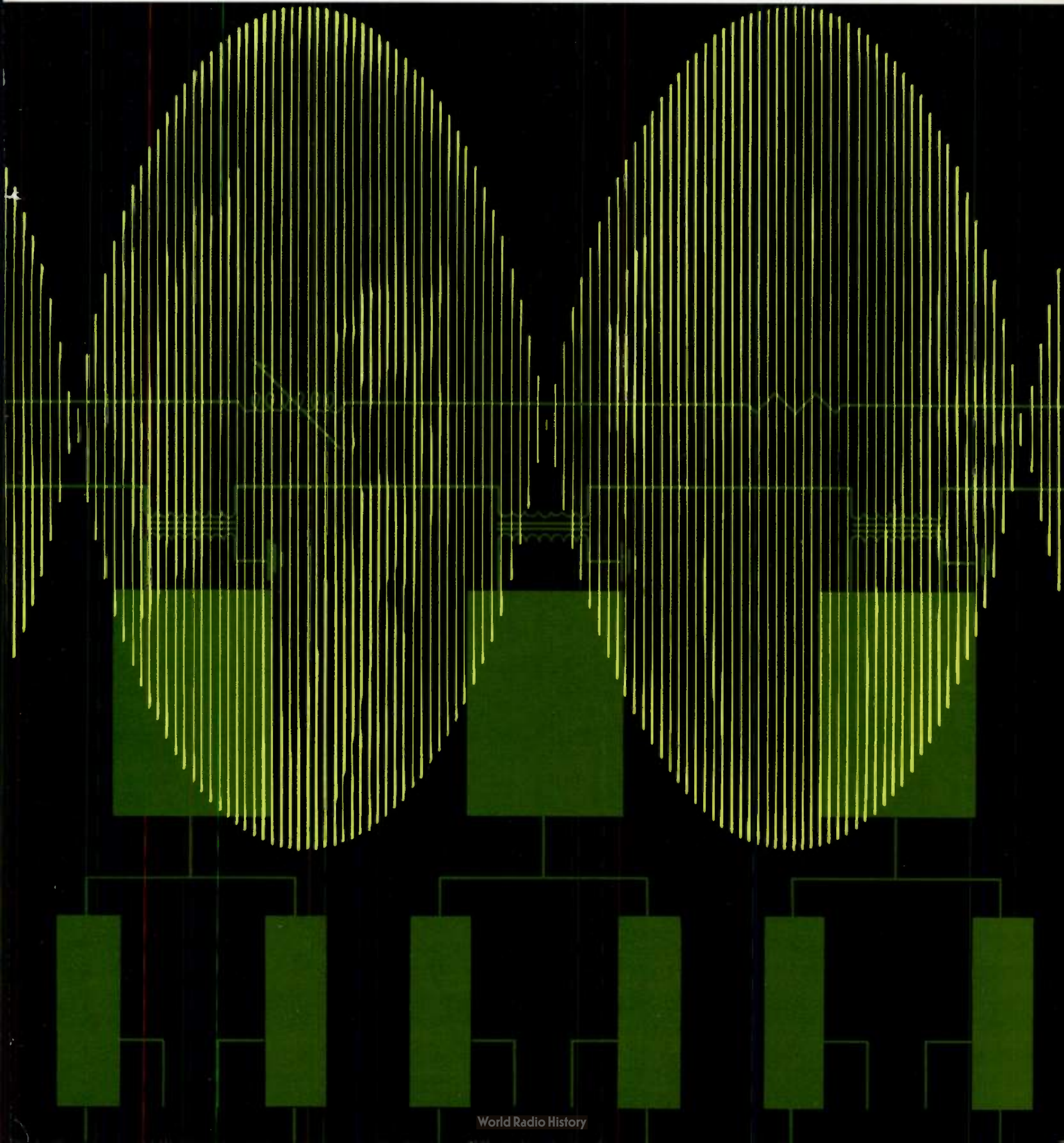
Westinghouse ENGINEER
September 1967



TV Pictures on a Laser Beam

The light modulator being demonstrated in the photograph is a new type that can handle frequencies up to 100 megacycles per second with an applied signal voltage of only 450 volts maximum, about one-seventh of the usual signal requirement in optical modulators. By using it to modulate a beam of light from a laser, its developers at the Westinghouse New Products Division have demonstrated its capabilities for applying the laser beam as a carrier of color television signals.

Laser beams have possibilities for large-scale mass communications in areas that run out of radio-frequency bands for all of their television, radio, mobile broadcasting, ham, and other kinds of electronic communications. In the visible portion of the electromagnetic spectrum, frequencies are so high that a single color, say yellow, has room for 10 million television channels. Another characteristic, the great directivity of a laser beam, could be exploited for long-distance communication in space.

Light from the helium-neon gas laser used in the demonstration is first passed through a polarizer that passes only light vibrating in one plane. It then goes to the modulator (the black cylinder at lower center in the photograph), which consists essentially of two transparent crystals through which the beam passes. The light beam then strikes a second polarizer that transmits only waves polarized at right angles to those passed by the first polarizer.

When no voltage is applied to the modulator, the laser beam passes through it unchanged, but is blocked by the second polarizer. However, when a voltage is applied to the modulator, the laser beam is rotated, allowing some light to pass through the second polarizer. If rotated 90 degrees, the full intensity comes through. Thus, fluctuating TV voltage signals applied to the modulator are impressed on the laser beam as fluctuations in brightness. The modulated beam strikes an optical detector that converts it to electrical signals for display as color pictures on a TV receiver.

The modulator is three inches in diameter, four inches long, and weighs about two pounds. Its transmission efficiency is 90 percent, and it is independent of temperature.

Westinghouse ENGINEER
September 1967, Volume 27, Number 5

New Concepts in VLF/LF Communications:

Editor
M. M. Matthews

Assistant Editor
Oliver A. Nelson

Design and Production
N. Robert Scott

Editorial Advisors
G. C. Hurlbert
T. P. Jones
Dale McFeatters
W. E. Shoupp
Robert L. Wells

Subscriptions: United States and possessions, $2.50 per year; all other countries, $3.00 per year. Single copies, 50¢ each.

Mailing address: Westinghouse ENGINEER,
P. O. Box 2278, 3 Gateway Center,
Pittsburgh, Pennsylvania 15230.

Published bimonthly by the Westinghouse Electric Corporation, Pittsburgh, Pennsylvania. Printed in the United States by The Lakeside Press, Lancaster, Pennsylvania. Reproductions of the magazine by years are available on positive microfilm from University Microfilms, Inc., 300 North Zeeb Road, Ann Arbor, Michigan 48106.

The following terms, which appear in this issue, are trademarks of the Westinghouse Electric Corporation and its subsidiaries:
Prodac; Kovar.

Cover design: Recent developments in solid-state circuitry and devices have made practicable high-power radio-frequency generation, symbolized on this month's cover by artist Tom Ruddy. Some of these developments are described in the three-article series that follows.

New Concepts in VLF/LF Communications

Although very low frequency (3–30 kilohertz) and low frequency (30–300 kilohertz) bands have been seemingly eclipsed by accomplishments at the high end of the radio spectrum, the use of VLF/LF for communications is now increasing. Low-frequency radiation is unique in that the ground wave travels long distances around the surface of the earth, making performance relatively independent of ionospheric conditions; this characteristic makes low frequencies particularly appropriate for communications or navigation channels that must operate over long distances without fade. Developments in solid-state technology that are particularly applicable to low-frequency equipment have provided improvements in reliability and performance, making VLF/LF communications even more desirable than ever.

Solid-State Equipment Improves Mission Reliability

Nelson B. Tharp

Communications links between the command centers and the major weapons forces in modern defense systems must be capable of operating without failure, even under the most severe environmental conditions. To provide such reliability, the Westinghouse Surface Division developed basic concepts for a "survivable" communications link; under contract to the military services, these concepts have been transformed into operational equipment. The transmitter and receiver designs that have resulted provide unequaled reliability in communications equipment.

Newly developed design techniques for radio transmitters include modular redundancy (the use of many modular elements operating in parallel) and exclusive use of solid-state active elements to minimize component failures. These techniques, although basic in principle, have provided a technological breakthrough in communications equipment performance. Moreover, they will have a profound effect on future transmitter and receiver reliability requirements, and on the design approaches necessary to achieve this reliability.

Molecular Circuits in Receivers

In low-power receiving equipment, the integrated molecular circuit has made possible the major improvement in reliability. Part of this improvement results from the fact that integrated molecular circuits inherently outlast circuits built with vacuum tubes—or transistors—and discrete circuit components (individual resistors, capacitors, etc.). Another advantage is that less heat is generated in the minute molecular circuit, creating a more favorable environment for long life in other electrical components.

The improvements possible with integrated molecular circuits can be demonstrated with the bistable (flip-flop) circuit shown in Fig. 1. If built with high-quality vacuum tubes, this circuit should have a random-failure rate of about 585 failures per 100 million hours of operation (calculated from prediction formulas used in current military specifications); built with interconnected transistors and other components, the failure rate is reduced to 36 failures per 100 million hours; the equivalent integrated-circuit package has a predicted failure rate of only 5 failures per 100 million hours.

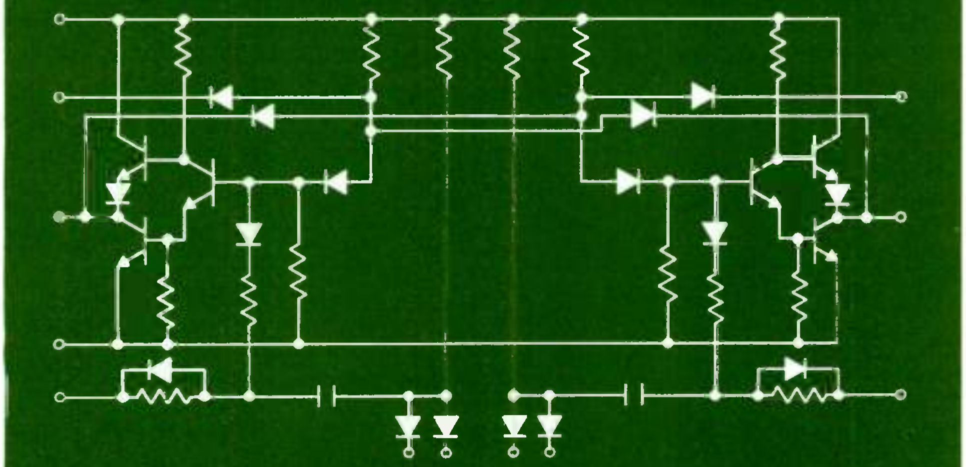
Another important improvement in reliability made possible by molecular devices can be attributed to their small volume, weight, and cost. A board mounting 15 typical molecular circuit units is shown in Fig. 2. Each molecular circuit unit (WS 294), although only 0.32 inch in diameter and 0.18 inch thick, contains the equivalent of all the circuit elements shown in Fig. 1—14 resistors, 14 diodes, 2 capacitors, 6 transistors, and 58 interconnections. With standard components, this circuit would require approximately 50 times the volume, weight, and input power of the molecular unit.

Because of this saving in volume and weight, many integrated circuits can be used to fashion redundant fail-safe arrangements so that each particular function in an equipment can have, in effect, built-in spares. This redundancy technique greatly extends equipment operating life, as expressed in hours of mean time between failure (MTBF)—in most electronic equipment, the reciprocal of failure rate. And since production cost with molecular circuitry is substantially lower than the total cost of an equivalent assembly of discrete components, improved reliability can be achieved for a reasonable cost. Also, with higher equipment reliability, a further saving results from the lower spare-part complement required.

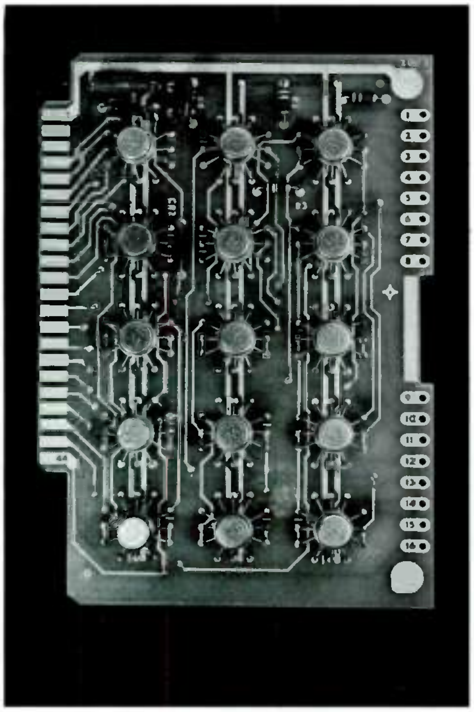
Another significant development made possible by the small volume, weight, and cost of molecular circuitry is more effective signal processing. In the last 20 years, the development of information theory has revealed that, with proper signal processing, a communications channel can be made to carry more intelligence over longer distances and work through higher levels of interference. However, with conventional components, the increased bulk and cost of building the necessary processing circuitry usually makes such signal processing economically infeasible; furthermore, with conventional components, the additional circuitry causes a loss in equipment reliability that soon offsets the gains in transmission reliability due to signal processing. On the other hand, molecular circuitry now makes these signal-processing techniques practicable—with regard to size, cost, and reliability. In fact, the increase in channel capacity and improved reliability, both resulting from the more effective signal processing that can now be

---

N. B. Tharp is Manager of Programs Development Engineering, DECO Communications Department, Westinghouse Defense and Space Center, Baltimore, Maryland.



1—Equivalent circuit diagram for bistable (flip-flop) integrated molecular circuit.



2—The use of integrated circuits with this typical board mounting reduces volume, weight, and power requirements by a factor of 50 over discrete component construction.

3—This demodulator chassis for an ultrareliable low-frequency receiver contains 439 integrated molecular units, the equivalent of more than 11,000 discrete components.

provided in a practical manner, is proving to be a really significant contribution of molecular circuitry to the communications art.

An example in which integrated molecular circuitry is used to obtain extremely high MTBF performance is a low-frequency receiver built by Westinghouse. The receiver is designed to take advantage of the techniques described, and it achieves a reliability that is at least ten times better than can be obtained with conventional techniques. Whereas an MTBF of 1500 hours might be considered high in a current design of a high-quality receiver, this new low-frequency receiver has demonstrated an MTBF well over 15,000 hours. This high reliability creates the interesting problem of how to test equipment and determine MTBF without running equipment for years. For practical purposes, many units are operated simultaneously to accumulate operating time. For example, reliability was demonstrated for this receiver by running 20 units for six weeks without a failure.

A typical chassis of such a receiver is shown in Fig. 3. This unit contains 439 integrated molecular units, the equivalent of over 11,000 discrete components and 23,000 interconnections; yet the volume of the receiver is less than one cubic foot and its input power requirements are less than 100 watts.

Solid-State Transmitters

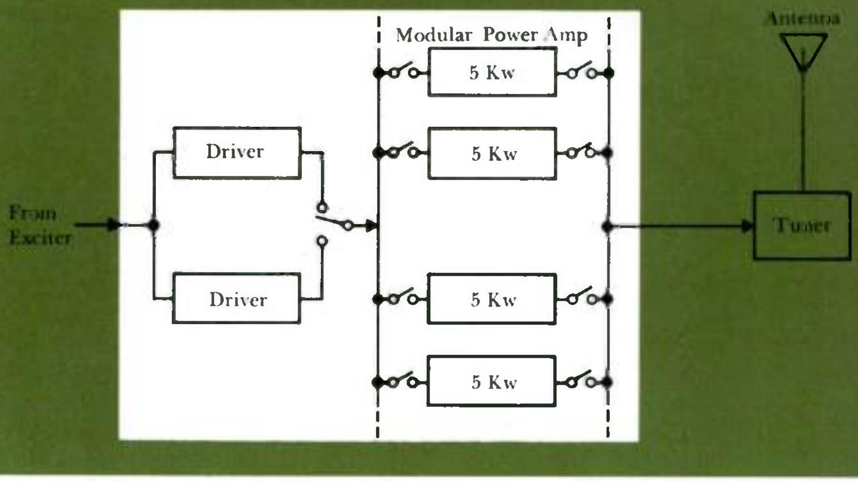
The need for reliability is particularly critical in transmitters because the transmitter is a common element to the entire system. Again, the goal was to achieve a major improvement over the conventional art. By going to an entirely new concept in high-power transmitter design, using all solid-state components in conjunction with extensive modularity, the reliability goal was surpassed—in fact, a new standard for transmitter reliability has been established that is from two to four times better than before.

The most significant improvement in high-power transmitter reliability comes from the use of modular design. If a particular module malfunctions, the defective unit can be quickly disconnected and the rest of the transmitter can continue to operate with only an incremental decrease in performance. This principal is illustrated in the simplified block diagram in Fig. 4, which shows how this modular principle is applied to the power amplifier. An amplifier module is automatically disconnected from both the input and output bus whenever the built-in sensor detects any substandard operation. The rest of the transmitter continues to operate with total output reduced.

A 5-kw power-amplifier module used in a high-power, low-frequency transmitter designed and built for an ultrareliable communication system is shown in Fig. 5. The transmitter is so designed that the power amplifier module or its associated power supply module can be quickly removed (both electrically and physically) from the transmitter, repaired, and replaced. Each amplifier has its own power supply module to avoid dependence on a common power source.

To reduce repair time and cost on the 5-kw amplifier, the modular principle has been carried down to an even lower level. Each 5-kw module contains 16 submodules, each with four power transistors (see Fig. 6). The submodule produces about 350 watts of r-f power. If a power transistor fails, the 5-kw module is automatically removed from the r-f output, r-f input, and power busses, and built-in fault circuitry identifies the faulted submodule. Meanwhile, the transmitter continues operating with reduced output. The faulty submodule can be quickly unplugged and replaced, and the entire 5-kw module returned to service. Such a modular arrangement materially reduces the size of individual components, so components can be handled and stored easily.

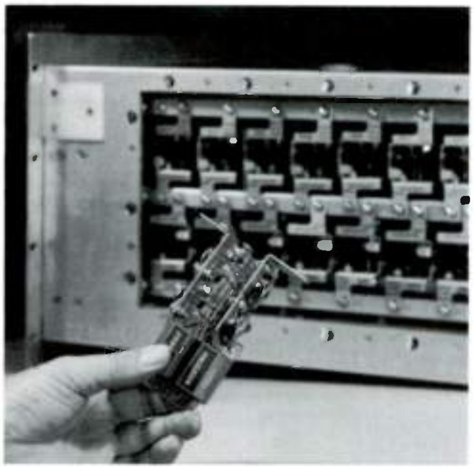
Various combinations of 5-kw modules can be used to produce a desired output



4—The modular concept is illustrated by this solid-state power amplifier. Each 5-kw module is automatically disconnected from the input and output buses for any condition of substandard operation, and the rest of the amplifier modules continue to operate.

5

6



7

5—A typical 5-kw power amplifier module designed and built for a VLF/LF communication system.

6—Each 5-kw power amplifier module (Fig. 5) consists of 16 of these submodules, each with four power transistors.

7—This ultrareliable low-frequency transmitter uses twenty-two 5-kw modules to develop 110-kw output.

power. For example, a low-frequency transmitter using twenty-two 5-kw modules produces a 110-kw output (Fig. 7); another mobile transmitter is made up of only four 5-kw modules to provide a 20-kw output. (A more complete description of the operating principles of these modules is in the article that follows.)

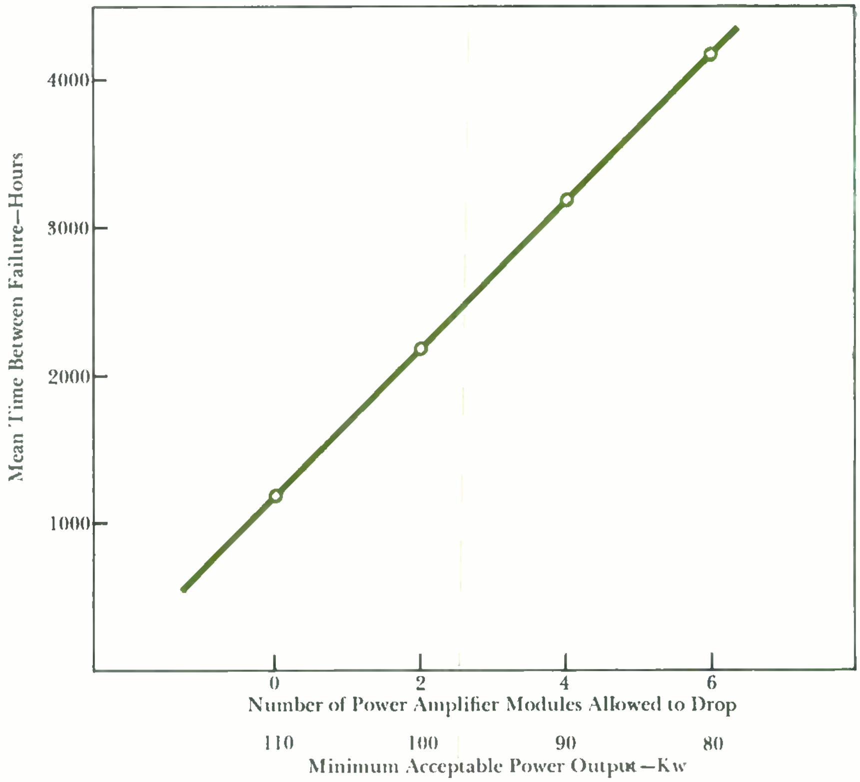
Many of the advantages of a modular transmitter with respect to improved reliability are obvious. If a component failure reduces power output by only an incremental amount (still within the acceptable level of performance) instead of reducing output to zero, the gain in reliability is significant. The benefits of this "graceful degradation" feature are illustrated in Fig. 8. MTBF's have been calculated for a 110-kw solid-state modular transmitter, allowing various numbers of power-amplifier modules to be removed from the output bus. For example, when a drop of two modules (110 to 100 kw) is allowed, the MTBF is almost doubled; proportionate increases in MTBF occur when additional module drops are permitted. If the minimum acceptable power level were 80 kilowatts, and the control circuitry designed to drop up to six modules, the MTBF would be increased from about 1200 hours to more than 4000 hours.

The MTBF figures are further enhanced when the effect of repairing faulted modules is considered. Since a faulted module can be replaced in a relatively short period (about five minutes), the MTBF of the transmitter becomes very large because the probability of additional modules failing during a five-minute repair period is almost negligible.

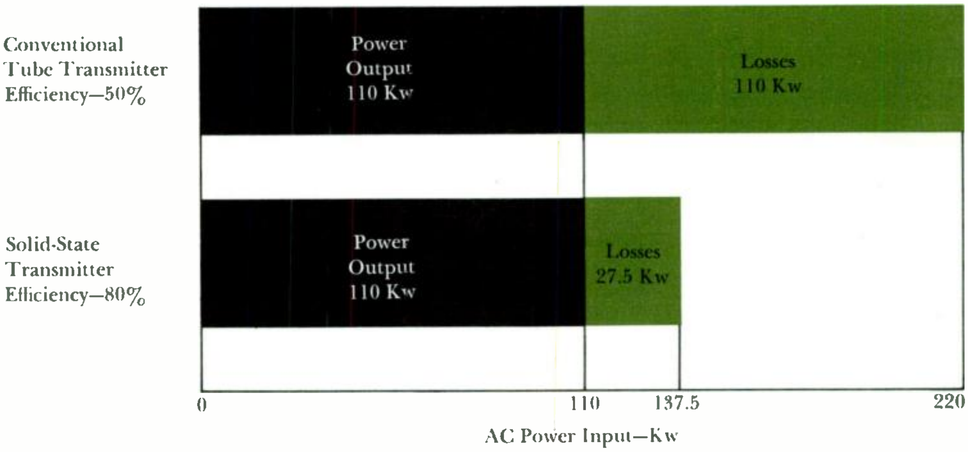
The use of solid-state devices for r-f generation has other important advantages in the high-power transmitter application. These advantages lie in the unusually high efficiency and in the reduced size and weight of the power amplifier.

Table I—Comparison of Transmitter Efficiencies

	100-Kw Transmitter		*Improvement Ratio*
	Solid-State	*Tube*	
Weight Efficiency (watts/pound)	10	5	2:1
Volume Efficiency (watts/cu ft)	300	60	5:1



8—(*Above*) The increase in mean time between failure (MTBF) for a modular transmitter is proportional to the number of modules allowed to drop.



9—(*Right*) The overall efficiency of a solid-state transmitter is about 80 percent, compared to about 50 percent for a conventional tube-type transmitter.

Although not directly a part of the reliability performance, these advantages are related to reliability and certainly are of benefit to the user.

In a radio transmitter, the overall efficiency is defined as the ratio of radio-frequency output power to total transmitter input power. The difference between input and output power is heat loss and must be removed. In high-power transmitters, heat losses should be kept to a minimum to reduce the input power costs and to avoid the complications of removing large amounts of heat.

A solid-state transmitter is particularly efficient, running over 80 percent in comparison with efficiencies of about 50 percent for conventional transmitters using filament-heated tube amplifiers. In addition to the power savings that result from eliminating the filament load, the solid-state amplifier also has low dissipation losses because of the low internal resistance of solid-state devices when used in a switching mode. In the switching mode of operation, the input signal is made to alternately open and close transistors as switches so that power gain and efficiency are dependent on transistor characteristics. Typical power gains for this mode of operation are more than 100.

The significance of high efficiency can be appreciated by comparing the losses of a conventional high-power transmitter with those for a solid-state transmitter for the same power output (Fig. 9). If input power is expensive to obtain or transmitter losses are difficult to dissipate, this increased efficiency is very desirable.

As a result of circuit simplification, reduced heat losses, and reduced insulation problems (a 110-kw solid-state transmitter uses a 240-volt dc power supply), the solid-state transmitter is significantly smaller and lighter than conventional tube designs. A comparison of volume and weight efficiency is shown in Table I. The reduction in size and weight is particularly attractive when space, weight, and fuel are at a premium, such as in mobile or underground applications.

Improved Cost Effectiveness

In both receivers and transmitters the use of solid-state techniques has made possible a major improvement in operating reliability. At the receiving end of the communications link, the small size, low input power requirements, and low cost of integrated molecular circuits have permitted processing gains in practical equipments—gains that greatly improve the efficiency of communication circuits. At the transmitting end, all solid-state designs combined with extensive use of modular design have produced a configuration capable of high reliability.

When operating reliability is significantly improved, the long-term support costs for spare parts and components, test equipment, and personnel skills are correspondingly reduced.

In addition, the improved efficiency of solid-state designs reduces input power and plant cooling requirements and thereby reduces overall operating costs.

With the increasing interest in "cost effectiveness"—minimizing total life-cycle costs rather than just initial purchase price—these new concepts for VLF/LF solid-state equipment will have a major influence on the design and procurement of the highly reliable communication systems of the future.

Digital Modulation for Solid-State Linear Amplifiers

M. L. Jones
J. R. Colgan

Although transistors have been widely applied to low-power receiving equipments, their use in transmitters for high-power r-f generation is not so well known. Recent developments have resulted in the successful application of transistors for this purpose.

High power at high efficiency is obtained by using transistors in a switching mode. Since the major power dissipative element with this arrangement is the small saturation resistance of the transistor, dc to r-f conversion efficiencies of over 95 percent are possible.

This switching mode technique has proven highly successful in a series of high-power transmitters that have been designed and tested. A typical 50-kw transmitter is shown in Fig. 1. This transmitter has ten basic amplifier drawers (Fig. 2), each with a nominal power rating of five kilowatts, operating in parallel to develop the total output. The advantages of this modular approach are discussed in the preceding article.

Linear Amplification

The various modes of modulation used to transmit information by radio frequency can be divided into two characteristic classes: constant-amplitude forms (such as frequency modulation, frequency-shift keying, and phase modulation), and those modes in which part of the information is derived from the amplitude of the r-f envelope. This latter class includes "on-off" modulation, such as continuous-wave (CW) telegraphy, and modulation in which the amplitude is constantly changing, as in single and independent sideband transmissions.

While a switching-mode amplifier is readily applicable to constant-amplitude or on-off modes of modulation, an amplifier of this type cannot directly reproduce amplitude information (linearly) without some form of external modulation. A new technique for providing this external modulation with a digital configuration has been developed.[1] This arrangement has made possible a general-purpose linear amplifier that takes advantage of the high operating efficiency of transistors operated as saturated switching elements.

Intermodulation distortion (modula-

M. L. Jones and J. R. Colgan are with the Surface Division, Westinghouse Defense and Space Center, Baltimore, Maryland.

[1] Based on original invention, "A Modulated Amplifier," by J. R. Boykin, Consulting Engineer, Westinghouse Electric Corporation.

tion of fundamentals and harmonics of two or more frequencies by each other) is inherently low in this digital linear amplifier because of the precise control of amplitude information that can be obtained with digital modulation. For example, intermodulation distortion levels of 45 db below the desired output signal are readily attainable.

Other important advantages that can be attributed to the use of solid-state components, such as higher reliability and reduced size and weight, are discussed in the preceding article.

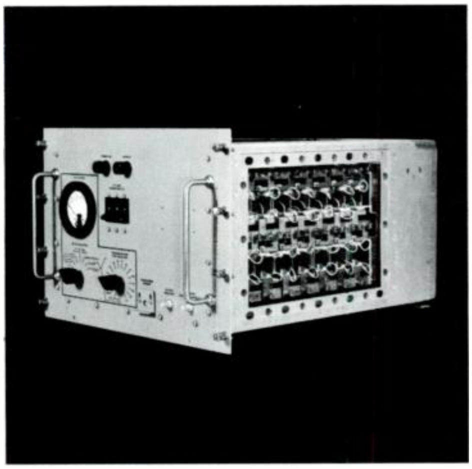
Principle of Operation

A typical switching amplifier module is shown in Fig. 3. The transistors alternately switch the output between V_{cc} and ground, producing a voltage square wave at the r-f frequency as received from the driver.

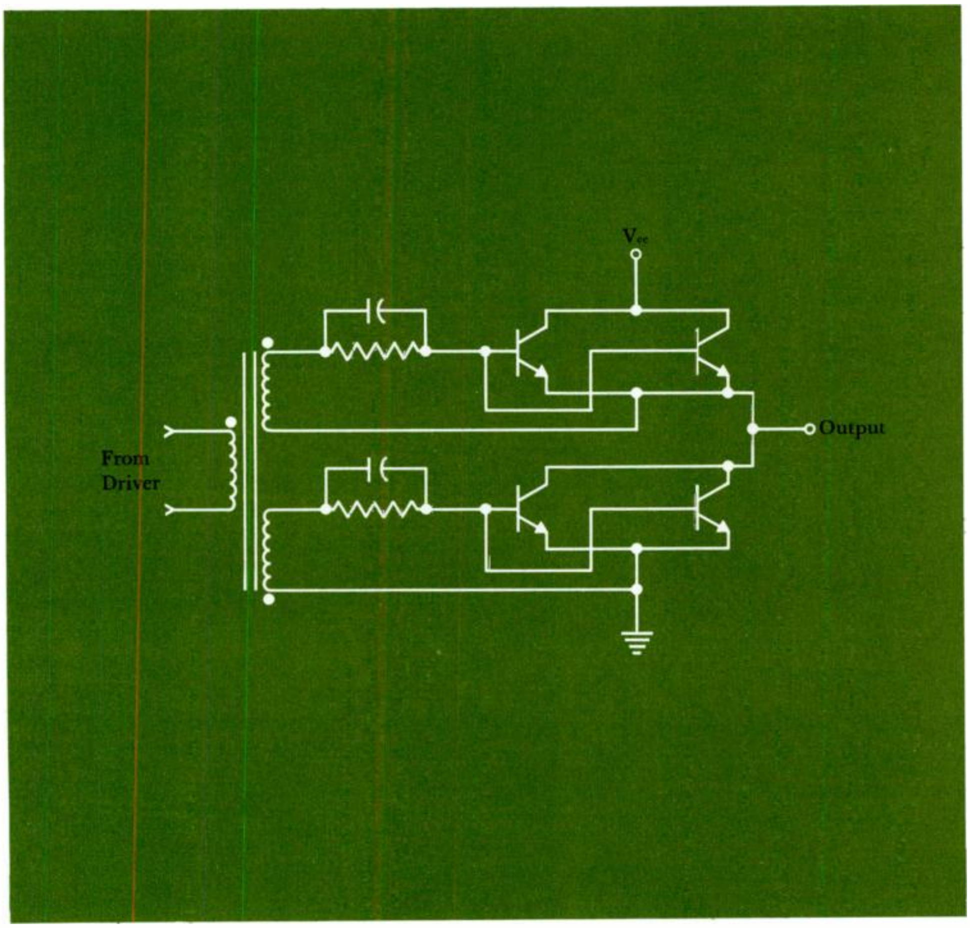
Power output is limited only by the hold-off voltage and the current-carrying ability of the transistors. Thus, with typical power transistors available today, an input driver power of about five watts to this four-transistor module can switch several kilowatts of output. Many modules can be paralleled to develop large power outputs.

A functional block diagram of a digital linear amplifier is shown in Fig. 4. The system consists of a number of separate saturating amplifiers, each of which delivers a constant-amplitude signal to a common load. The power-handling capabilities of the individual amplifiers are binarily related; that is, one amplifier is capable of supplying ½ P, another ¼ P, another ⅛ P, . . . where P is the total peak power generated by the system. The power capability of each amplifier is determined by the number of parallel modules it contains. The amplifier outputs are combined into a common load by connecting the secondary windings of the amplifier output transformer in series. The total power delivered to the load by the amplifiers in any sampled period is determined by the analog-to-digital (A/D) converter, which controls the polarity of the drive to the amplifiers. The r-f drive is supplied to each amplifier in one of two polarities, 0 degrees or

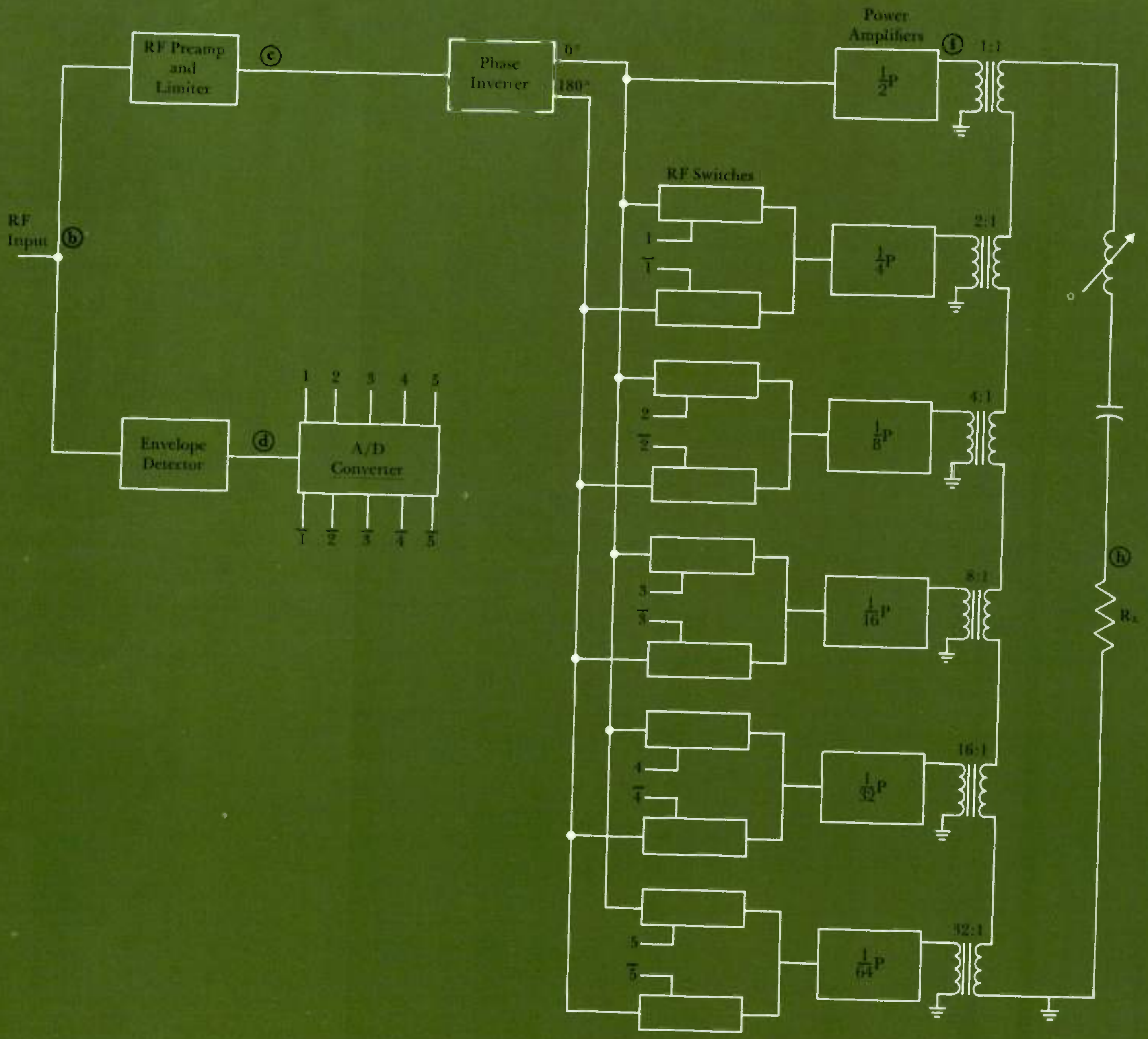
1—This 50-kw solid-state transmitter consists of ten 5-kw modules.



2—Each basic amplifier drawer develops a 5-kw output.



3—Typical four-transistor switching circuit alternately switches output between V_{cc} and ground to produce a square-wave voltage output at r-f frequency from driver.



4—Block diagram of solid-state linear digital amplifier. (Letters on diagram refer to the oscilloscope traces described in *Two-Tone Test* at right.)

180 degrees (with reference to the ½ *P* amplifier drive), as controlled by the two r-f switches that gate the input drive to each amplifier.

Operating on the detected envelope of the input signal, the A/D converter produces a digital word every sampling period. Each bit of this word controls the amplifier having the power capability proportional to the significance of the bit. The ½ *P* amplifier, however, is not controlled in this fashion, but is always driven with a 0-degree polarity drive. Therefore, the outputs of the other amplifiers are either positive or negative with respect to the ½ *P* amplifier so that the power into the load is the algebraic sum of the outputs of all amplifiers. Thus, the combination of relative amplifier output polarities reconstruct the input signal within the quantization error of the A/D converter. Since there is no limit to the number of bits that can be used, this error can be made arbitrarily small.

Those amplifiers driven in the 180-degree phase rectify the r-f power they are receiving and return it to the power supply. So that this power will not be wasted, all power amplifiers in a linear amplifier unit operate from a common power supply.

Since there are no power dissipative elements used in the digital linear amplifier, the theoretical maximum efficiency for all levels of operation is 100 percent. However, the actual d-c to r-f conversion efficiency obtained with a matching network and with practical devices, operating in the low-frequency region up to 100 khz, is 85 percent or better over about 70 percent of the power range. A comparison of the efficiencies of the digital linear amplifier and the conventional class-B linear amplifier is shown in Fig. 5.

The oscilloscope trace photographs illustrate the signal processing that takes place in a digital linear amplifier. (See *Two-Tone Test* at right.)

Operation at Higher Frequencies

To obtain optimum efficiency for wideband operation in the low-frequency region, a zero-crossing detector is used in conjunction with the A/D converter; this arrangement allows the amplifiers to

Two-Tone Test

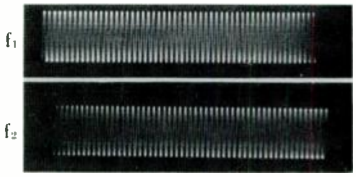
The operation of the linear digital amplifier can be described with these oscilloscope traces of a two-tone test. The input is a standard two-tone test consisting of two equal-amplitude r-f frequencies separated by 300 hz to produce a modulated envelope waveform (*b*), which is fed to the r-f preamplifier and the envelope detector (see Fig. 4). The output of the r-f preamplifier and limiter (*c*) provides an input of relatively constant amplitude to the phase inverter, which develops 0 and 180-degree polarity r-f drives for the amplifiers.

The output of the envelope detector (*d*) is fed to the A/D converter, which develops a digital word (*e*) each sampling period. The bits of this word control the r-f switches that gate the 0 or 180-degree input drive to each amplifier. Each of the power amplifiers develops a square-wave output voltage (*f*) and (because of the resonant output circuit) a sinusoidal current.

Total linear digital amplifier output to the load is the algebraic sum of the outputs of the individual power amplifiers. For the two-tone test, the output waveform (*h*) will be identical with the input.

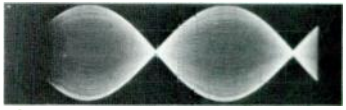
a

RF Generator Output



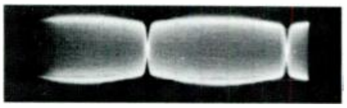
b

Two-Tone RF Input To Amplifier



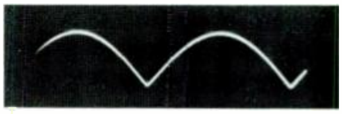
c

Amplifier—RF Limited Output



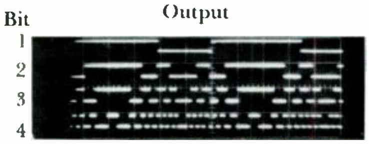
d

Amplifier—Envelope Det Output



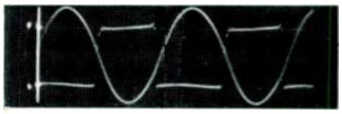
e

A/D Converter Output



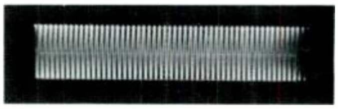
f

Typical Power Amplifier Switching Voltage and Current



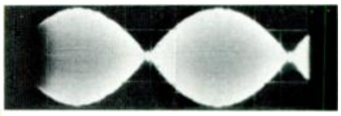
g

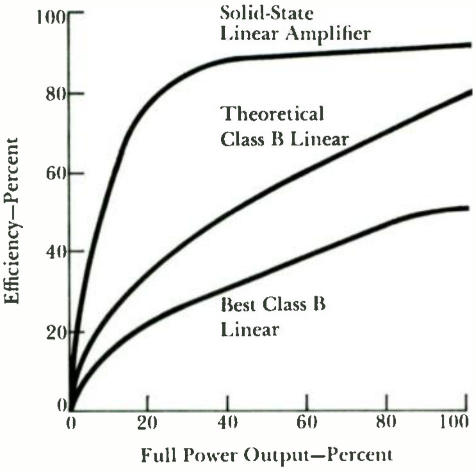
Amplifier Output Single Tone



h

Amplifier Output Two Tones





5—The efficiency of the digital linear amplifier is substantially better than that of a conventional Class B linear amplifier.

change polarity only when r-f load current is zero, thereby reducing power dissipation in the transistor.

As the number of r-f cycles per each step of modulation increases with the operating frequency, amplitude changes of other than the zero r-f crossing have less effect on the overall efficiency. When operating at frequencies in the region above 300 khz, the sampling rate is controlled by an internal clock rather than by the carrier frequency. The sampling rate is a function of bandwidth and is determined by the information to be transmitted. It is independent of carrier frequency.

The use of the digital linear amplifier for generating high power at higher frequencies is limited only by the availability of transistors with high power-handling capabilities at high frequencies. Extrapolation of present trends indicates that transistors will be available in the near future that will extend the frequency range to include at least the HF band (2-30 mhz).

In addition to the advantages of light weight, reduced size, high overall efficiency, instantaneous operation, and rugged construction normally associated with switching-mode solid-state equipment, this system has the additional advantage of performing linear amplification for essentially all modes of information transmission due to the versatility of the digital modulation technique. The solid-state linear digital amplifier is applicable where performance, low power consumption, small size, or reduced weight are criteria.

Thyristors Provide High-Power R-F Generation for VLF/LF Transmitter

G. R. Brainerd

The most recent contribution of semiconductor technology to the VLF/LF communication field is the use of the silicon controlled rectifier, or thyristor, for signal amplification in a high-power transmitter. This unusual solid-state transmitter operates in the 10 to 90 khz region, and can produce 150 kilowatts of output power at the low end of its frequency range. Transmitter efficiency (*r-f power out/dc power in*) is 86 percent, as compared to 50 to 65 percent for conventional vacuum tube transmitters.

The major goal in the development of the transmitter was to demonstrate a small, compact, but very reliable solid-state transmitter capable of developing high-power output with high efficiency—all at low cost. To this end, the thyristor has much to offer. This device, which is essentially a triggered rectifier, has been proved by years of rugged service in the power-frequency field. However, when applied at radio frequencies, it requires different circuitry and techniques to overcome the inherent difficulties that higher frequency operation introduces.

The relatively slow switching speed of the thyristor, the device's primary limitation, is circumvented with a digital technique in which thyristors are fired in sequence with precisely timed gating signals. This sequential firing arrangement is designed to provide the necessary time between successive firings so that each thyristor can recover after firing.

Thyristors Versus Transistors

In general, high-power signal amplifiers are operated Class C (or in a switching mode) for greatest efficiency. Transistors can be operated in this manner effectively, but they do not possess the high power-handling capability of the thyristor—which is designed as a high-power switch.

At low frequencies, a thyristor amplifier is also more efficient than a transistor amplifier. Two factors contribute to the thyristor's high efficiency: it is an extremely efficient power-handling device with low losses in the conducting direction; and its high output can be driven with digital signals at the 30-milliwatt level, which means an effective power-stage gain of 67 decibels (or five million times). This high gain contributes to efficiency because it eliminates the need for long chains of driver stages.

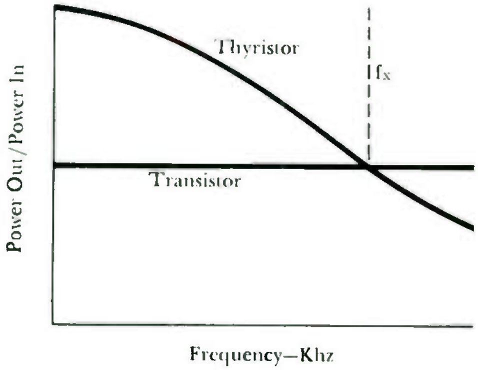
The rating of the thyristor varies inversely with frequency, whereas the rating of a transistor is constant over a wide frequency range. Thus, at higher frequencies, a transistor amplifier becomes more efficient than a thyristor amplifier. This relationship is shown in Fig. 1. The break frequency (f_x) is a function of transmitter design, but is usually about 50 khz.

Operation at frequencies below f_x with transistors may be necessary when linearity is required because the transistor performs well as a linear amplifier (Class B) whereas the thyristor does not.

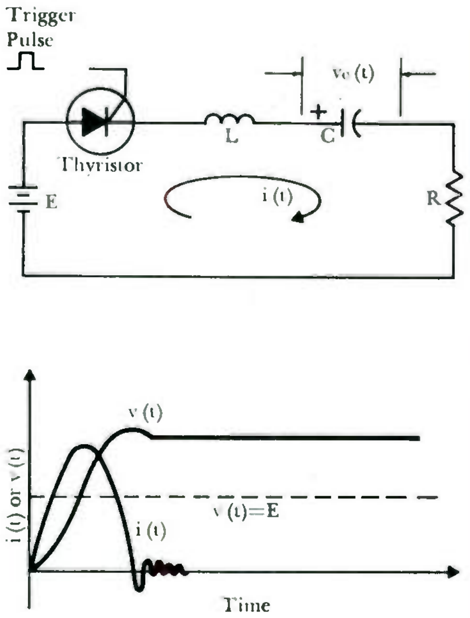
Gatling Gun Approach

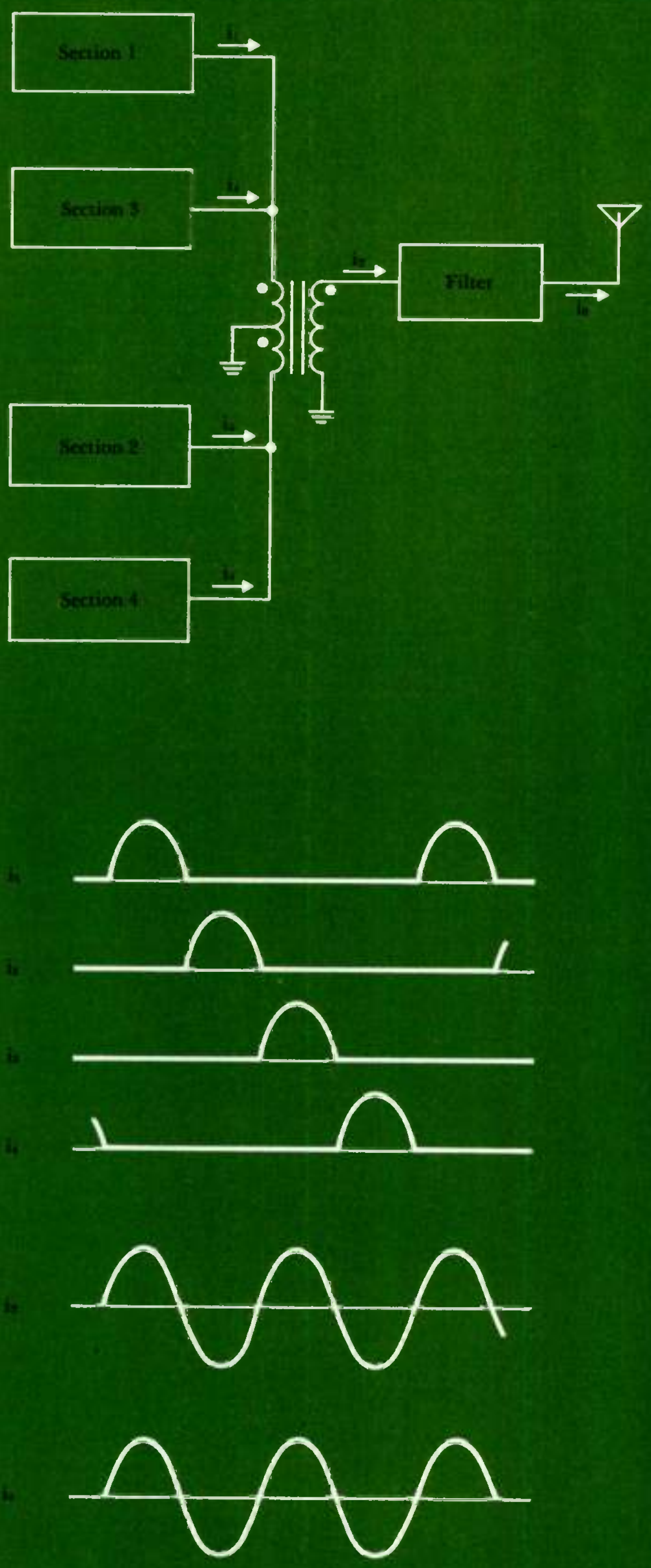
The greatest difficulty in using thyristors in the VLF/LF region is their relatively slow operating speed. Time is required for adequate turn-on, and time is required for recovery of forward blocking capability. The latter may run as high as 20 microseconds.

G. R. Brainerd is Solid-State Radar Program Manager, Surface Division, Westinghouse Defense and Space Center, Baltimore, Maryland.



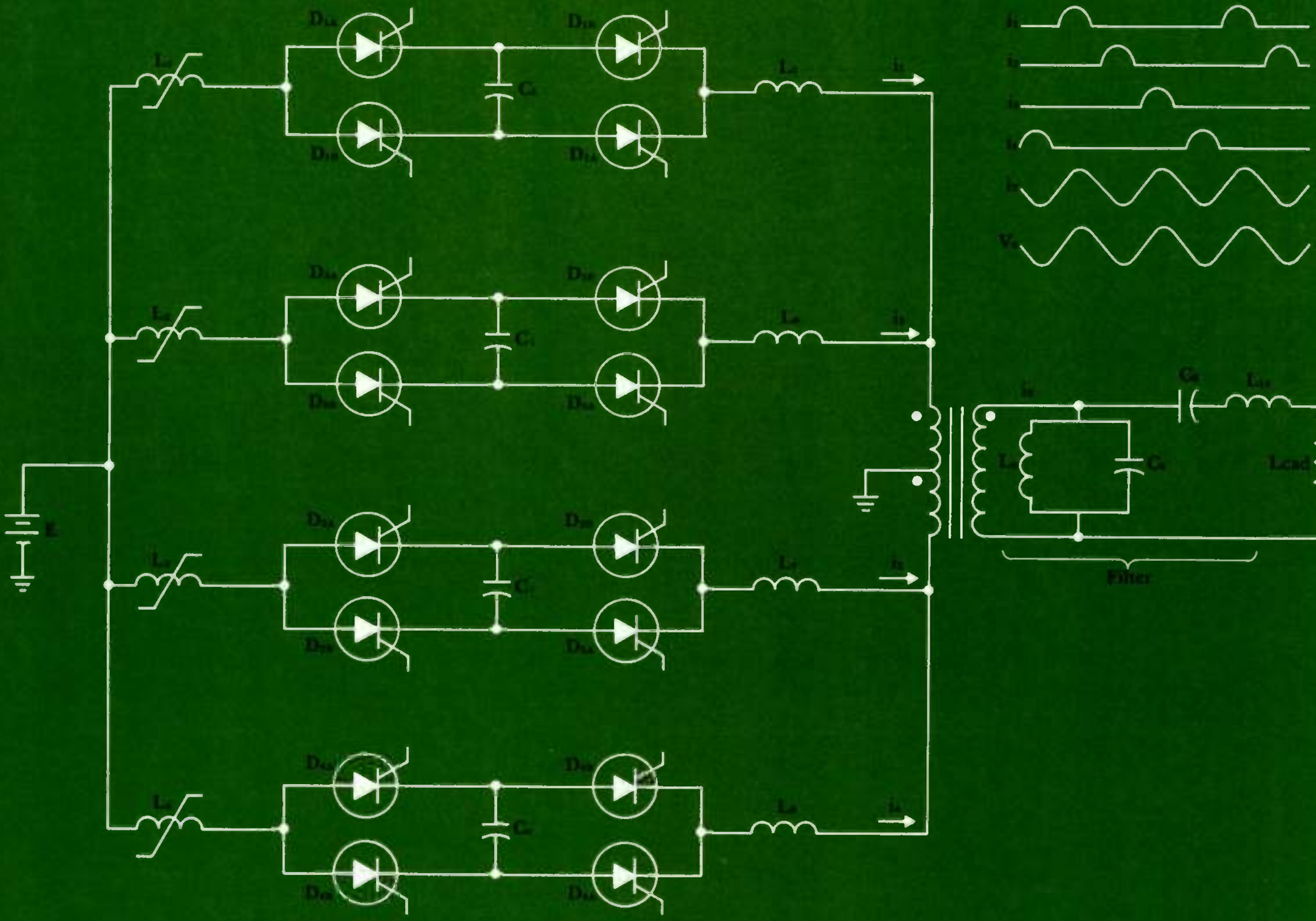
1—The efficiency of a thyristor is inversely proportional to frequency. The break frequency (f_x) depends on transmitter design, but is usually about 50 khz.



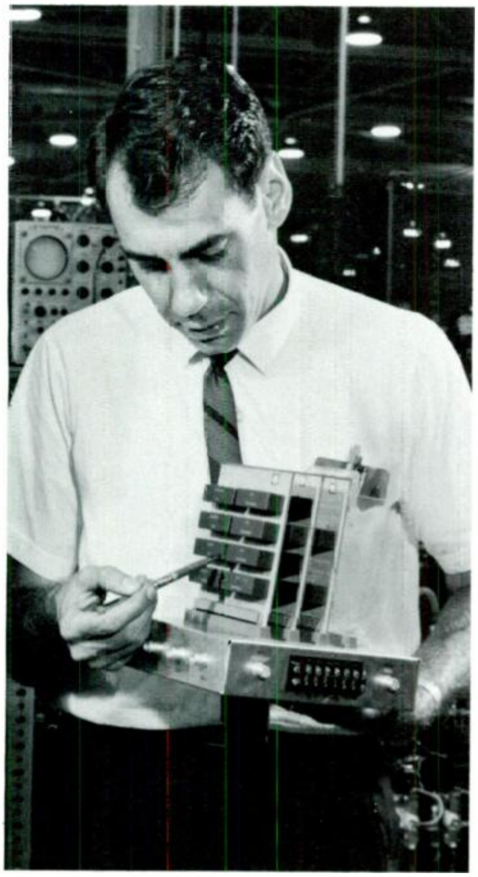


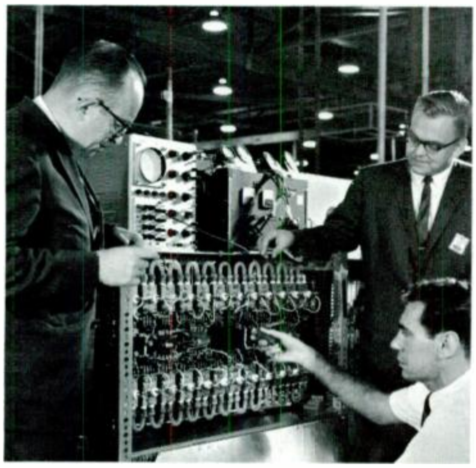
2—(*Above*) The basic concept employed for r-f generation in a thyristor transmitter is illustrated by this simplified circuit. An underdamped series resonant circuit produces an oscillatory current transient; but since the thyristor conducts only when current is positive, the resultant current waveform is a half sinewave.

3—(*Right*) Thyristor transmitter consists of four sections, fired in sequence to produce a sinewave output.



4—Each power amplifier section is shown as four thyristors; actually, each thyristor in the diagram represents six thyristors in series. To provide the sinusoidal waveform, thyristors are triggered in sequence (D_{1a}, D_{2a}, D_{3a}, D_{4a}, D_{1b}, D_{2b}, D_{3b}, D_{4b}); the centertapped transformer inverts the pulses from the two bottom sections. Saturable reactors (L_1 to L_4) protect thyristors from sudden current surges.





Top—The driver for the 150-kw thyristor transmitter is this small exciter, a solid-state logic circuit made up of digital modules.

Bottom—One power amplifier section of the thyristor transmitter contains 24 water-cooled thyristors. Four of these sections are used in the transmitter to produce an output of 150 kilowatts.

To circumvent long recovery time, thyristors are grouped into sections and these sections are operated in sequence—or fired in "Gatling gun" fashion. Each section, responding in turn to precisely timed gate signals, produces a pulse closely resembling a half sinewave. The half-sinewave shape is obtained by operating the thyristor as a switch in an underdamped series-resonant circuit; the concept is illustrated in Fig. 2. The actual circuitry of a pulse-producing section may take a variety of forms, but is basically a dc-to-ac inverter.

Each section is triggered and the outputs combined so that the composite output from all sections becomes a sinewave, as shown in Fig. 3.

Timing signals for firing the thyristor sections are derived from solid-state logic circuits. Unlike a conventional vacuum-tube or transistor transmitter, long chains of power-gain stages are not needed because of the extremely high effective power gain of the thyristor section.

A simplified schematic of a thyristor power stage is shown in Fig. 4. Each thyristor in this diagram actually represents six thyristors (Westinghouse 809M's) in series. Series operation is used to avoid the cumbersome current equalization methods that would be required with parallel operation.

Adequate turn-on time is the other major requirement of thyristors when operated at high frequencies and at high powers. During turn on, conduction begins at localized areas within the junction; full-current flow before the complete junction area begins conducting will produce high current concentrations in these small areas, which would damage the thyristor. Saturable reactors (L_1 to L_4) prevent junction damage by delaying full-current flow, thereby providing time for full-junction conduction to develop.

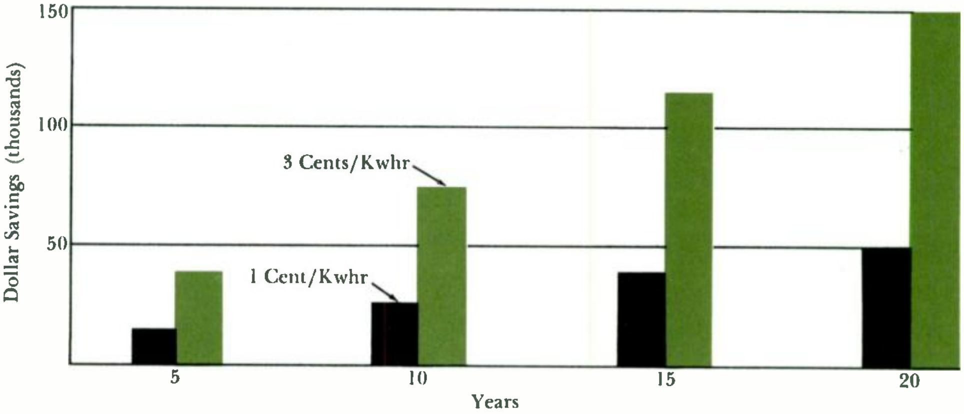
The output filter helps provide the desired waveform purity and reduces harmonics.

The thyristor transmitter was designed for a Navy communications program. It is presently on loan from the Navy to the Stanford Research Institute, and is operating in Antarctica as part of Operation Deep Freeze, the polar research and exploration program.

The transmitter has been tested and proven for applications in long distance communications and navigation. In addition to transmitting CW, the transmitter can be operated with other types of modulation, including keyed CW, frequency, phase, or amplitude modulation, and frequency-shift keying.

The thyristor transmitter offers another important benefit in addition to reliability, high power, and small size—economical operating costs. The savings for a solid-state transmitter over a vacuum-tube transmitter, for two typical power costs, are demonstrated in Fig. 5. This is an important benefit for transmitting stations located in remote areas.

5—Typical savings in operating costs for a solid-state transmitter compared to a vacuum tube transmitter.



Dynamic Control Improves BOF Steelmaking Process

N. R. Carlson
L. F. Martz

Economic operation of a BOF plant demands that the inherent speed capability of the process be utilized to the maximum by reaching the desired endpoint conditions at the end of a precalculated length of oxygen blow. The control system described here has more than doubled the frequency with which this optimum operation is achieved.

The basic oxygen process is the most revolutionary innovation in the primary steel industry since introduction of the open-hearth process because of its great speed and consequent productivity: it makes steel five to ten times faster than any other method. A new dynamic control system now increases speed and productivity still further by determining steel carbon content and temperature during the process instead of after the heat of steel is completed.

A basic oxygen furnace (usually known as a BOF but also called an LD or oxygen converter) makes steel by blowing oxygen into a molten iron bath to oxidize and remove impurities, to reduce carbon content to the desired level, and to heat the charge by these oxidation reactions. (See *The BOF Process*, page 145.)

Since there is no external heat source, it is important to thermally balance the charge by including the correct ratio of hot metal and scrap initially; ideally, this ratio results in thermochemical balance in the finished steel bath—impurities and carbon are reduced to the desired level at the same time the bath temperature arrives at the value desired for quality control.

Thermochemical balance, then, is needed for optimum product quality and productivity, but it has been difficult to achieve until now since neither the charge weight nor its exact chemistry has been accurately known. To add to the difficulty of achieving thermochemical balance, control is critical during the last few minutes of the blow because steel composition and temperature change rapidly. Such stringent demands on the operator and the control system have demanded a better technique to bring the steel in on target thermally and chemically. Moreover, the operator must maintain a tight schedule from heat to heat to realize the production capability of the BOF. With such a fast process, 10 minutes lost may mean 10 lost tons of production. Control equipment and strategy must be carefully engineered and coordinated to minimize charging time, minimize the amount of reblowing required to correct composition or temperature, and maintain control of schedules and the process.

The new control technique required has been achieved, and proved in practice, in the Westinghouse dynamic BOF control system. The system provides thermochemical balance and effective endpoint control, and it also performs the extensive control and supervision required for the cooling water flow, waste gas and dust removal, and weighing and charging of large quantities of materials in a short time.

Such a coordinated control system is extremely helpful because of the speed, number, and importance of the demands made on the operator. Since the timing for charging a specified weight of materials into the BOF vessel is critical, the operator must decide what the charge weights for hot metal, scrap, and flux will be for the next heat while the present heat is blowing. In the Westinghouse dynamic control system, a Prodac-50 programmed computer calculates these quantities for him on the basis of the hot-metal chemistry and temperature and the desired endpoint conditions (bath temperature, carbon content, and weight).

The first dynamic control system has been in successful operation for about a year at the Cleveland Works of Jones & Laughlin Steel Corporation.[1] Its use has improved the process control by more than two to one; that is, twice as many heats reach the desired endpoint temperature and carbon content without reblowing. A similar system went into successful operation this year at Granite City Steel Company, Granite City, Illinois.

Dynamic Control in Action

A Prodac-50 digital computer in the dynamic BOF control system integrates the various subsystems and makes rapid and extensive calculations to guide the process operator (Fig. 1). The computer plays a key role in each control function, acting on information from instrumentation subsystems (such as waste-gas analyzers and immersion thermocouples) and operator inputs. The system's major functions are initial charge proportioning, dynamic blowing control, ladle additive calculation, and record-keeping.

Initial Charge Proportioning—Heat specifications, each consisting of the weight, temperature, and chemistry of a heat of steel to be produced, are read into the computer from paper tape and stored in memory. The operator selects the next heat from this set of stored specifications. The first step in producing that heat of steel is to proportion the charge materials so that the heat will finish at the desired temperature, composition, and weight.

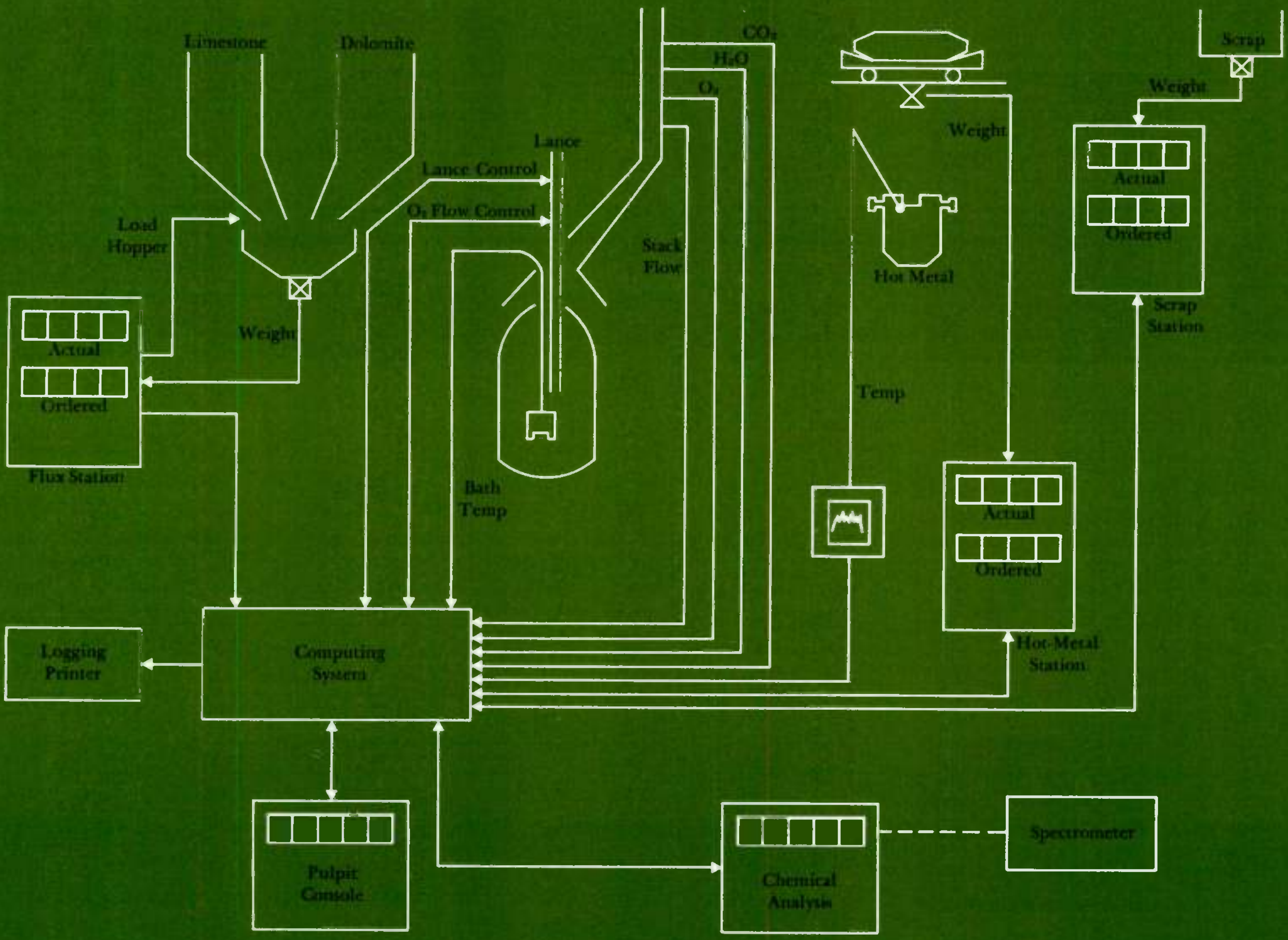
The operator sends a sample of hot metal from the submarine car to the chemistry laboratory, and then determines the temperature of the hot metal with an immersion thermocouple. Temperature and analysis are displayed for the operator, and the information is put into the computer memory along with blast-furnace cast number and the target heat weight, temperature, and chemical composition. The operator input controls are simple and require no specialized knowledge to use.

The operator then requests charge calculation, and the computer makes the calculation on the basis of the input information and its stored thermochemical model (a set of heat and material balances). The results are weights of hot metal, flux, and scrap to be charged, class of scrap if applicable, volume of oxygen to be blown, and lance operation policy. The material weights are so proportioned that the heat contained by the hot metal added to the heat produced by the steelmaking reactions will equal the desired amount of heat in the finished steel (plus

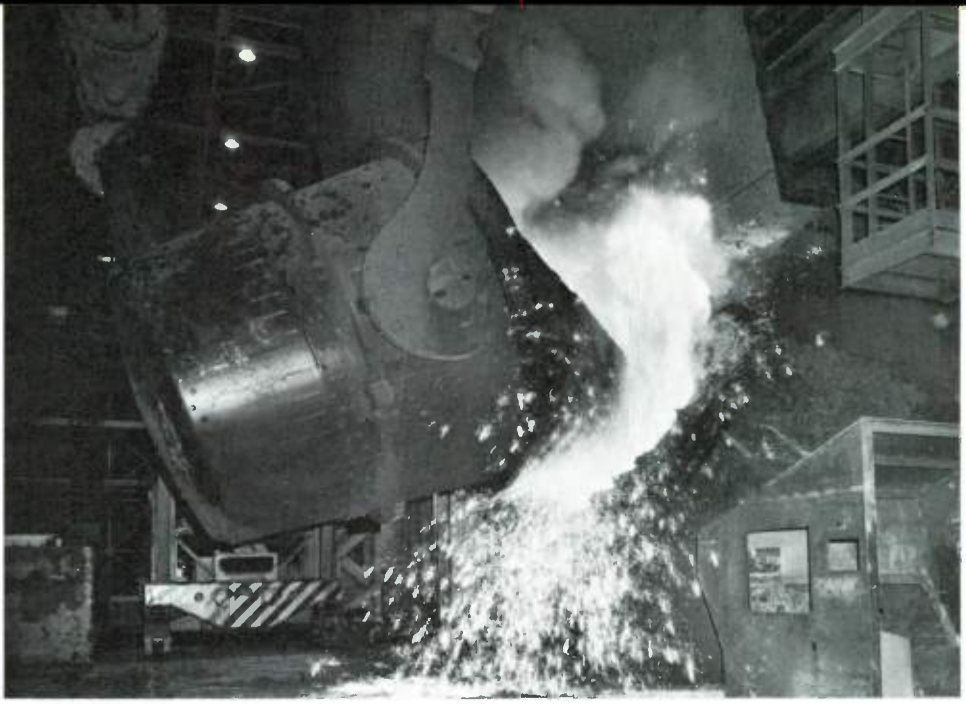
N. R. Carlson is a computer application engineer in the Computer Systems Division, Westinghouse Electric Corporation, Pittsburgh, Pennsylvania. L. F. Martz is a consulting engineer in Hagan Controls Corporation, a division of Westinghouse Electric Corporation, Pittsburgh, Pennsylvania.

---

[1] Meyer, H. W., and Glasgow, J. A., "Development and Operation of BOF Dynamic Control," *Blast Furnace and Steel Plant*, July 1966, p. 595.



1—Dynamic control system for the BOF process is based on a Prodac-50 computer that integrates the subsystems and makes key calculations. While the system is controlling a blow on the basis of oxygen flow, bath temperature, and waste-gas analysis, it is also calculating the proper proportions of charge materials for the next heat. The result is rapid and accurate operation of the process.



Molten iron is charged into a BOF steelmaking vessel, one of two 230-ton furnaces at Jones & Laughlin Steel Corporation's Cleveland Works. Scrap metal is the other main component of the vessel's charge. Scrap and hot-metal proportions are calculated by the plant's dynamic control system to provide the desired temperature and chemistry balance at the end of the blow. ***(Photos courtesy of Jones & Laughlin Steel Corporation.)***

vessel heat losses and the heat in the slag), while at the same time providing the desired ingot weight and composition. For even the simplest heat and material balance, the computations are so many and so complicated that use of a digital computer is the only practical way to perform them with the required speed and accuracy.

Results of the calculations are printed out at the main control station, and the calculated hot-metal and scrap weights are displayed for the ladle and scrap-charging operators also. Those operators admit the specified weight of scrap into a charging car and hot metal into a transfer ladle.

If the hot-metal weighman overpours or underpours by more than a preset amount, the computer notifies the operator, calculates a new scrap weight to make a thermally balanced charge, and displays that weight for the scrap weighman so he can adjust the amount. The computer records the actual weights charged and includes the information in the daily operating records.

The computer then converts calculated flux weights into digital setpoints for automatic flux batchers and displays the weights for the operator. If the weights are satisfactory to him, he pushes a button to charge the materials into a holding hopper while their weights are recorded by the computer.

With all materials now ready for rapid charging into the vessel, the sequence begins with the vessel being tilted and the scrap being dumped in. The hot-metal ladle is then brought up by the crane and the metal poured in. The vessel is returned to the upright position and the desired lance height set into the height control. The lance is automatically lowered into the vessel, and oxygen flow rate is brought up to the setpoint by the oxygen controller. Ignition occurs and refining begins. The computer automatically stores the lance height and flow rate for subsequent calculations and logging. After ignition, the fluxing materials are charged into the vessel.

Dynamic Blowing Control—During the oxygen blow, the computer periodically scans the oxygen flow rate and the lance height. At any time, the operator can demand printout of the lance height, flow rate, and total oxygen blown.

The computer also makes on-line calculations from chemical analysis and flow rate of the waste gas. From rate of removal of carbon in the initial stages of the heat and other on-line data, it determines if severe slopping (emission of molten material) will occur. If it will, the computer calculates a corrected lance height and blow rate. When the computer determines that the critical slopping period is past and the slag has formed, it calculates an adjusted lance height and blow rate for high-speed refining.

From oxygen flow rate, waste gas analysis, and stack gas volume, the computer establishes the amount of carbon being removed by a unit of oxygen—the so-called carbon removal efficiency. The value of this variable is related mathematically to the bath carbon content, and the computer uses the relationship to establish the current concentration of carbon in the steel. Because carbon-content calculations are begun well before the end of the blow, the computer is able to forecast the amount of additional oxygen required to reduce carbon content to target value.

This forecast is part of the endpoint control that the computer applies to attain target endpoint carbon content and temperature. During the critical few minutes near the end of the blow, the computer uses carbon removal rate and curve-fitting techniques to project a carbon endpoint curve (Fig. 2a). It then uses the curve to calculate the amount of additional oxygen needed to reduce the bath carbon content to target value. (The determination is independent of the initial quantity of carbon in the bath.) It displays this information to the operator, decrementing the display as the oxygen is blown.

Next the computer calculates the increase in bath temperature that will result from blowing the amount of oxygen required to reduce carbon content to target value. It then turns on a light to ask the operator to drop an immersion thermocouple into the bath. The temperature is read, displayed, and recorded by the computer.

Thermocouple temperature plus the rise in temperature calculated from the additional oxygen to be blown will be the bath temperature when the target carbon content is reached. If this projected temperature is acceptable (curve 1, Fig. 2b), the operator presses his *Accept* button and the blow continues as scheduled.

However, if temperature is off target, the computer tells the pulpit operator and recommends corrective actions. If, for example, the steel will be colder than desired when target carbon content is reached (curve 2), the computer advises blowing additional oxygen to generate additional heat, and it calculates and displays the quantity of additional oxygen needed to reach target temperature. The additional oxygen usually is blown with the lance raised five to ten inches above its normal blowing position; this tends to further oxidize the iron already in the slag rather than the carbon and iron in the bath. (But if carbon content is reduced below target value, it is easy to recarburize the steel with additions of carbocoke during tapping.)

If, on the other hand, the predicted temperature at carbon-content endpoint is too high (curve 3), the computer displays not only the amount of oxygen required to reduce carbon content to target value but also the amount of coolant limestone needed to reduce the temperature to target. The limestone is weighed out and added to the vessel during the remainder of the blow. The operator stops the blow when the display of oxygen volume remaining to be blown reaches zero.

All during the blow, the computer monitors the flow of all cooling water. If an alarm occurs on any of the variables, the operator can record the variable on a logging printer or a chart recorder, local-

The BOF Process

As in all steelmaking, the objective in the BOF process is to change the average chemical composition of the metallic furnace charge to the composition desired in the final steel. This change is effected mainly by blowing oxygen through a water-cooled lance into a molten iron bath for about 25 minutes. Oxidation removes such impurities as silicon, phosphorus, and sulfur, and it also reduces carbon content to the desired level.

A typical BOF charge consists of 66 percent hot metal, 28 percent cold scrap, and 6 percent burnt lime and spar (fluxing agents). The "hot metal" is usually basic pig iron from a blast furnace.

Scrap is charged into the BOF vessel first, in the amount calculated to prevent the temperature of the finished steel bath from exceeding the desired end temperature. Then hot metal, brought from the blast furnace in an insulated "torpedo car," is tapped into a ladle in a weighed amount and poured into the BOF vessel. The lance is lowered into the open top of the vessel to within a few feet of the bath, and oxygen under high pressure is blown through it. Carbon, impurities, and some of the iron in the bath burn in the oxygen atmosphere to begin the refining process. At this point, the flux materials are added. They form a slag that picks up the oxides not given off as gases.

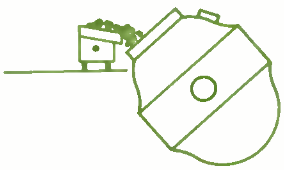
Gases and dust given off during the blow are collected by a water-cooled hood. Water sprays in a "spark box" in the exhaust system eliminate sparks and cool the hot gases. Dust is removed before the gas is vented to the atmosphere.

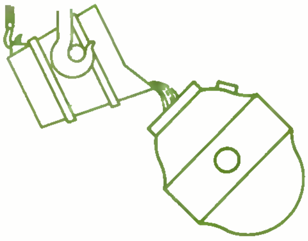
At the end of the blow, the lance is withdrawn and the vessel is tilted to pour the steel into a ladle. Various alloy materials are often added to the ladle to adjust the composition of the steel. The finished steel is then tapped from the ladle into ingot molds or into a continuous casting machine.

A typical two-vessel BOF shop may have a production capability of 2 to 2.8 million tons of steel a year. Production of this magnitude is achieved by tapping a heat of 300 tons of steel every 50 minutes of every day, 21 turns a week. Each heat requires storage and movement of perhaps 237 tons of hot metal, 102 tons of scrap, 21 tons of flux, and other charge and additive materials. Oxygen —21 tons for each blow—is manufactured and stored on the site.

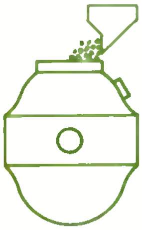
The intense heat generated by the oxidation reactions requires extensive water cooling facilities for the lance, furnace hood, and waste-gas ducts. Some six tons of dust must be removed from the waste gases during each blow.

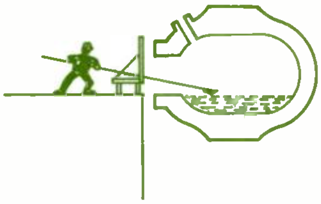
High production, rapid operation, and multiple operations have forced new concepts and facilities to emerge to control and service the BOF shop. Most modern shops have an integrated instrument and control system consisting of instruments for waste gas measurement and analysis, metal sampling equipment, temperature measuring equipment, lance height controls, and operator consoles for operation, communication, and supervision. Fault detection, alarm indication, and recording also are needed.


1. Charging Scrap

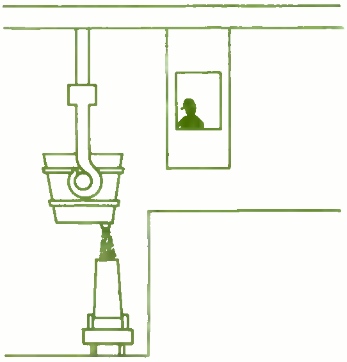

2. Charging Hot-Metal


3. Blowing with Oxygen


4. Charging Fluxes


5. Testing Steel


6. Tapping and Alloying


7. Teeming Steel

ize the difficulty, and initiate corrective action or shutdown if necessary.

At the end of the blow, the operator tilts the vessel down, takes a steel sample for carbon analysis, and measures bath temperature with an immersion thermocouple. The computer reads and records the results and displays them for the operator. If they are unsatisfactory, the operator initiates reblow calculation. The computer calculates the amount of reblow oxygen needed to bring temperature or carbon content to the desired level and prints out the amount, and the operator then initiates another blow with that amount of oxygen.

Ladle Additive Calculation—When bath temperature and analysis are satisfactory, the operator selects each additive with a switch. He then pushes a button to initiate the weight calculations for each additive needed to raise the concentrations of nonferrous elements in the steel to the desired levels. (Typical additives are ferromanganese, silicon, aluminum, ferrophosphorus, and carbocoke.) The computer makes the calculations and stores and prints out the results. The additive batches are then weighed out.

The heat of steel is poured into a teeming ladle and, at the same time, the additives are released into the ladle. The teeming ladle transports the steel to the ingot pouring aisle or to the continuous casting platform.

Computer calculation assures accuracy and consistency in ladle additions, an important advantage because of the appreciable expense of several of the additives and the possibility of missing grade specifications entirely by misuse of additives. Moreover, a certain portion of each additive is consumed by reaction with oxygen dissolved in the steel and therefore does not contribute to the final metallurgical analysis. To complicate the matter further, the fraction of an additive recovered in the final product varies with such steel characteristics as endpoint carbon content, endpoint temperature, ferrous oxide content of the slag, and the degree to which the heat is deoxidized. These variables in recovery factor are taken into account by the computer when it calculates a ladle addition; it determines the recovery value for that additive from a stored table and employs the value to calculate the required amount.

Meanwhile, the charge materials for the next heat have been readied while this one was in progress. The next cycle can begin immediately.

Record-Keeping—After each heat, the computer prints an accurate log, using a separate logger to keep the heat records from getting mixed with the information printed out on the operator's logger. The log lists all useful heat information—weights of charge materials, chemistry and temperature of hot metal, flux types and weights, volume of oxygen blown, lance practice, endpoint specifications, temperature and chemistry at end of first blow, vessel turndown reasons, corrective actions (if any) after first turndown, ladle additive weights, ladle analysis, ingot shipping information, process event times, and types of delay.

Additional information is punched on paper tape for off-line analysis. This off-line analysis is used to produce daily, weekly, and even monthly records of such things as the amount of oxygen blown per ton of steel produced, amount of refractory brick consumed per ton of steel, amount of fluxes used per ton of steel, summaries of delay types and frequencies, average tap-to-tap time, average time for tapping, and average time for charging.

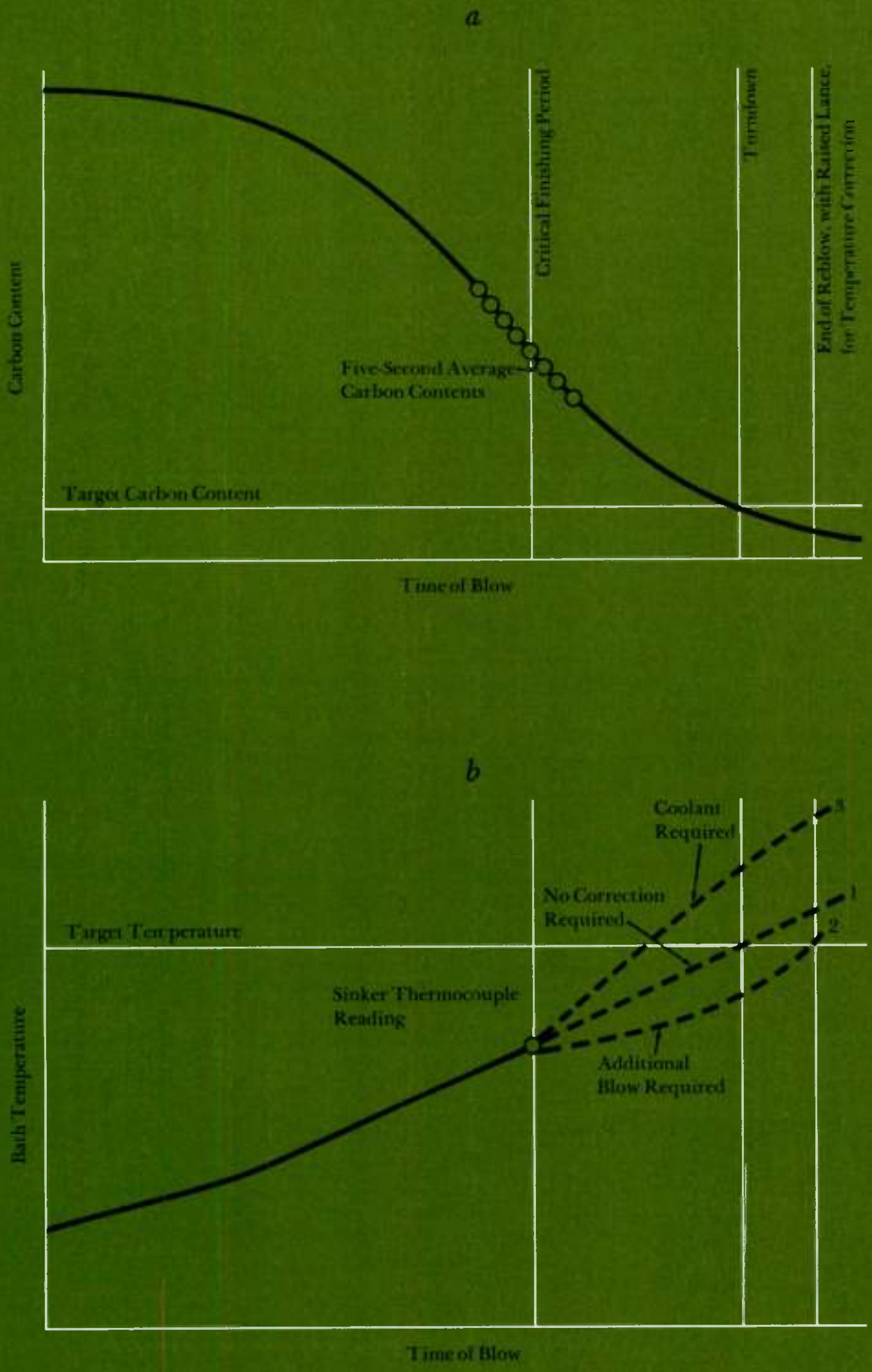
Computer production of records has several advantages over manual logging. First, much of the logged information is acquired automatically by the computer, eliminating human error and the cost of manual recording. Second, it is highly advantageous for operating management to be able to follow production on a heat-by-heat basis, because operating problems can be studied and corrected as they appear. Third, the detailed and accurate off-line summaries afford many opportunities for cost reduction because they permit analysis of time and cost items that are vitally important to the economics of the operation.

Analog Control and Instrumentation

The success of computer control depends largely on accurate instrumentation and capable analog control subsystems. The

More pyrotechnics result when oxygen is blown through a water-cooled lance lowered into the open top of the BOF vessel. By burning carbon and impurities out of the molten metal, the oxygen converts the bath to steel. Blowing time is critical because too little or too much necessitates adjustments that reduce plant productivity.

Control console in the operator's pulpit includes the control and monitoring devices that direct the charging, blowing, and other operations that produce a heat of steel. The dynamic control system enables the BOF to make steel faster, more economically, and with more uniformity.



instruments and control needed for any particular furnace depend on the philosophies and desires of the users, but a typical installation includes the basic vessel operation and control elements discussed in this section. (Those needed for material handling and measurement are beyond the scope of this article.)

For control of lance oxygen flow, a meter determines flow through the supply line and transmits a signal to an indicator, a total integrator, and a batch integrator on the pulpit panel. A flow controller uses this signal to operate a conventional flow-control valve. To initiate a blow, the operator positions the setpoint on the flow controller at the desired rate. Lance oxygen pressure is indicated in the pulpit, and pressure in the oxygen supply header is indicated and alarmed when low.

Slidewire transmitters driven from the lance drum measure lance position; the position is indicated for the operator and stored by the computer. A slidewire transmitter driven from the vessel trunnion measures vessel tilt, and an indicator displays the degree of tilt to the operator.

A remotely operated motorized valve controls inlet flow of lance cooling water, and an indicator displays the valve position to the operator. Inlet header pressure is recorded and alarmed when low, because low pressure indicates pump failure. Inlet flow and pressure are measured and recorded, and unsafe conditions are alarmed (low flow indicates throughput failure; low pressure indicates lance failure). Inlet and outlet temperatures are recorded sequentially on a multipoint recorder. High outlet temperature is alarmed because it indicates insufficient flow.

Flow of cooling water to the hood also

2—Near the end of a blow, the computer projects a curve of decreasing carbon content (*a*) and with it calculates the amount of oxygen required to reach the target carbon content. Then it calculates the increase in bath temperature that will result from blowing that amount of oxygen, and it adds the figure to the present temperature of the bath to determine endpoint temperature (*b*). If that temperature will be too high or too low, the computer recommends the type and amount of corrective action needed.

is controlled by motorized valves remotely operated from a manual station, with valve positions displayed to the operator. Pressures, flows, and temperatures are monitored, and deviations from norms cause alarms.

Spark-box sprays are arranged in several sets of four nozzles each. Two sets begin operation with the oxygen blow and continue throughout the blow, and an additional set is actuated for each 10-degree rise in temperature above 280 degrees F. Waste-gas temperature is measured just ahead of the precipitator and used to control the spray action. This temperature is recorded, along with spray flow and pressure. Low spray pressure, indicating nozzle failure, is alarmed; so is high temperature in the exhaust-gas main.

A controller for the induced-draft fan senses motor load by means of a current transformer. Its output is fed to the fan louver controller, which positions the input louvers to maintain uniform motor load irrespective of waste-gas temperature. This control prevents the fan motor from becoming overloaded when the vessel is tilted and cold air is passing through the exhaust system. The vacuum of the exhaust system is measured, recorded, and alarmed when low. (Low vacuum indicates fan failure or insufficient opening of the damper.) If there is more than one fan, each has an overload system.

A venturi section in the waste-gas stack develops a pressure differential that is transmitted to the computer. The computer calculates flow (in scfm) by extracting the square root of the differential and correcting for temperature. In addition, the waste gas is analyzed for its content of carbon dioxide, oxygen, and water and the analog signals for the concentrations of these constituents are sent to the computer.

The computer corrects the waste-gas flow reading for density and calculates the flow rate of carbon from the vessel by first changing flow to a dry-gas basis by correcting for moisture content, since carbon dioxide and oxygen analog inputs are on a dry basis. It then corrects the stack-gas volume, dry basis, for carbon dioxide infiltration into the hood and multiplies by the percent carbon dioxide concentration by volume; this result is the actual volume of carbon dioxide developed by the vessel. Carbon removal efficiency is computed continuously by dividing the volume of carbon dioxide by the input volume of oxygen to the lance.

The immersion thermocouple is an expendable cast-iron bomb. Lowered from the hood level through the oxygen-lance opening, it sinks below the slag surface of the bath. Bath temperature is recorded, displayed to the operator, and transmitted automatically to the computer.

Options

A number of control refinements can be added as options or as additions to a basic system. One is direct transmission of metal analysis to the computer from a vacuum spectrograph. Voltages corresponding to nonferrous weight percentages are read into memory through an analog-to-digital converter. The voltages also are converted to weight percentages for log printout.

Logic functions for automatic flux batching can be incorporated in the computer itself. The arrangement eliminates the need for separate batching controls.

Control of lance operation also can be given to the computer, with the operator able to override the control. The computer generates lance height and oxygen flow rate setpoints for the respective controllers.

Conclusion

The BOF dynamic control system makes complex calculations so precisely and rapidly that operators can take the correct and properly timed actions needed to assure good heats of steel in rapid succession. Its use improves control better than two to one over control based on operator decisions—more than twice as many heats reach the specifications without reblow.

Waste gases drawn off by the vessel's hood are analyzed, and the analysis is used by the computer to calculate carbon content of the bath. Results are recorded on these strip-chart recorders and also used by the computer to calculate the amount of oxygen to blow.

PAM Induction Motors—Two Speeds with One Winding

R. C. Robinson

An induction motor that combined the best characteristics of squirrel-cage and wound-rotor motors would give the user tremendous benefits. The PAM motor does not achieve this ideal, but it does offer an extremely useful compromise for many applications.

The squirrel-cage induction motor is simple, rugged, requires a minimum of maintenance, and is therefore preferred for many industrial drives. Unfortunately, it is essentially a constant-speed device, and in many processes an ability to change speed is necessary. The wound-rotor induction motor, while capable of variable speed, has the added maintenance problems of brushes and slip rings and also wastes power when run at much below synchronous speed. A useful compromise solution is provided by the PAM (*P*ole *A*mplitude *M*odulation) motor.

Pole Amplitude Modulation is a method by which an induction motor with a single winding can be made to run at two different speeds, not necessarily in the ratio of two to one. This new concept is an invention of Professor G. H. Rawcliffe of the University of Bristol, England. Westinghouse has a license to design and manufacture these motors in the U.S.A.

PAM motors are particularly suitable for driving fans, whether in power plants or in commercial heating and ventilating systems. They are also applicable to pump drives, both in power plants and in oil or slurry pipelines. In these cases, it is frequently desirable to reduce the flow below full rated capacity and this can be accomplished readily by switching the PAM motor to its lower speed. Its efficiency at the lower speed is comparable to a single-speed motor and thus much less power is wasted than by most other methods of reducing flow. As this unique motor becomes better known, many other applications should become apparent.

General Concept

The speed of an induction motor is determined only by the line frequency and the number of poles, so using a single stator winding to produce two distinct numbers of poles is quite remarkable. The pole numbers obtainable are virtually unlimited as a result of the generalization of PAM theory by Professor Rawcliffe and his colleagues at the University. The original concept was for close-ratio speed changing such as from 8 to 10 poles or from 4 to 6 poles, but the general theory now permits wide-ratio speed changing such as from 8 to 20 poles.

A typical PAM two-speed motor.

Generally, only six leads need to be brought out from the motor; the construction, including the stator coils, is standard in every respect. The unique feature, compared to a single-speed motor, is in the manner in which the stator coils are grouped and connected.

To those familiar with phase groupings used in single-speed induction motors, the PAM groupings may seem incredible. A conventional single-speed, three-phase, motor almost always has a perfectly regular and repeated grouping. With the three phases A, B, and C, and 60-degree phase belts, the sequence of coils might be:

AA -C-C BB -A-A CC -B-B . . . . .

For a PAM winding the sequence might well be:

A -B-B A -C AA -C-C-C BBB
-A-A-A-A . . . . .

Despite the appearance of complete disorder, such windings can be made to give perfect electrical balance between the three phases both in magnitude and phase angle, for both pole numbers.

The basic principle of Pole Amplitude Modulation can be grasped by recalling what happens when an alternating quantity of one frequency is modulated by a superimposed alternating quantity of another frequency. The result is two new frequencies, which are the sum and difference of the original and the modulating frequencies.

For example, visualize an ac generator operating with constant field current and producing a constant 60-cycle ac voltage at its terminals. If the field current is varied cyclically between a maximum and a minimum value at, say, two cycles per second, the output voltage will be modulated at two cycles per second. The resultant voltage will be exactly equivalent to two separate voltages of constant magnitude—one with a frequency of 58 cycles per second and the other with a frequency of 62 cycles per second.*

The heart of the PAM invention lies in applying this principle to the flux pattern in the air gap. Thus, if a 2-pole magnetic field is superimposed on, say, an 8-pole field, the result is a mixture of a 6-pole and a 10-pole field. The means of producing a superimposed 2-pole field is to reverse one half of each phase winding when switching to the second speed. Such a winding could be a two parallel star on high speed, and a series star (or delta) on low speed. In this respect it is like the familiar switching ("consequent pole") to give two speeds with a single winding, the speeds being in the ratio of two to one. Actually, the "consequent pole" winding is merely a special case of the generalized PAM concept.

In the 8-pole motor, after modulation (switching to the other speed connection), a mixture of a 6-pole and a 10-pole field was produced. This would be completely unsatisfactory, but a key part of the PAM invention makes it possible to completely remove the unwanted pole number. This

---

R. C. Robinson is a product development engineer in the Large Rotating Apparatus Division, Westinghouse Electric Corporation, East Pittsburgh, Pennsylvania.

*Mathematically, this can be expressed by the trigonometric identity:

$$\sin f_1 \sin f_2 = \tfrac{1}{2}\left[\cos(f_1 - f_2) - \cos(f_1 + f_2)\right]$$

is done by spacing the start of the B phase 120 mechanical degrees either ahead of or behind the start of the A phase, and the start of the C phase 240 mechanical degrees ahead of or behind the start of the A phase. If the B and C phases are started ahead of the A phase, the 6-pole field will disappear entirely and the result will be an 8/10-pole PAM motor. On the other hand, if the B and C phases are started behind the A phase, the 10-pole field will disappear entirely and the result will be an 8/6-pole PAM motor. The mathematical proof of these facts is in the listed references.

The reason PAM is not just a theoretically correct invention but also a practical proposition is the ease of switching the motor for the two speeds.

The connections required for a PAM motor are illustrated in Fig. 1. In either of these diagrams, low speed is obtained by connecting the line leads to *A*, *B*, and *C*. The leads, *a*, *b*, and *c*, are left open. For high speed, the line leads are connected to *a*, *b*, *c*, and the leads *A*, *B*, and *C*, are short circuited. Note that switching from one speed to the other produces a reversal of current direction in one half of each phase winding, which is the condition desired for modulation.

To switch a PAM motor, eight contacts are required compared to six contacts for the old two-speed, two-winding motor. The additional two contacts are to short circuit the leads *A*, *B*, and *C* in Fig. 1 in switching to high speed. The same eight contacts are required for the "consequent pole" 2:1 speed ratio motor.

For most applications push-button control is required. Control would therefore be accomplished by using (a) contactors, (b) switchgear (for the largest machines) or (c) a motor-operated switch.

Contactors—This method utilizes:

1) A conventional single-speed induction motor starter for low speed;

2) A five-pole motor starter for high speed (usually accomplished as in Fig. 2).

Switchgear—This method utilizes:

1) One three-pole breaker for low speed;

2) Two three-pole breakers (interlocked) for high speed.

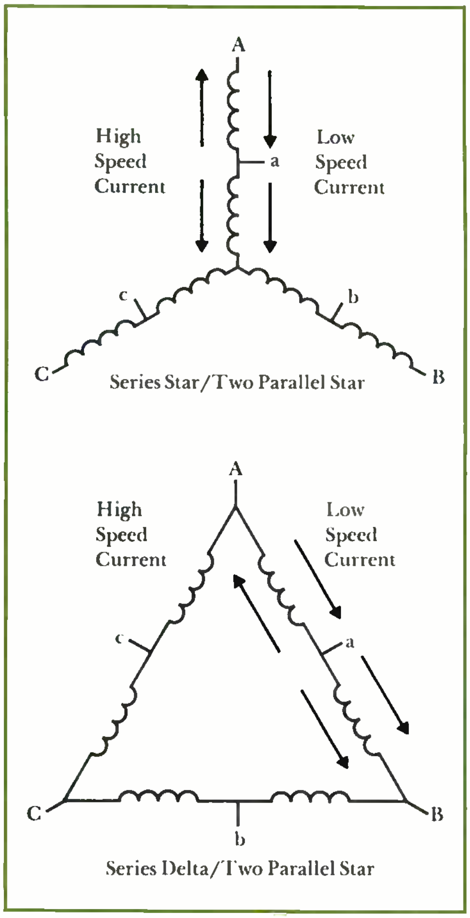
Motor-Operated Switch—This method, shown in Fig. 3, utilizes:

1) A conventional single-speed induction motor starter;

2) A five-pole double-throw motor-operated switch.

The speed change is accomplished with the PAM motor momentarily de-energized.

For infrequent changing of speeds, a manual five-pole, double-throw knife switch can be used. The connections would be similar to those of the motor-operated switch. For very infrequent changing, the terminal connections could be manually changed.



1—In the PAM motor, these connections are needed to give two speeds with a single winding. For low-speed operation, line leads are connected to *A*, *B*, and *C*, with *a*, *b*, and *c* left open. For high speed, *a*, *b*, and *c* are connected to line leads, and *A*, *B*, and *C* short circuited.

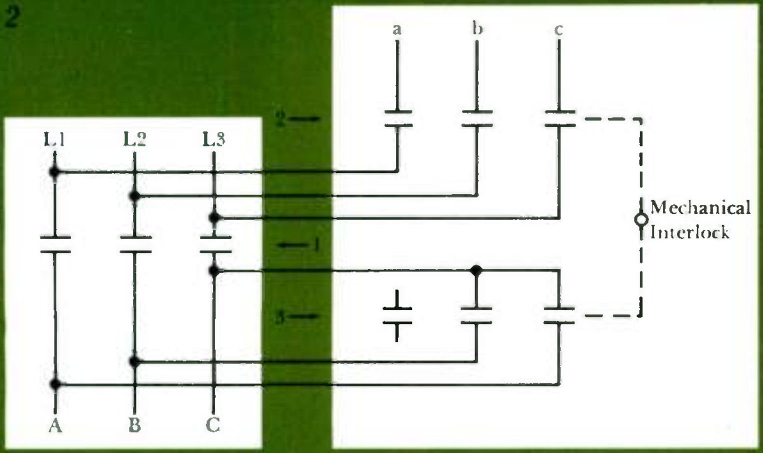
Typically, a large PAM motor will be from one half to one percent more efficient at both speeds than a two-speed, two-winding motor, and in addition, will be smaller and lighter. This is apparent from the fact that the two-winding motor uses only half of the copper at each speed while the PAM motor uses all of the copper at both speeds. For certain applications, where a few finite speed steps would be adequate, a wound-rotor motor may be replaced by a PAM squirrel-cage motor, eliminating the large loss in the secondary resistor. This may prevent a large power drain since, with a wound-rotor motor at speeds below synchronous, the secondary resistor loss is proportional to the slip. For example, if a wound-rotor motor has resistance inserted to pull its speed down to 40-percent speed, only 40 percent of the power delivered to the rotor gives mechanical power, while 60 percent of the power is lost in the resistor. Four speeds can readily be obtained by winding a squirrel-cage motor with two PAM windings, each giving two speeds.

With the irregular coil groupings used in PAM motors, it might be assumed that many harmonics would be created that could cause cusps in the speed-torque curve, low starting torque, or excessive noise. After three or four promising winding groupings are obtained for a given rating, each one is run through a special computer program, which prints out the percentage of each harmonic, including the subsynchronous (having a lower number of poles than the fundamental). The winding with the best overall performance is thus selected. In general, with careful design, the PAM motor performance can be expected to be comparable to single-speed motors and superior in some respects to two-speed, two-winding motors. These motors can be designed for variable torque, constant torque, or constant horsepower applications.

Some Applications

While PAM motors are new in the U.S.A., several hundred have been built and satisfactorily applied in England. Westinghouse has built several experimental motors and, in addition, a commercial PAM motor for driving a pump has been

2



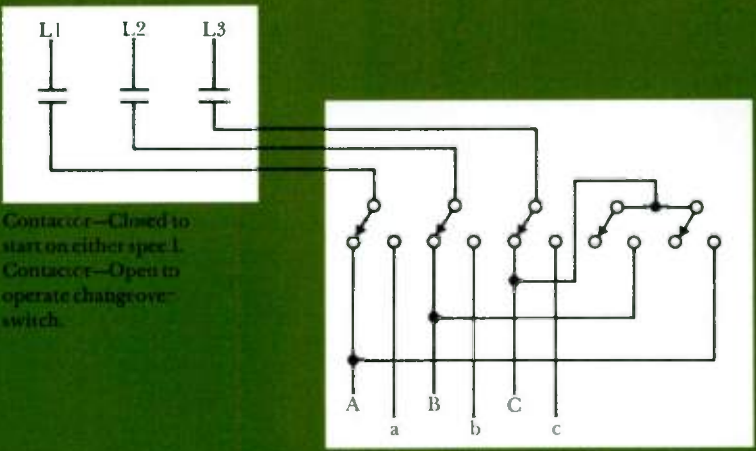
Low Speed

Contactor 1—Closed
Contactors 2, 3—Open
Give Series Delta/Star

High Speed

Contactor 1—Open
Contactors 2, 3—Closed
Gives Two Parallel Star

3



Contactor—Closed to start on either speed. Contactor—Open to operate changeover switch.

Changeover switch—contacts to the left give low-speed, series delta/star; contacts to the right give high-speed, two parallel star. Switch does not interrupt current.

2—For switching speeds with contactors, a conventional motor starter is used for low speeds, a 5-pole motor starter for high speeds.

3—Another means of switching speeds is with a motor-operated switch. This involves a conventional motor starter for low speeds, and a 5-pole, double-throw motor-operated switch for high speeds.

built and exhaustively tested. This motor is appreciably smaller and lighter and operates at a higher efficiency than a two-winding motor of the same rating. The rating is 1000/100 hp, 16/40 poles, 2300 volts, 3 phase, 60 cycles. The punchings, coils, mechanical parts, method of impregnation, etc. are all perfectly standard and the only unique feature of the PAM motor is in the grouping and connections of the coils. The test results showed very satisfactory performance and verified the calculated design values.

In manufacture at present is a PAM motor whose rating is 1200/600 hp, 8/10 poles, 2300 volts, 3 phase, 60 cycles, for driving a powerhouse fan; and in design is another PAM motor, whose rating is 500/333 hp, 4/6 poles, 4160 volts, 3 phase, 60 cycles, for driving a chemical mixing vat.

The fan application permits reduced flow to be obtained with high overall efficiency and at minimum capital cost. The use of the PAM motor for the mixing vat drive gives optimum speed for different stages of the chemical process, at high efficiency and minimum cost.

Thus the PAM motor seems a promising possibility for filling the gap between the essentially constant-speed standard squirrel-cage motor and the variable-speed wound-rotor motor.

---

[1] Rawcliffe, G. H.; Burbidge, R. F.; and Fong, W.; "Induction Motor Speed Changing by Pole Amplitude Modulation." *Proc. I.E.E.* (England) 1958.

[2] Rawcliffe, G. H. and Fong, W.; "Speed-Changing Induction Motors; Further Developments in Pole Amplitude Modulation," *ibid*, 1960.

[3] Rawcliffe, G. H. and Fong, W.; "Speed-Changing Induction Motors: Reduction of Pole-Number by Sinusoidal Pole Amplitude Modulation," *ibid* 1961.

[4] Rawcliffe, G. H. and Fong, W.; "Close Ratio Two-Speed Single Winding Induction Motors," *ibid* 1963.

[5] Fong, W.; "Wide Ratio Two-Speed Single Winding Induction Motors," *ibid* 1965.

[6] Rawcliffe, G. H. and Fong, W.; "Two-Speed Induction Motors Using Fractional Slot Windings," *ibid* 1965.

Compression Bonding Produces High-Voltage High-Current Fatigue-Free Rectifiers

Robert R. Shaw
James R. Shiring
Krishan S. Tarneja

The new Type 790 CBR (compression bonded rectifier) combines high voltage and current ratings to provide high-power rectification capability in a 10-ounce package. Compression bonding eliminates solder joints that can be a source of fatigue failures.

The advent of silicon rectifier diodes has made static conversion from ac to dc power attractive in increasing numbers of applications. Starting with low-power devices, semiconductor diodes have grown in power-handling ability until, in the Westinghouse Type 790 rectifier diode, industry now has a high-voltage high-current device that is also free from fatigue failure.

Its continuous rating of 2500 volts and 240 amperes makes the Type 790 diode among the highest in voltage rating of commercially available silicon diodes. (Users of high-voltage diodes had previously been limited to devices of 2000-volt maximum rating.) Moreover, development work is well along at the Semiconductor Division on devices with even higher ratings.

The advantages of high-power rectifier diodes include, of course, the *general* advantages of static equipment. Instead of the conventional ac-to-dc motor-generator set, for example, which requires considerable installation, maintenance, and initial cost, all that is needed is an ac generator and the static rectifier bank (or just the rectifier bank if utility power is used). These units together are much smaller, are more reliable, and require less maintenance than rotating dc generation equipment. Silicon diodes are physically rugged, can be mounted in any position, and require no elaborate cooling equipment nor stringent ambient operating temperature limits. They require no turn-on nor warm-up time, have higher system efficiency, and have a life expectancy greater than that of the original equipment in which they are installed.

One major *specific* advantage of high-voltage diodes over diodes of lower rating is the gain in system efficiency that they provide. Where high power is required, use of high voltage saves money by minimizing the sizes of conductors, heat sinks, and other circuit components in the system. Moreover, voltage of the level handled by the Type 790 diode previously required several diodes of lower rating connected in series; now one diode does the same job. One Type 790 diode, for example, can replace two series-connected 1200-volt diodes and thereby decrease power loss in the system. Its typical average-power loss in a single-phase system is about 350 watts, while loss for the two 1200-volt diodes is about 540 watts.

Besides increasing efficiency, use of only half as many diodes in a system halves the problems of reliability, cooling, mounting hardware, and cell matching (for balanced current and voltage distribution). It also reduces system weight and volume.

One of the keys to successful development of the high-voltage high-current diode is a construction technique known as compression bonding. This technique enables the device to withstand thermal cycling without failure or performance degradation from internal stresses induced by the cycling.

Why Compression Bonding

In its most elementary form, a silicon rectifier diode is a slice of single-crystal silicon that has had a *p-n* junction formed within it and electrodes attached to facilitate electrical connection. (See *Semiconductor Rectifier Diodes*, below.) But a diode of such simple construction is current-limited due to the limited amount of heat it can dissipate; the familiar "top-hat" TV diode with axial wire leads, for example, is limited to fractional-ampere ratings by its limited ability to dissipate forward-current power losses. With an external heat sink, however, the TV diode can conduct several amperes without overheating.

As *p-n* junctions of larger area were developed to handle higher current, it became necessary to solder the silicon slice to a copper stud base so it could be conveniently mounted to a heat sink. This development opened the "soft-solder era" of power devices. But, as the size of silicon junction areas grew, so also did the stresses resulting from mismatches in thermal expansion coefficients of materials. These stresses could damage the silicon during fabrication under unfavorable circumstances and degrade the electrical charac-

---

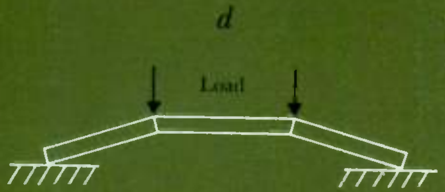
Robert R. Shaw is a design engineer at the Semiconductor Division, Westinghouse Electric Corporation, Youngwood, Pennsylvania. James R. Shiring is a manufacturing engineer there, and Krishan S. Tarneja is Manager, Rectifier Development Engineering.

Semiconductor Rectifier Diodes

A silicon semiconductor diode is essentially a solid-state junction, formed by two distinct regions within a single-crystal slice that are predominantly of opposite electrical charges. One region contains mobile negative charges (electrons) for electrical conduction and so is called the *n* side. The other region, instead of having electrons for conduction, is populated mainly by vacant atomic bonds ("holes") within the crystal lattice. For conduction, these vacancies behave like positively charged electronic particles, so the region where they predominate is termed the *p* side. The boundary between the two regions is called the *p-n* junction.

When a *p-n* junction is electrically forward biased, (i.e., when positive voltage is applied to the *p* side while negative voltage is applied to the *n* side), a relatively high current flows across the junction with low resistance loss. But when the voltage bias is reversed, the respective carriers are attracted away from the junction toward the applied voltage terminals. Extraction of the carriers, which are necessary for conduction, away from the junction results in a carrier-free or depleted region that serves as a sort of insulator, making it very difficult for electrons and holes to cross over. Essentially no current can flow, so the junction cannot conduct.

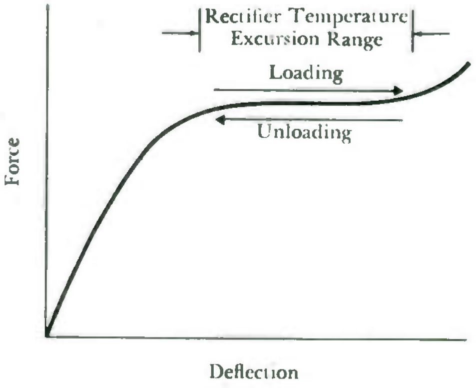
It follows, then, that when an alternating voltage bias is placed across the *p-n* junction, the crystal conducts current on the half cycle when the junction is forward biased and blocks current flow on the other half cycle. The result is rectification of the flowing current from alternating to direct. A single diode rectifies only half of an ac wave, but, by connecting diodes in bridges, a full single-phase or polyphase input can be rectified.



1—Production of a Type 799 CBR begins with diffusion of an *n*-type dopant into the surfaces of a *p*-type silicon wafer. Top surface is then lapped to remove the *n* layer there (*a*). Top and bottom contacts are attached to the wafer, edges are beveled, and a dielectric coating is applied to the edges to complete the basic diode assembly (*b*). That assembly is then fitted into the encapsulation and contact components (*c*). These components include three Belleville springs, which are dished disc springs that tend to flatten when a load is applied in the direction of the arrows (*d*). The load is applied in a press at assembly, and the components are locked in place with a retaining ring to maintain critical vertical interface pressure between contacts and basic diode assembly while still permitting lateral and vertical movement during thermal cycling.

teristics. To reduce stresses, various buffer materials were soldered as mounting discs between the silicon and the copper base; molybdenum, Kovar, tungsten, and other materials with thermal expansion coefficients nearly matching silicon were used successfully. This eliminated silicon cracking during manufacturing, and also during operation in applications that did not involve severe thermal cycling. However, large soft-solder devices are subject to fatigue failures when severe service applications call for on-and-off operation with consequent wide-ranging cyclic temperature excursions, as in electric welding machines and traction vehicles with high-torque motors.

Fatigue failure occurs mainly at the solder joint between copper base and mounting disc.[1] It is attributed to stressing the solder beyond its endurance strength (defining endurance strength as the number of thermal cycles to failure as a function of peak thermal stresses resulting from temperature reversals). Temperature excursions encountered with cyclic loads often subject the joints to plastic instead of elastic deformation, and the strain in the solder then does not leave when thermal stress is relaxed or removed. Repeated loading, even when temper-



2—Force and deflection characteristics of the Belleville spring system are such that the curve is linear until load reaches the design preload range of about 1000 pounds. Then the curve bends in a horizontal direction. Precise spring loading at assembly makes the expansions and contractions due to service temperature changes follow the near-flat portion of the curve, where force is essentially constant.

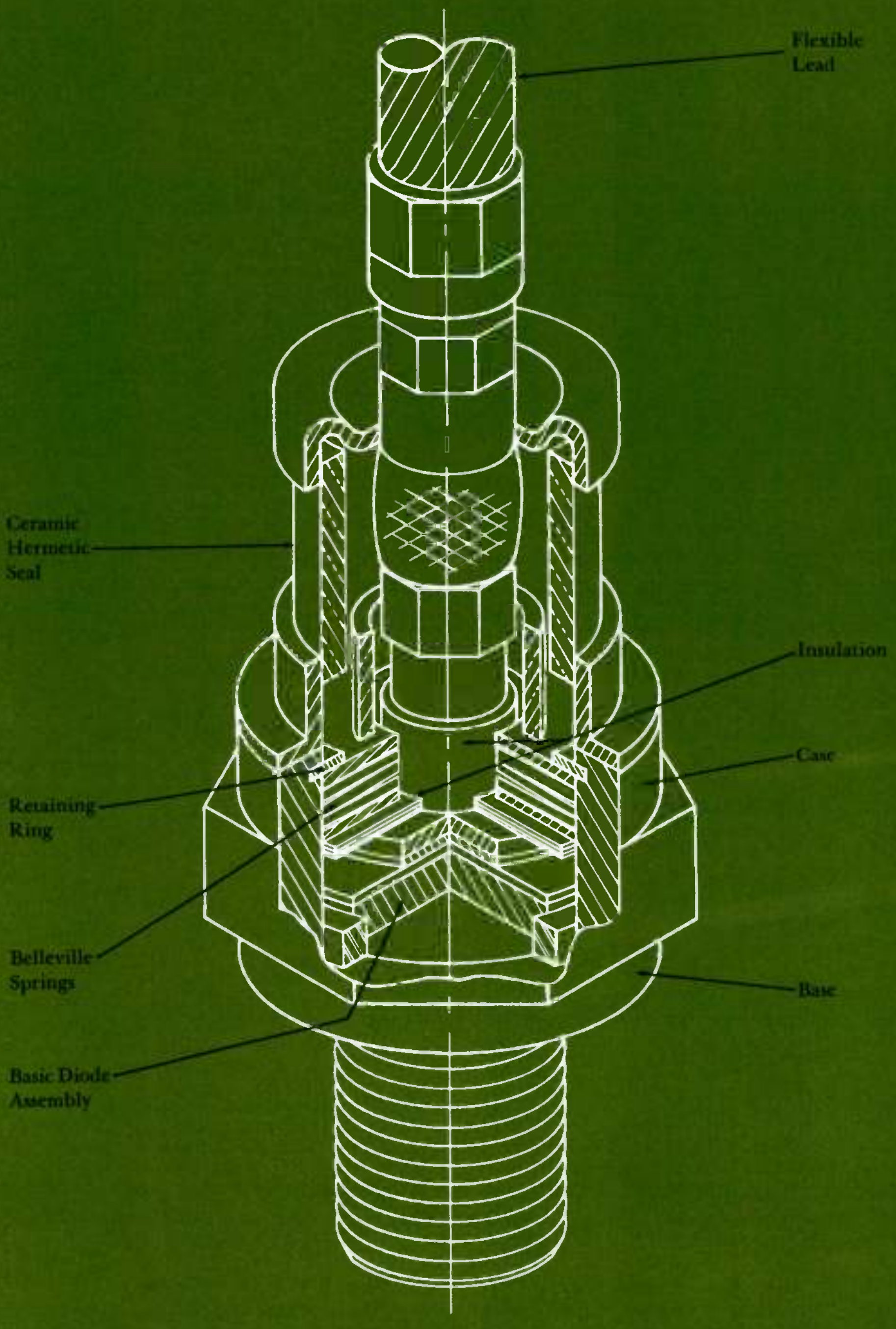
ature rises are small, causes cumulative increases in strain due to repeated changes in stress. The increasing strain soon induces fatigue cracks, which propagate slowly but tend to coalesce until large enough to initiate failure by rapid fracturing or by loss of the low-impedance thermal path to the heat sink.

As one of the earliest manufacturers of large-area devices, the Westinghouse Semiconductor Division recognized this thermal cycling limitation of high-power soft-solder diodes and removed it by substituting hard high-temperature silver-alloy solders. These solders provide diodes that perform satisfactorily under cyclic operation. However, although the joints no longer fatigue, some residual stresses remain in the diode due to differences in material expansion coefficients and to soldering temperature. These stresses, and the soldering temperature itself, limit the manufacturing yield of high-voltage soldered rectifiers.

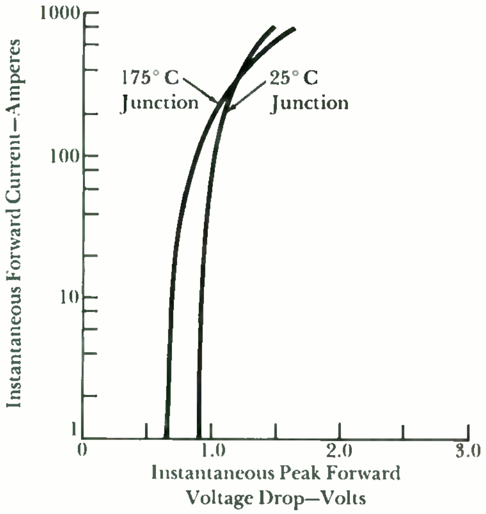
To eliminate once and for all the solder-joint effects encountered in contacting diode wafers to copper bases, Westinghouse engineers made use of a physically simpler bonding concept—compression bonding. The Type 790 rectifier diode described in this article employes compression bonding and is referred to as the CBR (compression bonded rectifier). Other Westinghouse rectifier diodes, and also other semiconductor devices such as thyristors and transistors, also employ compression bonding.

Type 790 CBR

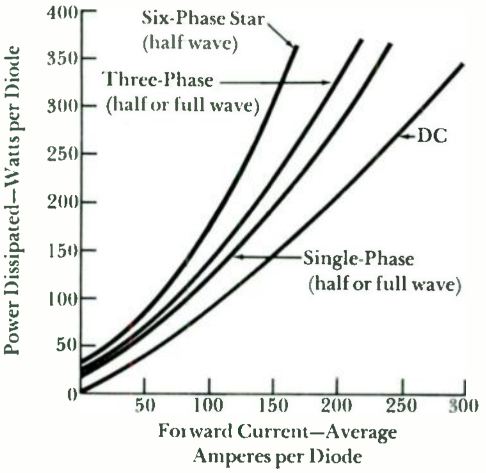
The device consists essentially of a basic diode assembly and the encapsulation assembly. The starting silicon for the basic diode is *p* type and of high bulk resistivity. This type of material is essential for high-voltage rectifiers because peak reverse voltage depends on bulk resistivity and electrical field intensity as well as on the thickness of the high-resistivity layer (termed the base width). Single-crystal silicon of the proper resistivity is cut into slices of the required thickness, which are then lapped to remove surface damage. The slices are chemically cleaned and put through a phosphorous gaseous deposition step



3—Completed Type 790 CBR has a welded hermetic seal to protect the diode, and a flexible external lead.



4—Electrical characteristics of Type 790 CBR at two extreme junction temperatures. Use of the Type 790 CBR makes a more efficient rectifier system than does use of two series-connected diodes of lower rating, since the maximum forward voltage drop is only about 1.6 volts peak whereas it would be about 2.6 volts with two lower-voltage devices.



5—Power dissipated by rectifiers is a function of forward current. The curves show typical maximum power dissipation for several types of rectifier circuit.

where an *n*-type dopant layer is deposited on the starting *p*-type silicon. The slices are then inserted into a diffusion furnace at high temperature (about 1200 degrees C) long enough to diffuse the dopant to a junction depth of about 0.003 inch. Since the phosphorous diffusion envelops all sides of the silicon wafer, one side must be lapped to remove the *n* layer (Fig. 1a). The final base width depends on the starting resistivity of the silicon and the peak reverse voltage capability desired.

A thin disc of molybdenum and a thicker disc of tungsten are fused to the *p* and *n* sides respectively with the proper solder to form good ohmic contacts. (An ohmic contact is one in which the potential difference across the contact is proportional to the current passing through it.) Sandblasting then removes the *n* layer surrounding the *p* region and bevels the edges at the proper angle to withstand high electric fields generated when the diode is in operation in the reverse direction. After chemical treatment, the beveled edge is coated with silicone resin to prevent arcing from *p* region to *n* region and to protect the junction from breaking down due to the high electrical surface fields that are generated (Fig. 1b). The coating is cured, and the basic diode assembly is prepared for encapsulation by lapping the faces smooth and parallel.

The encapsulation assembly consists of three major subassemblies—stud base, upper contact and spring system, and ceramic insulator seal (Fig. 1c). The stud base assembly consists of a high-strength copper stud to which is silver-brazed a steel hexagon case and a silver pedestal. The hexagon case serves both to house the innards of the diode and to provide a machined groove for the retaining ring that supports the spring reaction load. Nickel plating helps maintain low thermal and electrical resistance between the device and the mounting heat sink. The pedestal, given a fine surface preparation, is the mounting surface for intimate bottom contact to the basic diode.

Another silver face is hard-soldered to the molybdenum upper internal contact disc and similarly prepared for intimate contact by fine surface finishing. Three Belleville springs provide the compressive force that keeps the upper and lower internal contacts pressed tightly against the basic diode (Fig. 1d).

At assembly, the basic diode, the stud base, and the upper contact and spring system are placed in a hydraulic press, and a preload compressive force is applied through the Belleville spring system. The retaining ring is then snapped into its groove in the case to lock the springs.

The reaction force of the springs maintains intimate physical contact at the interfaces throughout all temperatures that will be experienced in service. Maintenance of this force is assured by measurements made while the load is applied and by spring characteristics (Fig. 2).

Next, the ceramic hermetic seal is welded to the hexagon case, in an inert atmosphere, to encapsulate the internal volume of the diode and thus protect the junction from any possible chemical contaminant or moisture-laden ambient atmosphere that might affect its characteristics. Attaching the external flexible lead completes the assembly (Fig. 3).

Compression bonding eliminates the stresses normally developed in conventional rectifiers when basic diode assemblies are soldered to bases. It also eliminates the performance degradation caused by the heat of hard soldering and the silicon surface contamination and damage that can be caused by soldering. Thus, the full potential of high-voltage *p-n* junction diffusion designs is realized with accuracy, reliability, and repeatability not possible with conventional soldering techniques. Most important, the CBR construction is truly fatigue free. Since the diode is not metallurgically bonded to the base, relative movement can occur at the interface for a theoretically infinite number of thermal cycles without any adverse effects. Fatigue failures of interface joints simply cannot occur.

Ratings and Capabilities

The Type 790 rectifier diode is made in both standard and reverse-polarity styles with repetitive voltage ratings to 2500 volts and transient voltage ratings to 2800 volts. Current-carrying capability is 240 amperes, with half-cycle surge current rating of 4500 peak amperes.

Diodes with such high voltage capabilities provide the user several important advantages. Since one Type 790 device can replace two 1200-volt devices in series with less power loss, the efficiency of a system is improved. Typical Type 790 forward voltage loss is 1.6 volts peak, compared with 2.6 volts for two 1200-volt devices. Typical average-power loss for a Type 790 device in a single-phase system is about 350 watts, whereas it is about 540 watts for two 1200-volt devices in series. Also, less space is required and reliability is improved when one device is used in place of two.

The small forward voltage loss and the high operating temperature (175 degrees C junction) make the Type 790 diode a practical device for applications where high power is needed (Fig. 4). Typical operating data for several types of rectifier assembly are shown in Fig. 5.

Applications

Type 790 rectifiers have been used since 1965 in diesel-electric locomotives to solve the problems of limited space availability and need for increased horsepower.[2] A large locomotive builder replaced the conventional dc generator with a much smaller and more efficient ac generator and a rectifier bank to produce dc power for the traction motors (Fig. 6). Results have been excellent.

Another use in transportation is for rectifying ac "third-rail" power for electric trains and rapid-transit vehicles. Westinghouse high-voltage diodes will be used in the cars being built for the Northeast Corridor Project, a high-speed transportation system that will link Boston, New York, and Washington. Cars will accelerate from standstill to 125 mph in two minutes, a type of service requiring diodes that can withstand large current overloads and major temperature excursions.

Westinghouse high-voltage devices are also used in the electrochemical industry. Some major uses are in aluminum and chlorine production, where a high-voltage low-loss device is required for efficient utilization of the large amount of electric power required.

In brushless-exciter ac generators, high-voltage high-current diodes are employed for dependable rectification to provide direct current for the generator field.[3,4] The Westinghouse Large Rotating Apparatus Division installs the diodes as an integral part of the armature in these electric-utility machines, thus eliminating the usual commutator and brush maintenance problems (Fig. 7). This use requires a device rugged enough to take the great centrifugal force developed by high-speed shaft rotation—more than 8000 g.

Type 790 diodes also have numerous applications in such power rectification systems as those for welding, high-voltage dc transmission, and electroplating. Use of six 2500-volt diodes instead of eighteen 800-volt diodes in a three-phase bridge assembly, for example, saves power and also increases reliability by reducing the number of devices by 12.

The Future

High-power high-voltage silicon rectifier diodes will continue to help industry meet its needs for reliable and efficient high-power systems. The Semiconductor Division is developing devices of even higher voltage and current rating than the Type 790 rectifier, and those devices will also employ compression bonding to achieve the desired performance and reliability. With them, designers will be able to take another giant step in simplifying rectifier systems and improving their efficiency.

Westinghouse ENGINEER **September 1967**

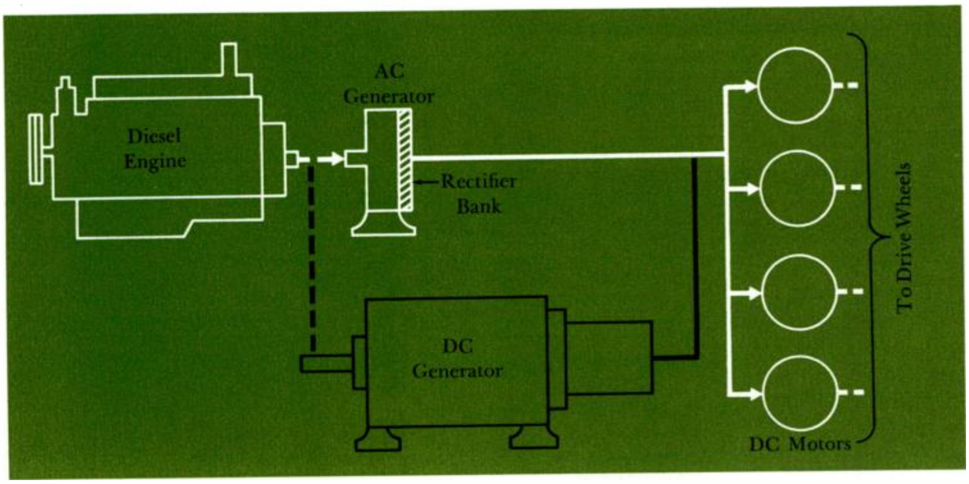
References:

[1] Green, W. B., "A Fatigue-Free Silicon Device Structure," *AIEE Transactions, PTI* (*Communications and Electronics*), Vol. 80, May 1961.

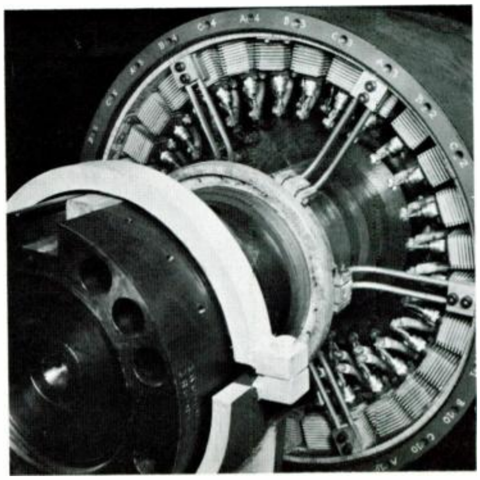
[2] "High Voltage-Current Diodes," *Electronic News*, June 7, 1966.

[3] Bobo, P. O., and Myers, E. H., "Brushless Excitation Systems," *Proceedings of 1966 Southwestern Institute of Electrical and Electronics Engineers' Conference.*

[4] Hoover, D. R., "Brushless Excitation System for Large AC Generator," *Westinghouse ENGINEER*, Sept. 1964.



6—An ac generator and 60 Type 790 CBR's replace a larger dc generator for producing dc traction power in new diesel-electric locomotives. The system develops 3600 horsepower.



7—Brushless exciter for an electric-utility generator employs Type 790 CBR's mounted in the armature to rectify generated ac power for exciting the main generator field. This exciter develops 1350 kilowatts.

Underground Transmission Studied in Major Test Project

An underground high-voltage transmission test program begun recently is a major electric power industry effort to test high-voltage power cable systems and related accessories with the dual purpose of developing underground electric transmission systems of higher capacity and finding ways of reducing their cost. The $5-million test facility being built for the program at Waltz Mill, Pennsylvania, will be one of the highest-voltage test projects in the world, capable of testing underground systems at voltages as high as 1,100,000 volts.

Initial testing is scheduled to begin in about a year. The project will be designed to test ac transmission systems at the outset, but it can be converted to test dc systems and advanced systems now in the experimental stage.

Overall design, construction, and operation of the project are being carried out by the Westinghouse Electric Utility Headquarters Department for Edison Electric Institute (EEI), which is administering the contract for the Electric Research Council (ERC). The program is expected to last 10 or more years. ERC comprises 12 representatives from the various segments of the electric power industry, including federal, state, and local agencies, cooperatives, and investor-owned companies through EEI. It makes possible joint financing of research that is of interest to the industry and its customers.

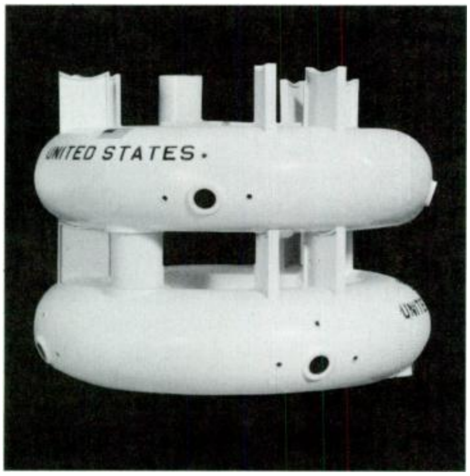
Facilities at the 60-acre test site will include 12 test bays, each 1000 feet long, in which sample underground transmission systems will be installed and subjected to a series of tests at specified voltages and temperatures above their nominal rated values. Systems to be tested range from 115,000 to 750,000 volts. (The highest voltage at which an underground transmission system is now operating in the United States is 345,000 volts.) Testing periods ranging from several weeks to several months are planned, giving an overall test on each cable sample of approximately two years. By regulating voltage and temperature levels, the planners hope to be able to simulate about 50 years of operating experience in the two years of testing.

A Prodac 50 computer will monitor and record voltage, current, pressure, and temperature readings at a number of locations in each test bay, and it will prepare daily summaries of operating conditions on each sample and assist engineers in preparing monthly reports. The computer also will monitor station operation, assist in orderly startup and shutdown of the different tests, and give notice of potential trouble at another location during unattended operation.

Manned Underwater Station Studied by Underseas Engineers

Men could live and work a month at a time a mile beneath the sea in an underwater station conceived as part of a study for the U.S. Naval Civil Engineering Laboratory, Port Hueneme, California. The station would house a five-man crew and be linked to a guide cable anchored to the ocean's floor. Several of the doughnut-shaped stations could be stacked to accommodate an undersea community of scientists working on a variety of oceanographic research projects.

Manned underwater station's design concept is illustrated by this model. Two or more stations could be stacked as shown to provide the desired amount of space.



The underwater station would measure approximately 40 feet in diameter, weigh about 150 tons, and have an operational area of 400 square feet. It would include all life-support equipment and provisions for safety, comfort, and recreation for the crew. The engineers who conceived it at the Westinghouse Underseas Division see the manned underwater station as one more tool in the United States' growing capability to exploit the oceans' vast untapped resources for economic purposes ranging from the use of marine life to drilling for oil. They are also studying potential military applications.

To combat the negative effects of isolation and confinement on the human personality, the engineers are working on ways to enhance the habitability of the station. A final design might include some of the features of Polaris submarines which, among other things, reflect the finding that privacy is extremely important to persons living in confined quarters.

The underwater station will be capable of mating with submersible vehicles for transferring personnel and supplies. Also, submersibles could use the station as a base for missions in the ocean depths.

Construction materials being evaluated include steel, titanium, aluminum, and plastics reinforced with fiber glass. Power probably will be supplied by a nuclear isotope power source. A backup power supply for emergency use would last five days beyond the normal mission duration of one month.

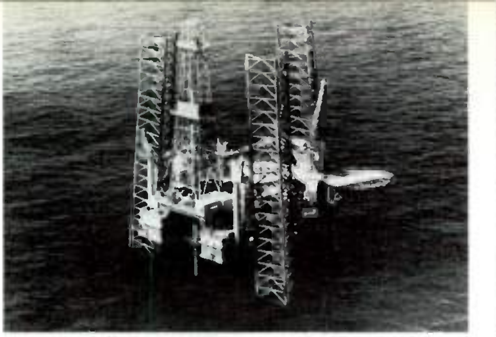
Sensitive Fire Detector Can Be Used at High Temperatures

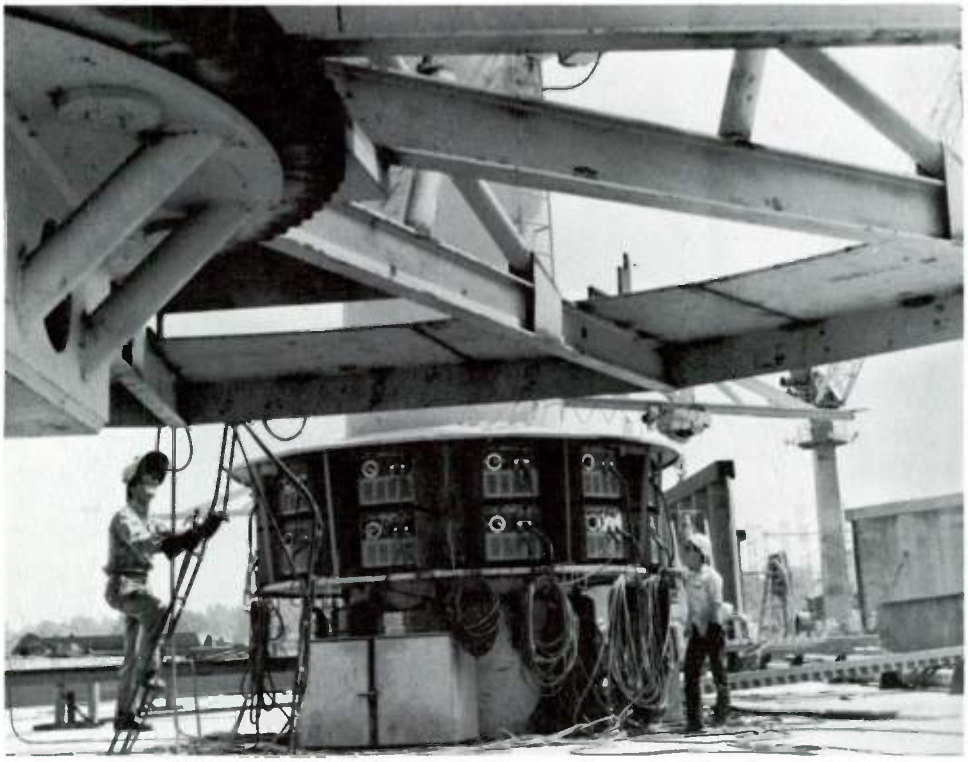
Fire-detecting devices have to be fast, reliable, and sensitive to fire while insensitive to normal ambient radiation. A new solid-state device meets these requirements and in addition can be used in ambient temperatures up to 500 degrees C.

The device is a silicon-carbide photovoltaic diode that is sensitive only to ultraviolet light in wavelengths emitted by fires. Because it is nearly blind to solar ultraviolet radiation, it cannot be triggered by sunlight. Blind also to infrared radiation, it can be used near furnaces, hot piping, engines, and other heat sources. Within microseconds after the ultraviolet radiation falls on the device, the diode produces a photovoltage that can be used to operate an alarm or an automatic extinguishing system.

The diode is a silicon-carbide single crystal grown from vapor, with a junction formed by diffusing a small amount of aluminum into the *n*-type crystal. Depth of the junction determines the wavelength of ultraviolet radiation to which the diode is most sensitive; the depth is adjusted after diffusion by removing some of the surface material mechanically or chemically. Diodes have been made with peak responses to wavelengths in the range from about 2800 to about 3800 angstroms.

The diode was developed by the Westinghouse Research Laboratories and Astronuclear Laboratory under contract to the U.S. Air Force Aero Propulsion Laboratory, Wright-Patterson Air Force Base, Ohio. Commercial versions also are being made.





***Above left*—This offshore oil drilling rig is at work in the Gulf of Mexico. The massive rigs are fabricated from steel and then floated to the drilling site, where legs are lowered to the ocean floor and the platform elevated above wave level.**

***Above right*—A completed rig is being "walked" into the river at left in this aerial view of the assembly site. Other rigs are in various stages of completion. At top right are the four jib cranes in the prefabrication area where major components are assembled and welded together.**

***Lower*—Solid-state welder power supplies surround the base of each jib crane for fast convenient welding. Although the welders are protected only by a roof, they give reliable trouble-free service.**

Solid-State Welders Facilitate Fabrication of Giant Drill Rigs

Much offshore oil exploration is done with massive steel drilling rigs that are floated to the desired position over the continental shelf. Once in place, they lower steel legs to the ocean floor and raise themselves safely above wave level. Many of these rigs are assembled by R. G. LeTourneau, Inc., at its Vicksburg, Mississippi, sites. Since the huge rigs have to be assembled outdoors, and conditions at the work sites are humid and corrosive, dependable solid-state welders are used for fabricating.

Steel for the 7000-ton drilling rigs is sheared to size for each part. It is a nickel alloy, N-20, with plate thickness ranging up to three inches. Some 200 tons of weld filler metal goes into the fabrication of a rig. The fillet and butt welds are made with coated-electrode metallic arc, submerged arc, cored wire, shielded CO_2, and other processes.

Some of the Westinghouse WSH welders are permanently mounted at the base of four jib cranes—26 at each crane. The cranes, of 25-ton capacity and 40 feet high, have booms that rotate 360 degrees and extend 60 feet from the jib. With the welders mounted all around the base, men can work at any point around the crane without having to look around for, or hook up, a welder. Power leads are 100 feet long. The welders are mounted five feet above the ground, two high, and with a metal roof over the top to protect them from rain. Otherwise, they are in the open, exposed to heat, dampness, and humidity, yet they have performed without attention, maintenance problems, or down-time since the first ones were installed at the fabrication site in February 1965.

The rest of the WSH welders, nearly 300, are used elsewhere at the river site and at the Vicksburg plant. They are used singly or in banks of nine on platforms that are crane-lifted to points where they are needed, such as onto the decks of rigs afloat on the Mississippi river for final assembly work.

When all land fabrication is completed, the rigs are "walked" on their legs to the river and then floated down to the Gulf of Mexico. Bridges across the river prevent final assembly of legs, derricks, and other superstructure (the legs extend up to 460 feet above the water when they are set in "floating" position), so those sections are barged down for final assembly at the drilling site. Rigs that are towed across the Atlantic to European and Middle East points travel with 150 feet of legs, and then the rest of the leg sections is assembled at the site. With legs in place, the crew levels the platform to 0.3 degree with pushbutton controls in the pilot house that energize rack-and-pinion drives on the legs. The rigs are of two basic designs: those with vertical legs are used in water up to 200 feet deep; those with slanted legs (as much as 15 degrees slant from the top) are used in depths to 350 feet.

Automatic Storage System Serves Large Parts Warehouse

More than 4000 different automobile parts are stored in 7830 storage bins in the parts warehouse opened recently by Fisher Body Division of General Motors Corporation in Euclid, Ohio. An automatic storage system reduces inventory errors, even with the vast number of part and location combinations possible, and also enables the company to store and retrieve parts faster, more efficiently, and in a smaller area than a manual system could.

The warehouse receives parts from hundreds of suppliers and from other Fisher plants—parts of all shapes, sizes, and weights. As the parts arrive by truck and rail, operators record them on punch cards and load them onto wheeled racks. Then automatic driverless tractors tow the racks to the stacking area, guided by signal cables in the floor. As they arrive, the racks are unhooked and put on the pickup station of one of 15 stacker cranes. An operator inserts the punch card for each rack into a reader, which activates the system's central Prodac-50 computer. The computer selects the closest empty storage bin, directs the crane to store the load there, and monitors the crane to make sure it does put the load into the proper bin. When the load has been deposited, the computer stores the location in its memory and also punches it on tape. The tape protects against accidental loss of memory in the computer and also is used to prepare cards for load retrieval and shipping.

As orders are received from assembly plants across the nation, new cards are prepared with the information necessary for the computer to instruct the proper cranes to retrieve the proper racks. An operator feeds these cards into the card reader, and the computer again puts cranes to work to retrieve the material. The computer is so programmed that the first parts of a given type received are the first retrieved. It has enough capacity to operate all 15 cranes at once—stacking, retrieving, or in combination.

Once a crane is activated, it completes its storage or retrieval cycle unless there is a fault in the system. If a crane breaks down or has some other difficulty, the computer types out a notice and description of the problem. The computer also notifies the operator by typewriter if a part that has been requested is no longer in the system.

Desalting Plant Relieves Key West Water Shortage

Residents of Key West, Florida, are now drinking water from the Atlantic Ocean, thanks to the world's largest single-unit desalting plant. The plant recently went into full-capacity operation, producing 2.62 million gallons of fresh water daily from the ocean salt water.

The new source of fresh water for the Florida Keys Aqueduct Commission has alleviated a critical water shortage in the lower keys area, permitting the lifting of restrictions on water use for washing cars and watering lawns. The Commission's storage capacity of 17.5 million gallons had gradually been reduced to approximately 2 million gallons because of prolonged drought, but the storage tanks have now been filled with water from the desalting plant.

The desalting plant employs the multistage flash evaporation process, in which salt water is heated by steam from an oil-fired boiler and sprayed into a series of chambers that are at lower pressure and temperature. Some of the water flashes into vapor in each chamber and is condensed into pure water. The Westinghouse Water Province Department was responsible for design, engineering, and construction of the plant, and it is operating the plant for a year. The plant produces water at a cost of less than 85 cents a thousand gallons.

Products for Industry

Data tape translator, capable of translating 34 days of field data in 8 minutes, makes possible high-speed data entry into a computer by using seven-channel magnetic computer tape instead of standard computer cards. The transistorized unit is designed for use with Westinghouse magnetic pulse tape recorders that record pulses proportional to time on one tape track and pulses proportional to load on another. The translator counts data pulses recorded in each time interval and enters the totals for each interval on computer tape. A computer can then use the tape to prepare bills, chart load profiles, and make system engineering studies. Many field tapes can be put on one computer tape. *Westinghouse Meter Division, Box 9533, Raleigh, North Carolina 27603.*

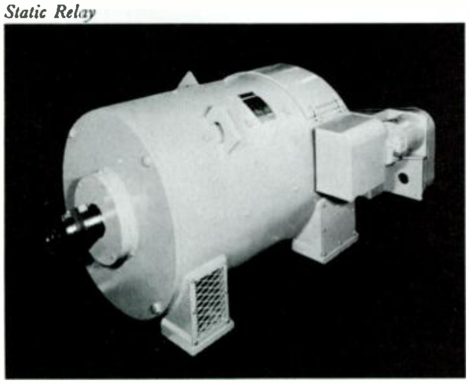
Dyna-Vac power capacitors with a new synthetic-film dielectric system have 50 percent less losses than conventional paper-askarel capacitors. Rating is 150 kvac, with the same dimensions as the conventional 100-kvac unit. Other benefits of the synthetic-film design include more constant capacitance over the entire operating range, lower internal operating temperatures, and better withstanding of transients. The capacitors are available in single- and two-bushing designs from 2400 to 14,400 volts. *Westinghouse Distribution Apparatus Division, P.O. Box 341, Bloomington, Indiana 47402.*

Type EFD load-break switch meets full switching requirements of underground distribution systems with pad-mounted transformers. Switching flexibility and safety are provided by compact "dead-front" construction that permits external mounting on the transformer. The switch is available on single- or three-phase transformers; it is applicable for grounded wye systems of the 15-kv class, either loopfeed or radial-feed distribution. *Westinghouse Distribution Transformer Division, Sharon, Pennsylvania 16146.*

Static relay, SGR-51, provides instantaneous reclosure of an electrically operated circuit breaker and automatically resets itself if the breaker remains closed for a predetermined time interval. It can also be adjusted to a reset time of 3 to 30 seconds. The timing function is accomplished by use of solid-state components mounted on printed circuit boards that facilitate maintenance and testing. The relay can function at either attended or nonattended stations, and its burden is only 45 milliamperes at 48/125 volts dc. *Westinghouse Relay-Instrument Division, Plane and Orange Streets, Newark, New Jersey 07101.*

Permanent-magnet motor rated 200 horsepower is the most powerful PM motor now available to industry. Designed originally for steel-mill applications such as straightener, screwdown, and table drives, the motor is also suited for many mining and manufacturing dc drive applications that require high torque and rapid response. It has improved high-energy Alnico magnets in place of the field windings in conventional dc motors; elimination of field windings results in higher torque capability, higher efficiency, simpler control circuitry, and lower installation and maintenance costs in applications where field control is not required to obtain desired variations in speed. Speeds range up to 1750 rpm. *Westinghouse Large AC/DC Motor Division, P.O. Box 225, Buffalo, New York 14240.*

Static Relay



Permanent-Magnet Motor

Services for Industry

A rapid motor repair process minimizes the time required to repair random-wound integral-horsepower motors up to 200 horsepower. Called the 824 Process, it gives motors a long-lasting insulation treatment that has outstanding resistance to contaminant atmospheres, mechanical shock, electrical stress, moisture, and overheating.

Because of the speed of the process, same-day service usually is possible; motors arriving at a repair plant by 8 a.m. can be rewound and on their way back to the customer by 4 p.m. the same day. The rapid process uses the concept of heating motor windings by circulating currents while applying the insulating resin. The process takes less than an hour, compared to the 24 hours or more of oven curing required for the traditional varnish dip and bake method.

Heating with circulating currents has been in limited use by Westinghouse for some time, but the process has now been greatly improved by use of a new type of thermal control unit that maintains precise winding temperature during resin application. The control employs a resistance-sensitive solid-state relay and an expendable resistance-type temperature sensor inserted in the motor end winding.

The initial low viscosity of the solventless epoxy resin blend that is used provides thorough permeation of the windings, aided by the tight winding temperature control provided. The resultant insulation coating has no voids, thus eliminating hot spots that shorten motor life. The epoxy blend has low weight loss during processing, with consequent high resistance to such mechanical defects as cracking and crazing.

The 824 Process is available at Westinghouse Repair Division plants throughout the country.

New Literature

Inspection and Test of Electrical Equipment is a quick-reference guide to plant maintenance of all Westinghouse metal-clad switchgear, power and distribution apparatus, and auxiliary equipment. The 330-page handbook (MB3051) gives recommended procedures and tests for inspection and maintenance. The tests can be applied safely to equipment of other manufacturers. Data and electrical values, tables, and formulas are included to aid in interpreting the situations encountered in maintaining a plant's electrical system. Copies available at $3 each from Westinghouse Electric Service Division, Churchill Borough, Beulah Road, Pittsburgh, Pennsylvania 15235.

Control of Chemical and Fuel Recovery Systems in Paper Mills is an illustrated booklet (AD-103-003) that describes how paper-industry processing chemicals can be recovered and reused and waste materials converted into fuels to reduce manufacturing costs. Included is a description of the brown-stock washer, evaporator system, recovery and bark-burning power boilers, and green-liquor system used in the sulfate wood-pulping process to recover and reconvert cooking chemicals to sodium hydroxide and sodium sulfide. The booklet also describes the connecting systems that must be controlled to complete the chemical and fuel recovery systems. Diagrams illustrate steps of each process. Copies available from Hagan Controls Corporation, Division of Westinghouse Electric Corporation, P.O. Box 11606, Pittsburgh, Pennsylvania 15228.

About the Authors

Nelson B. Tharp makes his third appearance on these pages to talk about his favorite subject—communications. This time, he discusses the solid-state variety, the latest development in communications equipment.

Tharp came to Westinghouse on the graduate student course after graduation from Northwestern University in 1941. He promptly accepted an assignment in what was then the Electronics Division in Baltimore to design radio equipment. He has since worked his way through a variety of assignments and covered the radio-frequency spectrum in the process—low-frequency transmitters, broadcast transmitters, microwave communications systems, and, most recently, the VLF/LF solid-state equipment that he discusses in this issue. He is presently manager of program development for the DECO communications department of the Westinghouse Defense and Space Center.

Tharp is equally interested in communications off the job, where he is known to many—including his wife—as W3EUN. In fact, Tharp's interest in communications includes his wife, who is W3MPU.

Martin L. Jones and **John R. Colgan,** who collaborated on the design of the digital linear amplifier, also join forces to describe the equipment in this issue.

Jones joined the Westinghouse Surface Division (then the Electronics Division) in 1956 as a design engineer to work on various phases of radar transmitter design. In 1960, he was made a supervisory engineer with responsibilities in both the design and testing of radar equipment. Jones switched from tubes to solid-state circuitry in 1965 when he was made a project engineer responsible for two programs: the development, design, and testing of a high-power solid-state antenna tuner, and the standard development program for the solid-state linear amplifier.

Before coming to Westinghouse, Jones had been chief engineer for radio station WCAO in Baltimore. He obtained his engineering education by attending night classes at Johns Hopkins University over a period from 1932 to 1947.

Colgan came to Westinghouse on the graduate student course upon graduation from Ohio University (BSEE) in 1965. The solid-state linear amplifier was Colgan's first major design assignment at the Surface Division. He is now applying solid-state design techniques to equipment for a Loran navigation system.

G. Reed Brainerd obtained his BSEE (With Distinction) from the University of New Mexico in 1950. However, his interest in engineering electronics began even before college, when he served in the U.S. Army Signal Corps (World War II) as a member of the teaching staff at Camp Murphy Radar School and overseas in Europe as the noncom of an ECCM team. After graduation, Brainerd was employed by the Ohio State University Research Foundation in its Antenna Laboratory to work in the fields of circuitry and systems. He also did graduate work, obtaining his MSEE from Ohio State in 1953. In 1954, he moved to the Light Military Equipment Division of General Electric to serve as project engineer of a classified solid-state ordnance equipment.

Brainerd joined the Westinghouse Electronics Division (now the Surface Division) as a senior engineer in advanced development in 1956. He was made a supervisory engineer for a solid-state application unit in 1957. Brainerd became manager of the Solid State Technology Section of the Advanced Development Subdivision in 1962 where he worked on such applications as the thyristor transmitter described in this issue and developed the microcircuity laboratory of the Surface Division. In 1966, he became solid-state radar program manager for the Surface Division and directed efforts in microwave microelectronics and solid-state power for radar. At present, he is an advisory engineer in science and technology in the Surface Division.

N. R. Carlson and **L. F. Martz** combine their talents to describe the dynamic control system for the BOF steelmaking process.

Carlson earned his BA in Physics at Dartmouth College in 1959, his MS in Electrical Engineering at Stanford University in 1961, and his PhD in Electrical Engineering at Stanford in 1965. He joined Westinghouse in 1961 as a summer intern in a program sponsored jointly by Westinghouse and Stanford University. He is responsible for technical aspects of computerized steelmaking at the Computer Systems Division and has contributed to development of the dynamic BOF control system.

Martz is a consulting engineer with Hagan Controls Corporation, a division of Westinghouse Electric Corporation. He provides internal consulting services on a wide variety of control systems for power plants and industrial processes. Martz joined Hagan in 1950 after graduating from Pennsylvania State University with a BS in Fuel Technology. He served as a service engineer and then as manager of field service before assuming his present position in 1965. Among the engineering developments he has contributed is the dynamic BOF control system described in this issue.

R. C. Robinson graduated from the University of British Columbia in 1938 with a B.A.Sc. in Electrical Engineering. He moved to the United States about a year later to join Westinghouse on the graduate student course, and soon went to work in the Transportation and Generator Division (now Large Rotating Apparatus Division). One of his first major projects was development of special high-speed motors for the Manhattan Project.

Robinson left Westinghouse in 1945 to go with another company, where he designed specialty motors. In 1950, he returned to Westinghouse to become a subdivision manager at the Atomic Power Division in charge of design and development of the control-rod drive for the submarine *Nautilus*. He holds a special patent award for that work.

Robinson moved to the Atomic Equipment Division in 1954, and in 1956 he came back to the Large Rotating Apparatus Division. He is an advisory engineer in charge of the product development section in the AC Motor and Generator Engineering Department.

The article on high-voltage compression-bonded rectifiers was written by **Robert R. Shaw, James R. Shiring,** and **Krishan S. Tarneja.**

Shaw earned his BS in Mechanical Engineering at the University of Pittsburgh in 1959, and he has since taken graduate work there and at Carnegie Institute of Technology in materials science and solid-state physics. He joined the Westinghouse Semiconductor Division product engineering department and worked on the mechanical design and development of semiconductor devices—encapsulation, hermetic sealing, and materials systems. He moved to the rectifier department in 1964; there he has been in charge of gaseous diffusion and mechanical design and responsible for design and development of high-voltage high-current rectifiers.

Shiring graduated from the University of Pittsburgh with a BSEE in 1963. He joined the Semiconductor Division immediately and has worked since then in manufacturing engineering. He has contributed to the development of manufacturing processes for high-power rectifiers, including the devices described in this issue.

Tarneja graduated from Delhi University, India, in 1952 with a BSc degree in Physics and from Banares Hindu University in 1956 with a BSc in Mechanical Engineering. He came to the United States the following year to enter Carnegie Institute of Technology, where he earned his MS in Mechanical Engineering in 1958.

Tarneja joined the Semiconductor Division in 1959. He worked in research and development on high-efficiency semiconductor solar cells and was one of the leading contributors to development of large-area solar cells made from silicon web material. Tarneja received a master's degree in Business Administration from Duquesne University in 1965 and is now studying toward an MS in Industrial Engineering. He became manager of the rectifier development engineering section last year, responsible for development of new and improved rectifiers in the medium- and high-power ranges.

These racks are part of the random-storage area of a semiautomatic system for storing and shipping products of the Westinghouse Medium AC Motor and Gearing Division at Buffalo, New York. They have 3600 storage openings and are served by three stacker cranes, one of which is seen at the end of the aisle. Other major parts of the system are a flow rack for brief storage and conveying of most-used products, a shipping facility, and conveyors that connect the parts. The system is tied in with the plant's central data-processing computer, which assigns storage locations and keeps track of the locations for later retrieval. The system greatly speeds truck loading and releases plant floor space.