Westinghouse
ENGINEER
MARCH 1964

This full-scale mock-up of the Westinghouse deepsea research vehicle, Deepstar, is being used by design engineers to determine the best location for equipment. The spherical inner hull will carry three crewmen. Tubular framing indicates the shape of the outer hull that will cover the vehicle. The box-like objects show battery locations; the cylinders forward and aft represent mercury ballast tanks used for vehicle pitch control; the tubular cylinders on each side of the vehicle are propulsion motor locations. Batteries, ballast system, and other equipment outside the crew's hull will be subjected to almost three tons per square inch pressure at the maximum diving depth of 12 000 feet. Crewmen are protected by the $1\frac{1}{4}$-inch-thick steel sphere.

The positions of crewmen and controls are shown in the interior view. The pilot of the craft and an observer are in prone positions, and can view marine life through the two portholes. The co-pilot is seated. To make the most of the Deepstar's 24-hour maximum allowable time beneath the surface, the craft will descend and rise in a near-vertical attitude. The co-pilot's seat will tilt over a range of 90 degrees when the vehicle is diving and ascending.

The project is directed by the Underseas Division in conjunction with Deepstar's designer, Captain Jacques Cousteau, famed French underseas explorer.

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Prodac, Kromarc

Cover Design: Both brawn and brains—a rolling mill and a sensitive control system—are needed to roll metal strip to consistent thickness. These two main elements of an automatic gauge-control system are combined by Thomas Ruddy of Town Studios, Pittsburgh.

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Strip-Mill Automatic Gauge-Control Systems

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Specialized feedback systems regulate rolling mills to hold product thickness constant in spite of changing rolling conditions.

A demand for more consistency in the gauge (thickness) of rolled metal strip has been an important trend in the metals industries in recent years. Producers need better accuracy to reduce their scrap and thereby improve the efficiency of their operations. Users demand it because gauge variations wear dies, jam them, and cause automatic forming equipment to malfunction.

Consequently, nearly all strip mills built in recent years have included automatic gauge-control systems, and most mills that were originally built without the systems have had them added. The systems range in complexity from a thickness gauge with simple control additions to completely integrated systems designed as part of the mill drive equipment and controlled by a computer. Best results are obtained when the system is planned carefully as an integral part of the overall mill system.

Fundamentals

The most important part of the mechanical mill system is the "roll bite," the portion of the rolls in contact with the strip (Fig. 1a). The roll bite is an extremely complex function that is difficult to define accurately and can vary with a change in any one of a number of mill variables (such as temperature, speed, pressure, tension, lubrication, roll surface condition, and angle of entry and exit) and with changes in the product's metallurgical properties, temperature, and dimensions (Fig. 1b).

The main purpose of an automatic gauge-control system is to readjust the mill drives to produce a consistent thickness as one or more of these variables change and upset the equilibrium conditions that were established. Another variable not at present considered part of the system, but which could be, is the difference in operating methods used by the various operators.

An automatic gauge-control system differs considerably from most other feedback control systems. For example, in most common feedback systems (such as speed, voltage, and current regulators), there is no transport time delay within the closed-loop system. System parameters are usually definable and relatively constant for all operating conditions that may be encountered.

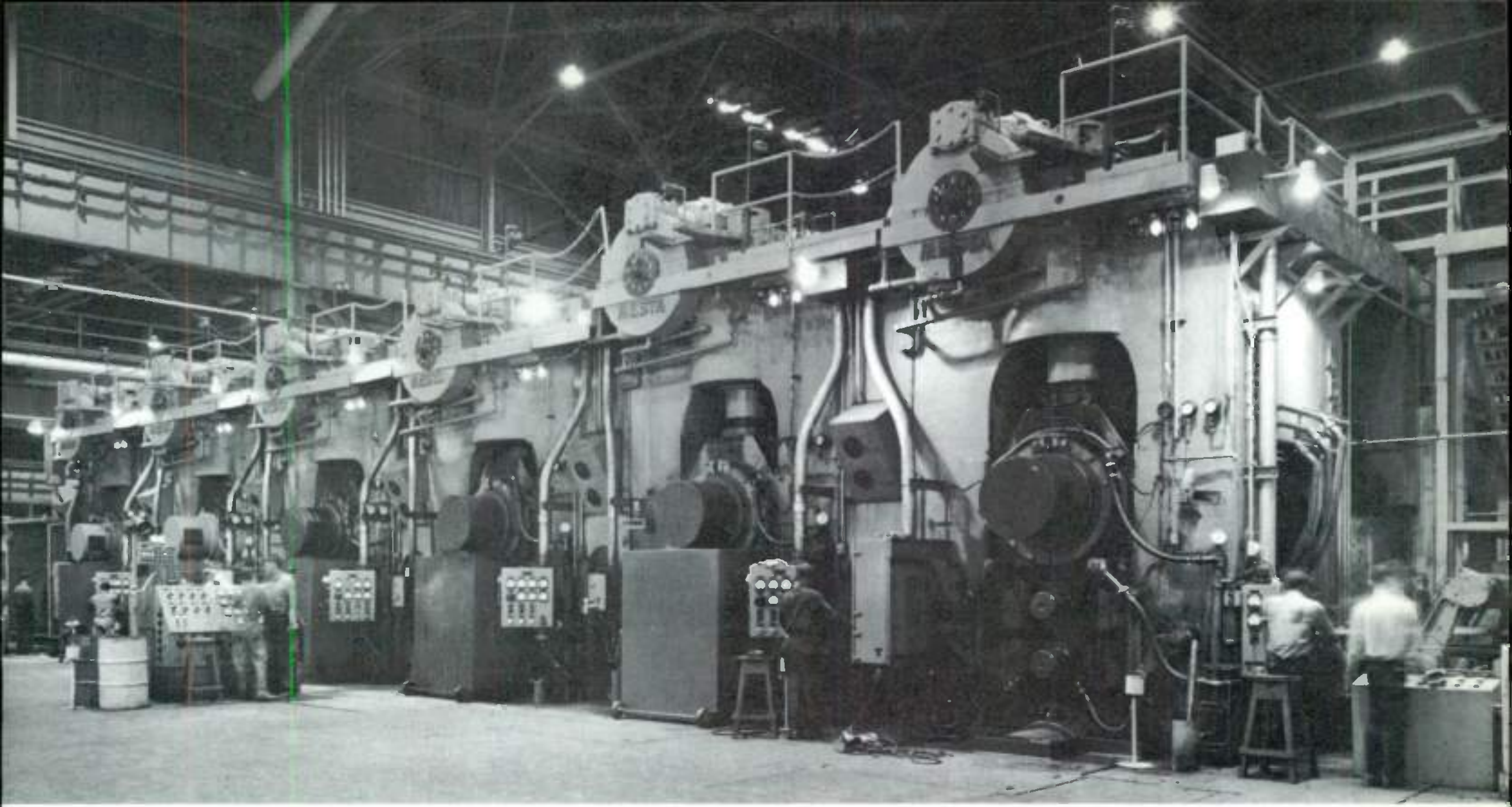
In an automatic gauge-control system, however, the controlled variable—gauge—generally is not measured in time phase with its actual occurrence, but a time interval later because of the mounting distance of the thickness gauge from the roll bite. This puts a transport lag in the feedback signal that varies with the speed the strip is moving. At high strip speed it is of negligible consequence, considering the other delays in the system. At lower speeds, though, it definitely must be taken into consideration; it often is the determining factor so far as speed of response is concerned.

The mill function portion of the overall system often varies widely during mill operation. The changes are quite rapid and, in general, not too predictable while the mill is being accelerated or decelerated. At constant running speeds the function usually stabilizes at a reasonably constant value for a given set of conditions. The value is not necessarily predictable and is generally determined empirically for various operating conditions of the mill. The gauge-control system must be flexible enough to cover quite a range of variation in the mill function.

Some of the variation is due to the way in which the mill reacts to changes in strip tension, screwdown setting, and speed. Variations in screwdown setting affect the pressure in the roll bite directly, and variations in tension affect the pressure in the roll bite by interaction with the pressure exerted by the rolls; thus, both factors affect the roll opening. Variations in mill speed affect the thickness of the oil film in the roll bite (besides having other effects), so this also affects the roll opening. The variations in roll opening, from whatever cause, affect gauge.

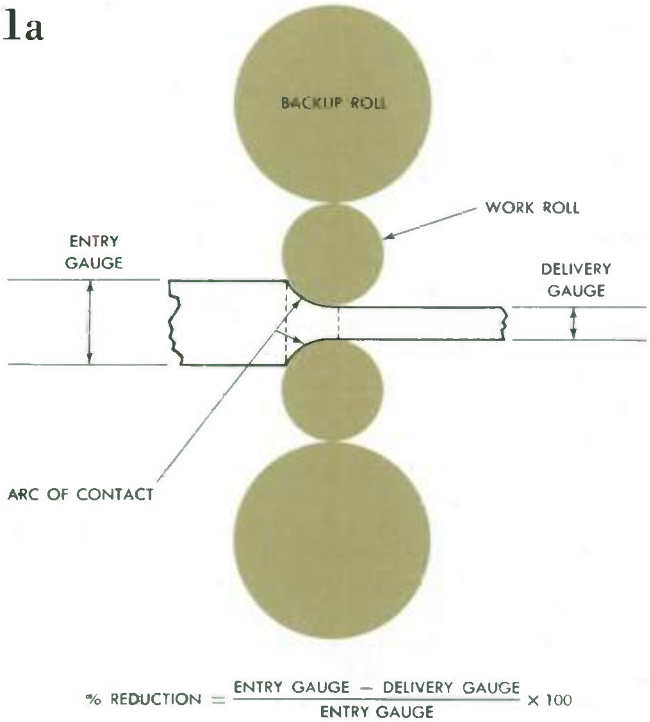
Partly because of the unpredictability of the rolling conditions and partly because of the transport time delay between rolling and measuring the thickness, stabilizing the automatic gauge-control operation can be a problem.

The possibilities for success of an automatic gauge-control system also depend on how the operator sets the mill initially and on how little he operates the controls once the mill is running. Most systems control the mill through the same basic means as the operator does; if he does not use discretion in changing the mill settings during running, he may introduce gauge errors and actually hinder the automatic gauge control.



SIX-STAND TANDEM COLD MILL reduces hot-rolled steel strip to tin-plate gauge at the Youngstown Sheet and Tube Company plant at Indiana Harbor, Indiana. Mill operators set the initial stand speeds and roll openings, and an automatic gauge-control system then measures strip gauge continuously and makes operating changes as required to keep gauge constant.

1a



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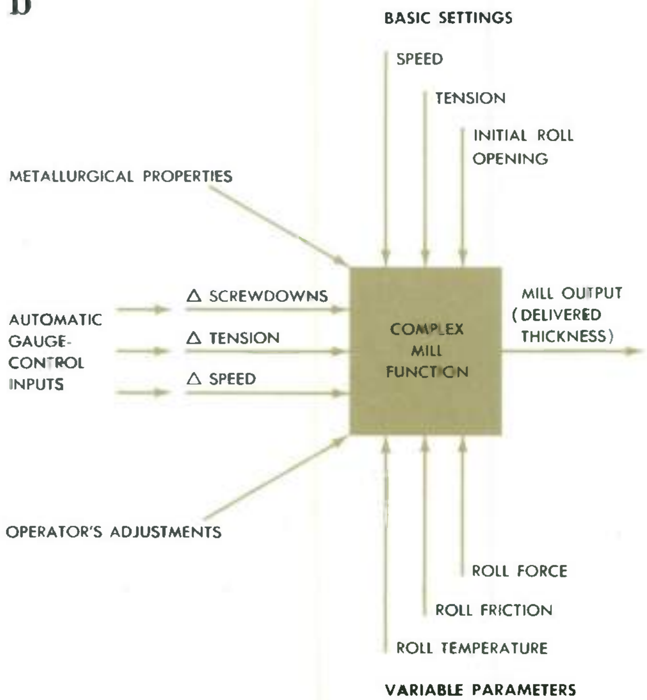


THE ROLL BITE (*a*), or the part of the work rolls in contact with the strip being rolled, is the critical area in a mill stand. Conditions in the roll bite vary with a number of different mill operating factors. Those conditions determine the amount of strip gauge reduction that is made. (*b*) The complex mill function is the sum of all the factors that affect the mill. It determines conditions in the roll bite and thereby determines the amount of gauge reduction that is made in the product.

Control Techniques

Signals are processed in the controller portion of an automatic gauge-control system mainly by transistor operational amplifiers. These are stabilized, high-gain, dc amplifiers that employ input and feedback impedances to perform such functions as summing, integrating, differentiating, and amplifying. Gain in the amplifier is sufficient to provide transfer-function accuracies of about 0.1 percent.

Logic, sequencing, and gating are performed mainly by mercury-wetted relays that combine the advantages of extremely long life with simple relay circuitry. They are also capable of rapid repetitive operation. Biased transistor amplifiers are used for voltage detection, except where signal-circuit isolation is required—bistable magnetic amplifiers then are used. Timing functions are provided by timing relays or transistorized timing amplifiers, depending on such requirements as repetitive operations, adjustability, and interlocking.

Gauge-Control Subsystems

All rolling mills operate in a generally similar manner, so they present a limited number of ways in which to control gauge. An overall automatic gauge-control system usually consists of a combination of basic subsystems. The type of subsystems used depends on the product to be rolled and the type of mill the system is to control.

Tension Type—This is used mainly with cold mills rolling the lighter strip thicknesses, especially when attempts to reduce gauge by increasing roll pressure would only flatten the rolls. Tension exerted on the strip combines with the pressure exerted by the rolls to increase the stress in the strip as it passes through the roll bite. In tandem mills, the correction signal is applied to one of two adjacent stands to cause the tension between these stands to change. In single-stand mills, the payoff reel receives the signal and changes the strip tension.

A sampled-data system can be used to advantage (Fig. 2). The gauge error signal is fed into a preamplifier and then through an error-sampling relay to an integrating amplifier. The output of this amplifier is the correction voltage that is transmitted to the tension-controlling drive on the mill.

The sampling system has two timers that continually cycle the control. During the *on* time, the error gate is switched to a conducting condition and the integrating amplifier adjusts tension quickly in response to any error that is present. The length of the *on* time is fixed by the *on* timer. When it has timed out, a signal appears in the output of the *on* timer that initiates the *off* timer. The *off* timer is automatically adjusted by a mill speed signal to be equivalent to the time it takes the strip to move from the rolls to the thickness gauge. During the *off* time, the error gate is nonconducting and the integrating amplifier remains at the output level set by the last previous *on* cycle. When the *off* timer has timed out, the error gate again switches to the conductive condition and the cycle repeats.

The integrating amplifier responds to the existing error, and its output at the end of the *on* time is dependent on the average value of the error during the *on* time. This gives a correction proportional to error, which allows a maximum rate of correction to be used. The rate of correction of a given error is set by the integration constant and the *on* time. The *on* time is set to be the mill response time or less, and the integration constant is set to correct as nearly as practical the total existing error in one *on* time.

When exceptional gauge errors occur, the integrator may reach a limit. When it does, a signal can be provided by an output voltage detector that unblocks a screwdown automatic gauge-control subsystem to correct further errors in that direction or, if desired, cause the tension system to go back within range. If the error reverses, the integrator reverses also and goes back within range automatically.

Screwdown Types—Two types of electric screwdown drives are in common use. One is the constant-voltage dc drive with motor power supplied from a dc bus. The motor is accelerated by use of armature resistance steps. More popular today is the adjustable-voltage dc drive, in which the supply voltage is varied to accelerate and decelerate the motor.

The constant-voltage screwdown drive must be carefully jogged to obtain precision in positioning, whereas the adjustable-voltage drive can be readily positioned with precision. Consequently, the latter type is a more versatile drive and permits a somewhat more sophisticated approach to automatic gauge control.

Constant-voltage drives usually are jogged for a given time period when a given gauge error is to be corrected. The time period may be made proportional, or roughly so, to the error to be corrected. This does not provide the most accurate control because position of the screws does not change in proportion to the time they are energized, due to acceleration and deceleration. Yet, the position change desired is proportional to error.

To obtain any degree of accuracy, the correction jog time must be made a function of error so that the position change is approximately proportional to error. In one way of doing this, a voltage-detecting system receives the error signal from the x-ray gauge. If the error exceeds the maximum allowable, the system senses the direction and magnitude of the error and energizes the screwdown motors for a given time to remove the error.

Three levels of error magnitude sensing are provided: for example, approximately one, two, and five percent error. For each of these levels, a corresponding timing circuit controls the *on* or jog time so that an appropriate screw change takes place. During the *off* time, initiated immediately on the stopping of the screw motors, no further correction takes place. The corrected strip in the roll bite is allowed time to reach the thickness gauge, and then the circuit is reset for another cycle when needed. The *off* time is automatically adjusted by the mill tachometer to be equivalent to the transport time.

Adjustable-voltage drives can be used with the same type of control system, but a more precise system generally is used. One method is to use a screwdown position-measuring device for feedback (Fig. 3). Screwdown position change then is proportional to gauge error. After the correction is made, a transport-time delay is introduced before another correction period can occur. If the positioning system is properly calibrated, the gauge error will have become zero by the end of the transport-time delay and another correction will not take place until a new error appears. An at-

Rolling is the fundamental process in production of metal strip. The initial reductions are made with the metal hot to make it easier to work, but finished strip is made by rolling at ambient temperature—"cold rolling." The two general mill types are tandem mills and reversing single-stand mills. In the former, the material passes through several sets of rolls (called stands) in succession. In the latter, the strip passes back and forth through the stand; the rolls are brought closer together between passes so that each pass reduces the strip.

Several variations of these general mill types are used, to suit the material a mill is to process and the product it is to produce. The products may be metal plate, sheet, strip, or foil.

An automatic gauge-control system is applied to a mill to make it roll its product to a constant thickness. The control is nearly always a vernier system that trims the coarse mill settings initially made by an operator, by an automatic programmer, or by a computer control system. A mill system with automatic gauge control is shown schematically in the illustration. It consists of the following basic parts:

A *thickness measuring gauge* that continuously measures thickness as the strip moves through it. The gauge is most often of the x-ray absorption type, which focuses an x-ray beam of controlled intensity on the strip. A sensor measures the radiation that penetrates the strip and compares it with the set intensity to produce a thickness-deviation signal. (Similar gauges using a radioactive material instead of an x-ray generator also are used, and some slower mills even have a contact micrometer.)

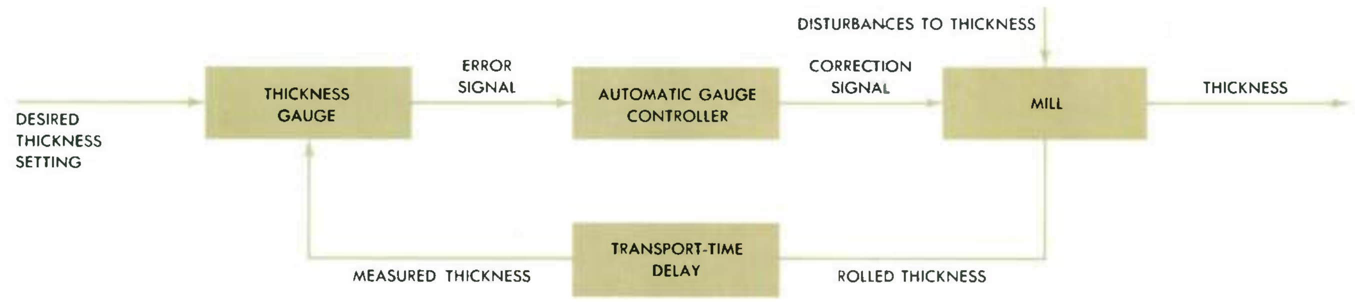
The thickness gauge is the reference setting device, the controlled-quantity measuring device, and the summing junction or error detection point that compares the reference value with the measured value and produces a signal proportional to the difference. (Thickness deviation is sometimes measured indirectly through roll force measurement. This is discussed in the text.)

A *controller*, consisting of amplifiers and other electronic circuitry to process the thickness error signal. It can be quite elaborate and complex, or relatively simple. Its output is fed into the control equipment for the basic mill drives.

The *mill drive equipment*, which is generally electrical but may be partially hydraulic. It includes the electric motors supplying power to the mill rolls, the devices and regulators that control this drive, the screwdown system motors and their control, and sometimes winding-reel drive and control equipment.

This equipment responds to the operator's control devices. The automatic gauge controller must also work into it to affect the mill's performance.

The *mechanical mill equipment*. This includes the rolls that actually contact the product and do the work on it; the gears, shafts, bearings, and so on that transmit power to the rolls; the mill housing or framework that supports the rolls; the screwdown threads, gears, and bearings that apply pressure to the rolls by pressing back against the mill housing; and the winding-reel mandrels, bearings, and gears. Guides and auxiliary mechanical devices aid in making the strip track through the rolls properly. A lubrication system applies a solution to the product as it is rolled to provide a proper frictional relationship between the strip and the rolls, and a cooling system helps maintain proper roll temperature with a deluge of water or other coolant.



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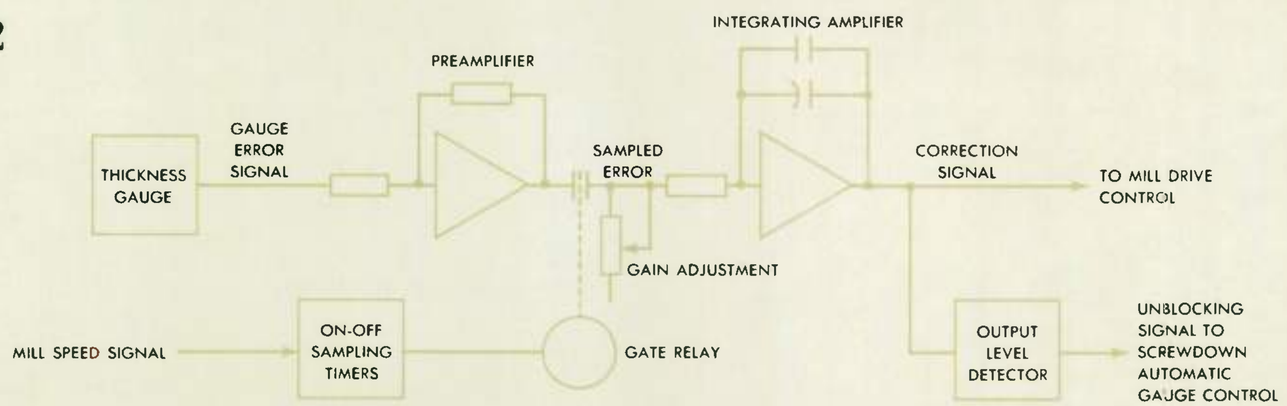

TENSION-TYPE automatic gauge control has an on-off sampling system to check the gauge of the strip leaving the rolls. Any gauge error detected is translated into a correction signal for the mill drive that controls strip tension.

tempt is made to correct the gauge error rapidly with one movement of the screws.

Another system sometimes employed does not have a position-measuring device but merely runs the screws until the gauge error goes to zero or at least to within a small dead band. The screwdown speed is proportional to error, and the system is a continuous feedback control system instead of a sampled-data system. The rate of correction of this system must be somewhat smaller than that of the sampling system to prevent overshoot. Thus, the time required for correction may be two to four times that of the sampled-data positioning system, especially at slow mill speeds where there is a large transport-time delay in the feedback loop.

Roll-Force Screwdown Type—This system uses roll force, as measured by load cells, as its input signal. Otherwise, it is similar to the first variable-voltage screwdown system described. Roll force does not provide an accurate measure of actual gauge but does provide an accurate measure of *change* in gauge from a reference value. Therefore, a thickness gauge is generally used to maintain the system in calibration at the desired reference gauge. This is done through a monitoring system that periodically, not oftener than once each transport delay, checks the actual gauge and modifies the roll force operating point. Some causes of thickness error, such as speed change and roll heating, are not sensed properly by a roll force system, but the monitor system compensates for these.

The system is energized automatically as strip enters the roll bite and a roll force signal is detected (Fig. 4). A roll force reference value has to be established immediately to enable the system to function. This reference value can be set manually, but it usually is set automatically by a memory circuit locking on the value of roll force present when the head end of the strip entered the mill. It can also be set by a control computer.

A gauge increase causes an increase in roll separating force. The control senses this increase and causes a screw movement to increase the roll force further as required to re-establish the proper gauge. The reverse operation occurs if gauge decreases.

The system adjusts the roll opening as a function of roll force and mill stretch, to regulate the gauge change dh to zero, in accordance with the following equation:

$$dh = MdF + ds$$

where M is the mill spring constant (which can be calcu-

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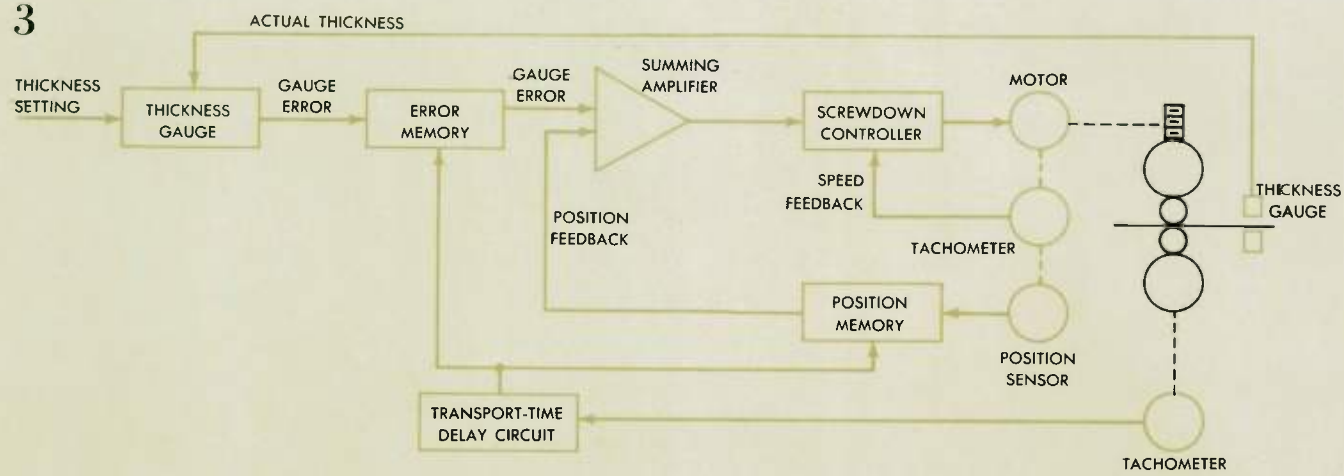

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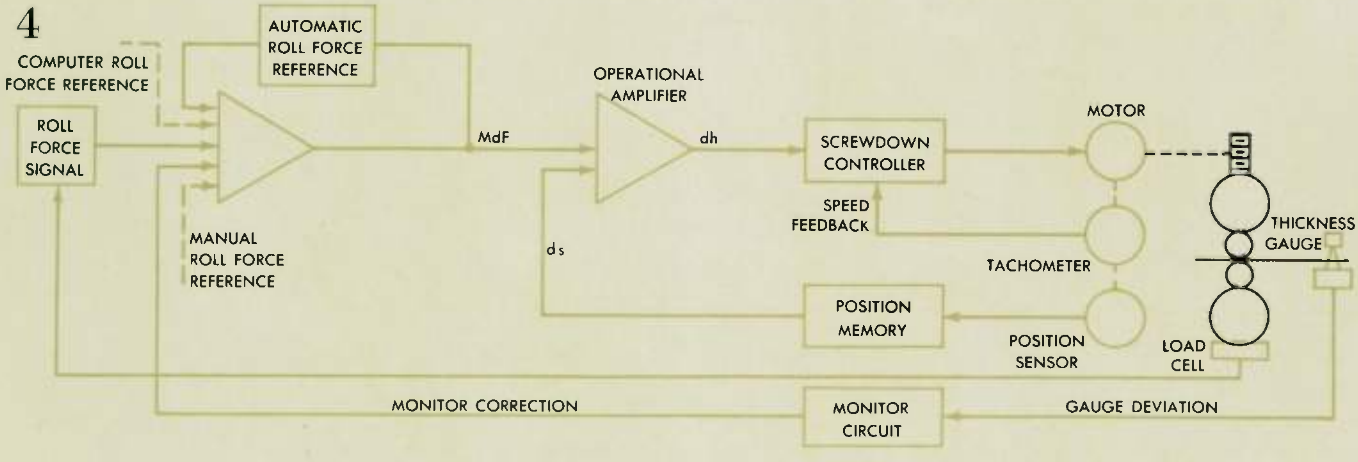

lated or determined by tests after the load cells are installed), dF is the change in roll force as measured by the load cells and subtracted from the initial reference value, and ds is the change in screw position.

An operational amplifier carries out the summation of the roll force equation. Its output, properly scaled, is a direct measure of the change in gauge. This value is used as the error signal to the screwdown drive. As the screws move, the error value goes to zero.

To minimize screw movement, a dead zone is usually provided so that the screwdown controller is not energized unless dh exceeds a set value. When dh exceeds that value, the entire dh signal is available to drive the screwdown controller until dh goes to zero. This eliminates the effect of regulating to one side or other of the dead zone.

Typical Overall Systems

Tandem Cold Mill—An automatic gauge-control system for a tandem cold mill is made up of several subsystems. These may include an entry-end subsystem, a delivery-end subsystem, and a subsystem operating during acceleration and deceleration to compensate for gauge change due to speed change.

The entry-end subsystem is usually a screwdown type, as large gauge variations occur there. It receives its error signal from a thickness gauge following the first or second stand or possibly from load cells on that stand (Fig. 5). It corrects for gauge errors that are already in the strip as it comes to the mill to remove part of the burden from the delivery-end subsystem.

The delivery-end subsystem is either a screwdown type or a tension type, depending on the material and thickness being rolled. The signal is taken from a thickness gauge following the last stand. This subsystem is considered a vernier, and it determines the gauge quality of the material produced.

Gauge variations are greatest during acceleration and deceleration, and they can be correlated somewhat to speed change. Because the gauge never stabilizes during these periods, a normal automatic gauge-control system could never catch up with the errors caused by the transport delay. (The errors can range from 25 percent to around 400 percent, depending on the material, the thickness being rolled, and the mill characteristics.) Therefore, the operating mode of the system may be modified during speed changes to leave out transport lag, and it may be biased to

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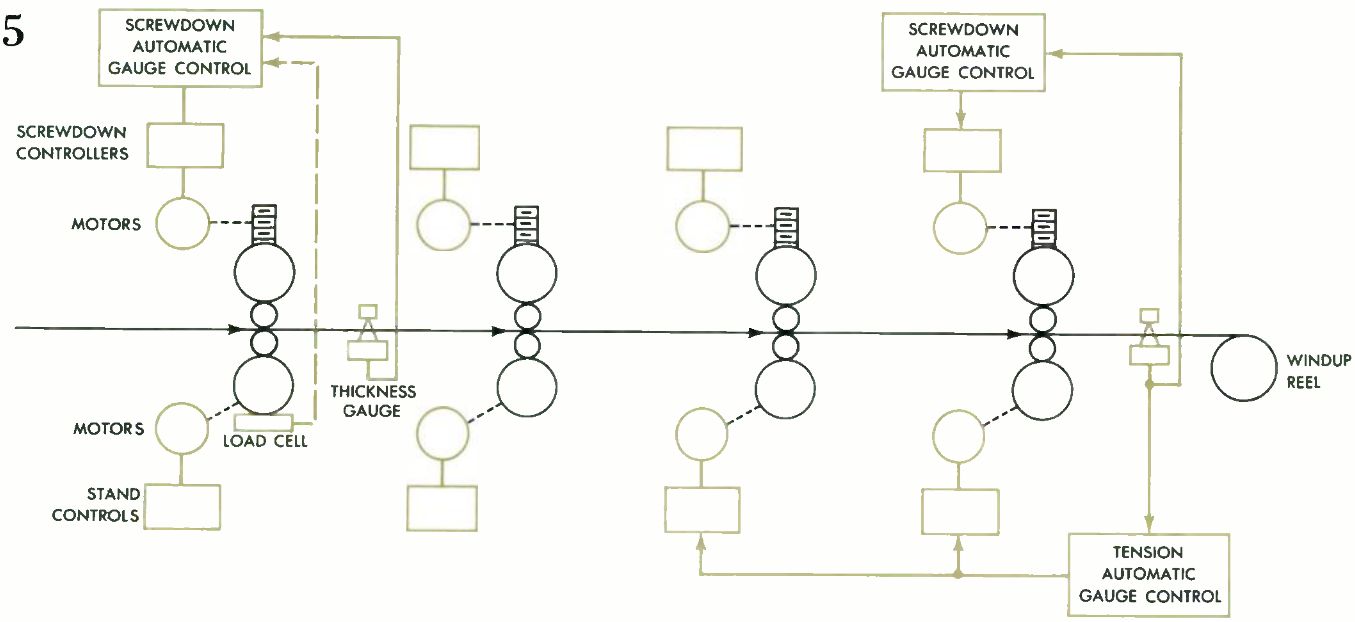

3) ADJUSTABLE-VOLTAGE SCREWDOWN TYPE adjusts screwdown settings to compensate for factors that would change gauge. The type illustrated has a screwdown position-measuring device so that screwdown position changes can be made proportional to gauge error.

4) ROLL-FORCE TYPE is similar to the screwdown type illustrated in Fig. 3. However, the primary input to the controller is a signal of strip gauge deviation provided by load cells that sense changes in roll force. A monitor circuit employing a thickness gauge maintains system calibration.

5) TYPICAL TANDEM COLD MILL automatic gauge-control system has both entry-end and delivery-end subsystems. The entry-end subsystem makes the initial correction of gauge errors, which are likely to be rather large because of deviations in the gauge of the incoming strip. The delivery-end subsystem makes the final corrections required.

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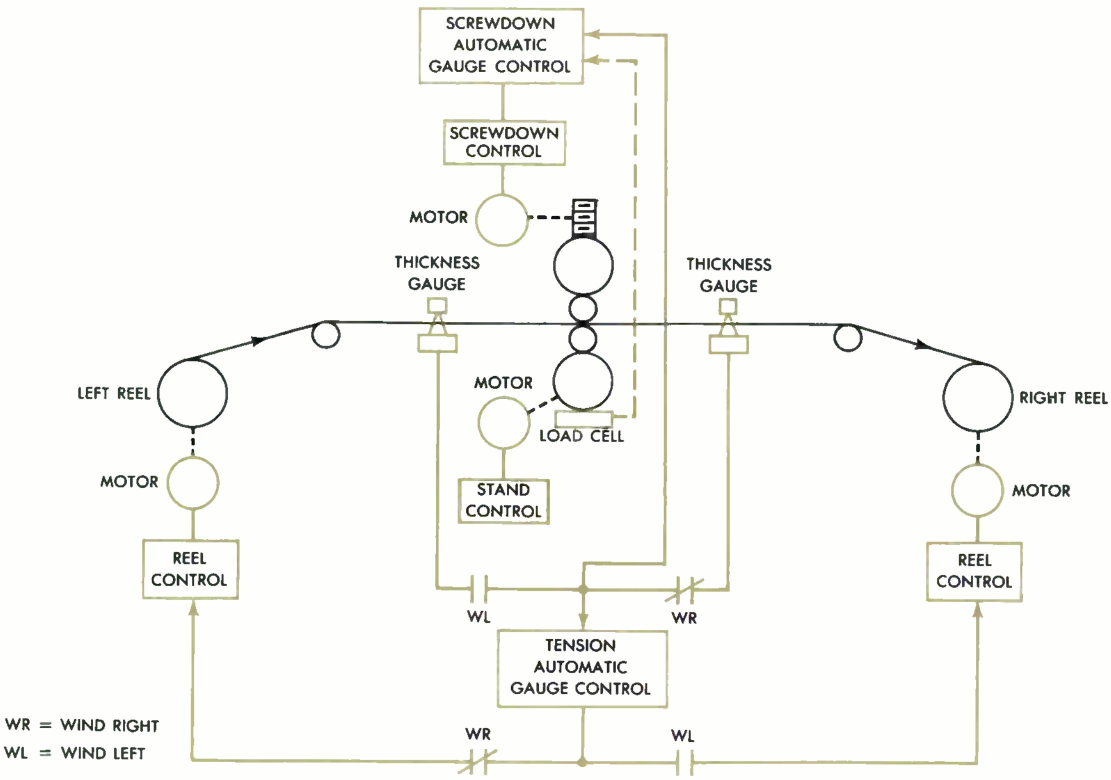

TYPICAL REVERSING COLD MILL system controls screw-downs and strip tension, either separately or in combination. The tension subsystem regulates the reel that is unwinding in each pass to control the tension of the strip entering the roll bite.

anticipate gauge error. Also, the screws may be operated or tension changed by programmed amounts to compensate for the effects of speed change.

Reversing Cold Mill—This type of mill presents some unique problems. The mill is accelerated and decelerated more often than a tandem mill is, the product's thickness changes with each pass, and the product's properties change with work hardening.

Generally, a thickness gauge is used on both sides of the mill, and load cells can also be used for gauge error signals (Fig. 6). A screwdown automatic gauge control is used for heavy-gauge passes. As the strip becomes thinner, control is shifted to a tension type working into the unwind-reel current regulator to vary entry tension. (Delivery tension is not so effective in reducing gauge.) A combination type is sometimes employed, controlling both tension and screws. The system automatically shifts from one thickness gauge to the other and from one reel to the other as the mill is reversed for each pass.

Speed-change problems are somewhat different, partly because speed changes can be taken in steps. Gauge can stabilize at each speed level before another change is made. Even so, it is well to compensate for speed change to provide more uniform gauge during the speed-change periods.

Hot-Strip Mill—Automatic gauge control was applied initially only to cold-rolling mills, as most final products are produced by cold rolling. However, the demand for tighter gauge tolerances has made it necessary to improve the gauge delivered to the cold mill. The cold mill can then produce better gauge quality because the incoming errors are reduced.

Hot-strip mills usually roll heavy gauges, so most of them use the roll-force screwdown method. The common hot-strip finishing mill consists of six stands in tandem. Automatic gauge control is applied to various numbers of stands, commonly two, three, or four, depending on the hardness of the material that is to be produced. Stainless steel may require that as many as four stands have the control; low-carbon steel may require only two. In conjunction, a tension-type vernier automatic gauge control may be applied to the last stand or next to last stand, using signals from a thickness gauge provided after the last stand. The thickness gauge also provides a monitor signal for the roll-force screwdown systems.

Conclusion

The complex interactions in a rolling mill, the many types of mills used, and the variety of materials and products rolled provide a great number and variety of problems to the designer of automatic gauge-control systems. The challenge will continue as new electrical devices become available and metal-forming methods progress. The rewards are commensurate with the effort applied, for a well-designed system can greatly improve the gauge consistency of the product and reduce the amount of off-gauge scrap.

Westinghouse ENGINEER Mar. 1964

Financial Mathematics for Economic Studies

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Present-worth and levelizing calculations convert future dollar requirements to equivalent present-day dollar amounts, so that economic comparisons can be made readily. The conversion takes into account the effect of minimum acceptable return—the return demanded by the investors of capital.

Economic comparisons are best made by evaluating future revenue requirements for competing proposals. Revenue requirements include all revenues that must be obtained to cover all expenses incurred, associated with and including the minimum acceptable percentage return on investors' committed capital. Certain components of the revenue requirements are conveniently expressed as percentages of capital investment, for they are functions of the amount of that investment. Other components, such as operation and maintenance and fuel expenses, are best calculated as annual dollar expenses. Included in economic evaluations must be all components of revenue requirements that contribute to differences between the costs of alternative proposals. After the components are calculated, each proposal will have a unique series of annual revenue requirements ready for comparison.

The final criterion of economic choice is the difference in present worth of all future revenue requirements of competing proposals, in all cases.[1] However, the same decision is reached by comparing annual revenue requirements directly, if they are a constant figure each year. The principle involved is illustrated in Fig. 1.

Annual revenue requirements are not a constant figure each year if "straight-line" depreciation is used for book purposes. In such case, present-worth arithmetic must be used to convert the unequal annual dollars to equivalent sums suitable for comparison.[2] These annually variable series of dollars may be converted into a single equivalent out-of-pocket payment, or they may be converted into an equivalent level annual figure, constant in each year. In the latter case, the series of unequal dollars is said to be *levelized,* which might be interpreted as "averaged, allowing for effects of interest."

**Until his recent retirement, Mr. Jeynes was Engineering Economist with Public Service.*

Present-Worth Arithmetic

The present worth of contemplated payments, as of a specified date (ordinarily the intial in-service date), means the immediate lump-sum payment that would be just as acceptable financially as some alternative arrangement for future payments, either lump sum or installments. In this sense, "payments" can mean either expenditures or receipts. Correct application of the *minimum acceptable return* establishes the amount of the immediate payment that would be just as acceptable as some future payment. The person who decides that immediate payment is acceptable indicates his percentage minimum acceptable return by that decision, whether he realizes it or not. Thus, in corporate economics, the investors in the company, as a body, decide the minimum acceptable percentage return to be used in determining the equivalency of present and future payments. Throughout this discussion of present-worth arithmetic, minimum acceptable percentage return will be referred to as "interest."

Thus, in the current discussion, interest will be used in its general dictionary sense, as the reward of productive use of capital, whether that capital happens to be in the form of debt or equity.

Interest

Simple interest is calculated on the initial deposit only. For example, one dollar deposited at 6 percent interest becomes \$1.06 at the end of the first year; this \$1.06, if it remains on deposit at 6 percent simple interest, is credited with another \$0.06 at the end of the second year.

Compound interest is the form more commonly used: one dollar at 6 percent compound interest becomes \$1.06 at the end of the first year; if this \$1.06 remains on deposit, it is credited with \$0.0636 interest at the end of the second year. Compound interest can also be applied over shorter periods of time.

Thus, if a dollar earns 3 percent at the end of each 6 months, it earns slightly more than 6 percent in 12 months; in the second 6-month period the \$1.03 available at the beginning of the period grows to \$1.0609 by the end of the year—the effective rate is 6.09 percent per annum. Similarly, 1.5 percent compounded quarterly will earn 6.136355 percent per annum.

Any desired number of compounding periods per year may be used as necessary or desired, so long as the resultant effective annual rate corresponds to the effective annual minimum acceptable return percentage. Ordinarily, it is sufficiently accurate to define "average" annual percentage as the *mean*, which is midway between first-of-year and end-of-year figures. Thus, unless otherwise specified, *annual compound interest* is assumed in economic studies.

Present-Worth Formulas

Six expressions are used to translate an immediate payment into its financial equivalent to be paid at another time, or for translating any series of payments into an equivalent alternative series of payments. These expressions are conveniently tabulated in many handbooks as functions of interest rate and the number of compounding periods. While they can be expressed as generalized formulas, they really have quite simple explanations:

Amount of $1 at Interest—If $1 is deposited at i percent interest compounded annually, the amount that would accumulate in n years is given by the formula:

$$s^n = (1 + i)^n \qquad (1)$$

Hence, if the minimum acceptable return is 6 percent, a payment of $1.06 in one year, or of $1.1236 in two years, or $1.1910 in three years all have the same present-worth of $1 cash today.

Present Value of $1 at a Future Date—The spot-cash equivalent of a future payment in n years, symbolized by v^n, is the reciprocal of formula (1):

$$v^n = \frac{1}{(1 + i)^n} \qquad (2)$$

This expression gives the present worth of $1 due at a future date. Thus, if the minimum acceptable return i is 6 percent, a payment of $1 one year from now is equivalent to $0.9434 spot cash now, a payment of $1 two years from now is equivalent to $0.8900 spot cash now and so on. Either alternative, the future payment or the immediate cash settlement, is equally acceptable to an investor whose minimum acceptable return is 6 percent.

Annuity That Will Amount to $1 in a Given Time—The annuity ${}_id$ is the regular year-end payment which, if deposited in a bank paying i interest, will amount to a balance of $1 by a specified date in n years. The formula is:

$${}_id = \frac{i}{s^n - 1} \qquad (3)$$

For example, a bank account of $1 can be accumulated by making a single year-end deposit of $1 in one year, or it can be accumulated by making two deposits of $0.485 at the end of each of two years (assuming $i = 6$ percent), or by depositing $0.314 at the end of each of three years.

Amount of an Annuity of $1—The inverse of the sinking fund factor of formula (3) is the future spot-cash equivalent of an annuity of $1. It may also be regarded as the amount in a bank account which earns i percent interest compounded annually, if $1 were deposited at each year end. The formula is:

$$s_{\overline{n}|} = \frac{s^n - 1}{i} \qquad (4)$$

Thus, if deposits earn 6 percent compounded annually, regular year-end deposits of $1 will amount to $1 at the end of the first year, or $2.06 at the end of the second year, or $3.184 at the end of the third year. The investor whose minimum acceptable return is 6 percent would just as soon accept the regular annual year-end payments of $1 each or the single payment at the end of the period.

Present Value of an Annuity of $1—The immediate spot-cash equivalent of a future annuity, or the present-worth of an annuity of $1 per year, is the equivalent of a single cash deposit placed in a bank account earning i percent compounded annually, which is sufficient to provide a withdrawal of $1 at the end of each year for n years. The formula is:

$$a_{\overline{n}|} = \frac{s^n - 1}{i\, s^n} = \frac{1}{i + {}_id} \qquad (5)$$

For example, if a deposit earns 6 percent compounded annually, a single deposit of $0.9434 would provide a withdrawal of $1 one year later; a single deposit of $1.8334 would provide for two successive year-end withdrawals of $1 each, etc.

Annuity that $1 Will Buy—The future annuity that is equivalent to $1, or the amount of withdrawal possible at the end of each year for n years if a single deposit of $1 is placed today in a bank account that earns i percent compounded annually, is found by the formula:

$$\frac{1}{a_{\overline{n}|}} = i + {}_id \qquad (6)$$

Thus, a single deposit of $1 now in a bank paying 6 percent interest compounded annually will provide a single withdrawal of $1.06 after one year, or $0.5454 each year end for two years, or $0.3741 each end for three years.

It will be noted that there are only three basic formulas (1, 3, and 5) in the above set, and the other three are reciprocals. All six are tabulated in Fig. 2 for six percent interest.

Application of Present-Worth Arithmetic

These six formulas do not necessarily reflect actual transactions of a company or its investors. They are pure expressions of equivalency, and transactions need not actually occur to justify present worth calculations.

To illustrate the present-worth concept, suppose future payments of wages by a company, acting as an agent for the investors in the company, are as follows:

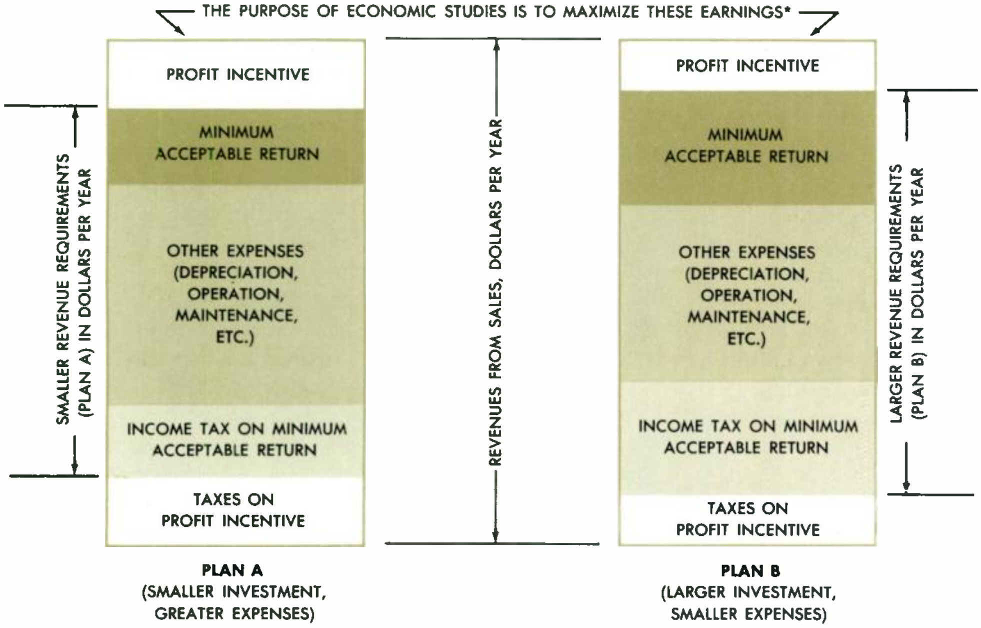
1 year from now —	$100 000
2 years from now —	150 000
3 years from now —	125 000
Total	$375 000

If the company's breakeven acceptable return is 6 percent, would its owners consider an immediate payment of $375 000 a fair settlement in lieu of the payments due on the schedule above? They would not, for the breakeven equivalent payment, calculated from present-worth factors in Fig. 2, is as follows:

Deferred Payments		Present-Worth Factors		Present-Worth of Payments
100 000	×	0.9434	=	$ 94 340
150 000	×	0.8900	=	133 500
125 000	×	0.8396	=	104 950
Equivalent present-worth			=	$332 790

Therefore, if the company must pay wages in advance, its owners would regard anything more than $332 790 as excessive if paid now. Economists call this reasoning the *concept of indifference:* it is a matter of indifference to suppliers of capital funds as to which of the breakeven alterna-

1 DIAGRAM OF INTENT AND BASIS FOR IDENTIFYING THE ECONOMIC CHOICE



"Profit incentive" is the margin of actual earnings over and above the minimum acceptable return. Maximizing this margin, as by selecting Plan A in this example, maximizes earnings for existing owners (pre-project investors). Out of the same revenues, the profit margin is maximized by minimizing revenue requirements.

Calculated revenue requirements include minimum acceptable return at the same percentage for both alternatives. But the superior plan, by increasing profit margin, tends to reduce minimum acceptable return, thus reassuring its superiority.

2 SIX PERCENT COMPOUND INTEREST FACTORS

	Single Payment		Uniform Annual Series			
	Amount of $1 at Interest	Present Value of $1 at a Future Date	Annuity Which Will Amount to $1 in a Given Time	Amount of an Annuity of $1	Present Value of an Annuity of $1	Annuity Which $1 Will Buy
n	s^n	v^n	$_id$	$s_{\overline{n}\rceil}$	$a_{\overline{n}\rceil}$	$\frac{1}{a_{\overline{n}\rceil}}$
1	1.0600	0.9434	1.0000	1.0000	0.9434	1.0600
2	1.1236	0.8900	0.4854	2.0600	1.8334	0.5454
3	1.1910	0.8396	0.3141	3.1836	2.6730	0.3741
4	1.2625	0.7921	0.2286	4.3746	3.4651	0.2886
5	1.3382	0.7473	0.1774	5.6371	4.2124	0.2374
6	1.4185	0.7050	0.1434	6.9753	4.9173	0.2034
7	1.5036	0.6651	0.1191	8.3938	5.5824	0.1791
8	1.5938	0.6274	0.1010	9.8975	6.2098	0.1610
9	1.6895	0.5919	0.0870	11.4913	6.8017	0.1470
10	1.7908	0.5584	0.0759	13.1808	7.3601	0.1359
15	2.3966	0.4173	0.0430	23.2760	9.7122	0.1030
20	3.2071	0.3118	0.0272	36.7856	11.4699	0.0872
25	4.2919	0.2330	0.0182	54.8645	12.7834	0.0782
30	5.7435	0.1741	0.0126	79.0582	13.7648	0.0726
40	10.2857	0.0972	0.0065	154.7620	15.0463	0.0665
60	32.9877	0.0303	0.0019	533.1282	16.1614	0.0619
80	105.7960	0.0095	0.0006	1746.5999	16.5091	0.0606
100	339.3021	0.0029	0.0002	5638.3681	16.6175	0.0602

3 ILLUSTRATION OF PRESENT-WORTH PROCESS

Plan	Year	Revenue Requirements	Present-Worth Factor	Present-Worth of Revenue Requirements
A	1	$100,000	0.9434	$ 94,340
	2	500,000	0.8900	445,000
				Total $539,340
B	1	300,000	0.9434	$283,020
	2	300,000	0.8900	267,000
				Total $550,020
				Superiority of Plan A $ 10,680

tives is adopted. Note that the breakeven minimum acceptable rate of return on the investors' pool of capital must be used to determine this equivalency. It does not matter which project the wages are associated with, what that project is earning, nor what the company is earning as a whole in the particular three-year period, since these factors do not affect the equivalency.

In comparing alternative plans, present-worth factors are applied to the annual revenue requirements estimated for each competing plan. The present worth of all future revenue requirements is determined by simply adding the present worth of each year's revenue requirements. A simple example is shown in Fig. 3 in which plan A has revenue requirements of \$100 000 the first year and \$500 000 the second year, while plan B has revenue requirements of \$300 000 in each of the two years. The calculations of present worth are made assuming the revenue requirements to occur (be payable) at the end of the first and second year, and they are referred to the beginning of the first year with a present worth factor based on a minimum acceptable return of 6 percent. Thus, plan A is superior by \$10 680 in immediate-payment dollars.

Depreciation Annuities

The simple objective of corporate depreciation accounting is to recover the investors' initial capital, less ultimate net salvage, during the service life of the facilities. This recovery can be accomplished by the application of any arbitrary formula subject to regulatory approval. The resulting periodic charge does not represent the true periodic outlay for depreciation. This outlay occurs only when the unit is retired. Replacement or renewal of the initial equipment bought with the capital is not a consideration. Neither is change in price levels.

Using any of the arbitrary methods of depreciation accounting, a plant unit generates depreciation reserves which displace investors' committed capital in that unit. This displaced capital is then available for the purchase of other new facilities. Thus, the investor's return on his capital comes partly from that residual portion still in the initial equipment purchased and partly from the displaced portion reinvested elsewhere.

Any series of periodic charges that recover the initial investment less salvage is simply a means of spreading the initial cost of the equipment over its service life. The lifetime-levelized revenue requirement for depreciation is not a function of the method of depreciation accounting, which may be the sinking fund approach, or straightline, sum-of-the-years-digits, declining balance, or some other formula method. None of these various accounting methods are attempts to accurately reflect depreciated *value* in the books of account, occasional statements to the contrary notwithstanding.

The *depreciation annuity*[3] is a method for reducing the total cost to be recovered to a levelized percentage of plant investment in service in each year of service life, by the method shown in formula (3). The depreciation annuity is equivalent to any and all other nonlevelized versions of the revenue requirement for depreciation, such as the sum-of-the-years-digits, declining balance, or other formula methods. The method of write-off affects income taxes, but in all cases the total dollars to be depreciated remains the same depreciable value—the initial investment less the ultimate net salvage. The revenue requirement for the depreciation annuity is a function of four variables.

1) *Probable average life*, which is the period from the date of installation to the probable date of final retirement and removal from the plant account.
2) *Type of retirement dispersion*, meaning the pattern in which retirements of property units are scattered about average life. Approximately 50 percent of retirements can be expected to occur earlier than average, and 50 percent later.
3) *Ultimate net salvage*, the final scrap value less removal cost. Ultimate net salvage value often is negative.
4) *Minimum acceptable rate of return*, the interest rate used to calculate the depreciation annuity.

Once these four essential factors have been estimated, the lifetime-levelized revenue requirement for depreciation is simply a matter of present-worth arithmetic. If the property unit has no dispersion of retirements, the depreciation annuity is given simply by the uniform annual *sinking fund factor* ($_id$) for the appropriate years of life applied to the initial investment less net salvage. This level annual amount plus salvage will recover the initial investment exactly by the retirement date.

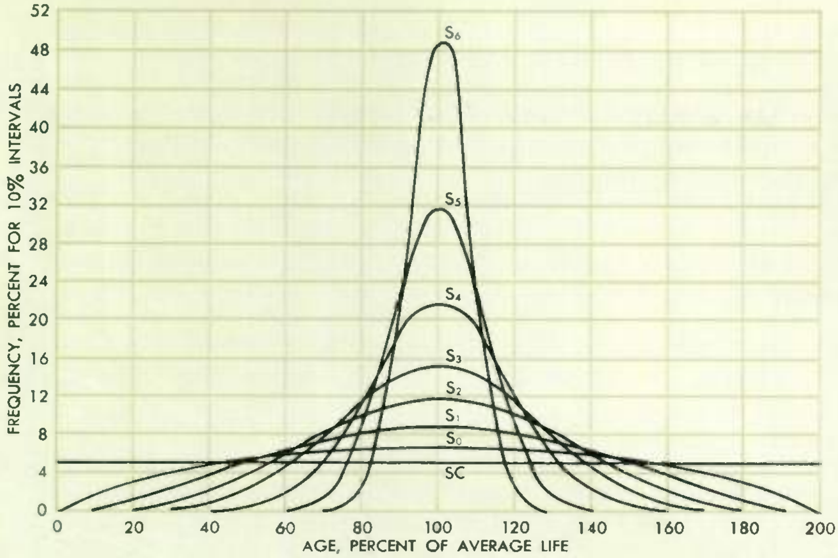
This is illustrated in Fig. 2 by considering an investment of \$1 in a unit of equipment having no retirement dispersion. The uniform annual sinking fund factor $_id$ (column 3) gives the depreciation annuity that will exactly return \$1 at the end of the unit life n years hence.

Capital Recovery Costs—From an annual revenue requirement, two considerations must be applied to committed capital—return *of* committed capital, and return *on* committed capital. Depreciation annuity provides for the return of committed capital, and *minimum acceptable return* is the necessary return on the committed capital. The sum of these two returns is the *capital recovery cost* ($i + {}_id$, which is equivalent to formula 6). Thus, the *capital recovery factor*, tabulated in column 6, Fig. 2, is exactly \$0.06 higher than the sinking fund factor (column 3). The capital recovery factor will always be i percent higher than the sinking fund factor in any table of compound interest factors. Therefore, the present-worth of capital recovery costs is always equal exactly to initial investment, providing that minimum acceptable return is used in calculating the annual revenue requirement for return and is also used as the interest rate in the present-worth calculation.

Retirement Dispersion

A second important point about the depreciation annuity and the concept of present-worth developed from Fig. 2 is that absolute certainty was hypothesized in the predictions of time periods and lives. However, actual plant retirement experience is characterized by probabilities of uncertainty. Thus, retirement dispersion, which describes the scatter of retirement age for individual property units about average life for the group, must be considered. It is impossible to predict, with accuracy, when any particular property unit will be retired. However, the *probable* average life of property units can be estimated, and their depreciation costs may be calculated in the same way that life insurance premiums are developed from

4a



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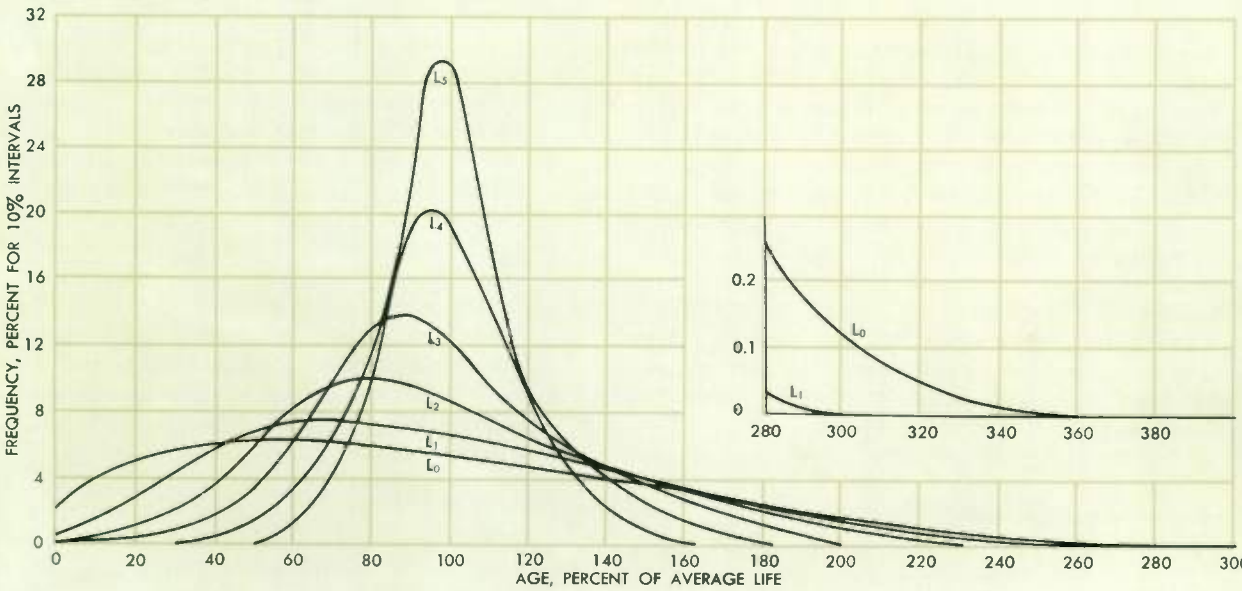

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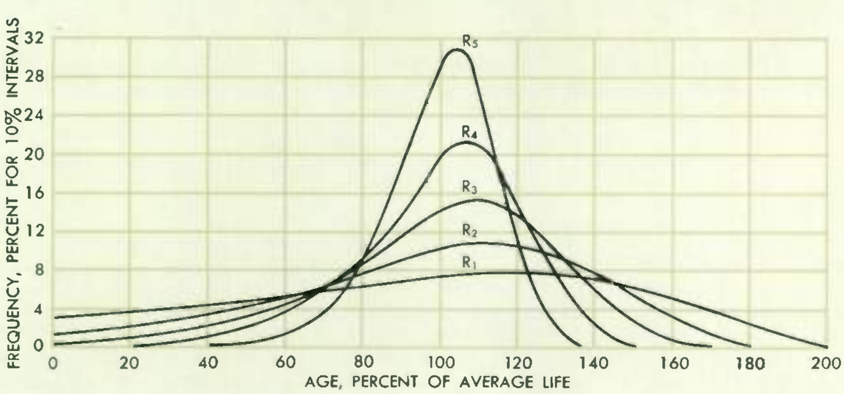

CODIFIED SYSTEM OF RETIREMENT DISPERSION is shown by curves for (*a*) symmetrical mortality dispersion, (*b*) left-moded dispersion, and (*c*) right-moded dispersion.

(From Iowa Engineering Experiment Station Bulletin 155 by Robley Winfrey.)

similar statistics for human mortality.

Any estimate of a probable average life recognizes that some lifetimes will fall below and some above the average. For example, it is commonly believed that old turbine-generators, still on the books but far past their estimated life, are 100 percent depreciated. This is not the case when depreciation charges are made on a group basis, as is usual practice. It is essential that depreciation charges be made on units past probable average life because first cost of the earlier-than-average retirements could never be fully recovered if these last survivors were not depreciated over their longer lifetime.

A convenient codified system for describing patterns of retirement dispersion has been developed at the Engineering Experiment Station of Iowa State University. Each retirement pattern in the Iowa State system is described by a letter, *S*, *L*, or *R* and a numerical subscript, 0 to 6, as shown in Fig. 4. The letter refers to the behavior of rate of retirement at each age, a plot of which resembles the normal bell-shaped probability curve where retirements are slow at first, increase to a maximum rate near average life, and then decrease until the last survivor is retired. A curve that is symmetrical with respect to average life is type *S* (Fig. 4a). If the maximum rate of retirement occurs before average life, the curve is left-moded, type *L* (Fig. 4b). If the mode occurs after average life, it is right-moded, type *R* (Fig. 4c). If retirements occur at nearly the same constant rate at all ages, a subscript near zero is added. At the other extreme, if retirements all occur in a short period near average life, the subscript approaches 6. No retirement dispersion at all is called type *SQ*, and a completely uniform symmetrical rate (approached by S_o) is called *SC* (Fig. 4a).

The depreciation annuity, including the effect of retirement dispersion, can be calculated from these retirement dispersion curves and the tables of present-worth factors. The formula is:

$${}^{\beta}_{i}d = \frac{\Sigma\, v^x\, Retirements_x{}^*}{\Sigma\, v^x y_x} = \frac{1}{\Sigma\, v^x y_x} - i^{**}$$

where v^x = present-worth factor at age x;

${}^{\beta}_{i}d$ = present-worth group-basis depreciation annuity where β indicates that the annuity is the level percentage applicable to the group of units whose retirements are dispersed about average life;

x = age in years;

i = minimum acceptable rate of return;

$\bar{y}_x$ = mean annual survivors in year x; and

$Retirements_x$ = retirements in year x.

**This is the generalized expression for ${}^{\beta}_{i}d$. It applies whether a single vintage plant, continuing plant, or growing plant is under consideration.*

***This expression applies to a single vintage of plant only.*

Depreciation annuities (${}^{\beta}_{i}d$) for several types of retirement dispersion and several average lives for a minimum acceptable return of 6 percent are listed in Fig. 5. The annuities given in Fig. 5 must be adjusted for ultimate net salvage. For example, if 10 percent net salvage is expected, the adjusted annuity is 90 percent of the tabulated figures. The column marked *SQ* applies for the assumption of no dispersion, and it is identical to the uniform annual sinking fund factors of Fig. 2 (column 3). While no dispersion is the most unlikely of all possible assumptions regarding retirement, unfortunately, it is the one most commonly used. If there is no evidence for a better estimate, a more reasonable assumption for industrial equipment is a type R_1 dispersion.

The table shows that recognizing the effect of dispersion can sometimes mean as much as a doubling of the estimated revenue requirement for depreciation in actual experience. For example, compare the *SQ* (no dispersion) case with a type R_1 for a 40-year probable average life: a 0.65-percent versus a 1.27-percent depreciation annuity. Depreciation accountants make continuing statistical studies of average lives and dispersion patterns for various types of equipment so that the revenue requirement for depreciation can be estimated with reasonable assurance. When new types of equipment are encountered in economic comparisons, the accountants and the economists must anticipate the average lives and dispersions that are the most likely to result from the future events that control dates of retirement.

Income Taxes

Another important component of the revenue requirement is that for income tax. Income for any corporation can be split into two components, one associated with the

5 DEPRECIATION ANNUITY IN PER UNIT OF CAPITAL INVESTMENT FOR VARIOUS PROBABLE AVERAGE LIVES AND VARIOUS TYPES OF DISPERSION FOR A MINIMUM ACCEPTABLE RETURN OF SIX PERCENT

Probable Average Life (Years)	L_0	L_1	L_3	L_5	SC	S_0	S_1	S_3	S_5	R_1	R_3	R_5	SQ
5	0.1897	0.1857	0.1808	0.1781	0.1880	0.1843	0.1821	0.1793	0.1779	0.1843	0.1799	0.1781	0.1774
6	0.1555	0.1517	0.1467	0.1442	0.1540	0.1503	0.1480	0.1452	0.1438	0.1503	0.1458	0.1439	0.1434
7	0.1313	0.1274	0.1224	0.1200	0.1298	0.1261	0.1238	0.1210	0.1196	0.1260	0.1215	0.1197	0.1191
8	0.1131	0.1092	0.1043	0.1019	0.1117	0.1080	0.1056	0.1029	0.1015	0.1079	0.1034	0.1016	0.1010
9	0.0991	0.0952	0.0903	0.0878	0.0977	0.0939	0.0916	0.0888	0.0875	0.0940	0.0894	0.0876	0.0870
10	0.0878	0.0840	0.0791	0.0767	0.0866	0.0828	0.0805	0.0777	0.0763	0.0828	0.0783	0.0764	0.0759
15	0.0547	0.0509	0.0461	0.0437	0.0538	0.0499	0.0475	0.0447	0.0434	0.0499	0.0453	0.0435	0.0430
20	0.0386	0.0349	0.0301	0.0279	0.0379	0.0340	0.0316	0.0288	0.0276	0.0341	0.0295	0.0277	0.0272
25	0.0292	0.0256	0.0210	0.0189	0.0288	0.0248	0.0225	0.0198	0.0186	0.0250	0.0205	0.0187	0.0182
30	0.0232	0.0197	0.0152	0.0133	0.0230	0.0190	0.0167	0.0141	0.0130	0.0193	0.0148	0.0131	0.0126
40	0.0159	0.0127	0.0087	0.0070	0.0162	0.0122	0.0101	0.0077	0.0067	0.0127	0.0084	0.0068	0.0065
60	0.0093	0.0065	0.0033	0.0022	0.0100	0.0064	0.0045	0.0027	0.0020	0.0070	0.0033	0.0021	0.0019

minimum acceptable return on the investors' pool of committed capital and the other associated with the earnings or profit margin over and above minimum acceptable return (Fig. 1). In economic studies using the revenue requirements approach, the revenue requirement for income tax is an estimate of the taxes associated with the break-even minimum acceptable return only. Thus, it is not a forecast of actual taxes to be paid by the company, which include both components.

At present, corporate taxable income is subject to a 52 percent tax.* Taxable income is found by subtracting deductible items from revenues, as provided by the tax law, or in economic studies, by subtracting deductible items from revenue requirements. Revenue requirements equal the sum of capital recovery costs $(i + {}_{i}^{\beta}d)$, income tax, and other expenses. Tax deductible items are (1) operation and maintenance expense, (2) taxes except for the federal income tax itself, (3) interest paid on debt, even though interest is really a part of return on committed capital, and (4) deductible depreciation expense. Thus,

$$\textit{Taxable Income} = (i + {}_{i}^{\beta}d + T + e) - (e + \textit{interest on debt} + d')$$

where:

- e = other expenses (operation, maintenance, other taxes);
- T = federal income taxes; and
- d' = book depreciation charge = deductible depreciation for tax purposes (in this case).

The above formula assumes that the same depreciation is used both for book purposes and for tax purposes, so that the book depreciation charge is deductible along with interest on debt. If B equals the amount of capital investment represented by debt and b is the interest rate payable on that debt, then the portion of the i percent minimum acceptable return represented by deductible interest on debt is Bb/i. If this is deducted from the depreciation-adjusted income, and the tax rate t applied to the remaining taxable income, the revenue requirement for income tax is:

$$T = \frac{t}{1-t}\,(i + {}_{i}^{\beta}d - d')\,(1 - \frac{Bb}{i}),\ \text{in per unit of plant in service.}$$

When this value of T is multiplied by the value of the plant in service, the levelized annual tax in dollars is obtained. In economic studies it is usually applied to the initial capital investment instead of the plant in service, the theory being made that there is a continuing plant, maintained at its initial level by making replacements in kind and at the same unit cost when retirements occur.

In 1954 the tax laws were changed to permit the use of liberalized depreciation for plants installed after 1953 in calculating income taxes. The liberalized method permits use of deductible depreciation at a rate faster than the straight-line rate in early life, although the total dollars recovered within the lifetime of an investment remains the same, *viz.*, the original cost. Approved methods, such as the sum-of-the-years-digits or the double-rate declining-balance, depreciate plants more in early life, and these higher depreciation charges are deducted from revenues to determine taxable income. The result is to reduce taxes in the early life of the plant but increase them in later life. For most purposes, it is sufficient to assume the effect of liberalized depreciation to be a 30 percent reduction in T, as calculated if "straightline" depreciation was used for both book and tax purposes.

The adoption of liberalized depreciation is a means of reducing revenue requirements. This is the case regardless of the accounting treatment given to the savings. Two accounting treatments are in use, *flow-through* and *normalization*. Flow-through, most commonly used, arranges for the tax benefit, even though temporary, to flow through to the owners in dividends or to retained earnings. Only actual taxes are taken to be an operating expense. The normalization procedure consists of calculating the savings in taxes each year, charging them also as an operating expense, retaining them in a special account, and reinvesting them in the business. These savings then become a temporary source of capital similar to the depreciation reserve. A special liability account, such as Accumulated Deferred Income Taxes, is set up for the funds. But because these funds were obtained from revenues and not from investors, no return on such temporary capital is to be included in the revenue requirements.

Note should be taken of the effect of recent tax legislation concerning "guide lines" and the "construction credit." For most companies, these allowances will have but small effect on profitability of a project and much smaller effect on the difference between alternative proposals. Their sole impact is on taxes, economic advantage by way of cash flow being mostly imaginary. Exact effect of either provision is calculable if all the relevant assumptions can be agreed upon, but it is complicated. As a rough general allowance, the construction credit may be assumed to reduce federal income tax (T) by about 0.25 percent (e.g., from 2.50 percent to 2.25 percent). However, this will be affected by the accounting procedure adopted, and various procedures are currently permissible.

Other Components of the Revenue Requirement

Other components of the revenue requirement are often expressed as functions of capital investment besides return, depreciation, and income tax. For example, most analysts include real estate taxes, miscellaneous taxes, and taxes levied on gross receipts. Some include insurance charges and general and administrative overhead expenses as well. A few include operation and maintenance expenses, although these are not usually a function of capital investment. The total revenue requirements to be used in the comparison of alternatives must include all of these components as well as revenue requirements for such expenses as raw materials, supplies, sales expense, and so forth, unless they are common to all alternatives.

When total revenue requirements have been determined for each of the alternatives, present-worth arithmetic can be applied to reduce the series of annual sums to equivalent present dollars or to equivalent level annual dollars for comparison.

Westinghouse ENGINEER Mar. 1964

Substantially 52 percent for large corporations. The first $25,000 of taxable income is taxed at 30 percent.

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Simple Structure of Nuclear Particles Proposed

Is all matter really made up of only a few basic particles instead of the 30 or more different "pieces" now assumed to compose it? At one time scientists thought so. But this was before the host of new atomic particles, and antiparticles, discovered in recent years through large-scale atom-smashing experiments.

These new, heavy, short-lived particles—called mesons and hyperons—now account for most of the known entities linked to the atom's nucleus. All of them have average lifetimes of less than a millionth of a second. They have so complicated the originally simple concept of the atom that many physicists believe that matter cannot possibly be as complex as it now appears and are seeking a simpler explanation of its structure.

Such a unifying concept was proposed recently in a paper presented[1] to the American Physical Society by Dr. E. J. Sternglass, advisory physicist at the Westinghouse Research Laboratories. Dr. Sternglass suggested that two familiar, lightweight particles—the *electron* and its positively charged counterpart, the *positron*—may be the building blocks from which mesons are put together. The many heavy, unstable mesons are explained as pairs of positively charged and negatively charged electrons, arranged in various combinations, but always in high-speed rotation according to the principles of relativity theory.

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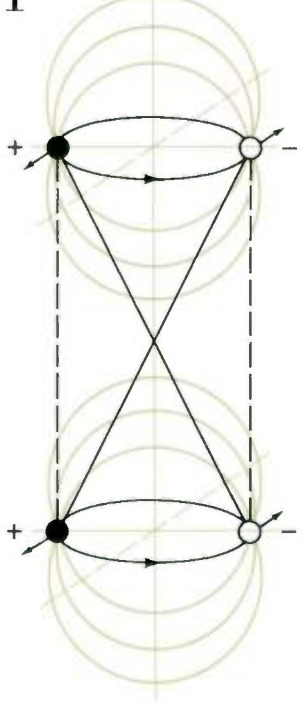


Single Electron Pair Is Basic Grouping

The simplest grouping is a single electron-positron pair, whirling around at nearly the speed of light in a tiny orbit about 100 000 times smaller than the diameter of a hydrogen atom. This simple system, first proposed[2] by the Westinghouse physicist in 1961, is shown to have the basic properties of the so-called neutral pi meson (π°), including its mass, decay behavior, lifetime, size, spin and parity. This meson is considered a key particle in explaining nuclear structure. It is thought to be present in the nucleus of the atom, where it supplies the nuclear force that holds the nucleus together.

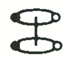
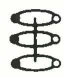
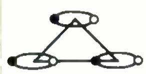
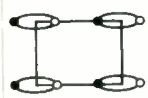
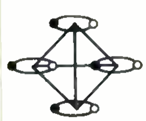
Recent studies have extended the earlier work in two important respects: (1) it explains this nuclear force as arising between electron-positron pairs (pi mesons), and (2) it then extends the electron-positron pair concept to other nuclear particles.

Dr. Sternglass explains the great strength of the nuclear force by the extremely high velocities and close spacings of the electron and positron in the pi-meson system. These charges, moving at extreme speeds, create very strong magnetic fields, which can attract a similar system only at close range. This force, however, is some 500 times stronger than the attraction of similar charges at rest. Nuclear forces thus would be understandable in terms of ordinary electromagnetic attraction, analogous to the forces that bond molecules together.

Once the nature of the forces is established, it is possible to construct systems of two or more electron-positron pairs and to compare them with the newer, heavier mesons. The simplest such system (two electron pairs, or two pi mesons)

THE SIMPLEST SYSTEM is composed of two electron-positron pair structures, or neutral pions, corresponding to the θ-K and the rho meson structure. The rotating electric dipole fields result in strong short-range attraction between the two pair-systems. When oriented in the phase relation shown, unlike charges have large relative velocities, producing strong magnetic attraction (solid lines), while like charges have zero relative velocity, resulting in weaker electrostatic repulsion (dotted lines).

2 TYPICAL PARTICLE MASSES CALCULATED ON THE BASIS OF THE ELECTRON-POSITRON PAIR MODEL

Number of Electron-Positron Pairs	Structure Type	Angular Momentum Quantum Numbers	Particle Symbol	Calculated Mass (Mev)	Observed Mass (Mev)
1	+  −	0	π°	134.5	135.0
2		0 1 2	K (θ) ρ_1 *	484 764 1324	494 750 *
3		0 1 2	η α ω_1	543 613 753	548 625 765
		0 1,1 1,0	K (τ) * ω_2	473 683 753	494 * 765
4		0 1,1 1,0	K ζ †	490 595 630	494 575 635
		2,2 2,1} 2,0}	ρ_2 K*	770 875} 910}	750 880
		3,3 3,2} 3,1} 3,0}	φ° f°	1015 1190} 1295} 1330}	1012 1250
		0 1,0 1,1	— — —	386 498} 512}	395 520
		2,0 2,1 2,2	— — —	722} 736} 778}	750

**Predicted states not yet observed.*

mathematically accounts for the masses and internal spins of two additional mesons, the K meson and rho meson, as shown in Fig. 1.

Additional Heavy Particles Predicted

Other systems, made up of three, four, and five electron-positron pairs, similarly account for the masses of all the recently discovered heavy mesons to within a few percent of their observed values. Several typical particle masses calculated on the basis of the electron-pair model are shown in Fig. 2. In addition, other more-energetic mesons are predicted and should be observed experimentally when more-powerful atom-smashing experiments are performed.

Finally, by combining electron-positron pairs with the proton as a nuclear building block, the properties of hyperons—unstable particles which break up into mesons and protons—can be explained.

Throughout the calculations, relativistic motion of the basic electrons and positrons is assumed. The theory of relativity dictates that the mass of an object increases with its velocity. Under normal conditions the effect is negligible. But moving at speeds near the velocity of light, the electron and positron increase in mass some 274 times.

The electron-positron model has not yet been extended to explain the structure of the proton and neutron. However, both particles are now known to annihilate into mesons, with no other kind of entity left over, so that all matter may eventually be understandable in terms of electrons and positrons alone.

Of all known particles, electrons and positrons have unique qualifications that suggest their choice as fundamental particles: stability, sameness and indivisibility. They are stable, even under bombardment from cosmic rays and the largest atom smashers; they always have the same properties under the same physical conditions; and they have never been found to break apart into smaller fragments. When they do disappear, they vanish together as a whole, with all their mass converted into radiation.

REFERENCES:
[1]Presented at the January 1963 meeting of the American Physical Society in New York. A more detailed account appears in the "Proceedings of the International Conference on the Structure of the Nucleon." (Stanford University, June 1963)
[2]*The Physical Review*, Vol. 123, No. 1, pp. 391–8, July 1, 1961.

High-Temperature Insulation in AC Motors

R. F. Woll, Fellow Engineer, Motor and Gearing Division, Westinghouse Electric Corporation, Buffalo, New York.

Future standard ac motors will have high-temperature insulation for larger rating in a given physical size.

An understanding of the advantages and limitations of higher-temperature insulation becomes ever more important as progress is made in more effective utilization of electromagnetic materials. Such progress gives manufacturers the ability to put more and more rating into a given physical size of motor, and this makes temperature rise an increasingly limiting design factor. This in turn fosters consideration of higher-temperature insulation systems as one way around the temperature-rise design limitation.

Most electric motors built in the United States have had Class A insulation. Many users view motors with higher-temperature insulation with uncertainty or suspicion; they think of them as being less reliable or shorter lived than those with Class A insulation because of the higher operating temperatures. This is simply not the case, although there are differences in the practical design and application considerations between motors with Class A insulation and those with B, F, or H insulation.

Insulation Classes and Operating Temperatures

Motors with Class B, F, and H insulation have had extensive use over the past years, but they have been primarily of special or semispecial design and used in relatively small numbers. Motors with these insulations will soon be standard, though, because of the advantages inherent in the reductions in size and weight that are possible.

Each class of insulation affords equivalent life expectancy at its temperature rating. To illustrate, the temperature rise by resistance and the hot-spot temperature for each class of insulation are shown in Fig. 1. Motors with the four insulation classes compared in this figure have the same life expectancy, even though one operates at 60 degrees C rise by resistance, one at 80 degrees rise, one at 105 degrees rise, and one at 125 degrees rise. This equivalency of life expectancy is based on exhaustive tests of materials, of motorettes (sets of coils wound to simulate actual conditions in a motor), and of complete motors.

The most significant aspect of higher-temperature insulation is that it permits designing motors with larger ratings in a given physical size. The degree to which ratings can be so increased is influenced by three factors:

Economic Balance—In time, this will undoubtedly prove the determining factor. Although smaller physical size inherently tends toward lower cost, there are offsetting factors that make it difficult to define precisely the true economic limits. For example, high-temperature insulating materials cost more than standard Class A materials, and reduced physical size, if carried to extremes, imposes additional labor costs due to cramped working space. Higher operating temperatures, unless compensated for, reduce efficiency. This article does not explore the complicated economic picture; instead, it presents the major technical considerations from which the economics will evolve.

Direct Effect of High Temperature on Motor Design—Since the major losses in the induction motor are copper losses, which are proportional to absolute operating temperature, higher temperatures detract from the rating potential. This is discussed in the section that follows.

Indirect Effect of High Temperature on Design and Application—In addition to influencing the electromagnetic design and the rating potential, higher temperatures must be considered in terms of their effect on motor bearings, on nearby driven machinery or other equipment, and on personnel. These factors, too, are discussed later.

Direct Effect on Design

If the effect of increased operating temperature on copper losses could be neglected, rating potential could be assumed to be approximately proportional to the allowed rise by resistance (Fig. 2). However, this neglecting of the effect of increased operating temperature is erroneous because the copper losses are a predominant factor in the motor temperature rise, especially for totally enclosed fan-cooled motors. The lower curve in the figure takes account of the increased operating temperature; it is the upper curve reduced by the inverse ratio of the absolute temperature. The curve shows how temperature reduces actual rating potential, especially for the two higher temperature classes.

The preceding analysis of rating potential is premised on maintaining appropriate designs for any given rating. For example, assume that it is desired to produce a higher-rated motor in the same frame size as that of a 10-horsepower motor, with Class A insulation, by use of Class B insulation. The 26-percent increase in rating indicated as possible (Fig. 2) entails modification of the electromagnetic design for the new 12.6-horsepower rating.

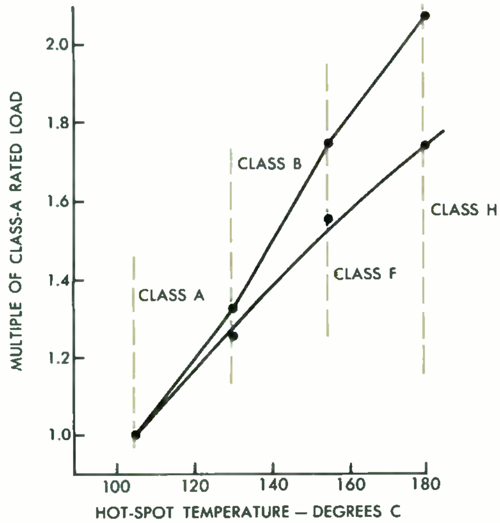
An analysis of the results if the original 10-horsepower design were simply operated at 12.6 horsepower is given in Fig. 3. The basis of this series of curves is that the temperature rise of a specific motor is proportional to the square of its load and to the absolute temperature. Fig. 3, then, shows the rise by resistance that would be attained on motors designed for various rises by resistance at rated

1 TEMPERATURE RELATIONS FOR DRIPPROOF AND TOTALLY ENCLOSED FAN-COOLED AC MOTORS

Insulation Class	A	B	F	H
Ambient Temperature	40	40	40	40
*Temperature Rise by Resistance	60	80	105	125
Hot-Spot Allowance	5	10	10	15
Hot-Spot Temperature	105	130	155	180

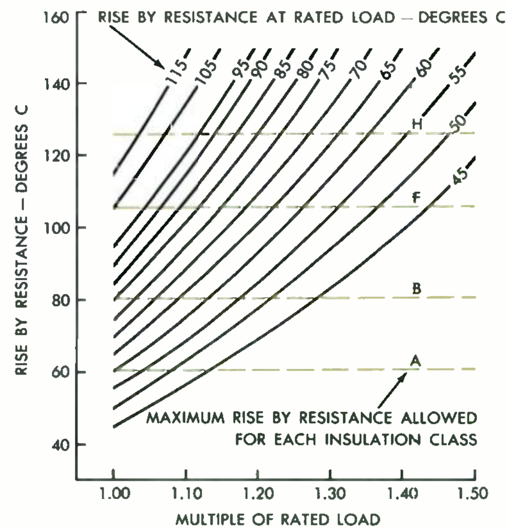
***Rise=0.9 (Hot-Spot Temperature—Ambient Temperature). Rounded off to nearest 5 degrees.**

2



MOTOR RATING POTENTIAL would be approximately proportional to the allowed temperature rise by resistance if the effect of increased operating temperature on copper losses could be neglected (upper curve). However, this effect cannot be neglected, and the lower curve shows how increasing temperature diminishes the theoretical gain in rating potential.

3



INCREASING THE MOTOR LOAD increases the winding temperature rise by resistance of motors designed for the rated-load rises indicated.

4 RELATION BETWEEN RISE BY RESISTANCE AT RATED LOAD AND AT 1.15 LOAD, FROM VARIOUS SOURCES

Source	Rise by Resistance (Degrees C)		Ratio
	Rated Load	1.15 Load	(1.15 Rise/Rated Rise)
From Curves in Fig. 3	50	69.5	1.39
	64	90	1.40
	81	115	1.42
Author's Analysis Test Data on 28 Motors	32 to 48	—	1.36 (median)
Consensus, NEMA Task Force	50	65	1.30
	66.5	90	1.35
	82	115	1.40

load if the load were increased. This information is significant in considering service factor, which is the multiple of rated load permitted on certain motors that have a deliberate margin under the allowed rise by resistance at rated load.

In determining standards for temperature rating of motors with higher-temperature insulation and with 1.15 service factor, it is first necessary to establish the relation between the rise at rated load and at 1.15 load and to judge whether this relation varies for different levels of temperature rise. The curves in Fig. 3 provide a good basis for obtaining this relationship, in that they logically account for both the effect of load increase and the influence of actual operating temperature on the copper losses. This observation is supported by Fig. 4.

The first group of data in the table is taken directly from Fig. 3. The second comes from the writer's review of test results on 28 dripproof Design B motors, Class A insulation, two through eight poles, frames 213 through 326U. Each test reviewed included a temperature run at rated load and at 1.15 load, with the rises by resistance at rated load ranging from about 32 degrees C to 48 degrees C. The

5 TEMPERATURE RELATIONS (DEGREES C) FOR DRIPPROOF MOTORS WITH 1.15 SERVICE FACTOR, BASED ON RELATION BETWEEN RISE AT RATED LOAD AND AT 1.15 LOAD, PER FIG. 3

	Alternate 1				Alternate 2				Alternate 3			
	Retains 10° C margin for service factor per past Class A general-purpose motors for all insulation classes. Same insulation life at rated load as past Class A, but shorter insulation life at 1.15 load for Classes B, F, and H insulation than formerly attained on Class A at 1.15 load.				No change from past practice for Class A insulation. For Classes B, F, and H insulation, provides longer insulation life at rated load and about same insulation life at 1.15 load as formerly attained with Class A insulation.				Retains hot-spot temperature at 1.15 load at Fig. 1 values for each insulation class. This provides longer insulation life at 1.15 load than formerly attained from Class A general-purpose motors at 1.15 load. Provides appreciably longer insulation life at rated load than former practice.			
Insulation Class (Fig. 1 hot-spot temperature)	A (105)	B (130)	F (155)	H (180)	A (105)	B (130)	F (155)	H (180)	A (105)	B (130)	F (155)	H (180)
Ambient Temperature	40	40	40	40	40	40	40	40	40	40	40	40
Rise by Resistance (Rated Load)	50	70	95	115	50	64	81	95	44	57	75	88
Rise by Resistance (1.15 Load)	70	98	135	165	70	*90	*115	135	60	80	105	125
Hot-Spot Allowance	5	10	10	15	5	10	10	15	5	10	10	15
Hot-Spot Temperature												
At rated load	95	120	145	170	95	114	131	150	89	107	125	143
At 1.15 load	115	148	185	220	115	140	165	190	105	130	155	180

**New NEMA standards for future designs.*

median ratio of the temperature rise at 1.15 load to the rise at rated load for all 28 motors was 1.36. The third set of data is the consensus arrived at recently by a NEMA task force after many discussions of the relative temperature rises of motors at rated load compared with their rises at 1.15 load, for various levels of temperature rise.

Although there is not exact agreement in the data from the three sources, the disparity is not excessive. This indicates that Fig. 3 is reasonably accurate. It provides a convenient basis for estimating the temperature rise of a motor at any increased load over a wide range of base temperature rises.

The next question settled by the task force was what insulation life expectancy (in terms of past practice) should be provided by new temperature rating standards for motors with higher-temperature insulation and with 1.15 service factor. Answers can be based on many different approaches, but the proper technical answer depends largely on how motors are applied. Unfortunately, so far as the question of temperature rating is concerned, application practices vary widely. They can be described generally as follows:

Essentially Continuous Operation at Service-Factor Load—If normal insulation life expectancy is necessary or desired, one might think a motor with Class A insulation and 60-degree rise by resistance at the service-factor load should be used. However, there has not been a standard general-purpose motor in this category. The standard general-purpose motor with 50-degree rise at rated load has a history of successful service in a wide range of applications, some presumably involving continuous operation at service-factor load. One can only conclude that, under such conditions, an adequate insulation life was obtained.

Essentially Continuous Operation at Rated Load, With Occasional Intermittent Operation at Service-Factor Load—A Class A motor with 50-degree rise by resistance at rated load is entirely adequate and will provide more than normal insulation life expectancy. This is the type of application for which the standard general-purpose, open, 50-degree-rise motor with Class A insulation was originally intended. Such motors probably are applied this way so far as intent is concerned, but not always so in practice.

Essentially Continuous Operation at Less Than Rated Load, With Occasional Operation at Rated Load and Rare Operation, If Ever, at Service-Factor Load—Application of a Class A motor with 50-degree rise by resistance at rated load is ultraconservative, and one having 60-degree rise at service-factor load is even more conservative. Loading surveys indicate that this form of motor application occurs frequently, and that actual loads are very low percentiles (less than 50 percent) of rated load. Unfortunately for economy, this is probably the most common type of application. Marked underloading generally stems from insertion of a number of "safety factors" as motor requirements are relayed from the ultimate user to the manufacturer.

In discussing the proper full-load temperature rating to assign to a motor with service factor, the task force referred the foregoing application examples back to the open (or dripproof) motor with Class A insulation. This is the only motor for which a temperature-rating standard embodying a margin for service factor formerly existed. Former temperature rating standards for motors with Class B, F, and H insulation did not have any margin for service factor.

Future standard general-purpose motors will use the higher-temperature insulations. When these are to be with service factor, suitable temperature-rating standards must be applied. Three alternate proposals for such standards were studied (Fig. 5). The proper choice from among these alternates (or from any others) was not easy, for no one choice is correct for all conditions. Weighing all factors, NEMA adopted alternate No. 2 for Class B and Class F insulation.

This is a logical choice, avoiding the extremes represented by alternates 1 and 3 and affording new general-purpose motors with Class B and F insulation about the

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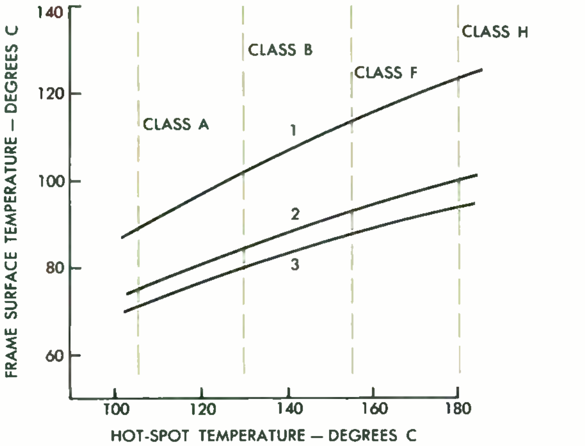


APPROXIMATE SURFACE TEMPERATURES of motors operating in 40-degree ambient and having winding temperature rise at maximum value allowed for enclosure and insulation class. Curves are for: (1) totally enclosed non-ventilated, (2) drip-proof, and (3) ribbed totally enclosed fan-cooled motors.

same insulation life at 1.15 load as past Class A motors, but longer life at rated load.

The data in Fig. 5 is presented in terms of equating hot-spot temperature to the sum of ambient, rise, and hot-spot allowance; the explanatory comments concerning relative insulation life expectancy are then based on the difference between the hot-spot temperatures so obtained (and shown across the bottom lines of Fig. 5 for each insulation class and each alternate) and the Fig. 1 hot-spot temperatures for each insulation class. Although this method of presentation entails inclusion of the hot-spot allowance and the hot-spot temperature in determining insulation life expectancy, the writer elected to use it because he feels it more conveniently illustrates the comparison among the three alternates than would a similar analysis based only on relative temperature rises.

Indirect Effect on Design

Higher operating temperatures are an inevitable consequence of full use of higher-temperature insulation. The influence of higher temperatures on rating potential and motor performance is important mainly to the designer, but the external surface temperature to be expected is important to the user. The approximate frame surface temperatures of three types of motors are shown in Fig. 6. These values were determined by observing and plotting test data from a large number of motors, frames 182 through 445U, the great majority of which had Class A or Class B insulation.

Although individual reactions vary to some extent, a surface having a temperature of 50 or 55 degrees C is about the hottest a person can press his hand against and hold it there without marked discomfort. Even the Class A surface temperatures in Fig. 6 are above this value, but Class A machines have been generally accepted for many years as presenting no surface-temperature problem. A factor contributing to this is that although 50- or 55-degree surface temperature produces discomfort to the touch, appreciably higher temperature is required to cause a burn. Also, many factors contribute to actual or apparent lower surface temperature on motors.

Among these factors are ambient temperature less than 40 degrees C, winding rise less than the allowed maximum, and operation at less than rated load. These conditions, individually or in combination, probably occur frequently. The most commonly used open general-purpose motor tested did not operate at the allowed maximum winding rise at rated load because of the 10-degree margin provided for service factor. Also, with ribbed totally enclosed fan-cooled machines, the surface temperature may feel lower than it actually is because a hand placed on the surface is in the cooling air stream and contacts the tips of the ribs (which are the coolest parts of the frame surface).

These same factors will apply to future motors built to the newly adopted standards for Class B and F insulation.

As Fig. 6 shows, dripproof and ribbed totally enclosed fan-cooled machines with Class F and H insulation have approximately the same range of frame surface temperatures as totally enclosed nonventilated machines with Class A and B insulation. This range has well-established usage acceptability. However, totally enclosed nonventilated machines with Class F and H insulation are beyond this surface-temperature range; they may be less acceptable.

Bearing operating temperature is an important consideration and it is related to frame surface temperature. In totally enclosed nonventilated machines, the bearing temperature approximates, but generally never exceeds, the frame surface temperature. Bearing temperatures in dripproof machines may vary from appreciably below to slightly below frame temperature, depending on the ventilating system. In totally enclosed fan-cooled machines, the bearing temperature at the end opposite the cooling fan approximates, but does not exceed, the frame surface temperature. Since standard bearings have been proved adequate for totally enclosed nonventilated machines with Class A and B insulation, the same bearings will be satisfactory for dripproof and totally enclosed fan-cooled machines with Class F and H insulation. Standard ball bearings with a reasonable field relubrication schedule (or sealed prelubricated bearings with a temperature-stable grease) are generally expected to give satisfactory service at operating temperatures up to 95 or 100 degrees C. Only totally enclosed nonventilated machines with Class F and H insulation are beyond this range and require special heat-stabilized bearings and high-temperature grease.

Summary

The use of Class B insulation in any enclosure, and Classes F and H insulation in dripproof and totally enclosed fan-cooled enclosures, for future standard motors presents no extreme technical problems. Application of such motors may sometimes require more care. In general, though, past practices can be followed with satisfactory results, assuming that standards other than temperature rating remain unchanged. The choice of Class B, F, or H insulation determines the rating attainable in a given physical size. The recently established NEMA rating standards are realistic and permit attainment of a sound overall economic balance.

Westinghouse ENGINEER Mar. 1964

THE ASTOR . . . A Deadly Undersea Weapon

Potentially more deadly than any of the ocean's finned inhabitants, the "fish" shown on these pages are actually the U. S. Navy's sophisticated, electrically powered ASTOR torpedos. Also known as the Mark 45 torpedo, the weapon is being built by the Westinghouse Underseas Division.

The ASTOR is a high speed, long-range weapon and is capable of destroying enemy submarines as well as surface ships. It can be carried by conventional as well as nuclear-powered submarines. The performance details of the ASTOR are classified but the painstaking work that goes into its manufacture is not; the photos shown here indicate some of this work.

Torpedo parts take shape on the machining lathes. In the foreground is a tail cone, which houses propeller shaft and control mechanisms. Nearest the camera, on a lathe, is the nose cone, and in the background is the center portion, or "after body," of the weapon. Machining tolerances are such that the various sections of the ASTOR will be interchangeable with each other.

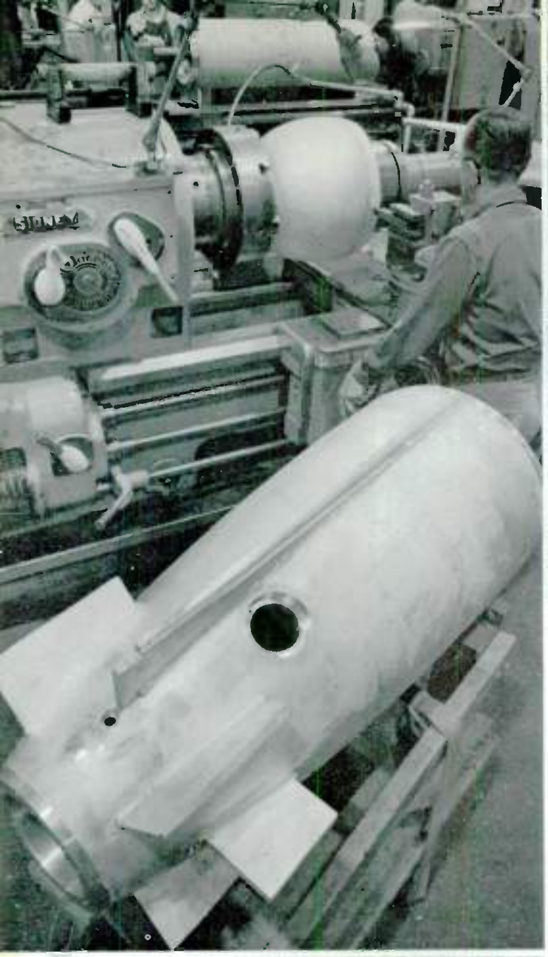
Preparing the tail cone of an ASTOR torpedo for a hydrostatic pressure test. This is one of many tests to which torpedo components are subjected during the manufacturing operation. After the tail cone is inserted into the testing chamber, large bolts at right will be tightened down, the chamber will be flooded with water, and the pressure applied. Any leakage will be cause for rejection of the component.

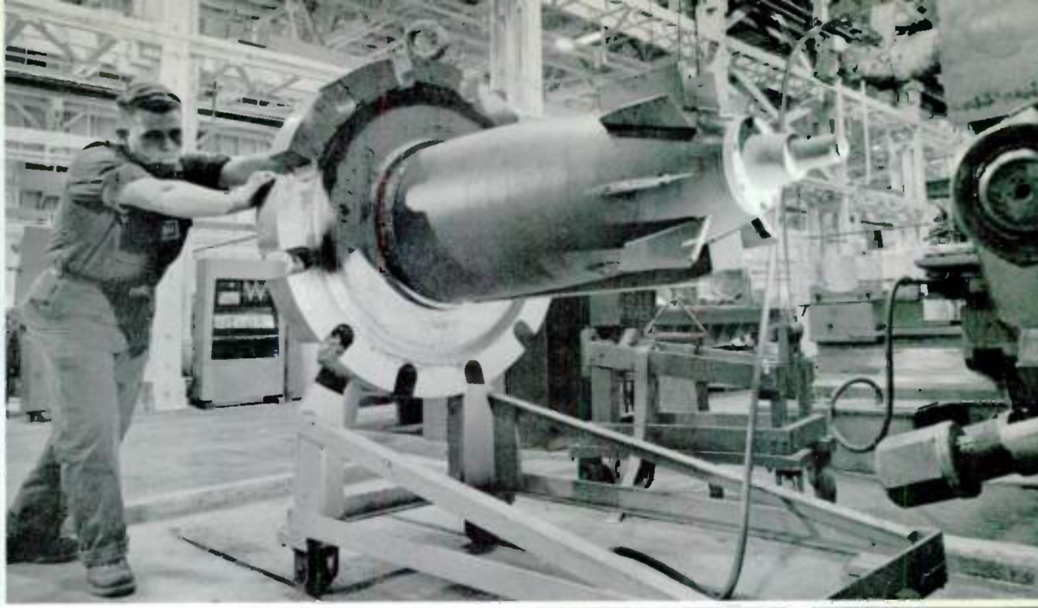
Tail cone of torpedo, viewed from this angle, looks like a ship's steering wheel. Here, an inspector examines every weld inside the tail cone to make sure of the component's structural integrity.

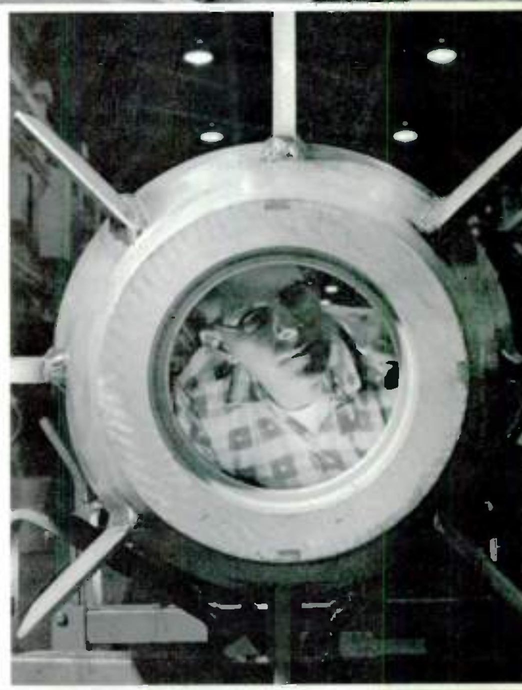
Final assembly of the U.S. Navy's ASTOR torpedo is shown in this picture. Each component of the weapon is fully tested, including the propulsion meter and the steering and control gyroscopes, before being accepted by Navy inspectors. Shown here is a nearly completed torpedo; the torpedo will be disassembled prior to shipment in special containers.

The steering mechanisms of the torpedo are assembled in the dust- and lint-free atmosphere of this super-clean room at the Westinghouse Underseas Division. The unit on the test table is being checked by testers. They are simulating conditions the torpedo might encounter on its mission—roll, pitch, motor vibration, and the effects of wave action.

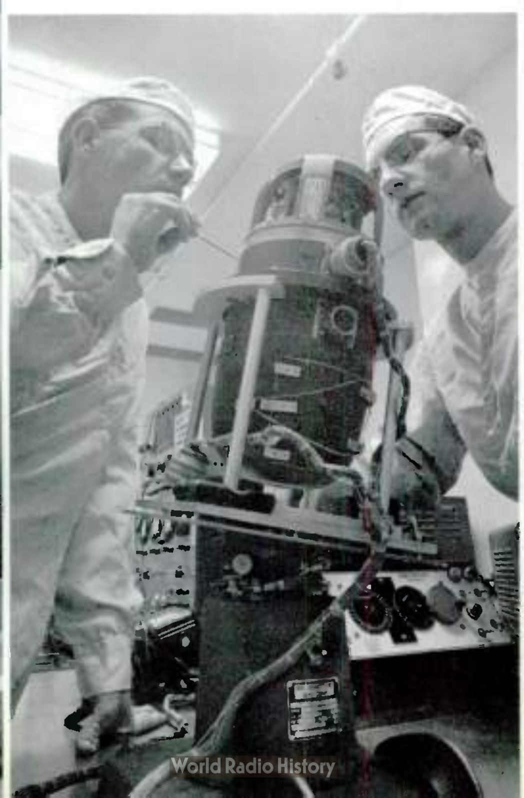
With the precision of a jeweler, a technician checks an adjustment on a gyroscope motor. This motor spins at 24 000 revolutions per minute. It is one of the many precision components that go into the control system of the Navy torpedo. The work is performed in a special "clean" room; air in the room is filtered, and temperature and humidity are controlled to prevent contamination of the delicate, precision-made parts of the torpedo's "brain."

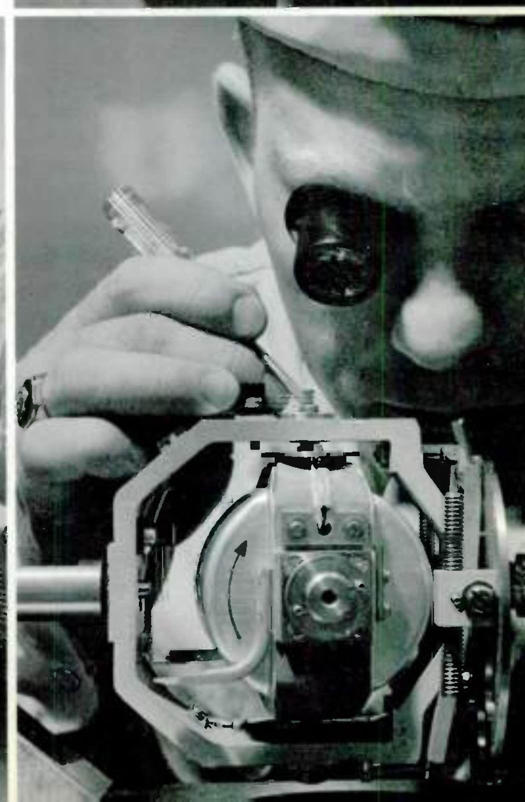







QUALITY
ASSURANCE





TECHNOLOGY IN PROGRESS

All-Digital Utility Computer System

The first all-digital systems operation computer in the electric power industry will be built for the Kentucky Utilities Company. The Prodac 510 high-speed solid-state process control computer is the heart of the system. On an on-line or shared-time basis, it performs the following functions:

Load frequency control scans the individual generation and interconnection tie-line loads and automatically controls the output of the generating units to maintain the desired net interchange and the system frequency. The control system repeats the control cycle as often as every 2.5 seconds.

Economic dispatch determines precisely the economic load assignments for each generating unit, considering both transmission line losses and incremental generating costs of each unit. These quantities are computed as often as every two minutes to supply varying system loads. In addition, a subroutine program is included to insure that adequate generation capacity is maintained in spinning reserve.

Data logging scans and logs power system conditions and alarms, including telemetered generator outputs, opening or closing operation of 200 power circuit breakers, manual entries to the computer by the dispatchers, and various alarms. Expandability of this function is practically unlimited.

Unit commitment determines each day an optimum operating schedule of all generating units to meet predicted system loads. It actually computes the cost of production based on various combinations of operating units and selects the most economic combination for each hour. Production costs and load forecasts are additional subprograms included.

Evaluation of sale and purchase of power makes precise determination of the economics of buying or selling power each hour with each of the interconnected neighboring utilities.

The digital dispatch and operations computer system is scheduled for shipment early in 1964 to the Kentucky Utilities Company's Dispatching Center at Dix Dam, 30 miles from Lexington, Ky. ■

New TV Camera Tube Can "See in the Dark"

A versatile new television camera tube named the SEC-vidicon has special features that make it particularly promising for TV exploration in space. It can virtually "see in the dark," yet shows no blackout or flare from sudden bright sources of light.

The reason for the tube's performance is a unique kind of electronic process used to convert a visible image into electrical signals that can be amplified and telecast. The phenomenon, called secondary electron conduction (SEC), occurs in solid materials so light and porous that only two percent of their volume is solid matter. The rest is a vacuum, in which secondary electron conduction occurs.

The SEC-vidicon tube produces pictures of high television quality at low light levels. In addition, the tube has several other characteristics that make it particularly suited to space use. Among these are: the wide range in light levels it can tolerate and respond to without overloading or requiring delicate adjustment; the ability to slowly build up, or integrate, and store an electrical image over long periods of time without loss in picture quality; the high speed with which it can create an image and erase it in preparation for the next one; the tube's uniform operation over a wide range of temperature; and its low background "noise" and good electrical stability.

Such capabilities are especially valuable for television-equipped satellites and space probes. For example, a space vehicle carrying the tube could observe the dark side of the moon, holding the pictures directly until asked to relay them to earth.

Another application could be in an earth-circling satellite, which is exposed to a wide range of light and shadow as it watches the earth's surface day and night. The SEC-vidicon could tolerate these extremes in light level without remote electronic adjustment from the earth's surface.

The SEC-vidicon consists essentially of three key components: (1) a sensitive photocathode that releases electrons in proportion to the light energy striking it; (2) a thin porous film, or target, in which the accelerated photoelectrons generate a large number of secondary electrons. These secondary electrons are swept out of the film by applied electric fields, leaving behind an amplified charge image; and (3) an electron gun that scans the target, releasing the electrical charge pattern as a series of amplified pulses representative of the original light image. The electrical pulses are used to reproduce the image on an ordinary television picture tube.

Travel of the secondary electrons by conduction through the vacuum space of the porous target differs from ordinary electron conduction in solids. It is faster and more uniform. These factors, plus an information storage capacity approaching that of photographic film, suggests that this new TV camera tube may be capable of removing many of the limitations on seeing now imposed by conventional types.

The SEC-vidicon is the latest product of a long-term Westinghouse research program in electronic image brightening, particularly in the field of secondary emission. Work on the SEC-vidicon tube was supported in part by the Electron Tubes Division, Electronic Components Department, U. S. Army Electronics Research and Development Laboratory, Ft. Monmouth, N.J., and by the Electronic Technology Division, U. S. Air Force Avionics Laboratory, Wright-Patterson Air Force Base, Ohio. ■

Time Capsule Under Construction

The slim, torpedo-shaped crypt that will preserve for 50 centuries a record of man's notable achievements of the past 25 years is nearing completion. The glistening seven-and-one-half-foot structure is known as the Westinghouse Time Capsule; it is made of Kromarc, a super stainless steel alloy that was developed at the Westinghouse Research Laboratories.

At the close of the 1964–65 New York World's Fair, the Time Capsule will be lowered 50 feet underground to lie beside the original Westinghouse Time Capsule interred on the site of the 1939–40 New York World's Fair. By documenting the unprecedented progress of mankind in the past 25 years, the new Time Capsule will update the permanent record of 20th-century civilization preserved in the original.

An exact duplicate of the new capsule is also being fabricated. This duplicate, which will be suspended from three 100-foot steel towers above a reflecting pool, will be the central feature of the Westinghouse pavilion at the 1964–65 Fair.

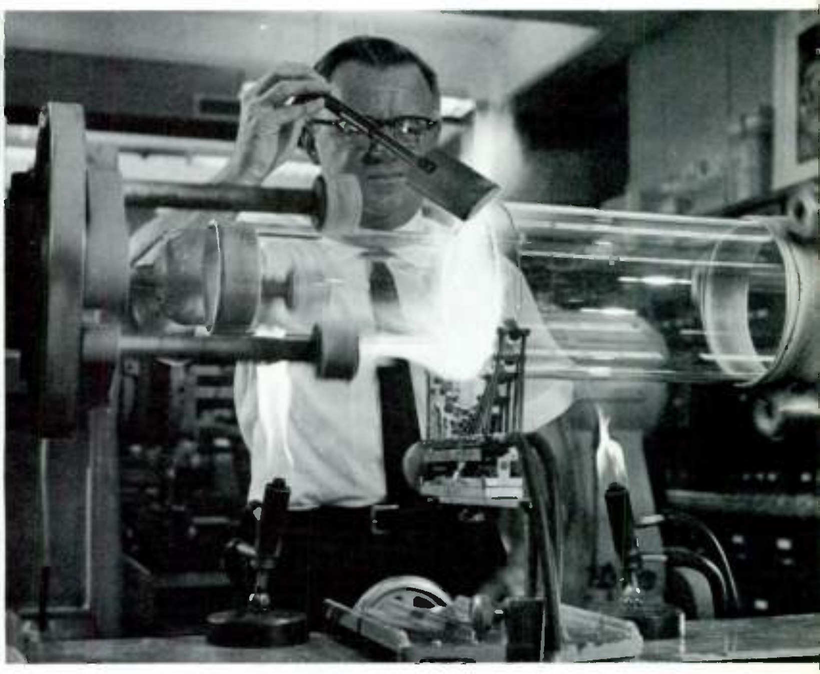
Kromarc stainless steel was chosen as the structural material for the new Time Capsule by a committee of research scientists. The alloy's outstanding strength, toughness, and resistance to corrosion were important considerations in selection of the material for its 5000-year task. The capsule is made in three sections, which are welded together into the final structure. The center section is a tube 62 inches long and 8⅜ inches in diameter. The finished capsule has walls one-half inch thick and weighs about 300 pounds.

A thick glass envelope, or liner, will fit inside the capsule and house the items to be preserved in it. The envelope will be filled with an inert atmosphere and sealed airtight to give maximum protection to the materials the capsule will preserve. ■

Wayside Control System for Mass Transit

A wayside control system designed for use with existing or new rapid-transit systems permits single cars or trains to be automated to almost any degree desired.

ONE OF THE END PIECES of the new Westinghouse Time Capsule is welded to the center section. The capsule will be filled with the documentary evidence of man's progress in the past 25 years, and then the other end piece will be welded on. The stainless-steel capsule will be buried at the New York World's Fair to supplement the record left there, for people 5000 years from now, at the close of the 1939–40 Fair.



A GLASS INNER ENVELOPE, shown being fabricated, will fit inside the Time Capsule. When the capsule has been packed, the envelope will be filled with inert gas and sealed.

Wayside controllers at each station, under monitoring control of a central supervisory and control computer station, can automatically regulate train speed, start and stop the trains, open and close doors, announce trains, perform all supplementary functions needed for safety and service, and otherwise monitor train performance. The system assures on-time operation and less than two-minute station waiting time—features that commuters have long desired but seldom experienced.

This elevator-type automation does not eliminate the need for attendants to police the system, assist people in distress, and prevent vandalism and passenger annoyance, but it does make reduced expenses and better service possible. An important feature of the system is that it can be applied either to a main line of a rapid-transit system, to one or more feeder routes, or to the entire network.

The heart of the system is the supervisory and control center, which feeds major operating instructions to, and receives feedback information from, the wayside stations. The main component in the center is a high-speed, on-line, stored-program digital computer with associated input-output, display, and logging equipment. Communication with wayside controllers, yard, station terminal, and interlocking local equipment is handled by its associated high-speed, solid-state data-handling system. Provisions are incorporated for the dispatcher to alter the stored program and take overriding action on the system operation at any time.

The center monitors the wayside controllers and programs the complete network operation, from requesting trains out of storage to removing unwanted cars and trains after rush hours. It details train lengths, originating terminal and leaving time, operating pattern (such as local, express, and skip-stops), disposition at the destination terminal, and time and location references used by the train movement supervision.

A single comprehensive display shows all data and parameters monitored on the network. For example, a separate display associated with each train-position indicator and station shows train failures, substandard performance, schedule and interval deviations, and excessive station stop time.

Controls for dispatcher use in system operation and for two-way voice communication with wayside stations, train attendants, and passengers face the monitoring display. Logging typewriters record schedule deviations, excessive stop time, corrective actions, and so on. Communication with trains is over an inductive FM carrier link superimposed on the respective section of track wire used for communication between the wayside control stations and the trains.

The control can accommodate sudden service changes needed because of weather conditions, special events, provision for emergency service, and so on—in addition to having manual provision for adding or removing individual trains as required for normal load variations. It maintains train schedules by such means as varying station leaving time and running speed, rerouting trains, lengthening or shortening the run, and skipping stops.

Wayside stations overlap in control to prevent such incidents as station component failures causing a shutdown of network operations or serious accidents. Each controller runs through a diagnostic routine every second or so to check internal components, then signals its adjacent neighboring wayside controller of this fact. If trouble has developed in one controller, its neighbor takes over control of the train in that area, and if trouble arises in central supervisory control, each wayside controller continues to function to maintain service within its jurisdiction. Manual control aboard the train enables the attendant to operate at low speed, bring the train to a stop, and manipulate the car doors. ■

Adjustable-Voltage Electric Drive for Cargo-Ship Winches

Cargo handling is one of the major expense considerations in the operation of a cargo vessel. The cargo winches represent a significant percentage of the total cost of shipboard equipment, and they also represent approximately 60 percent of the in-port electrical load, reflected in fuel consumption for power generation.

Regular hoist loads can now be handled with greater dispatch, and without the in-between delays for rerigging occasional overweight loads, by a faster-response adjustable-voltage electric winch drive. The system can handle double loads up to six tons for short periods.

Another factor of practical importance is the 500-pound reduction in drive weight as compared with that of conventional equipment. Since most cargo ships have 20 or more winches, this dead-load saving makes room for extra tons of cargo. This and the lower dock costs and faster turnaround add up to a materially lower operating cost per ton-mile.

The complete drive package consists of a three-unit motor-generator set with two generators, each serving a winch motor, two five-point master switches, and a control cabinet. All of these are weatherproof and fitted with moisture drains and space heaters. The m-g set motor is a 440-volt, 60-cycle, 75-hp, 3500-rpm, ac unit. Each generator is a dc, compound-wound, 300-volt, 40-kw machine. Winch motors are 50 hp, 240 volt, 600 rpm, dc.

The adjustable-voltage drive obtains its faster maneuverability and stability through specially designed generators and motors, a timing relay, and a permanently closed bridge-circuit loop provided between the generator and motor armatures.

The generator is a high-speed unit with low field-time constant, which enhances the speed of response to give a fast rise in voltage—up to 140 percent of normal. Quicker response in winch-motor acceleration and deceleration is the result of designing less mechanical inertia into the armature and brake wheel. This decreased inertia also means higher operating efficiency. Another important feature of the motor is its high torque-per-ampere design, which keeps internal flux high. This prevents the development of excessively high currents when high torques are required. These characteristics provide high light-line speeds without excessively weakening the motor field.

The time constants of the various fields, the proportion of ampere turns between the differential fields, and the low inertia of the motor rotating parts all work together to provide smooth operation during plugging. Thus, severe torque pulses with their accompanying mechanical strains are not encountered.

Speed control of the Westinghouse system using the closed bridge circuit between generator and motor armatures provides maximum safety, reliability, and efficiency of power consumption. The circuit permits using a minimum of control components for simplicity of operation and maintenance, and the low energy levels handled by the contactors assure them a long, troublefree life. Running maintenance is further simplified because motor brush tension remains constant throughout full brush life.

In operation, the bridge permits positive (cumulative) series ampere turns in the first three hoisting positions of the control, and negative (differential) ampere turns in the fourth and fifth positions. This shapes the generator volt-ampere curves for best speed-torque characteristics. Reversal of the motor series field is prevented by a blocking rectifier.

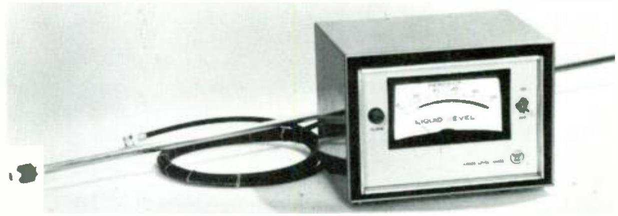
A combination of dynamic braking and a "killer" generator field enhances the safety to both load and personnel by quickly reducing the generator voltage to practically zero. Deceleration of the motor is accomplished by regeneration and dynamic braking. The mechanical brake, therefore, is not required to absorb motor torque but only to be capable of holding the load.

In event of simultaneous failure of the brake and ac power, the drive is able to lower any load safely, including double loads, at 30 to 40 fpm, the equivalent of dropping the load less than 1/10 of an inch. For normal operation, the drive features empty-hook lowering speed unmatched by conventional drives.

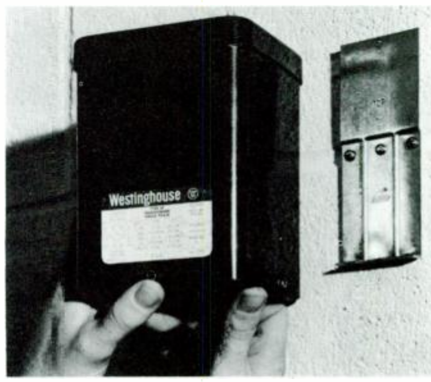
The special control uses a first-point lowering system (adjustable down to 10 fpm) for accurate spotting and handling of any load. This eliminates the usual jogging between first-point lowering and "off" for spotting loads. Any load within the winch drive capacity can be hoisted on any point of the control without the motor running backward and regenerating in the lowering quadrant.

Basic features and reliable performance of the adjustable-voltage winch drive also make it suitable for many other applications on docks and in power shovels, powerplants, shipyards, foundries, and pumping stations. ▪

PRODUCTS FOR INDUSTRY



LIQUID LEVEL GAUGE does the job when mechanical or visual systems are impractical. Gauge can be used for any nonconducting liquid with a difference in the dielectric constants of its liquid and gaseous phases equal to or greater than liquid helium. It is accurate within three percent over full scale and operates from minus 269 degrees to plus 200 degrees C. Probes are available on special order for a wide range of liquids and container depths. *Westinghouse Scientific Equipment Department, P. O. Box 868, Pittsburgh, Pa. 15230.*



EASIER TO MOUNT DRY-TYPE TRANSFORMER also has better electrical performance. Bracket is first fastened to wall and then transformer is hung on bracket, eliminating need to hold a heavy transformer against wall while mounting. Ratings of EP transformers range from ¼ to 2 kva, and impedance is improved over previous units. *Westinghouse Specialty Transformer Division, Greenville, Pa.*

PREFABRICATED STRESS CONE for pad-mounted transformers is faster to install, more effective in use, and more economical than conventional stress cones. Wescone is for terminating high-voltage cables on 15-kv systems. It consists of a parabolic metal cone that fits around the cable sheath; cone is held in place by a plastic housing and is electrically connected by a clamping band. Advantages are easier assembly, more uniform insulation structure, lower electrostatic stresses, higher corona inception level, and lower RIV level than built-up stress cones. No special tools are required. *Westinghouse Electric Corporation, P.O. Box 868, Pittsburgh, Pa. 15230.*

WALK-IN CLEAN BOOTH can be used as complete small clean room or as superclean work station inside conventional clean room. Construction is modular so several booths can be joined together to form larger clean areas. Booth design eliminates turbulence in airflow pattern, operators can work without special attire, and the work is protected from contaminants by a layer of clean air. Three types are available: enclosed, for installation anywhere; open, for installation in relatively clean surroundings; and bench type for use in existing clean rooms. *Westinghouse Environmental Contracting Department, P.O. Box 868, Pittsburgh, Pa. 15230.*

Fundamental Noise . . . The Limit of Observation

Russell Fox, Manager, Physics Department,
Max Garbuny, Consulting Physicist,
Robert Hooke, Manager, Mathematics Department,
Westinghouse Research Laboratories, Westinghouse Electric Corporation, Pittsburgh, Pennsylvania.

Editor's note: This article has been based on selections from THE SCIENCE OF SCIENCE, the first volume of a new series to be called Westinghouse Search Books. These books are being written by scientists actively engaged in industrial research. This situation is somewhat unusual in that most books written by working scientists (as opposed to educators or professional writers) are intended for fellow scientists; the audience for this series is the talented high school student and the college undergraduate. The books are designed to supplement standard textbooks and conventional courses in the physical sciences and mathematics.

Fundamental concepts of science will be presented from a variety of viewpoints—from the physicist, the chemist, the mathematician, or the engineer. Each will interpret these concepts from the standpoint of his individual scientific discipline, and will share knowledge that he has gained in applying these concepts to his work.

The series is being guided by an editorial board of laboratory staff members, with Dr. John Coltman, Associate Director, as chairman. The board is working closely with the executive editor, Sharon Banigan, who is responsible for coordinating the program, guiding individual authors, and acting as liaison with the publisher, Walker & Company, New York.

The first two volumes, THE SCIENCE OF SCIENCE, and ENERGY DOES MATTER, were introduced in January and March 1964. Two more are planned for publication this year; ELECTRONS ON THE MOVE and SCIENCE BY DEGREES.*

Other books in the series will deal with such subjects as chemical bonds, crystals, mathematics, plasma, optics, and magnetism.

Contributing authors for this first book, THE SCIENCE OF SCIENCE, are Russell Fox, Manager of the Physics Department, Max Garbuny, Consulting Physicist, and Robert Hooke, Manager of the Mathematics Department. The book describes scientific methods, their effectiveness, and their limitations. The authors use actual examples of scientific investigation in today's research to illustrate these methods. The material for this article has been condensed from their discussion of the limitations imposed on observation and measurement by the very structure of matter.

We believe that you will find this unusual interpretation of science by scientists interesting reading.

**Each volume 256 pages, $5.95.*

Few dreams have so haunted man as that of extending the limits of his senses. To see the farthest stars, to watch the smallest microcosm, to feel the slightest force, to hear sounds produced far away or long ago; these aspirations require only the extension of human powers for their realization. All the principles on which these direct or indirect extensions of the human senses are based can be refined, magnified, and stretched to achieve greater and greater sensing powers, and it often appears that such improvements can be endless.

Suppose, however, there were reason to investigate the sounds made by insects, the pitch, the modulation, and perhaps the meaning of messages from one to another. The whir of a fruit fly's wings must exist, for example, although it is inaudible to the most sensitive human ear, and there may or may not be such emanation from all that crawls, hops, or flies. A study of this tiny world of sound would require extremely delicate instruments. A suitable ultramicrophone would have to be equipped with a membrane which is small and light enough to respond to the minute changes in air pressure produced by such a source of sound. However, as the microphone is made more and more sensitive, a limit is reached: depending on the bandwidth of the amplifier, a hissing or crackling sound becomes audible. This disturbance goes on even in the absence of any specimen, drowning out all other sound that is smaller; no improvement in microphone construction nor increase of amplification can eliminate it—it is indeed the din of the individual air molecules striking the membrane.

Thus, the very medium that carries the sound also carries its own noise, and no device can circumvent or remove this inherent disorder. A fundamental and irreducible noise limitation has now been encountered.

Fundamental Noise

Thus, deeply rooted in the nature of the detection process there are disturbances generally called fundamental noise. These perturbations limit measurement or observation in a manner that, in principle, cannot be remedied by amplification or magnification. But these limitations are of interest in their own right; their very existence may reveal aspects of nature which had been undetected by any other approach. Hence, the noise is sometimes more important than the signal.

Anything used for or subject to measurement is of atomistic structure, consisting of discrete entities. Current is a measure of the number of electrons passing each second through a plane; density of a substance is determined by the number of atoms and molecules per unit volume; even the measurement of energy, which to all appearances is a smooth function of such variables as height, turns out to be "quantized." The atomistic structure of mass, charge, and energy had been undetected for so long because of the enormous number of individual entities needed to make up macroscopic amounts. An ampere-second or coulomb consists of 6.25×10^{18} electrons, a gram of iron is composed of 1.08×10^{22} atoms, and a watt-second or joule of radiant energy—delivered, for instance, as green light—consists of 3×10^{18} photons. Indeed, it is mainly when the process of detection or measurement is pursued to its limits that the finiteness of the numbers involved becomes apparent.

If these atomistic entities are randomly distributed in time or space, their number will fluctuate when counted under otherwise equal conditions. Thus, an inherent uncertainty, which may be called noise or error, attaches itself to any measurement that deals with randomized particles. All this means that every measurement is of statistical nature—not just the measurement concerned with the number of individuals exercising free choice of one or the other alternative, or the measurement of biological occurrences, but the physical measurement of nature's universally and eternally constant values.

Indeed, were it not for this fundamental flaw of our universe in exhibiting atomistic structure, even the smallest signals would be detectable, and there would be no limit to the accuracy with which anything could be measured. Nor would there be, from the physicist's point of view, much of anything worth measuring.

For the evaluation of the limits set by noise, it is necessary first to establish the relationship of conventional units, such as units of current or heat content, to their basic atomistic entities. The second step is to compute the fluctuation of this number according to the law of mean deviation. The third step is to convert this number back into practical units, and this is the desired answer, since it represents the noise.

Sometimes the second step presents real difficulties when there is not complete randomness for the events counted. Instead, there may be partial restrictions on the freedom of occurrence for the individual events, and this leads to a different "statistics," which in turn generates its own kind of fluctuation law. Rather than deplore this vexing complexity of nature, adversity may be turned to advantage by exploring the noise itself.

Shot Noise

Perhaps the most important of the disturbances that plague those intent on delicate sensing, detecting, or measuring are associated with the observation of very small electric quantities. In a typical situation, a stream of electrons emerges from a metal surface (cathode) and passes through a vacuum toward another metal surface (anode). This happens in phototubes and is also characteristic of thermionic current; indeed it is characteristic of the passage of any particle stream through or onto a barrier, regardless of the nature of the medium, whether it be from solid to vacuum, from vacuum to solid, or from solid to solid.

When the current flow from the cathode is sufficiently small, the beam appears grainy. Such nearly expiring current, amplified and fed to a loudspeaker, generates a noise similar to the sound of lead pellets falling irregularly on a hard surface. Hence this effect is called *shot noise* (also, less ambiguously, *Schottky noise*, after its discoverer).

How can the noise current be expressed in terms of these fluctuations? To answer this, three steps are required:

First, electric current i is defined as the amount of charge passing per second through a real or imaginary boundary; if the current is observed for a time t a charge $i \times t$ will have passed, and since such a charge is atomistic, consisting of n electrons of unit e, it follows that the number of electrons that pass through the barrier is:

$$n = \frac{i \times t}{e} = \frac{i}{e \times 2\,\Delta f}.$$

On the right of this expression, the observation time t is replaced by its reciprocal value, $t = 1/2\,\Delta f$, where Δf is the bandwidth, the width of frequencies the apparatus will admit around the tuned value.*

As a second step—since the emergence of electrons

*The relationship between Δf and t is given by:

$$t \cong \frac{1}{2\Delta f},$$

where t is the time the resonant system needs to respond with a sharpness of bandwidth Δf. This equation implies that a bandwidth of one cycle per second (for instance, a band pass between 10 000 and 10 001 cycles per second) necessitates an observation time of one second by order of magnitude. By the same rule, if one admits only a change of one cycle every 100 seconds ($\Delta f = 0.01$ sec^{-1}), it obviously requires an observation time in the order of 100 seconds to notice a change in amplitude or phase. Thus, the "listening range" is limited by admitting a limited frequency interval, and noise in other frequencies is rejected—but the listening time must be extended. Since Δf is the range of frequencies the system will accept, it follows that it will "tolerate" Δf changes in amplitude per second and, therefore, have a memory or observation time in the order of $1/\Delta f$. A somewhat involved mathematical treatment corrects this by a factor of ½ for the integration time of random noise.

through the barrier is an unrestrained random process—the root-mean-square deviation law is applied:

$$\langle(\Delta\, n)^2\rangle_{av} = \frac{\langle\Delta\, i^2\rangle_{av} \times t^2}{e^2} = n,$$

where $\langle(\Delta n)^2\rangle_{av}$ is the *mean square deviation* in the number of electrons passing through the barrier.

Finally, the fluctuations in the number of electrons and the corresponding fluctuation of the current i_n are interpreted as noise, and this yields:

$$i^2_n = 2ei\,\Delta f = 3.18 \times 10^{-19} \times i\,\Delta f,$$

which is the shot noise formula for a current i (in amperes). This basic relationship describes the ultimate limitation of photoelectric sensors and thermionic current devices. It also applies to the random generation and recombination of charge carriers in semiconductors, and thus to photoconductors, transistors, and other solid-state devices. The limitation is best explained in terms of the ratio of the signal current i to the noise current i_n (the rms-value being understood):

$$\frac{i}{i_n} = \sqrt{\frac{i}{2e\,\Delta f}} = \sqrt{\frac{i}{3.18 \times 10^{-19}\,\Delta f}}.$$

Thus the signal-to-noise ratio increases directly as the square root of the current. For instance, at television bandwidth, (Δf = 4 megacycles/sec), the signal-to-noise ratio is about unity for a current of 10^{-12} amperes. This example illustrates the nature of the limitations the fundamental noises impose on the performance of electronic devices.

In semiconductors, an interesting variation of shot noise occurs. Here the fluctuations arise from the random events of the birth and death of charge carriers. An important mechanism, for instance, is one in which there are impurity centers capable of donating, at the slightest provocation, an electron which can carry its share of current for a while, until, after a mean life τ it recombines with an empty impurity state, and thus disappears from circulation. Therefore, at any moment there is an average electron population composed of a number n of individuals per unit volume. But because of the random nature of generation and recombination, the actual count during an observation time τ will fluctuate from one measurement to the next. Since the average lifetime is τ, t/τ generations of carriers are counted per observation time, and all together the total is:

$$N = nt/\tau = \frac{n}{2\,\tau\,\Delta f},$$

where N is the number of individual electrons on the average. The mean square of the noise voltage is then proportional to the reciprocal of this value. Thus, the generation-recombination noise is:

$$V_{n,rms} \propto \left(\frac{2\,\tau\,\Delta f}{n}\right)^{1/2}.$$

Since one man's noise is another man's signal, this last relation can be used to derive the lifetime of the carriers in the semiconductor from the generation-recombination fluctuations at a known bandwidth.

Photon Noise

The radiation from sources of visible and invisible light—or even from radio antennas—consists of discrete entities, the photons. The fluctuation law is not exactly the same as in the cases discussed so far. If during a given time interval, an average arrival contingent of N photons of sufficiently short wave lengths is counted in the visible or X-ray region, the usual $N^{1/2}$ rms deviation is still observed. But as this experiment is repeated for longer wave lengths, the fluctuations systematically increase so that they assume several times the normal value in the far infrared and beyond.

The reason for this behavior has to be sought in the nature of the randomness with which photons are emitted. If this phenomenon is explored in greater detail, it is found that individual emissions are not completely independent of each other. A process exists that is the exact opposite of absorption; an incident photon encountering an excited state is not absorbed, but instead generates a second photon. This is called *stimulated emission* or *negative absorption*. The first photon creates the stimulated photon in its own image, so to speak, giving it the same frequency, the same timing or phase, and even the same direction. For fluctuation theory, these radiation processes imply that photons emerging from a black body have a chance to be absorbed and then they are concealed from observation; those that are observed, however, have a finite chance of belonging to a pair, one stimulating and one stimulated. Thus, there is a deviation from complete randomness when the arrival of a photon is not completely independent of the arrival of the next; this deviation from the normal fluctuation law generates the larger noise.

The situation is important to the designer of detecting equipment. He may carefully avoid any disturbances caused by contact graininess or surface impurities, shield his apparatus from all unwanted irradiation, cool his detector to the lowest attainable temperatures to eliminate all thermal fluctuations; yet there is still an irreducible minimum of noise that comes with the radiation he receives as a signal.

Heat and Disorder

Not all fluctuations manifest themselves directly as deviations from a mean number of electrons, photons, or atoms. In other words, the procedure adopted so far for the interpretation and determination of noise in terms of an rms-deviation $\langle \Delta n^2 \rangle$ is unsuitable in certain instances. This is the important class of thermal fluctuations; aspects of its laws of randomness are apparently different from those discussed so far.

The incessant random motion of atomistic particles, which from the microcosmic point of view is the very essence of heat, cannot be observed directly because of the great speed and small size of the atoms. Indirect experimental evidence, however, comes from the observation of thermal fluctuations and noise. One such perturbation is called *temperature noise*, which shall be derived in the following in heuristic fashion.

Suppose a medium contains N particles, each free to assume a position which can be described by m coordinates ($m=3$ for ideal gases). The system is then characterized by mN degrees of freedom; it takes mN numbers to determine completely the instantaneous configuration of the system. As a result of heat, these mN numbers are random —on a macroscopic scale their values are unpredictable from moment to moment. However, there is a law of equipartition, which states that each degree of freedom is endowed with an average energy of $kT/2$ (where k is Boltzmann's constant). Thus, the heat content is the total of $mN \times kT/2$ random contributions (in addition to certain "latent" energies for melting, vaporizing, and other phase changes). If a measuring device or system with the equivalent of n degrees of freedom is exposed to the medium, a thermal noise level of $nkT/2$ is encountered, and observations are limited to that extent.

Thus, regardless of the type of thermal interchange, two aspects of thermal energy always manifest themselves. First, if an object is at a temperature T the mean energy value fluctuates between zero and the order of kT. In other words, $kT/2$ represents both mean and noise level for a single degree of freedom.

How does a system of many atoms behave in this respect? Clearly, if there are n degrees of freedom, all of them can be assumed to have direct, or indirect, thermal interchange with the surroundings of the object. Therefore, the heat energy of the object, which on the average is $nkT/2$, must also fluctuate. Since the individual contributions at any instant are random, the total energy of fluctuation is $\sqrt{n}\, kT/2$, according to the mean square deviation law. This heat fluctuation is observable through a fluctuation of temperature as $C\Delta T$, where $C=nk/2$ represents the heat capacity of the object. Thus, we have:

$$C\Delta T_{\text{rms}} \cong \sqrt{n}\,\frac{kT}{2} = \sqrt{\frac{2C}{k}}\,\frac{kT}{2}.$$

Hence,

$$\langle \Delta T^2 \rangle \cong \frac{kT^2}{2C}.$$

This is a rough derivation, of course, of the mean square temperature fluctuation correct by order of magnitude. A more rigorous treatment changes this result by a factor of two (which can be explained in the model by a deviation from randomness in the energy addition, since pairs of degrees of freedom add to kT). Thus, the temperature noise, in terms of the mean square fluctuation, is

$$\langle \Delta T^2 \rangle \cong kT^2/C.$$

This result implies that the temperature of an object is never exactly constant, but fluctuates more and more as samples become smaller with correspondingly smaller heat capacities.

In principle, temperature noise could limit the performance of radiation detectors in which the incident power is first converted into heat and evaluated as a temperature change by some mechanism. In practice, however, other disturbances are apt to be much more important. The ultimate reason is that in a sense temperature noise is a second order effect, consisting of fluctuations in the state of disorder; it is the noise of noise.

Johnson Noise

In 1928, the physicist J. B. Johnson observed a curious thermal agitation of electricity in conductors. The phenomenon consists of a fluctuation voltage generated across the terminals of a conductor, the magnitude of the effect being independent of the material and of the presence or absence of a current impressed externally. The mean value of this Johnson noise voltage, or the resulting noise current, is obviously zero, since otherwise formidable charges would build up at the terminals. The average noise power, proportional to the square of the voltage, is not zero, but has the value:

$$P = kT\Delta f,$$

where Δf is the bandwidth which is being observed. It is worth noting that this relation has all the aspects of a universal law: its validity is not restricted to any material, resistance, or magnitude of current, and it is remarkable that it does not make any reference to the fundamental electronic constants of charge and mass, even though it describes an important aspect of electricity.

There are many ways that lead to the Johnson noise formula. Perhaps the most direct and revealing method of describing it, although it is here more concise, follows the general line of reasoning first used by Nyquist.

Suppose the electrons in a conductor of length L between the terminals are capable of performing oscillations—not independently, but cooperatively, like the atoms in a vibrating string. Now, this picture applied to solids appears to be in violent contradiction to the one of particles moving in complete disorder and independence. Yet this lack of beauty must be only in the eye of the beholder, for it is possible to assert that either model is valid and capable of explaining the observed facts. Therefore, the thermal motion of electrons and atoms in solids must follow from a superposition of their "natural" vibrations, provided all possible modes are taken into consideration. The number of all possible vibrational modes is enormous—even in the one-dimensional case of the vibrating string.

To explain this concept of modes in a little more detail, it is assumed that the ends of the string are clamped. The vibrations are then the oscillations that all points describe, each with fixed amplitude, although from point to point this amplitude varies sinusoidally. This is the picture of standing waves, and it is characteristic that these consist of an integer number n of half-waves between the clamped (or reflecting) ends, so that

$$L = \frac{n\lambda}{2}, \text{ or } L = n\frac{v}{2f}.$$

In the second equation the frequency f (the pitch) has been introduced. This corresponds to wave length λ by virtue of the relation $\lambda f = v$, where v is velocity of propagation. Of course, in the case of standing waves, propagation has a special meaning: the vibrational mode is constituted of two running waves—the first moves in one direction and then, reflected at the end, returns as the second wave, thus forming the standing wave pattern. Therefore, all possible frequencies are multiples (harmonics) of the fundamental. Nevertheless, there is an upper limit, which is reached when the half-wave is just equal to the inter-atomic distance. The number of possible vibrations is thus equal to the number N of atoms in the string. Two degrees of freedom may be assigned to each vibration; there are then, altogether, $2N$ degrees of freedom available to the motion of the string.

The string vibrations can be compared with the possible electrical modes in a conductor. It follows from the equation for the allowable number of half-waves, viz. $n = 2f\,L/v$, that there are $4L\Delta f/v$ degrees of freedom in a frequency interval Δf, corresponding to a thermal energy of $2L\,kT\Delta f/v$ for the entire conductor. Of this amount, a fraction $v/2L$ passes each second in each direction through any point of the conductor, including its terminals. Thus, the fluctuation power is

$$P = \frac{v}{2L} \times \frac{2LkT\Delta f}{v} = kT\Delta f,$$

which, of course, is the Johnson noise formula.

The limitations imposed by these fluctuations are at least as important as those of shot noise. Johnson noise and shot noise cause the "snow" that appears on television tubes when the gain is turned high to receive a distant station.

An important example is the limitation in the measurement of photocurrent which, in a range still undisturbed by shot noise, cannot compete with the thermal noise generated in the resistors of the amplifiers. Thus, there is a need for amplification without the use of resistors, and this principle underlies the cascading of secondary emission stages in photomultipliers. The electron multiplier makes it possible to measure levels so small that the current is limited only by shot noise. In the limit of response—one photoelectron for each photon—the observation threshold is then determined by the photon fluctuations themselves; in other words, by the noise that comes with the signal.

Summing Up

The deepest implication of all this is the question of *causality*. All physical measurement is based on the implicit expectation that, if precisely controlled and identically repeated, every sequence of events should run the selfsame course. And yet it has become apparent that on the scale of atomistic events nature itself does not know, and that it is *in principle* impossible to tie together precise conjugate values of individual systems. Therein, then, lies the ultimate limitation of all observation; there always remain, in fact, questions for which precise answers do not exist.

About the Authors

J. W. Wallace served as an electronics technician on Navy destroyers in the Pacific in World War II. He attended Case Institute of Technology after the war, graduating in 1951 with a BSEE. He joined Westinghouse on the graduate student course, but then was called back into the Navy for 16 months during the Korean conflict. Returning to civilian life, he completed the graduate course and was assigned to the control division in Buffalo. There, he contributed to the development and application of industrial regulating and control systems, including automatic gauge- and tension-control systems. He was assigned primary responsibility for automatic gauge control in 1957, a responsibility he retained on his transfer to the metal-working section, industry engineering, in 1961. This group is now the Metals Province, Industrial Systems, and Wallace is a special project engineer in it.

Paul H. Jeynes and *Clarence J. Baldwin* are coauthoring the second of a series of articles on engineering economics in this issue. Jeynes, with Public Service Electric and Gas Company of New Jersey, and Baldwin, with Westinghouse, have worked together in this field since 1958.

Jeynes graduated from Sheffield Scientific School in 1918 with a PhB degree, and from Yale Graduate School in 1920 with an ME degree. He started with Public Service as a cadet engineer in 1920. He has held assignments in both the engineering and accounting departments, and was involved in many phases of engineering economics. His work led to his appointment to the position of Engineering Economist for the company in 1957, the position he held until his retirement in September 1963.

Baldwin is a graduate of the University of Texas (MS in EE) and holds a professional EE degree from MIT. Shortly before the first article in this series appeared (Jan. 1964), Baldwin moved from Manager of the Generation Section of the Electric Utility Engineering Department to Manager of the Advanced Development Section. The new job includes his previous responsibilities for development in power system generation plus new assignments in power system transmission and distribution development.

R. F. Woll graduated from the University of Pittsburgh in 1937 with a BS degree in electrical engineering. He joined the Westinghouse motor division in East Pittsburgh as a tester and in 1939 became an ac motor designer in the industrial motor engineering department. Woll's primary interests have been in design and development of ac motors ever since. He moved to Buffalo when the Motor and Gearing Division was established there, and he carried the primary design responsibility for the Life-Line A motor line introduced in 1953. He is now a Fellow Engineer in the ac development section, medium motor product line, with design responsibility for new ac motors.

Drs. R. E. Fox, M. Garbuny, and *R. Hooke* are the contributing authors to *THE SCIENCE OF SCIENCE*, the first volume of the new *Westinghouse Search Books* series. The article on fundamental noise, which appears in this issue, is based on selections from this new book.

Dr. Fox obtained his BS degree from Hampden-Sydney College (1938), and his MS and PhD in Physics from the University of Virginia. Much of his work during his 20 years at the Westinghouse Research Laboratories has dealt with basic studies of ionization processes by electrons in atoms and molecules. This work has included development of mass spectrometers for analytical purposes. During World War II, Dr. Fox worked in this field on the Manhattan Project. He is presently Manager of the Physics Department.

Dr. Garbuny received his Dipl. Ing. and Dr. Ing. at the Institute of Technology, Berlin. His experience at the Westinghouse Research Laboratories includes research on various phenomena in atomic physics and spectroscopy, the development of microwave and radio-frequency devices, and research and development in the area of infrared detection and imaging devices. He was Manager of the Optical Physics Section from 1952 until 1960. He is now a Consulting Physicist, responsible for special programs in the area of optical physics and thin-film superconductivity.

Dr. Hooke obtained his BA and MA degrees from the University of North Carolina (1938 and 1939) and his PhD from Princeton University (1942). Prior to joining Westinghouse, Dr. Hooke taught mathematics at North Carolina State College and University of the South (Sewanee), did operations research for the Navy, and carried on research in statistics and in military problems at Princeton.

He came to the Westinghouse Research Laboratories in 1955. Dr. Hooke was manager of the statistics section from 1956 until 1963, where he did the original mathematical work on the Opcon optimizing control, helped develop a new method of numerical analysis called "direct search," and participated as a consultant in experimental design in a number of programs. Dr. Hooke was recently appointed Manager of the Mathematics Department.

This 350-ton-a-day continuous pulp digester at the Demopolis, Alabama plant of the Gulf States Paper Corporation was placed under direct control of a Westinghouse Prodac 580 computer system in late 1963, making it the first closed-loop, on-line computer system in the pulp and paper industry.