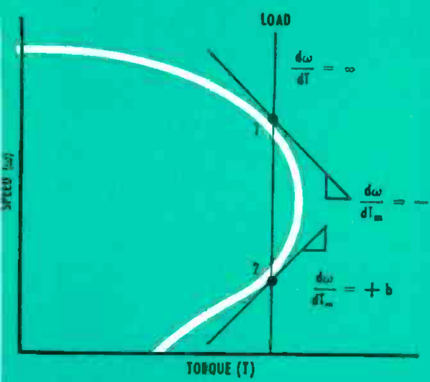


Fig. 6—Speed-torque curves of core-type winder with constant delivery speed.





For stability,

$$\frac{dT_l}{d\omega} - \frac{dT_m}{d\omega} > 0.$$

Or,

$$\frac{1}{\left(\frac{d\omega}{dT}\right)} - \frac{1}{\left(\frac{d\omega}{dT_m}\right)} > 0.$$

For point 1:

$$\frac{1}{(\infty)} - \frac{1}{(-a)} = 0 + \frac{1}{a} > 0$$

and this point is stable.

For point 2:

$$\frac{1}{(\infty)} - \frac{1}{(+b)} = 0 - \frac{1}{b} < 0,$$

and this point is unstable.

Fig. 3—Conditions for stability.

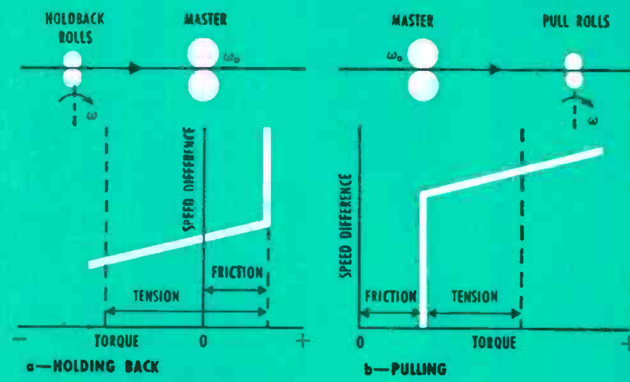


Fig. 4—Speed-torque curve of active tension load for (a) holding back, and (b) pulling.

chine, destructive conditions, or more fortunately, acceleration to equilibrium at some other speed. This is implicit in the familiar equation of mechanics, that the summation of torques must equal zero.

$$T_{\text{motor}} - T_{\text{load}} - J\frac{d\omega}{dt} = 0$$

See how this equation applies to the simple example of Fig. 1, a squirrel-cage motor applied to a fan. The intersection of these curves represents a stable operating point.

This equilibrium point is termed stable since any momentary disturbances produce corrective forces tending to restore equilibrium. The stability of an equilibrium point rests with the type of intersection that the load curve makes with the drive curve. The *relative* slope of the two curves at this intersection is the determining factor. The conditions for this kind of stability are shown in Fig. 3.

load characteristics

Broadly speaking, loads can be classified as *passive* or *active*. Passive loads absorb energy and demand torque only in opposition to motion. Active loads, on the other hand, can transmit energy, demanding torque whether or not there is motion. In the latter category are tension loads, gravity loads, and wind loads. Included also are certain combinations whose load demands change with time, such as core-type winders.

Constant torque—This is the most common *passive* load requirement because it is the characteristic of friction loading. Friction force is essentially constant regardless of speed; therefore the torque demand of such a load is also constant (Fig. 2a). Common applications characterized by a constant-torque demand include paper machines, printing presses, feed drives on machine tools, many conveyors, most textile machines, packaging machines, office machines, motor-generator sets, and a wide variety of general purpose machinery. Where equipment consists of rolls, belts, or cylinders turning in bearings, and where little energy is transferred to the work material itself, the load demand is typically constant-torque. (Drive motors for generators are usually constant-torque because of the generator capability.) Certain types of bearings may require extra

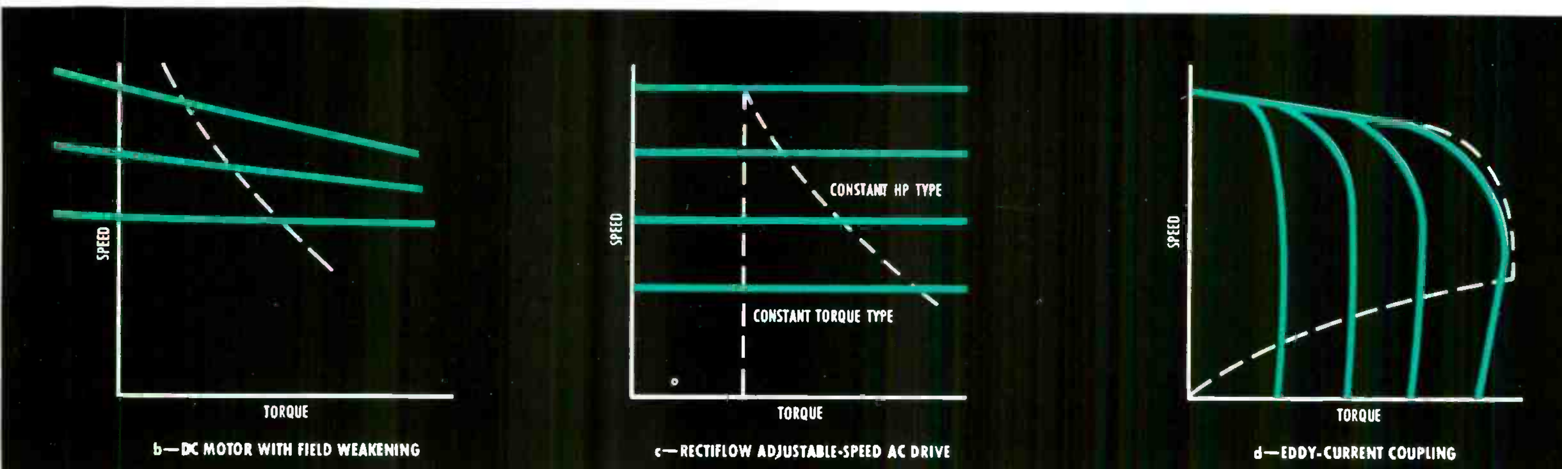


Fig. 7—Inherent speed-torque characteristics of typical adjustable-speed drives: (a) Adjustable-voltage dc drive; (b) Dc motor with field weakening; (c) Rectiflow adjustable-speed ac drive; (d) Eddy-current coupling.

torque at *starting* to overcome "breakaway friction." This condition is shown in Fig. 2c.

Variable torque—This classification is given to passive loads that are characterized by viscous or fluid friction effects (Fig. 2b). Fans, blowers, and compressors fall into this class because their hydraulic loading is usually viscous friction. The "windage" effect associated with motors, or other parts rotating at high speed, is primarily viscous friction, and it also displays the "variable-torque" demand. This windage load often appears in combination with constant-torque loads at higher speeds. (See Fig. 2c.)

One important exception concerning pumps should be noted; not all pumps operate against fluid friction loads. A boiler feed pump, for example, usually operates against a constant pressure in pumping feedwater into a steam boiler. This results in essentially a *constant* torque demand.

Tension—An often encountered *active* load is that of holding tension. Tension loads can appear in several forms: pulling or holding back, either against constant-speed delivery rolls, or against tension-setting "dancer" or "compensator" mechanisms. In these latter devices, often used in the textile and rubber industries, the fabric is looped through a movable roll that is weighted to establish the sheet tension. Multiple loops and rolls may be ganged together to provide storage of fabric under tension during momentary differences in input and output speeds.

The case of holding tension against delivery rolls is shown in Fig. 4, for both pulling and holding back. An example of dancer tension is shown in Fig. 5. In both, the load demands torque whether or not there is motion. Of course, limits exist in either case; either the delivery rolls pull until the fabric breaks, or the dancer pulls until its travel is used up. In both examples, energy is transmitted by means of the load.

Consider further the curves of Fig. 4, where tension is held against constant-speed delivery rolls. Ordinarily there is a friction component to this load due to roll bearings, and this is the *only* load until the roll surface speed matches the delivery speed. Any further speed difference establishes tension. (Increase in surface speed for pulling; decrease, for holding back.) This accounts for the near-horizontal slope of the load curve, which is dependent on product elasticity and machine geometry.

The dancer mechanism, which establishes tension in the material regardless of roll speed—at least within its limit of travel—is described in Fig. 5. While within limits, the constant dancer tension produces a constant-torque demand. Different delivery speeds result in a different operating point on the same curve. The dotted lines indicate existing limits of travel, after which the dancer plays no part in load determination.

Time-changing loads—Included in this category are loads that vary with time—for example, the core-type winder, found in nearly all phases of industry. This load is time-changing because roll radius increases with time. For any given roll radius the load demand is the familiar tension characteristic curve. As the radius grows, however, both load torque (product of tension and radius) and drive speed (surface speed divided by roll circumference) change. A family of tension curves will describe the winder load at different values of roll build-up, as shown in Fig. 6. To hold constant sheet tension during build-up, the operating

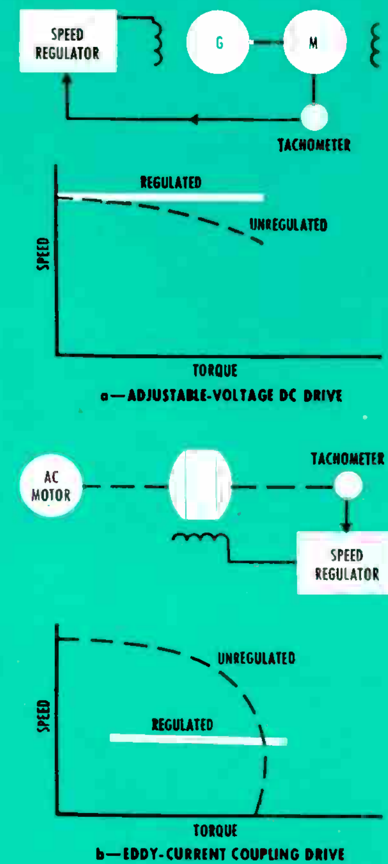


Fig. 8—Modification of inherent drive characteristics by speed regulator on (a) adjustable-voltage dc drive, and (b) eddy-current coupling drive.

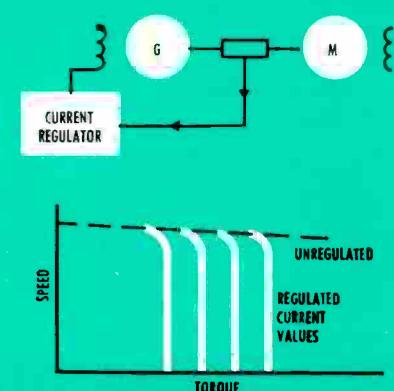


Fig. 9—Modification of dc drive characteristics by current regulator (torque regulator).

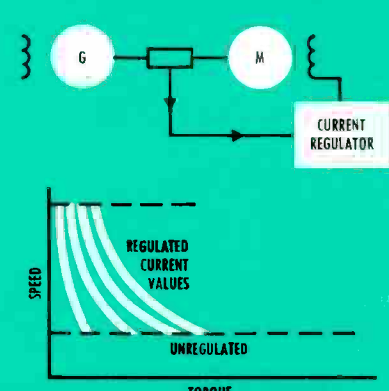


Fig. 10—Modification of dc drive by current regulator in motor field (horsepower regulator).

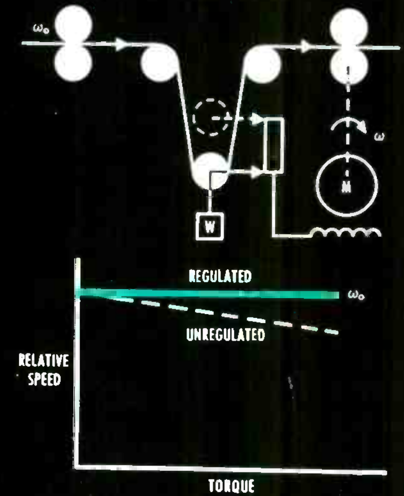


Fig. 11—Modification of inherent drive characteristics by dancer roll regulator.

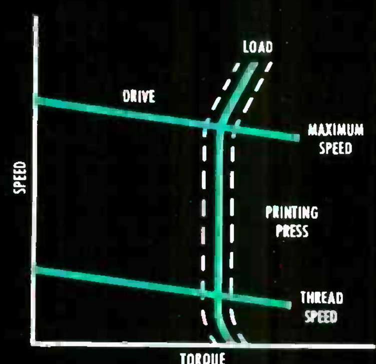


Fig. 12—Curves show match of adjustable-voltage dc drive to constant-torque load.

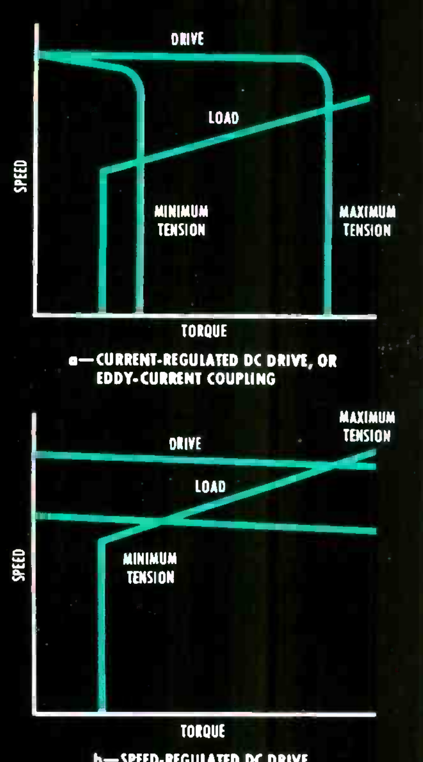


Fig. 13—Curves show match of (a) current-regulated dc drive and (b) speed-regulated dc drive to a tension load (such as a fabric stretcher).

point must shift gradually along a prescribed path. This path is the dotted curve shown in Fig. 6, which is a *constant-horsepower* curve. (If tension and surface speed are both constant, their product, which is a measure of tension horsepower, is also constant.)

It is important to recognize that the locus curve for constant tension is the *desired* curve, but that at any particular roll radius the *actual* load is the solid curve. Therefore, the drive must constrain operation to only those points lying on the dotted curve.

drive characteristics

Drives for adjustable-speed operation can be described by two curves. The first can be termed the *characteristic* curve, which is the familiar speed-torque curve, or family of curves. This curve describes the ability of the drive to meet load demands.

The second curve can be called the *capability* curve, which describes the *maximum continuous* load that the drive is capable of carrying at any speed in its operating range. The *capability* curve is usually a thermal limitation of the drive. The reason for this twofold classification is that the drive motor will develop only as much torque as the load demands, regardless of its capability to deliver more. Thus load variations will occur along the *characteristic* curve even beyond the *capability* limit, if the load demand is not sustained continuously.

The inherent characteristic and capability curves of common adjustable-speed drives are shown in Fig. 7.

The dc drive with armature-voltage control (Fig. 7a) has a constant-speed characteristic curve, and a constant-torque capability curve. Constant torque arises from constant flux and maximum current (torque = flux×current).

The dc drive with field-weakening control (Fig. 7b) has a constant-speed characteristic curve with a constant-horsepower capability curve. Constant horsepower is implied by constant line voltage and constant maximum current (power = volts×amperes).

The Rectiflow adjustable-speed ac drive (Fig. 7c) has constant-speed characteristic curves. It is built to have a capability curve that is either constant-torque or constant-horsepower, depending on the application.

The constant-torque nature of the eddy-current coupling drive is shown by the characteristic curves in Fig. 7d. The upper capability curve is set by the maximum excitation, and the lower curve is determined by the machine's ability to dissipate the high heat losses at low speeds.

modification of drive characteristics by regulators

Since adjustable-speed drives furnish a limited number of inherent characteristics, it is sometimes desirable to modify these characteristics to match a particular load requirement. Regulators or other special controls can be used in this way to increase the flexibility of a basic drive. Furthermore, a regulator can supply precision that often is not inherent in the characteristics of an unregulated drive. Obviously, an unregulated drive is simpler and less expensive than a regulated drive, and should be used where possible. If a regulator is required, however, the drive can take on an entirely new set of characteristic curves.

Speed regulator—A tachometer can be used to measure actual drive speed, and when combined with proper regu-

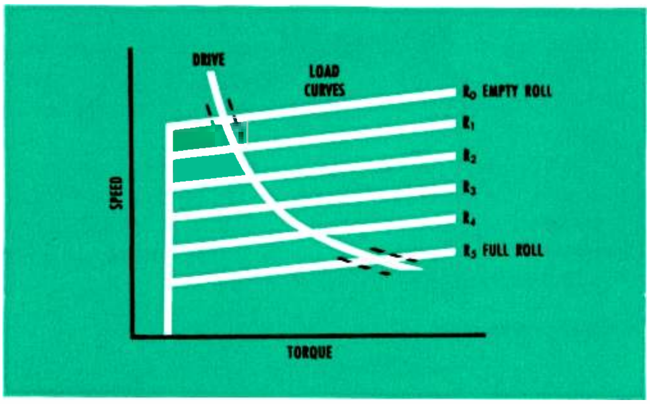


Fig 14—Matching dc drive to time-changing load by means of a constant-horsepower regulator.

lating elements, can correct drive speed to keep it precisely constant. The result is shown in Fig. 8, where the regulator effectively removes the speed droop from the unregulated characteristic curve.

Current regulator—This type of regulator, when used with an adjustable-voltage dc drive (Fig. 9), produces a major change in the speed-torque curve. The new characteristic curves are constant-torque, since motor torque is proportional to current for a fixed value of excitation. Different values of regulated current produce different constant-torque curves as shown.

The same current regulator, when used as shown in Fig. 10, also forces a complete change. The new characteristic curve is constant-horsepower, resulting from a fixed voltage and constant current.

Dancer regulator—The use of the dancer mechanism to establish fabric tension was discussed under tension characteristics. The dancer can be further utilized to provide a control signal for regulating the relative speed of one motor with respect to another. The *position* of the dancer mechanism is directly proportional to the relative angular difference between the pullrolls and holdback rolls. Thus, if the position of the dancer is maintained constant by means of a dancer regulator, the controlled drive will be synchronized with the other drive (Fig. 11).

matching examples

Printing press—Large newspaper presses are good examples of constant-torque loads. A multiplicity of impression cylinders, ink rolls, forming rolls, and guide rolls carry the lightweight sheet of newsprint through the press sections. The loading is predominantly friction, with a slight windage component at high speed.

The operating requirements are relatively constant speed, 2-to-1 production speed range, low threading speed, and fine acceleration control to avoid sheet breaks.

An adjustable-voltage dc drive is commonly used, especially since several similar section drives can be fed from the same power supply. The intersection of drive and load curves (Fig. 12) results in stable operation. Variations in load torque, which might result from different cylinder or inkroll pressure, produce little change in speed. Smooth acceleration is obtained by gradually increasing dc voltage applied to the drive motors.

Stretching machine—Heat-setting requirements of certain man-made fibers require several pull-roll sections to operate together, some pulling and some holding back. Requirements include: constant tension, reasonably constant speed, and in the case of holdback tension, ability to absorb power. Two approaches are often used; one employs a current regulator, and the other uses a speed regulator. In either case, one section of the stretcher is designated the *lead* section with the others pulling against it. The lead section is usually speed-regulated to establish overall production speed.

The first approach, illustrated in Fig. 13a, uses a current-regulated adjustable-voltage dc drive. The intersection of the characteristic curves is stable. Good tension control is provided, with the fabric serving to tie drive speed to the lead section. Small changes in production speed produce little or no change in tension.

In the second case (Fig. 13b), a speed regulator is used to set tension. A precise regulator is required since slight changes in drive speed will produce large fluctuations in tension. The intersection of load and drive curves indicates very high stabilizing forces in response to disturbances. Paradoxically, this condition can result in overshooting and oscillations if there is insufficient damping in the system. Such a system does not lend itself to good stalled-tension control, because at zero speed the speed regulator sees an indeterminate condition.

Winding reel—A modern five-stand tandem cold mill, using very large drives, produces steel strip that is wound at high speed on a collapsible-mandrel winding reel. Requirements of the reel drive for this application include: 3000–6000 fpm, 50–100 fpm threading speed, and coil build-up of more than 5 to 1. Good tension control is required, also over a 5-to-1 range, to accommodate different gages and widths of strip. Acceleration control is critical because the entire mill must accelerate without disturbing the speed relationships between stands. In addition, the acceleration period should be kept as short as possible because off-gage material will be produced during this time.

An adjustable-voltage dc drive is used to accomplish the desired functions. Controlled application of generator voltage gives rapid and smooth acceleration. A special combination of current and speed regulators, for both the generator and reel motor, gives a constant-horsepower characteristic to the drive (Fig. 14). This characteristic fits the desired constant-tension locus, with stable intersections at all coil diameters.

These examples highlight a few applications encountered in industry today, and serve to illustrate the method of attacking such problems. First, load requirements must be examined to determine load characteristic curves. Second, available drive characteristics are checked for possible solutions. Load and drive curves are matched to determine performance suitability. If more than one suitable solution is possible, the problem becomes one of economic choice. Such factors as initial cost, installation cost, operating and maintenance expenses, and flexibility for future use must be considered. One choice will then generally show overall superiority. Such a procedure should insure a sound application, and will take maximum advantage of technological progress, as tempered by pertinent economic considerations. ■

THE ADVANCED MECHANICS SCHOOL
... its role in mechanical engineering at Westinghouse

Mechanical engineering is entering a new era in the electrical industry. Experts in advanced mechanics will be needed to pave the way.

R. E. PETERSON
Research Laboratories
Westinghouse Electric Corporation
Pittsburgh, Pennsylvania

Although it seems anomalous, mechanical engineering plays a vital role in the electrical manufacturing industry. One indication of the importance of mechanical engineering is the fact that Westinghouse employs over 2600 mechanical engineers with a bachelor's degree or higher.

A closer look at the structure of Westinghouse discloses apparatus that is entirely or primarily mechanical: steam turbines, condensers, heat exchangers, pumps, industrial gas turbines, fans, blowers, gear units, aviation gas turbines, automatic washing machines, refrigerator-freezers, air-conditioning equipment, and many others. In other apparatus, such as generators, motors, atomic equipment, and transformers, many of the major problems are mechanical in nature.

Consider, for example, the development of a new and larger generator. The designer is faced with many difficult questions: the adequacy of larger forgings, the vibration behavior, the provision of sufficient cooling, the adequacy of the bearings, the stress analysis and design of coil retaining members, and so on. These are the main factors that limit design possibilities, and, conversely, solutions obtained in these areas extend design possibilities and enable more efficient apparatus of larger capacity.

Looking beyond present products, new forms of power generation and utilization—the thermoelectric and magnetohydrodynamic devices, the space applications—will require information from the mechanical engineering areas of thermodynamics, heat transfer, and fluid mechanics.

Thus mechanical engineering will continue to play a major role in the electrical industry, and among the talents needed are experts in the more advanced aspects of mechanics. To help fill this need, an Advanced Mechanics School was established at Westinghouse in 1956.

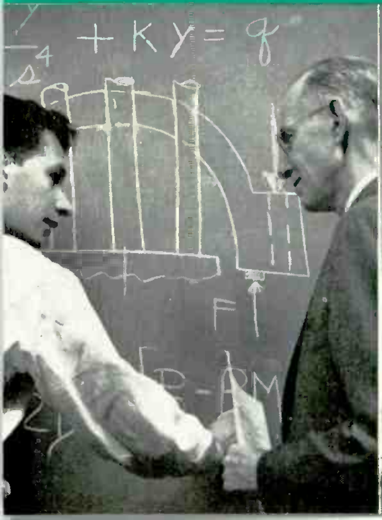
why an advanced mechanics school?

Mechanical engineering is advancing rapidly because of: (1) fundamental work in the applied mechanics field, (2) use of high-speed computers, and (3) use of new instruments and techniques.

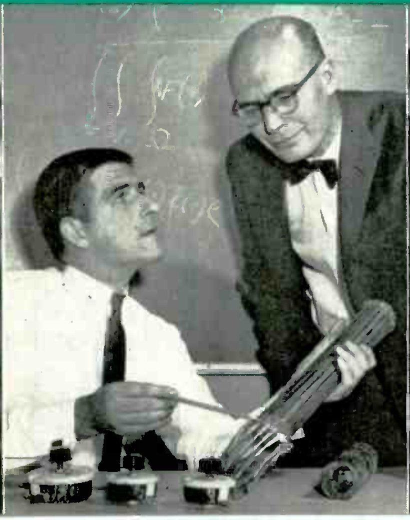
The final stages of many engineering problems are now being solved by large computing machines; a few examples are indicated on page 53. The most difficult phase, and the one requiring advanced training, is that of understanding the physical concepts involved, visualizing the problem, and formulating a mathematical representation that can be turned over to programmers for translation into machine language. Thus the formulation of the problem is a critical step, that once accomplished leads to elimination of calculation drudgery and saving of valuable time. For example, extensive analytical work on the transmission of vibration through machinery foundations has been put in a form suitable for the digital computer, with the result that calculations requiring a man-year of time (using a desk calculator) can be run off in eleven minutes on the high-speed computers. The computing machines make it possible for the engineer to extend his horizons and tackle problems that in the past seemed too formidable.

All problems cannot be solved mathematically. In many cases knowledge is insufficient to formulate the problem adequately. In other cases the problem is too complex. An

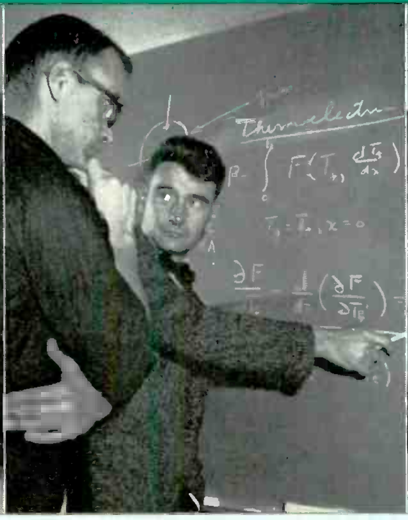
Bill O'Donnell discusses application of thesis project to nuclear reactor with Dr. Wahl.



Don Bryson reviews thesis work on magnetohydrodynamics with Dr. Way.



Dr. Somers explains satellite thermoelectric application to Mike Roldt.



Dr. Tsu discusses solar sail and space problems with Al Holmes.

example of this kind is the accurate determination of the stresses in a nuclear pressure vessel head, a thick, curved member, with numerous holes for control rods and bolts. Recent advances in three-dimensional photoelasticity have made possible a precise solution of this problem. Another type of problem has been solved by an experimental method based on membrane analogy.

Providing the continuous flow of new fundamental knowledge is the function of the Research Laboratories. The task of applying this new knowledge, however, falls largely to advanced development groups throughout the company. In both places, mechanical engineers with advanced training are vitally important.

Table I—MASTER'S CURRICULUM—ADVANCED MECHANICS SCHOOL

	Fall	Credits
ME 104	Theory of Elasticity	3
ME 150	Advanced Thermodynamics	3
ME 173	Incompressible Flow	3
Math 153	Advanced Mathematics	3
ME 197	Thesis Survey	1
		13
	Spring	**Credits**
ME 122	Advanced Stress Analysis	3
ME 120	Dynamics-Vibrations	3
ME 152	Advanced Heat Transfer	3
Math 154	Advanced Mathematics	3
ME 200	Thesis	3
		15
Summer	ME 200 Thesis	3
	Total	31

Table II—TYPICAL THESIS SUBJECTS

Membrane analogy applied to air foils in cascade.
Study of jet flap for single stage gas turbine.
Electrolytic tank analogue.
New method of turbine blade design for digital computer solution.
Damping of rotor whirl due to skin friction.
Investigation of plastic strain patterns.
Photoelastic study of blade-notched disk subjected to rotation and thermal stress.
Gas vibration analysis in compressor systems.
Heat transfer study of finned construction.
Elastic-plastic relations for beams of various cross-section in bending.
Wave effects in muffler design.
Laminar axial flow of compressible fluid through annulus with an inner rotating channel.
Effect of strain rate and temperature on pressure distribution in hot rolling.
Effect of boundary layer on pressure distribution about air foils in cascade.
Magnetohydrodynamic effects on the flow of a conducting fluid in the entrance of a cylinder.
Magnetohydrodynamic thrust on a cylinder.

the advanced mechanics school

The new school was established in 1956 and is an outgrowth of the well-known Mechanical Design School, which had been in existence for over 30 years. The old school was limited to thirteen weeks annually. The new school is more extensive and covers an entire year, with the summer utilized for thesis work; during the year no company work is assigned to the student. The program, if successfully completed, meets the requirements for a master's degree at the University of Pittsburgh.

About ten students are selected each year for this program and usually these are the top students at their respective schools. The candidates are required to pass a graduate student entrance examination given by the University of Pittsburgh.

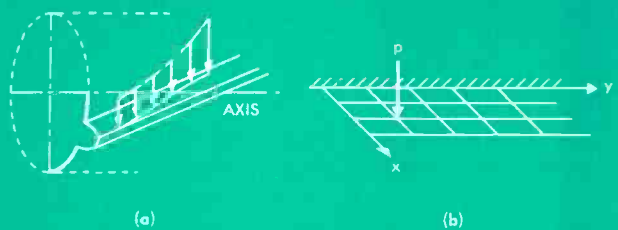
Courses covered in this program are shown in Table I. These are daytime courses conforming to the scholastic calendar of the University of Pittsburgh. Credits and requirements are the same as for the resident students at the University, some of whom participate in individual courses of the program. The spread of subjects is greater than is usually found in a master's degree program where a major and minor are selected; such a broader base is advantageous in a company as diversified as Westinghouse. Course work in the Advanced Mechanics School is of a high-level basic type, involving intensive use of advanced mathematics, so that the graduates are well equipped to effectively utilize the powerful aid provided by the computers.

In addition to the class work, a thesis survey course and a master's thesis are required. The thesis work is especially valuable, because expert scientists are available as thesis advisors, including over forty specialists in the various areas of applied mechanics. Also available, for consultation or special help, are experts in many other fields, throughout the Laboratories, and the facilities of the entire Laboratory and its shops. Typical thesis subjects are shown in Table II.

The students are located at the Research Laboratories and are encouraged to participate in activities of the Laboratories, including seminars and department meetings. The students obtain knowledge of the company through visits and guidance, and are placed in positions according to their interests and opportunities. Graduates of this new school are now located at eleven different departments in Westinghouse, including those concerned with advanced system planning, computer operations, atomic power, turbines, generators, and advanced design and development.

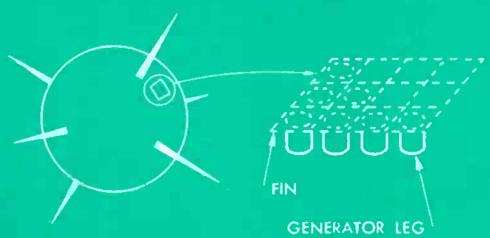
In summary, mechanical engineering in the electrical industry is entering into a new period. Although the conventional role of the mechanical engineer will continue in the future, experts in advanced mechanics are needed to develop and put to work the new fundamental knowledge that is so rapidly extending our frontiers. Only the most proficient will be capable of meeting the challenge. ■

STRESSES AND DEFLECTIONS IN HELICAL GEAR TEETH



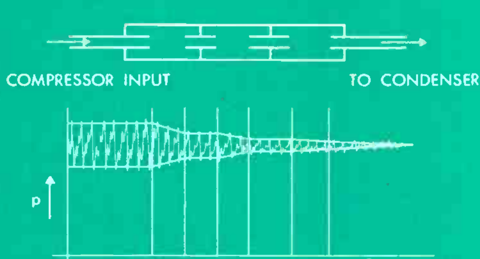
The actual gear tooth (a) under diagonal line loading over part of its length is idealized as a grillage of interconnected beams (b) subjected to concentrated loads P. Three rows of beams were used parallel to the *y* direction and 21 parallel to the *x* direction. The compatibility of these beams at their points of juncture required the solution of 45 algebraic equations.

SATELLITE AUXILIARY POWER UNIT



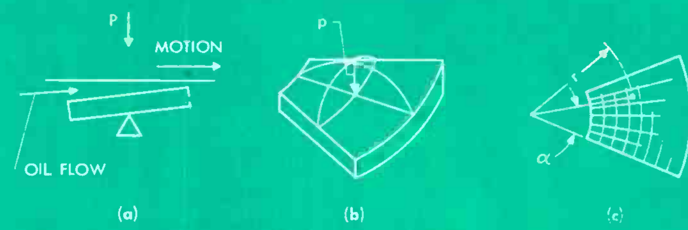
Heat is dissipated from a thermoelectric generator by radiation from the satellite surface. Each generator leg can be considered to have a thermal dissipating fin attached to it as indicated in the subsection sketch. The differential equation describing the heat rate loss from the fin surface is nonlinear and can only be conveniently solved with the aid of a computer.

MUFFLERS FOR GAS VIBRATIONS IN AIR-CONDITIONING SYSTEMS



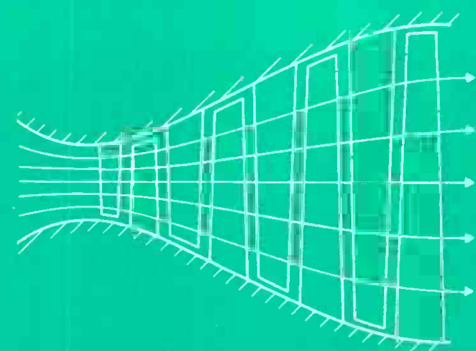
A muffler filters out complex pressure and flow fluctuations. To obtain the ratio of output pressure variation to input pressure variation, equations are written for each tube length and volume element in a section. The equations are connected by matching the boundary pressures and flows. Solutions have been obtained involving 64 equations corresponding to four muffler sections.

PRESSURE DISTRIBUTION ON THRUST BEARING FOR WATER WHEEL GENERATOR



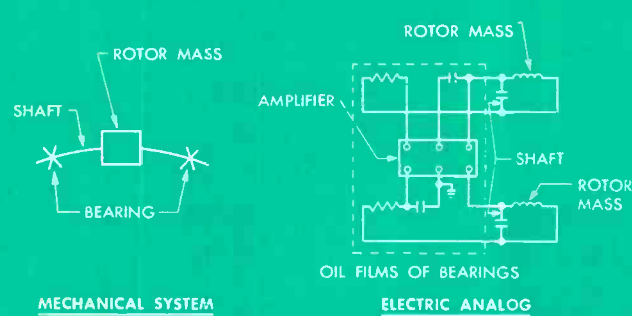
Hydrodynamic lubrication is based on the principle of a converging film which develops the pressures, *p*, to carry the load *P*. To obtain the pressure distribution for a shoe-type thrust bearing, the segment (c) was divided into a grid of elemental areas and a solution was obtained for the corresponding 256 equations.

STEAM TURBINE DESIGN—AERODYNAMIC CALCULATIONS



The flow through a turbine is governed by the equations of continuity, momentum, and energy, a condition line, and an optimum loading criterion. This involves the solving of 25 to 35 simultaneous, nonlinear, algebraic and difference equations. One such problem has been programmed for a high-speed automatic computer. After programming, the calculation of complete velocity triangles through a turbine stage took only three and a half minutes. The same calculations, if done manually with a desk calculator, would require six to eight weeks.

OIL-WHIP OF A FLEXIBLE ROTOR

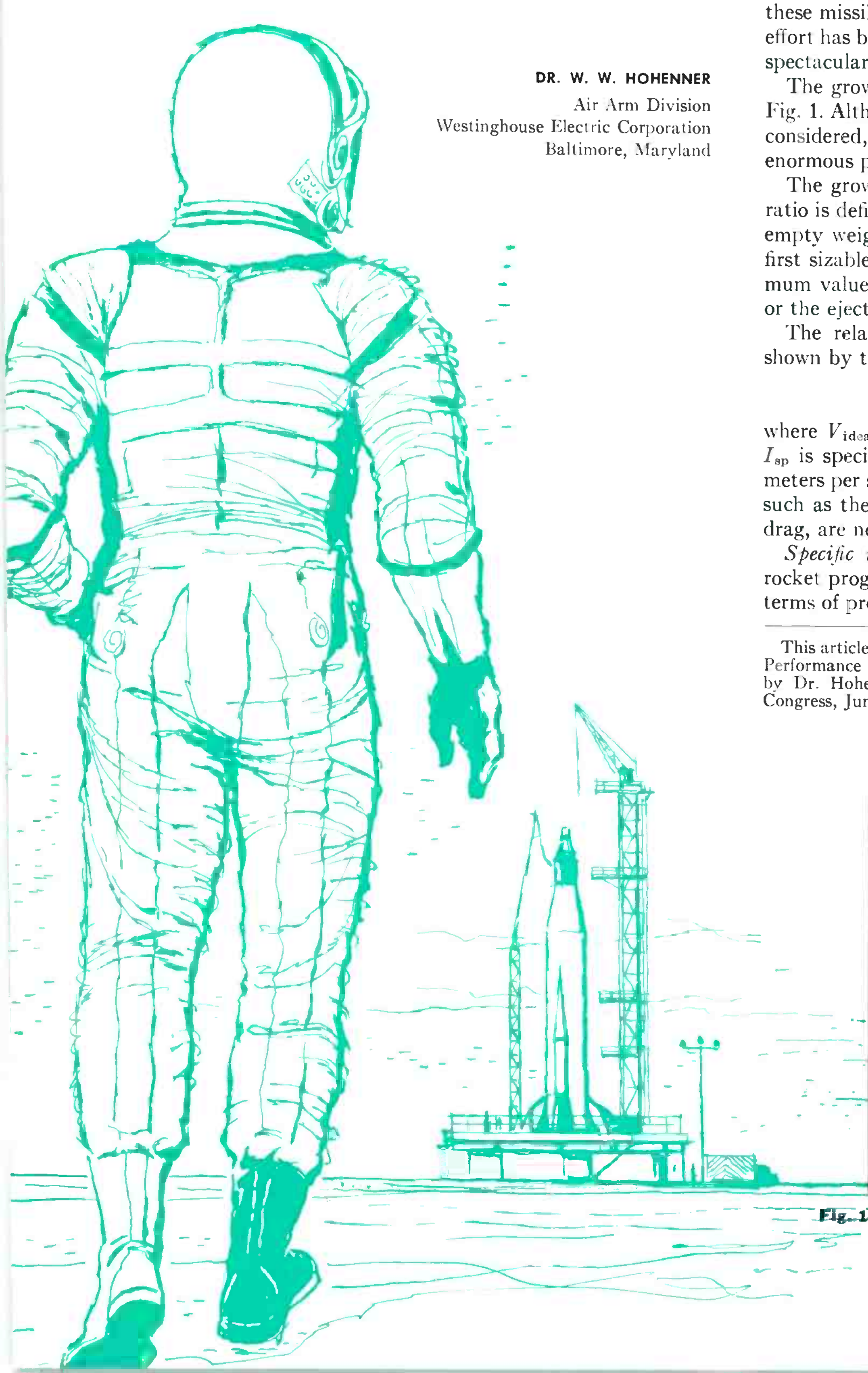


Oil-whip is a self-excited vibration of a rotor caused by oil-film pressures. An analogous electric circuit governed by the same basic differential equations has been utilized to provide an improved understanding of this stability problem. The oil-film representation includes capacitors (flexibility), resistors (positive damping), and amplifiers ("negative damping"). A systematic schedule of circuit proportions has given the regions for stable rotor operation.

MANNED ROCKET FLIGHT
... requires a trade-off between performance and complexity

A rocket trip to the moon? This "down-to-earth" analysis of today's accomplishments shows why reliability is the most serious deterrent to manned space flight.

DR. W. W. HOHENNER
Air Arm Division
Westinghouse Electric Corporation
Baltimore, Maryland



The art of propelling and controlling large rockets has advanced rapidly during the last 20 years. This has been particularly true for those missiles that follow a ballistic trajectory during flight to a predetermined target. Since these missiles are obviously of great military value, much effort has been expended in their development, resulting in spectacular progress.

The growth in *launching weight* since 1944 is shown in Fig. 1. Although the curve is incomplete since range is not considered, gains in launching weight alone emphasize the enormous progress made.

The growth in *mass ratio* is illustrated in Fig. 2. Mass ratio is defined as the ratio of the launching weight to the empty weight. Mass ratio has progressed from 3.2 for the first sizable ballistic rocket, the V-2, to the present optimum value of 8 to 9. Beyond a mass ratio of 10, staging or the ejection of expended tanks appears necessary.

The relationship of mass ratio to missile velocity is shown by the equation:

$$V_{ideal} = I_{sp}\, g \ln M$$

where V_{ideal} is maximum velocity in meters per second, I_{sp} is specific impulse of the propellant, g is gravity in meters per second per second, and M is mass ratio. Losses, such as the effects of gravity during acceleration and air drag, are not considered in this equation.

Specific impulse (I_{sp}) is obviously a major factor in rocket progress. Specific impulse is a measure of thrust in terms of propellant consumed per second. A listing of spe-

This article has been abstracted from a paper, "Trade-Off Between Performance and Complexity in the Design of Ballistic Rockets," by Dr. Hohenner, presented at the Second International Rocket Congress, June 18, 1959, Paris, France.

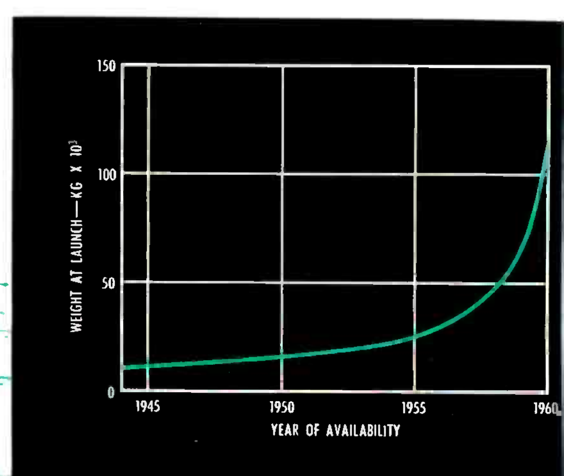


Fig. 1—Increase in missile launching weight since 1944.

cific impulses for the most common propellant combinations, and some propellants known to be under development, is given in Table II. The workhorse combination of liquid oxygen (LOX) and kerosene is listed with a specific impulse of 250 seconds. For purposes of comparison, propellant combinations with specific impulses in excess of 275 seconds have been listed. While it would be interesting to discuss some of the typically disadvantageous properties of the high specific-impulse propellants, such as their poor stability, corrosiveness, and poisonous characteristics, it is sufficient to point out that a specific impulse of 275 seconds is still very difficult to obtain. Even this would only represent a 10 percent increase over the 250-second value, which was available in 1944.

When compared with improvements in mass ratio, progress in specific impulse seems insignificant. Yet, the effort that has been expended to attain this 10 percent improvement is about equal to that required for the threefold increase in mass ratio.

Several solid propellants and their specific impulses are also listed in Table II. The lower limit of the range in specific impulse for each propellant can be considered present state-of-the-art for large rockets. The upper limit, though feasible, is not yet available for the types of rockets considered in this article. The problems of manufacturing, storing, and handling 10 000- to 100 000-pound solid propellant grains are not sufficiently solved to allow use of specific impulses of 250 seconds or more.

A summary listing of the physical characteristics of six large rockets, ranging from the early V-2 to the sophisticated *Vanguard* is shown in Table III. The gains in mass ratio, burning time, final velocity, and thrust are obvious from this listing.

required rocket performance for space flight

These gains have made possible great strides in unmanned military applications of the ballistic rocket. However, it is of interest to compare present rocket capabilities with the requirements for manned rocket flight. A logical comparison can be made by matching today's capabilities with the requirements of a *manned* space trip to the moon.

Velocity—The velocities required to conduct a trip to the moon are listed in Table I. The required velocity for a round trip to the moon is about 19 000 meters per second (42 500 mph). At present, about half this velocity capability can be attained even assuming an extremely minute payload. Thus for the defined mission, the velocity deficiency is about two to three.

Payload—A manned space probe might require a payload of 9000 to 23 000 kilograms (19 000 to 50 000 pounds). Present capability (at much reduced velocity) is about 900 to 2300 kilograms, or a deficiency of about 10.

Guidance and Control Requirements—Some of the conditions required for a successful moon voyage—specifically, required cut-off velocity as a function of initial path angle —are shown in Fig. 3. Present state-of-the-art permits control of velocity to within 0.3 meter per second (1 foot per second), and angular orientation to within about 1 degree or less. Both these capabilities are sufficient for a manned moon trip. Space vehicle stabilization within plus or minus 0.5 degree is obtainable and is also sufficient if monitoring prevents an increase of this error with time. Similarly, the required thrust variation and control within a ratio of 10 to 1 seems feasible. Repeated firings of the propulsion motors in different directions is feasible. Therefore, the deficiency in guidance and control is not great—perhaps between 1 and 2.

Reliability—Reliability requirements for the moon trip can be divided into propulsion and electronic categories.

Propulsion reliability: Assume that the reliability requirement for each stage of the rocket propulsion system is 0.99. At present, rocket motors can be built to meet the guidance and control requirements previously stated. However, these complex motors have an estimated reliability of only 0.80 per mission. Therefore, the deficiency in the reliability of the propulsion system is 20.

Electronic reliability: Assume an electronic reliability requirement of 0.99 for a trip duration of 200 hours. To determine what can be achieved today, suppose that 250 vacuum tubes or equivalent transistors are employed in the electronic circuitry. Using conventional reliability theory, the mean life required of the electronics equipment

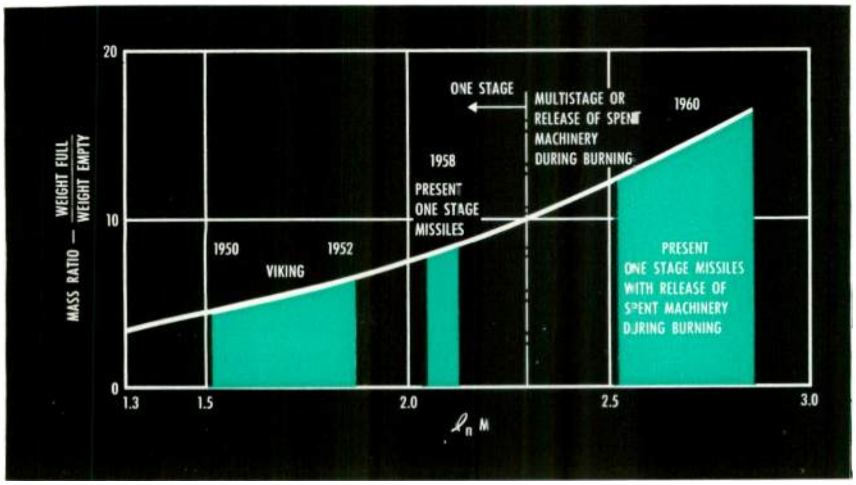


Fig. 2—Increase in mass ratio of single-stage missiles.

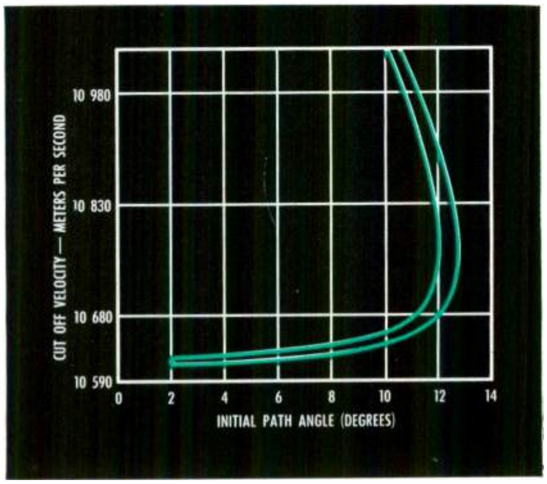


Fig. 3—Conditions required to obtain missile impact on the moon.

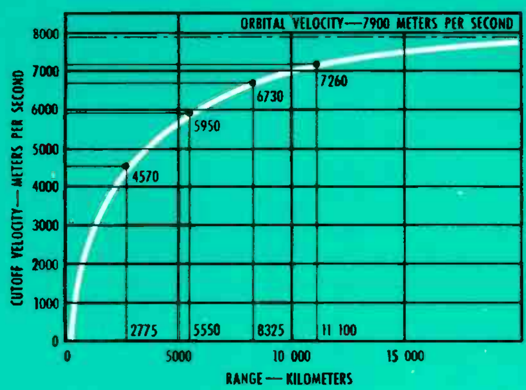


Fig. 4—The obtainable ballistic missile range in kilometers versus the final velocity in meters per second is shown above. The final velocity of a ballistic missile is reached at the moment of cutoff of the motor. In computing the curve, cutoff altitude was assumed to be 122 kilometers, a typical, though not a required value. In addition, the optimum cutoff angle, defined as the angle of the velocity vector against the local horizontal or vertical direction that results in the greatest range for any given velocity, was used in the computation. The curve shows that range tends towards infinity as velocity approaches about 7900 meters per second (25 800 feet per second). Infinity range is obtained if the vehicle orbits around the earth. Therefore, for intercontinental transports, velocities from 2000 to 7900 meters per second are sufficient. It can be seen that as orbital velocity is approached, a small increase in velocity has a great effect on range. For each increment in speed above minimum orbital velocity, the missile can go deeper into space. At 11 200 meters per second (35 800 feet per second), a missile can reach the moon.

Table I—REQUIRED VELOCITIES FOR A MOON VISIT

	Meters per Second
Velocity required to reach the moon (V_1)	11 200
Retro velocity to make safe landing (V_2)	2 840
Take off velocity from moon surface (V_3)	2 420
Transfer from approach ellipse into circular orbit around earth (Retro) (V_4)	2 380
Slow down to dip into atmosphere (V_5)	160
Total velocity capability required for mission ($V_1+V_2+V_3+V_4+V_5$)	19 000

to correspond to 0.99 probability of success for 200 hours, can be determined as follows:

$$R = e^{-t/m}$$

where t is time period (200 hours), m is mean life, and R is probability of successful operation (0.99). If these assumed values are inserted in the equation, m will be 20 000 hours—the required electronic equipment mean life.

A useful first approximation to obtain present-day electronic system reliability is:

$$m = 5000/n$$

where n is the number of vacuum tubes or equivalent transistors in the system (250). Solving for m, the mean life presently obtainable is 20 hours. Thus the deficiency in electronic system reliability is about 1000.

the complexity problem

The large-scale use of extremely complex machinery in modern rocketry has presented a particular problem in reliability—the overwhelming number of different possible modes of failure. Simple devices designed to perform a simple function can have from two to six different modes of failure. Once these modes are recognized and analyzed, sufficient engineering can improve the device. However, complex machinery has so many different modes of failure that only a few of the most frequently occurring modes can be recognized and investigated.

One requirement for rapid maturing of complex equipment is to have a large number of devices in use simultaneously and under a wide spectrum of environmental conditions. Many failure observations, under different operating conditions, permit the efficient analysis required to improve the design.

An additional factor that makes the rapid maturing of complex equipment difficult is the extreme difficulty of performing failure analysis on rockets that have become a pile of twisted metal as a result of the failure. In many cases, the failure can only be localized to some major assembly. The specific cause of the failure—a marginal design, or a random failure—frequently remains unknown.

Extensive testing of component parts and assemblies under simulated launching conditions might yield some clues to locate weak points in a design. However, the modes of failure are so numerous that only extended testing of extremely large samples can give a clear picture of the overall resistance of a part to the many environmental and service loads.

Failures caused by interaction between components in the system are even more difficult to analyze, pin down, and recognize. Particularly, failures caused by interferences of system components have the tendency of appearing to be random, though actually they are typical design shortcomings. The inadvertent nonuniformity between sets of complex machinery caused by random assembly of plus or minus tolerances, although produced with utmost care, makes an analysis and distinction between random and typical modes of failures extremely difficult.

Progress in reliability over 10 years of enormous effort has not been great, as illustrated in Table IV. Records of present ballistic missile systems are not published. Specifically, if figures are mentioned, the definition for failure

Table II—PROPELLANT COMBINATIONS

A. LIQUID PROPELLANTS

OXIDIZER	FUEL	SPECIFIC IMPULSE I_{SP} (Seconds)
Oxygen	Kerosene	250
	Boro Hydride	276
	Lithium Boro Hydride	306
	Lithium	318
	Hydrogen	345
Ozone	Hydrazine	277
	Hydrogen	373
Fluorine	Ammonia	295
	Methyl Alcohol	298
	Hydrazine	300
	Lithium	335
	Hydrogen	371
White Fuming Nitric Acid	Hydrogen	298

B. SOLID PROPELLANTS

Ammonium Perchlorate + Polyurethane	210–250
Boron Metal Components + Oxidant	200–250
Lithium Metal Components + Oxidant	200–250
Aluminum Metal Components + Oxidants	200–250
Perfluora Type Prapellants	250 and above

Table III—A SUMMARY OF PHYSICAL CHARACTERISTICS OF LIQUID PROPELLANT BALLISTIC MISSILES

	V-2	REDSTONE	JUPITER	THOR	ATLAS	VANGUARD
Height (Meters)	14	21	17.7	19	30.5	22
Diameter (Meters)	1.65	1.83	2.68	2.44	2.6	1.14
Payload (Kilograms)	1000					9.5
Propellant (Kilograms)	8650	15 700	42 000	43 000	105 000	
Weight, Empty (Kilograms)	4000	7000	5730	5700	14 100	
Weight, Full (Kilograms)	12 800	22 700	47 700	48 500	124 000	10 000
Mass Ratio (W Full/W Empty)	3.2	3.2	8.25	8.4	13	
Thrust (Kilograms)	30 500	35 500	68 000	68 000	177 000	12 300
Burning Time (Seconds)	69	110	161	130	140	296
Ideal Velocity (Meters Per Second) ($V = I_{SP} \times G \times \ln M$)	2790	2800	5180	5230	7100	

Table IV—RELIABILITY OF SOME HISTORICAL MISSILES

	V-2	VIKING	BUMPER 2 STAGE VEHICLE		
Number Launched	68	12	8	First Stage 3 Good 37% 2 Usable 63% 3 Failing 37%	Second Stage 3 Good 66% 2 Failing 34%
No Known Malfunction	32	6	2	1 Combination Reached About 80% rated Performance	
Satisfactory for Purpose Intended	45	7	1		
Reliability:					
Correctly	47%	50%	25%		
Usable	67%	58%	37%		
Failures	33%	42%	63%		
	Wartime Record of V-2 About 65%	Failure Defined With 20% Below Rated Performance	Failure Defined as More Than 20% Below Rated Performance		

that has been employed is usually not stated. In the examples listed in Table IV, failure is defined as system performance below 80 percent of rated performance. This below-par performance is assumed to sufficiently degrade the flight so that the launch objective cannot be met. Obviously, most performance requirements cannot be degraded 20 percent without rendering the mission a failure.

reliability and manned space flight

Presently, as in the past, ballistic missiles are used almost exclusively for military purposes, or for studies related to military purposes. Traditionally, military thinking does not consider that the reliability of any one missile would have a decisive influence on the overall military objective. Instead, redundancy or salvo firing is the usual *modus operandi*. This concept of redundancy reduces the individual reliability requirement. The amount of this reduction can be seen by comparing the probability of success equations for a series process, in which all items must operate for success, to the parallel process, where only one of many items must operate:

Series Case: $P_{s\ overall} = P_{s1} \times P_{s2} \times P_{s3} \ldots P_{sn}$

where P_{sn} is probability of *success* of the nth item.

Parallel Case: $P_{f\ overall} = P_{f1} \times P_{f1} \times P_{f1} \ldots P_{fn}$

where P_{fn} is probability of *failure* of the nth item.

Hence, from a military standpoint, trade-off between the cost of reliability improvement programs and unimproved missile costs is allowable. For example, an expenditure of several million dollars to effect a five-percent reliability improvement on a relatively inexpensive missile may be wasteful, since the military mission can tolerate lower reliability systems provided a sufficient number of missiles are available.

While optimum or most economical military system reliabilities (which vary from system to system) could be postulated, obviously, reliabilities as low as 65 percent—which have been obtained with historical missiles—are insufficient for military, commercial, or scientific missions in which human passengers are involved.

approach to the complexity problem

A discussion of the minimum reliability required for a commercial application of ballistic rockets is somewhat fruitless. To obtain an exact figure of reliability requires *large numbers* of *identical* equipments, used under *defined* conditions. These three postulates cannot usually be met. Any figures of reliability published thus far, with the exception of the V-2 record, are not particularly meaningful.

Most present equipment suitable for ballistic rocketry was developed for military purposes, where the balance between performance and reliability can be optimized in favor of performance. For civilian applications, the present balance is unacceptable. New equipment is required, created with a different design philosophy. For any commercial application of ballistic and space rocketry, *reliability* is of prime importance. This means sacrifices in performance, at least to the same extent that present sacrifices in reliability have been made.

The consequences of these implied sacrifices in performance are far reaching—particularly any reductions in the specific impulse of the propellants. Twenty years of effort of many capable scientists and engineers has not yet provided motors with sufficient reliability to give hopes of accomplishing even minimum goals. The results to date rather indicate that a phenomenon has been encountered, which can be termed the *complexity phenomenon*. The reliability requirements of a large number of components in series often seem incompatible with the purity of material, as obtained either from natural sources or from the laboratory. The inadvertent inhomogeneities in material produce sufficiently large deviations from the required tolerances that extended strings of parts in series often drift outside required performance specifications, regardless of how carefully components are selected.

These observations indicate that one of the best approaches to the design of high-reliability equipment for commercial rocketry is *simplicity*.

In many cases, simplicity means loss of performance. The table of propellant combinations (Table II) illustrates this point. All combinations of liquid propellants require complex machinery to transform fuel energy into thrust. In comparison, solid propellant motors are extremely simple (20 to 50 vital parts, compared to more than 1000 for a liquid propellant motor). Reliability of present solid-propellant motors is high; values of one failure per several thousand firings have been reached with rockets in the 1000- to 10 000-pound weight class. However, the specific impulse of solid propellants is significantly lower than that of the liquid propellants. The sacrifice in performance has paid off in reliability.

Desirable as simplicity is, it may not be applicable in many places. Similar reliability payoffs may be obtained in other ways. Redundancy of equipment in the vehicle will increase the reliability to any required or desired degree. The price is added weight, and therefore, loss in performance as a result of an unfavorable change in mass ratio. Increased safety margins in the structural design also result in heavier hardware of better reliability, again with a loss in performance.

Economic considerations will also have an influence on performance. The motors of the various stages, the tankage, and numerous equipments in the guidance and control system are expensive and are designed with such large safety margins that they are not worn out by one launching. Recovery of such parts for re-use seems advisable. Recovery appears technically feasible if appropriate provisions are included in the design. The equipment required for recovery is heavy, however, and will therefore adversely influence the mass ratio, resulting in a further degradation of performance. Some system reliability also may be lost as a result of the additional complexity.

To summarize, a performance loss of up to 20 percent in any of the vital components of a ballistic rocket employed for commercial purposes should not endanger the mission. This design consideration is of far-reaching influence and means that many of our dreams for space flight will not be realized soon. This postulated component safety margin of up to 20 percent requires large increases in systems performance. This advancement of the technical performance needs a concerted effort, which will stress heavily the national resources. Huge as this effort will be, it seems small against the required effort to obtain performance reliable enough to wage space flight. ■

ELECTRIC FREQUENCY GOVERNOR

...an improved electric governor system for prime mover speed control

This universal governing system exceeds the original "precise power" performance specifications adopted for frequency-sensitive equipment.

G. M. DAMON, Sales Manager
Electric Governor Project
Westinghouse Electric Corporation
Buffalo, New York

Two major objectives have influenced development and design of governors since the first simple fly-ball governor was conceived—automatic action and accurate control. Recent developments in such frequency-sensitive equipment as guided missiles and radar warning systems have made these objectives absolute requirements. The need for extremely accurate power-supply frequency regulation led to the development of the first successful "precise power" electric governor in 1952. This was the load-sensing Mark I governor, which was thoroughly field tested from 1953 through 1956, and was placed in production in late 1956[1].

the EFG governor

Further development of the Mark I system led to the incorporation of the Harder transistor oscillator into the electric control component of the Mark I governor. This resulted in a governor that performed far better than required by the original performance goals of the Mark I—the "precise power" specifications (listed in Table II).

This refinement in the electric control circuitry made possible further simplification in the system: During development of the Mark I governor, the load-sensing wattmeter did appear necessary for stability in 60-cycle service, but was found marginal in 400-cycle service. A design analysis indicated the feasibility of eliminating the wattmeter altogether in the new system. Tests revealed that performance was improved over that of the Mark I (load-sensing) governor.

The new EFG (electric frequency governor) model is capable of holding steady-state frequency regulation to plus or minus 0.10 percent or better. Frequency deviation on full-load transients in some cases can be controlled to within plus or minus ½ percent, with recovery to steady state in less than ½ second.

speed sensing vs. load sensing

The reductions in the time constants for the new EFG governor over the Mark I design are shown in Table I.

[1] "The Electric Governor" by J. G. Gable, *Westinghouse ENGINEER* September 1956, p156-7.

Table I—RESPONSE TIMES COMPARED FOR MODEL EFG GOVERNOR vs MARK I (LOAD SENSING) GOVERNOR

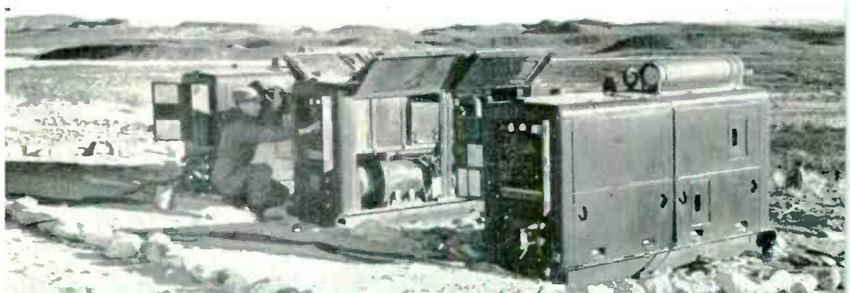
Load Change	Frequency Circuit Response—Seconds*		Magnetic Amplifier Response—Seconds*		Actuator Response—Seconds*	
	EFG	Mark I	EFG	Mark I	[illegible]	Mark I
4/4 On	.002	.002	.003	.010	.006	.016
4/4 Off	.002	.002	.003	.012	.006	.016
3/4 On	.002	.002	.003	[illegible]	.008	.016
3/4 Off	.002	.002	.003	.010	.007	.014
3/5 On	.002	.002	.003	.010	.006	.021
3/5 Off	.002	.002	.003	.012	.008	.020
1/4 On	.002	.002	.003	.012	.008	.022
1/4 Off	.002	.002	.003	.019	.007	.023

*Time from instant of load change to change in output of listed governor element.

Table II—PERFORMANCE DATA FOR MODEL EFG GOVERNOR COMPARED WITH "PRECISE POWER" SPECIFICATIONS

Load (Percent)	Steady State Speed Regulation			Load Transients[1] Frequency Deviation		
	EFG[2]		"Precise Power"	EFG[2]		"Precise Power"
	60 Cycles Percent	400 Cycles	Percent	60 Cycles Percent	400 Cycles	Percent
0	±.1	±.1	±.25			
25	±.1	±.1	±.25	−.4	−.4	−1.5
50	±.1	±.1	±.25	−.5	−.5	−1.5
75	±.1	±.1	±.25	−.6	−.6	−1.5
100	±.1	±.1	±.25	−.75	−.75	−1.5

1—Sudden load increase 0-25.%, 0-50.%, etc.
2—On 30 kw, 1200 rpm, diesel generator set



These electric-governor controlled generators power a military radar field installation.

At first glance, it seems inconsistent that straight frequency (speed) sensing could be more sensitive than load-sensing with its speed-change anticipation feature. However, the EFG governor frequency reference circuit is affected temporarily by voltage transients in such a way that reduced-voltage transients signal an impending speed drop, and increased-voltage transients signal an impending speed increase. Since load increase or decrease is accompanied by a transient voltage decrease or increase respectively, the EFG governor is likewise speed-change anticipating. (See *Governor Operation*.)

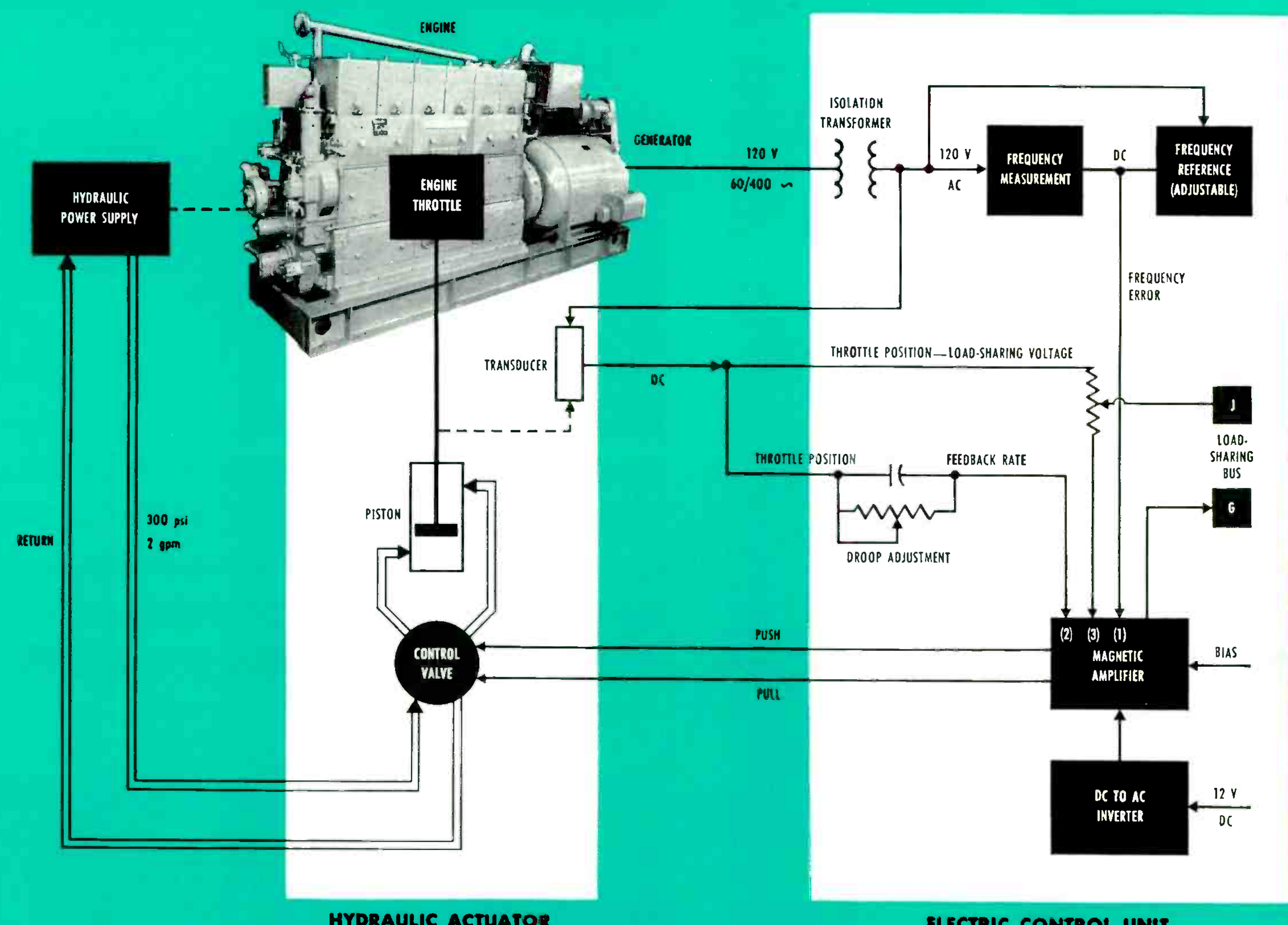
Actual performance data for the EFG governor as compared with "precise power" specifications are listed in Table II. The EFG data were taken from laboratory performance records on a 30-kw diesel-generator set at 1200-rpm engine speed.

The 60-cycle data were obtained by sensing main generator frequency in the normal manner. The 400-cycle data were obtained by operating the same generator set; however, a small 400-cycle permanent-magnet generator was connected directly to the engine to supply power and the frequency signal to the governor control unit.

This illustrates an important additional feature of the EFG governor: it can be applied to prime movers driving a mechanical load, and will provide the same precise speed regulation obtained with electric-generator set operation.

field experience

Performance data from field installations are reported typically as frequency control under one percent for full-load pickup, on sets under 300 kw and engine speeds over 720 rpm, with recovery time of less than one second. On lower-speed, higher-capacity sets comparative figures are 2 percent and 1.5 seconds approximately.



Steady-state regulation is typically within plus or minus one-fourth percent. Speed regulation from no-load to full-load is isochronous. This characteristic permits isochronous operation of two or more sets in parallel. Automatic kilowatt load division is maintained to closer limits than is possible with other type governors. Hence, generator sets can be operated nearer their capacity limits.

application

The EFG governor is a universal prime mover accessory, applicable in any situation where constant-speed control is required. Continuous speed adjustment within plus or minus five percent of base speed is possible. For systems in which the prime mover is driving a mechanical load, a small (50 watt) direct-connected permanent magnet generator can be added to supply 120-volts ac for power supply and frequency (speed) signal.

Initial applications of the EFG governor have been to diesel engines in line with the Government "precise power" diesel generator program. However, extended testing of this governor system on steam turbines and gasoline engines has consistently shown improved results over conventional hydraulic governors.

For steam turbines, an electric-sensing component is used for automatic load division in parallel operation to compensate for the throttle-step characteristic of the multiple steam inlet valves. Also, since considerably higher forces are required to move steam valves than to operate diesel throttles, a modified hydro-mechanical valve actuating mechanism is needed.

The precision performance possible with the electric governor has already established it for critical power supply application; the electric governor bids fair to become a widely used governing system in the future. ■

GOVERNOR OPERATION

The Model EFG governor consists essentially of an *electric control unit* and an *electrohydraulic actuator*. The control unit is a sensing element that receives, mixes, and amplifies three signals: (1) the electrical error between generator frequency (engine speed) and the frequency reference, (2) a throttle position rate signal, and (3) a signal proportional to load on the engine in parallel operation.

An electrical summation of these is magnetically amplified and the resulting signal is applied in push-pull across the electrohydraulic actuator. The actuator is in effect an electrohydraulic servo-motor, which receives electrical intelligence from the control unit and converts this signal to proportional movement of the actuator piston for positioning the prime mover throttle to maintain engine speed.

A transistor oscillator in the control unit inverts 12-volt dc supply to approximately 1000 cps, which is applied to the magnetic amplifier power winding. Hence, the magnetic amplifier operates at higher than generator frequency in both 60- and 400-cycle service, providing both high sensitivity and good stability.

Under steady-state conditions, slight excursions from pre-set base frequency cause negative or positive voltage differences in the net output between the frequency-measuring and frequency-reference circuits. These voltage differences operate through the magnetic amplifier frequency winding to cause the actuator to move the prime-mover throttle automatically in the direction of more or less fuel admission.

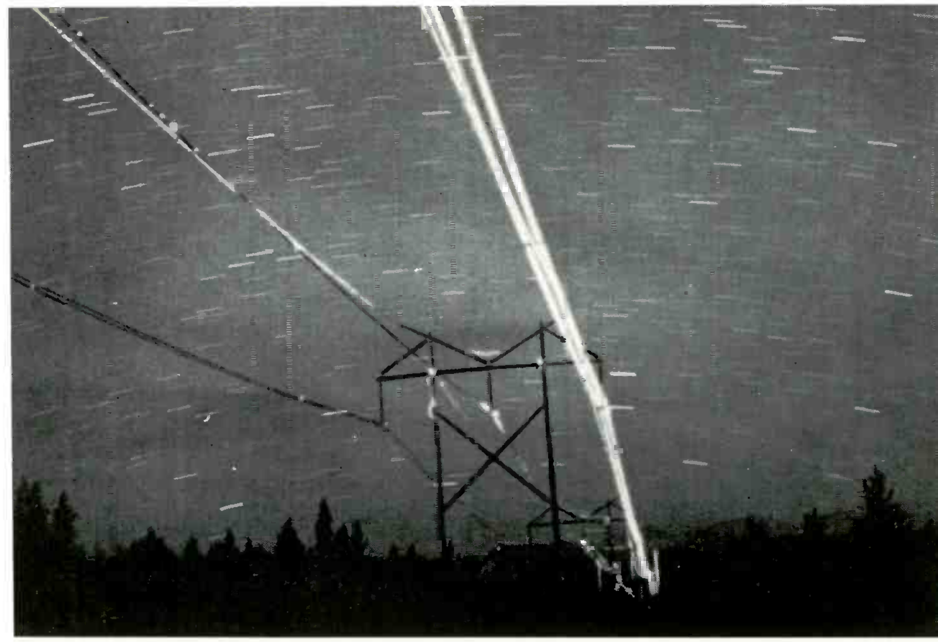
As the throttle is moved toward the open or close position, negative feedback signal is generated by the throttle position feedback transducer, which is mechanically connected to the actuator piston. This feedback signal provides a stabilizing influence through the feedback winding in the magnetic amplifier.

Since this feedback voltage returns to zero when the throttle is at rest, the governor is able to maintain isochronous speed control. This applies to parallel and single-unit operation. Moreover, the feedback transducer output is proportional to throttle position. Therefore, it is also used to indicate engine load in parallel operation.

Operation under load-change conditions is similar to steady-state operation except that the frequency-error signal is stronger and therefore creates greater forcing action by the actuator on the prime-mover throttle. Furthermore, transient load changes characteristically cause transient voltage changes in the main generator output voltage, which is the source of frequency (speed) sensing by the governor. These transient voltage changes are translated immediately by the frequency reference into signals of impending speed change.

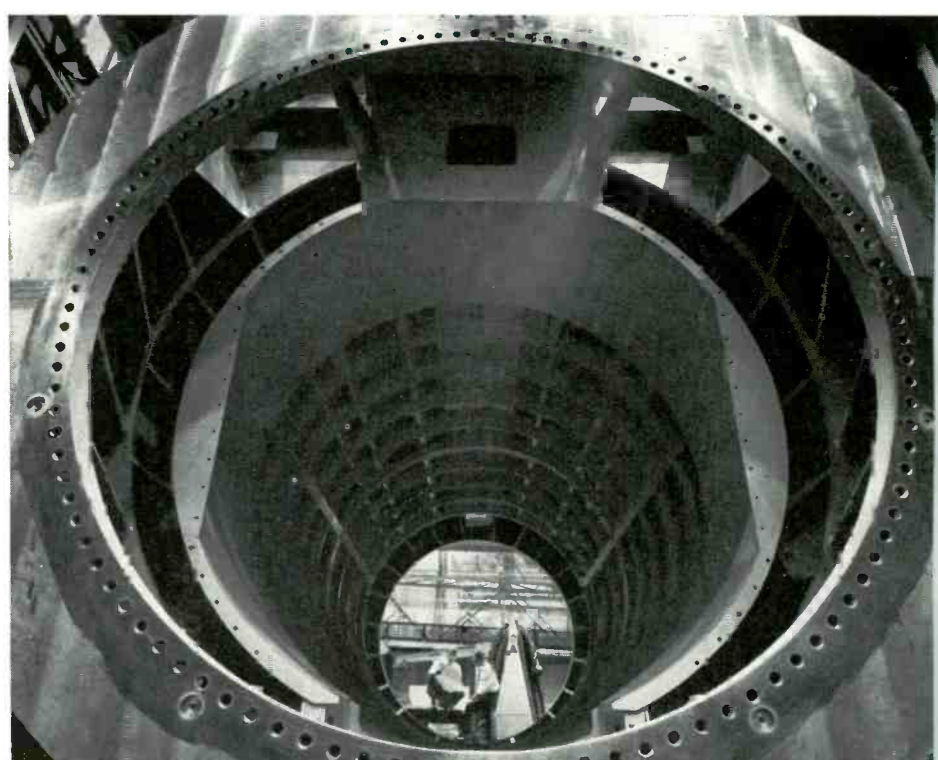
This anticipatory action takes place as follows: Both the frequency-measuring and frequency-reference circuits are activated from the same power source. A characteristic of the frequency-measuring circuit is that it lags the frequency-reference circuit by a finite time. Under steady state or gradual change of activation voltage, the two circuits are affected substantially equally, and the governor is essentially unaffected by slight changes in main generator output voltage. During load transients, generator voltage is changed momentarily and this is first noted in the frequency reference.

A load pickup, for example, causes a momentary voltage decrease of substantial magnitude. This in turn causes the frequency reference to take a new position in the direction of a higher-speed setting. In other words, the governor immediately opens the engine throttle to attain the new speed setting. This is a transitory action, and is dissipated in a matter of milliseconds, but it serves to anticipate speed drop and initiate throttle movement before generator speed actually changes.



This photograph of the extra-high voltage electric transmission test line at the Leadville Substation of the Public Service Company of Colorado was taken using high-speed film and long-time exposure. This technique, made possible by new high-speed films, is enabling transmission engineers to learn more about the nature of corona, arcing, and potential noise sources of extra-high voltage lines.

WHAT'S NEW IN ENGINEERING



More than 14 feet in diameter and 30 feet long, this steel frame will house the world's largest 3600-rpm turbine-generator. Rated at 384 mva, the completed unit is scheduled to be delivered to the Arkansas Power and Light Company's new station near Helena during the summer of 1960.

NEW JOINING TECHNIQUES FOR NUCLEAR CORES

Since the beginnings of atomic power, the development of materials to satisfy the unusual needs of nuclear reactors has been one of the major difficulties. Part of the problem has been that of finding satisfactory methods of joining the metals used in the core.

In the first reactors, the major effort was devoted to finding practical methods that would do the job. Now the attention has turned to finding better methods—either from the standpoint of better joints, simpler procedures, or less cost. Three processes now being investigated at the Atomic Energy Commission's Bettis Laboratory are typical developments.

Electron Beam Welding—An intense and highly concentrated beam of electrons in a vacuum can melt or vaporize any metal in its path, and if accurately controlled can be used for precision drilling of holes. In fact, devices of this type have been used for several years to put holes in watch jewels. More recently, much attention has been focused on a similar process for welding, and during the past year extensive development work has been devoted to the use of electron beam welding in the manufacture of nuclear cores.

In electron beam welding, when the high velocity beam of electrons strikes the metal surface, the thermal energy is highly concentrated and cannot be readily absorbed by conduction. Therefore, both melting and vaporization occur in a small area. A conical cavity is formed as a result of the vaporization, and, as the beam traverses a weld seam, molten metal flows into this cavity and resolidifies.

Most electron beam welding equipment in this country uses low voltages (under 50 kv) and high currents (approximately 1 ampere) and the resultant weld is similar to that obtained by other welding methods—its width is several times as great as its penetration. The equipment used in experiments at Bettis, however, operates at high voltages (above 50 kv) and low currents (under 20 milliamperes), and produces strikingly different results.

The high-voltage electron beam welding process appears to have many attractive possibilities, particularly in the welding of highly reactive metals in vacuum, and in making special situation welds that might be extremely difficult or impossible with other welding techniques.

At present, two factors may limit the use of this process for production purposes. With present equipment, the control of the weld penetration is not accurate enough from weld to weld, because of the difficulty of maintaining machine settings. A second problem may be encountered in the build-up of heat within the workpiece during multipass welding. Since electron beam welding is conducted in a vacuum, heat dissipation is more difficult than with inert gas shielded welding. Neither of these problems seems insurmountable.

Pressure Bonding — Metallurgists have searched for years for a good method of bonding metals using only pressure and temperature. A method now being evaluated at the Bettis Atomic Power Laboratory may provide just such a process for the manufacture of nuclear fuel subassemblies.

Basically, the process consists of stacking the components of a fuel subassembly in "sandwich" fashion. Such a "sandwich" consists of a cladding material cover, the fuel core material, another cladding material cover, and so on until a subassembly of suitable size is built up. An insert is inserted at localities in this sandwich where channels for water flow are desired. This insert is removed by acid after the bonding is complete.

The entire sandwich—consisting of finish-size components — is stacked within a metal container, which is subsequently closed by welding, evacuated through a small tube, and sealed under vacuum. The evacuated container is then placed in a high-pressure vessel and brought up to pressure and temperature in an argon atmosphere. The combination of temperature and pressure forms an effective joint by interdiffusion of the metals.

The advantages of such a process are obvious. Finish-size components can be cleaned, assembled, and then joined in one operation. The fabrication of a fuel subassembly from finish-size components could become a one-step instead of a multi-step operation.

Diffusion Bonding—A diffusion bonding process being developed is one of the processes that may help make metallic-clad uranium oxide plate-type elements possible. Based on the present stage of development, these elements consist of three different components: (1) the uranium-oxide fuel, pressed and sintered in the form of flat rectangular-shaped wafers (each assembly contains many wafers); (2) a fuel receptacle plate which holds the fuel wafers in separate compartments; and (3) cover plates of a cladding material. The cover and receptacle plates are joined by diffusion bonding, thus effectively sealing the entire fuel element.

The new process, more precisely called *eutectic diffusion bonding*, is a method of joining the cladding components and involves the formation of a molten eutectic alloy film between solid mating surfaces under the application of an external gas pressure (60 psig). The eutectic alloy film is formed by diffusion of a preplaced thin layer of a pure metal (copper) on the surfaces of the receptacle plate. The diffusion occurs during heating of the assembled components to the bonding temperature (1900 degrees F). On reaching the melting point of the eutectic alloy, local melting occurs and effects bonding of the solid and higher melting point cladding components. Holding the assembly at the bonding temperature for an extended period (30 minutes) results in diffusion of the bonding agent into the mating cladding components. The microstructure of the bond is noteworthy because there is no solid eutectic alloy layer in the bond interface as in brazing. In fact, there is a complete disappearance of the original cladding component interface and a replacement by a uniform and homogeneous microstructure.

Testing thus far conducted shows adequate strength and ductility and no problems with dimensional changes during thermal cycling. ■

THE TAMING OF TUNGSTEN

Tungsten is one of the most difficult metals to work with. It is brittle at room temperatures, and therefore all processing must be done at high temperatures. But with uncharacteristic "friendliness," single crystals of tungsten are ductile at room temperature, and thus far easier to process. Because of this fact, research engineers at the Westinghouse lamp division are now experimenting with a method of growing large single crystals of tungsten.

The method involves focusing an electron beam on a tungsten rod in a vacuum, then moving the beam progressively along the length of the rod. At the proper rate, this process grows a single crystal, and at the same time zone refines the tungsten, boiling off many of the impurities.

As an example of the startling results thus far obtained, the brittle to ductile transition temperature of the pure single crystal is approximately *minus* 150 degrees C, as compared to plus 300 to 400 degrees C for ordinary tungsten.

The electron beam zone refining process also reduces gaseous impurities by a factor of about four, and virtually eliminates metallic impurities—to the point where they are nondetectable.

The new process raises the possibility that single crystals could be grown from sintered ingots. The entire tungsten processing system might thus be shortened considerably.

Thus far no practical problems in the single crystal process have been encountered, but the development is still in early experimental stages.

Several interesting sidelights have been discovered in the course of experiments. On one specimen, a two mil surface layer of heavily worked tungsten resulted from machining a crystal. If the two mil layer was left on the metal, the transition temperature was about that of ordinary material. But when the layer was removed, the transition temperature suddenly dropped to the minus 150 degree C level. This leads to the conclusion that a tiny crack initiated in the thin surface layer continues through the layer and then through the pure material, even without the presence of a grain boundary. While the situation is quite different with ordinary polycrystalline wire, this fact may help explain some of the brittle nature of tungsten. ■

DUCTILE IRON FOR GENERATORS

Ductile iron—a material with characteristics between those of cast iron and a cast steel—is rapidly making a name for itself as a structural material for large generators. The nonmagnetic variety of ductile iron is being used in several applications in place of stainless steel. Ductile iron offers several advantages: The nonmagnetic properties of ductile iron are about on a par with stainless steel, but because the resistivity of ductile iron is higher, eddy current losses are reduced. For parts configurations, where complicated welding and machining operations are required with stainless steel, ductile iron can be easily cast. Furthermore, a ductile iron casting is considerably stronger than the weld joints required in a steel fabrication. The material machines readily, so that critical surfaces can be easily machined on the casting. Herein also lies a major economic advantage of ductile iron; where the part configuration is such that casting patterns can be built, manufacturing costs can be appreciably reduced. An example are the core support plates used in a large turbine generator. Cast ductile iron cuts more than a third from the fabrication cost of the previous stainless steel version.

As a result of the success in applying the material, design engineers are checking many of the stainless steel parts for possible substitution. Machines now in manufacture have stator coil and core supports made of ductile iron, and many other parts are under investigation, such as the stator blower shroud and supports, and gland seal brackets.

Ductile iron materials consist of a group of nickel alloyed cast irons containing 18 to 36 percent nickel, which are specially treated with magnesium. In regular cast iron, graphite is in a flake form, and the material is brittle; in ductile iron, the magnesium treatment serves to convert the contained graphite to a spherical form, which results in a material with high ductility. Ductile iron has a ductility of 20 to 40 percent, whereas cast iron has practically none. The material has good corrosion resistance, and is extremely easy to machine. The material was developed by the International Nickel Company, and is being made by authorized foundries, such as the Westinghouse Foundry in Trafford, Pennsylvania. Conventional melting and founding practice is employed. ■

DEVELOPMENT OF INDUSTRIAL CONTROL COMPUTER ANNOUNCED

Plans are under way to build an industrial control computer whose speed, input-output capacity, and memory can be precisely matched to the needs of a particular process by the addition of semistandard "function-modules." The new computer will be sufficiently versatile for use in general industrial and electric utility applications, and sufficiently rugged for use in industries with severe environmental conditions, notably the chemical, paper, petroleum and steel industries.

The flexibility afforded by this new approach will make it possible to supply a great variety of complete control computer systems. It will also be a major economic benefit to the user of the system since the computer installation can be modified as process requirements change.

Also contributing to flexibility will be the computer's construction. Design engineers plan to use static devices exclusively in the basic computer so that it will have reliability equal to or better than that of typical heavy-duty production equipment.

This computer development program was undertaken because of a conviction that industrial computers must be compatible with the electrical and electro-mechanical equipment used by industry; not only in function, but in every aspect of performance.

The functions of the system are grouped in three divisions: quantitative data processing and control; logical data processing and control; and priority direction.

The quantitative data processing and control function consists of measuring analog quantities or preconverted digital equivalents, providing analog outputs, logging of data, accepting data from operating personnel, and performing calculations.

The logic operation portion of the computer receives instructions stored in a magnetic core memory, and under their guidance, controls off-on devices such as valves, and breakers, and performs other logical operations.

The priority director can control a number of sequential operations of equipment simultaneously on many parallel paths. In addition, it will control the interruption of any or all of the sequence paths when predetermined variables move out of limits, and designate the location in the memory unit to which the computer control will transfer if an off-limit quantity occurs. ■

PERSONALITY PROFILES

E. C. FOX joined Westinghouse after graduation from Duke University with a BSEE in 1951. However, after only one month on the Graduate Student Program, the Navy called for his services. Fox served as an electronic technician until late 1952, when he returned to Westinghouse. Fox was selected for Design School in early 1953, and then went with the general mill section of industrial engineering.

Here, he has worked with a variety of industries, such as rubber, textile, lumber, paper, and glass (of which he writes in this issue). Fox has also been involved in several special development programs—a computer program for crane duty cycles, application of 400-cycle magamps, paper machine digital speed regulators, and several computer studies on regulator drive systems.

Fox obtained his MSEE from the University of Pittsburgh in 1959.

C. G. HELMICK, a graduate of the University of Michigan with a BSEE and MSEE in 1951, is setting a steady pace for himself. His article in this issue is his third in as many years. (And we already have him committed to his fourth, to keep his string intact.)

Chuck is a member of the general mill section of industrial engineering, and concentrates on the man-made fiber industry. One of his special projects at the moment is the application of solid-state devices to new concepts in fiber spinning machine drives.

People from many engineering fields, including many outside of the electrical industry, know **R. E. PETERSON** well for his skill in mechanics of materials. As a result of this reputation, Peterson's know-how has, either directly or indirectly, affected the design of a large number of widely different products, from airplanes to large generators. Stress analysis and fatigue of materials are particularly strong points of his know-how.

Peterson earned his bachelors degree in mechanical engineering from the University of Illinois in 1925, and his masters degree in 1926. While at Illinois he met Dr. Stephen Timoshenko, world authority in the field of mechanics, and then an engineer at the Westinghouse Research Laboratories. Peterson was attracted to Westinghouse as a result of this meeting and joined the Laboratories. Several years later, in 1931, he became head of the Mechanics Department at the Research Laboratories.

Any attempt to single out a few achievements of Peterson and his department since that time would be unfair, because they are so numerous and cover such a wide field of devices. Suffice it to say that it would be difficult to find a Westinghouse product that Peterson's department has not somehow affected.

But Peterson's accomplishments are not confined solely to mechanics as such. As his article about the Advanced Mechanics School in this issue implies, he has played an important role in the development of young scientists and engineers. "Alumni" of the Mechanics Department play important roles in many divisions of the company.

Peterson has also contributed much to engineering association activities, and has served as chairman of numerous committees of ASTM, ASME, ASA, and as president of SESA. Peterson is the author of about 50 technical papers, as well as a book on stress concentration.

In this issue, **W. W. HOHENNER** dwells on his favorite theme, of which he has spoken and written about frequently: the reliability barrier in complex weapon systems. Dr. Hohenner graduated as a mechanical engineer from the Technical University, Munich, Germany and obtained his Ph.D. from the Technical University, Darmstadt. He joined the German Research Institute for Soaring and eventually advanced to Director of the Physical Department. After World War II, he came to the U. S. and worked at the U. S. Naval Air Missile Test Center, Point Mugu as Head of the Specialist Section. Staying with the Navy he later transferred to the Naval Air Development Center, Johnsville, Pa. and was then called into the Special Project Office as Technical Advisor for the Fleet Ballistic Missile System (Polaris). In 1957 he joined the Westinghouse Air Arm Division as Senior Advisory Engineer. Dr. Hohenner is presently Chief Scientist in weapons systems engineering.

Dr. Hohenner has spent most of his professional life in the development of weapons systems. During this process, he has become thoroughly familiar with the subject of his article. He assures us that the slightly pessimistic hue, appearing here and there, should be regarded as professional experience. In his personal appearance, he does not show much of this pessimism. He enjoys cross-breeding all sorts of technical advances in an effort to break down the reliability barrier, of which he is so much concerned.

G. M. DAMON's first association with Westinghouse came in 1929, when he participated in lightning research, as a member of the miscellaneous engineering department. He left Westinghouse in 1930 to go with a midwest utility company.

He rejoined Westinghouse in the new products department in June 1939, after studying Management Engineering at Carnegie Tech. In 1940, Damon joined the U. S. Army, presumably for a one-year term with the Ordnance Branch. But World War II stretched the "one year" term to nearly five, and included service in India and China. Damon was released with the rank of Major.

He returned to the new products department in 1946. Here, he has been associated with such new developments as powder metallurgy, the heat pump, aircraft turbochargers, guided missiles, and the electric governor. The last named subject, which he describes in this issue, now takes up all his time. Damon is presently sales manager for the electric governor section of the systems control sales department.

INSIDE SUPERSONIC TUNNEL

This is an inside view of the huge supersonic wind tunnel nearing completion at the Arnold Engineering Development Center at Tullahoma, Tennessee. The tunnel is a key facility for testing space vehicles, missiles, propulsion systems—and components—of the future. Speeds of approximately 3000 miles per hour at simulated altitudes of more than 100 000 feet will be created within the tunnel by means of the largest rotating machine ever built. Supplying this vast amount of power will be two 83 000 horsepower motors, and two smaller "starting" motors of 25 000 horsepower each. The scaffolding seen here supports workers who are installing the layer of patchwork-like insulation material that will absorb temperatures ranging as high as 650 degrees F. Tunnel diameter at this point is about 55 feet.