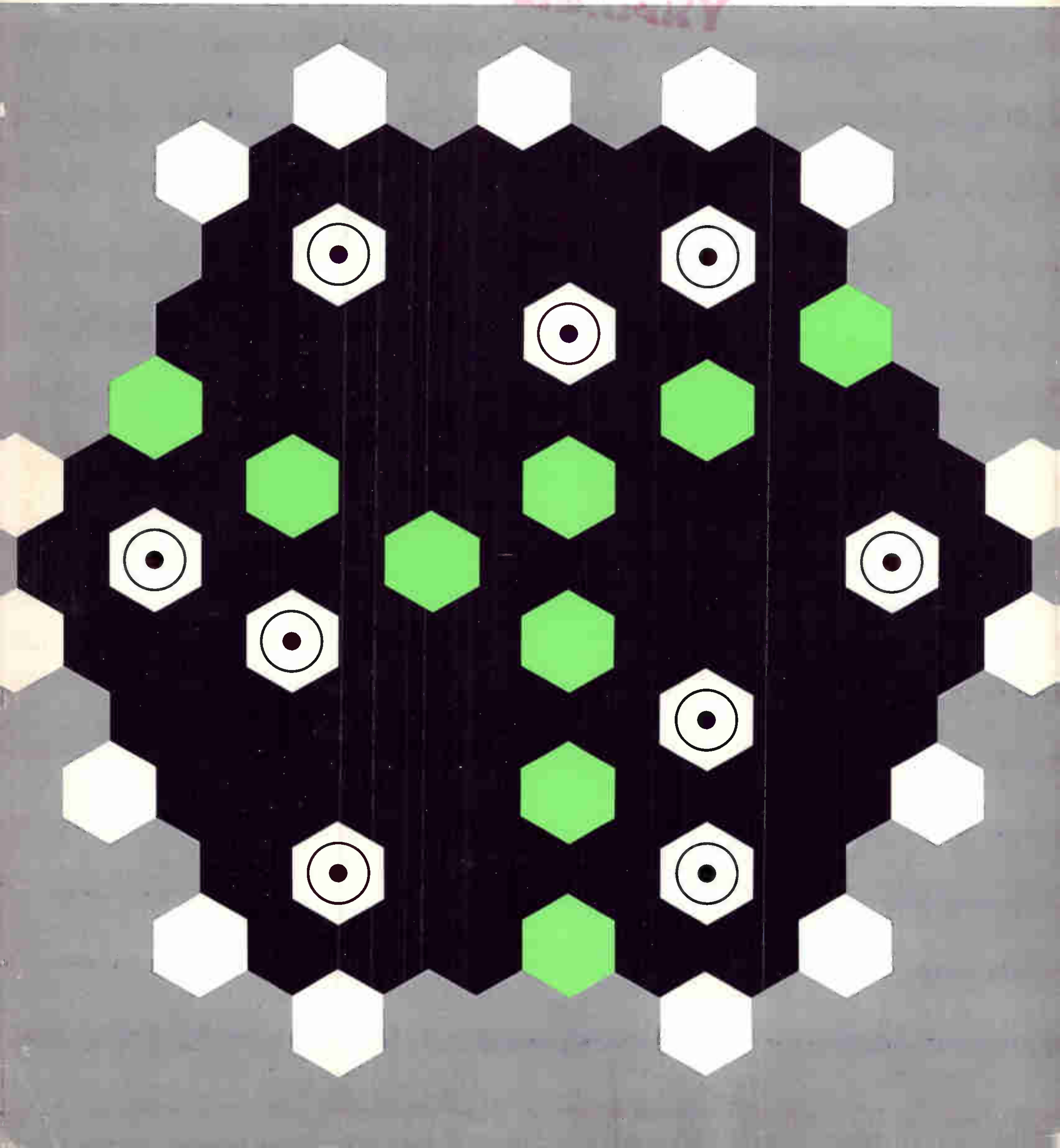
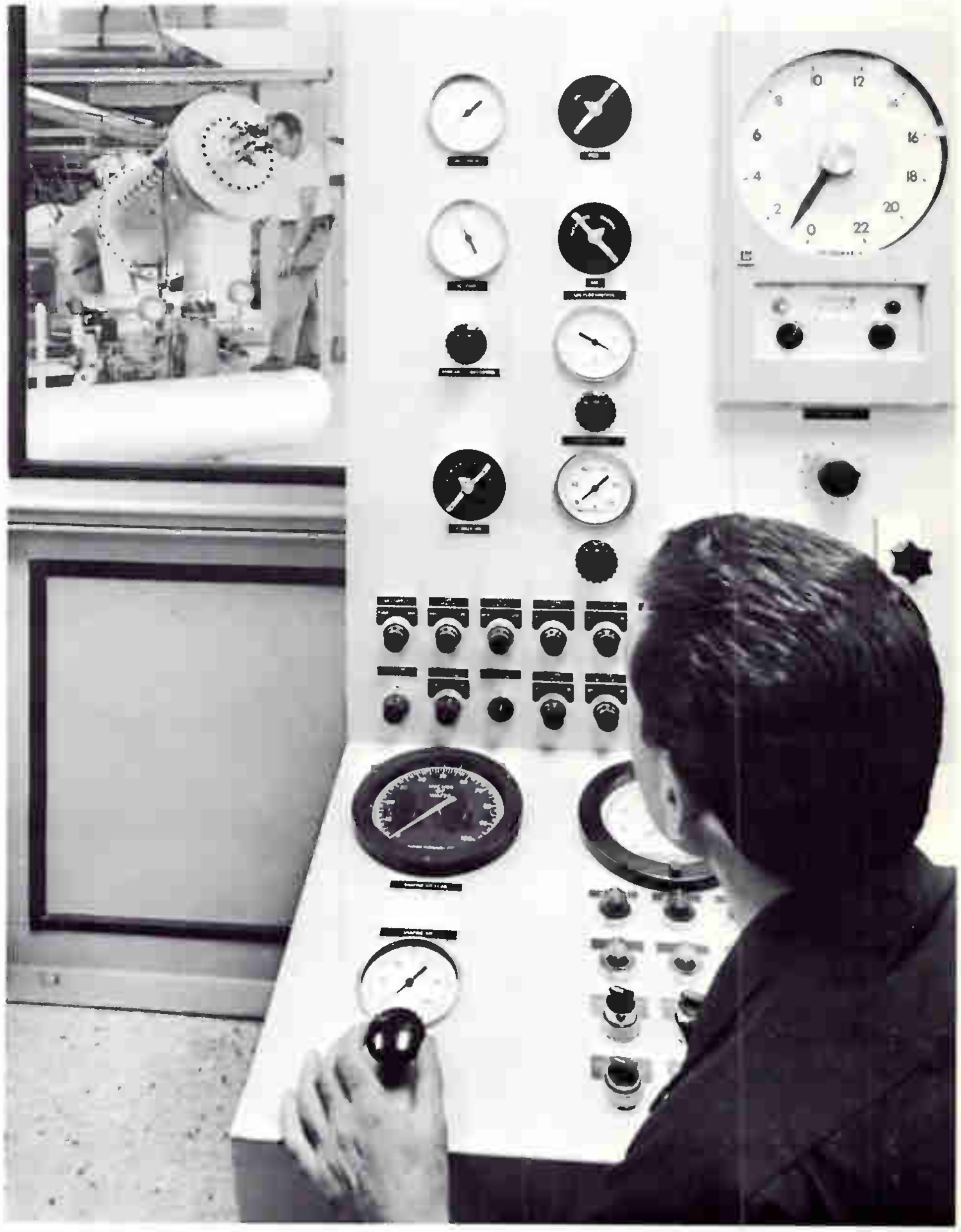
Westinghouse ENGINEER November 1969





A combustion test laboratory is helping the Westinghouse Small Steam and Gas Turbine Division develop gas-turbine components at its Lester, Pennsylvania, works. Its three test stations, visible to operators through viewing windows, can be operated independently of each other so test rigs can be built in one station while the others are in use. Equipment tested in the new facility includes combustion chambers, turbine components such as blades and vanes, and instrumentation.

Compressors supply air to the test passages at flow rates up to 40 pounds per second and pressures up to 9 atmospheres. The air can be preheated to 800 degrees F, and temperature at the combustor exhaust can range up to 2500 degrees F. By permitting testing at full operating pressure, flow rate, and component size, the facility eliminates possible scaling errors and thus permits the small accurate dimensional adjustments necessary for smoke control and design of efficient turbines.

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Front cover: The conceptual design selected for the FFTF reactor has a Y-shaped pattern for the test loops to facilitate access to the reactor core. The cover design by artist Tom Ruddy suggests this pattern, and the FFTF project is described in the article beginning on the following page.

Back cover: The highly detailed mask in the man's hand produced the corresponding design for a high-density array of interconnected integrated circuits on the silicon wafer. An experimental process employs electron imaging rather than coarser-grained light to crowd large numbers of integrated circuits into a given area. (More information on page 187.)

FFTF—Fast Flux Test Facility for Developing Breeder Reactor Technology

E. R. Astley
J. C. R. Kelly, Jr.

The Fast Flux Test Facility, to be built near Richland, Washington, will be the major fuels and materials test irradiation facility in the AEC's Liquid Metal Fast Breeder Reactor Program. A conceptual design has been selected, and preliminary engineering design has just begun. The plant is scheduled to go critical in late 1973.

In 1968, the Liquid Metal Fast Breeder Reactor (LMFBR) program was assigned the highest priority in the U.S. Atomic Energy Commission's overall program to develop civilian nuclear power reactors. This priority assignment came in recognition of the gap that was rapidly developing between the commercial need for breeders and the base of technology required to design and build a commercial breeder plant.

The commercial need stems from the breeder's desirable characteristic of creating fissile plutonium (Pu-239) from fertile uranium (U-238) faster than it consumes fissile plutonium at the same time it is producing usable power. This mode of operation will use the large supply of otherwise-unusable fertile uranium available and thereby keep fuel and operating expenses much lower than they will be if only "burner" reactors are used.[1]

Efficient breeder reactors will operate predominately in a fast (high energy) neutron spectrum, as contrasted to today's water-moderated burner reactors that use the thermal (low energy) end of the spectrum. To achieve an economic breeder within the constraints posed by fast reactor systems, specifications for materials, fuel element geometries, and chemical processes are much more demanding than are encountered in thermal reactors. For example, fuels must be driven to burnups of 100,000 to 200,000 megawatt-days per tonne—substantially greater than has yet been demonstrated with light-water systems. Fuel cladding and other core components must fulfill their structural functions adequately despite irradiation from flux intensities many times greater than those in today's water reactors. In addition to the severity of the neutron flux, sodium coolant temperatures of 1000 to 1100 degrees F are desired to maximize plant thermal efficiency. This will pose additional problems of material selection and call for expanded knowledge of sodium chemistry and structural materials properties.

Unfortunately, the base of technology required to solve the engineering and materials problems posed by the commercial breeder plant is still incomplete. This need for breeder technology led to the concept of the Fast Flux Test Facility (See *Development of the FFTF*). The FFTF is a test reactor[2] designed to provide safe and convenient access to a fast neutron environment for comprehensive breeder fuel and material testing.

The test reactor power is about 400 thermal megawatts, with a very high neutron flux, nearly 10^{16} neutrons per square centimeter per second. The test reactor has instrumented closed and open loops and facilities for rapid insertion and removal of test specimens. Plant facilities are provided for interim fuel examination. The FFTF will occupy a role in breeder development analogous to that of the MTR, ETR, ATR, and other thermal test reactors in the water reactor development program.

Selecting a Reference Design

Many basic characteristics of the FFTF test reactor are implicit in any fast reactor of this rating. To obtain the very high neutron flux required at near-minimum volume, the core must be approximately cylindrical, with a height-to-diameter ratio of about one. With the flux and testing constraints, the resulting core volume is about 1000 liters. The top of the reactor must provide access to the core for removal and replacement. The reactor plant uses primary and secondary

1—Core configurations considered for the reference design were vertical, conical, and skewed arrangements.

E. R. Astley is Manager of the FFTF Division for Battelle-Northwest; J. C. R. Kelly, Jr., is General Manager of the Westinghouse Advanced Reactors Division.

Development of the FFTF

The concept of a Fast Flux Test Facility had its beginning in the late 1950's. Several conceptual studies had been sponsored by the U.S. Atomic Energy Commission by the early 1960's, but those early studies proceeded at a modest pace because the major effort was then concentrated on introducing the water reactor as a commercial nuclear power plant. The water reactor had yet to prove itself an economic commercial plant.

However, the rapid transition of the water reactor from technical to economic feasibility resulted in much faster acceptance of nuclear power by the electric utility industry than anyone had predicted in the early 1960's. And the sudden acceleration in orders for water reactor plants, beginning in 1966, immediately advanced the timetable most desirable for developing the breeder reactor.[1]

As the commercial need for the fast breeder materialized, the Atomic Energy Commission placed increased emphasis on its LMFBR program and made the FFTF the major test facility of the program.

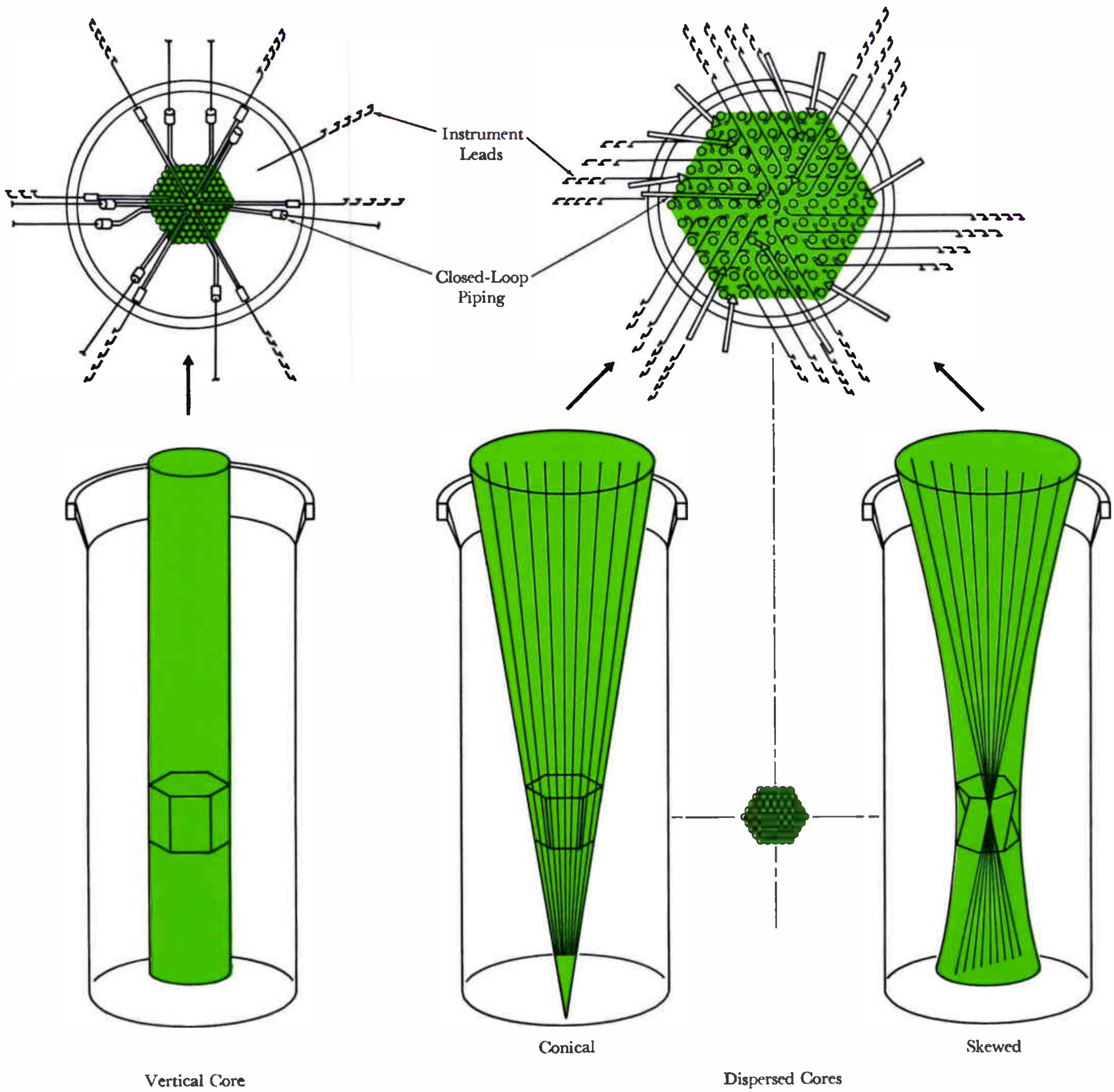
In 1966, Battelle-Northwest (BNW), a Division of Battelle Memorial Institute, was assigned project management responsibility for developing a conceptual design for the FFTF. A number of industrial firms were employed by BNW to submit preliminary conceptual designs, from which a conceptual reference design would be developed.

By 1968, several conceptual designs for an FFTF had been submitted, all of which had the potential of satisfying the AEC specifications to varying degrees, and the time had come to form a team to design and build the facility. Overall project management was assigned to Battelle-Northwest. Bechtel Corporation was chosen to provide architect-engineer and construction management services to BNW. Westinghouse was named the reactor plant designer with responsibility for design and procurement, under prime contract with Battelle-Northwest. The Atomics International Division of North American Rockwell Corporation was selected as the subcontractor to Westinghouse for design of certain systems of the reactor plant.

During the latter half of 1968, concerted effort went into the evaluation of these conceptual alternatives. By January 1969, Battelle-Northwest, with participation by Westinghouse, Atomics International, and Bechtel, had developed an integrated reference concept. Preliminary engineering design based on this reference design is under way, and, although some design changes will still be made as engineering progresses, the basic FFTF will closely resemble the conceptual reference design described.

When the facility goes critical, it will become the AEC's major facility for irradiation testing and post-irradiation examination of fuels and materials being developed for fast breeders.

1


Instrument
Leads
Closed-Loop
Piping
Vertical Core
Conical
Dispersed Cores
Skewed

sodium coolant systems and an air dump heat exchanger. Austenitic stainless steel is used for vessels and piping in the primary and stainless or low alloy steel in the secondary sodium systems. Reactor control is accomplished with poison rods.

Three major conceptual features required considerable study—the *reactor core geometry*, the *reactor refueling system*, and the *containment system*. Of these design features, the choice of core configuration is the most difficult and also the most crucial because it exerts a major influence on the other features, especially reactor refueling. The difficulty in choosing a core configuration stems from the need to satisfy two fundamental but conflicting test reactor requirements:

1) High availability is needed, approaching that of a power reactor, even though the reactor must be shut down frequently for experiment handling and core reloading;

2) The mass of test instrumentation and test loop piping creates challenging problems of access to the core.

The inherent conflict in these two requirements was apparent in the core configurations that were considered for the reference design. Basically, the choice was between a vertical core and two dispersed configurations (Fig. 1). A vertical arrangement simulates a power reactor environment most accurately, but the limited space above the tightly packed fuel rod bundles complicates access to the core. Either of the dispersed core geometries—the conical or the skewed[3] configuration—improves accessibility to the reactor, but either dispersed arrangement departs from conventional LMFBR core geometry and would yield less information for direct application to a commercial fast breeder design. Of the alternatives, a vertical configuration was selected, with special modifications to adapt it to testing service.

Reactor Reference Core

The FFTF reactor active core consists of a vertical hexagonal array of driver fuel assemblies, made of stainless-steel clad, mixed uranium-plutonium oxides. The purpose of these driver fuel assemblies is to provide the neutron flux and power level for the desired test conditions. Test-loop positions are located in a Y-shaped pattern in the active core area (Fig. 2). A major advantage of the Y-shaped pattern is that the test loops do not have to be disturbed when the driver fuel instrumentation is moved to gain access to the core for refueling.

Outside the active core area are three rows of reflector elements and four to six rows of shielding elements. The first reflector row contains the peripheral control rods for shim control.

The driver fuel assemblies are contained in hexagonal ducts and include axial shielding, the driver fuel pin bundle (a 217-pin hexagonal array of 0.23-inch-diameter fuel pins), a lower inlet for primary sodium coolant and an upper outlet region. The outlet region receives an instrumentation probe and contains gripping surfaces for fitting to the fuel-handling machine.

Reactor Nuclear Control—The main constraint upon in-core and peripheral control elements, from a core arrangement standpoint, is to maintain adequate control and a symmetrical geometry. The in-core shut-down control rods are fully withdrawn during normal operation and are inserted during refueling operations or for emergency shutdown.

The control rods have electromechanical drive mechanisms mounted on the reactor vessel head. During refueling, the space between the reactor head and the core is cleared to permit changeout of test assemblies and driver fuel assemblies. The rod drive train is fitted with a removable hanger rod between the drive mechanism and the poison subassembly.

Reactor Refueling System

Normal access to the reactor core is provided by three refueling plugs, each containing an in-vessel fuel handling

Doubling Time and the LMFBR

If the breeder reactor is to effectively conserve uranium ore supplies and stabilize fuel costs, doubling time—the time required to double the total fissile inventory in the reactor plus that being reprocessed—must be no greater than the forecast doubling time for electric power demand (approximately 10 years). Nuclear characteristics establish theoretical breeding ratios that can be achieved by the various fuels in fast and thermal reactors, but engineering design constraints and compromises reduce those theoretical breeding ratios and lengthen the doubling times that can be achieved in practice. Typical ranges of practicable doubling times cited for several proposed breeders are shown in the table.

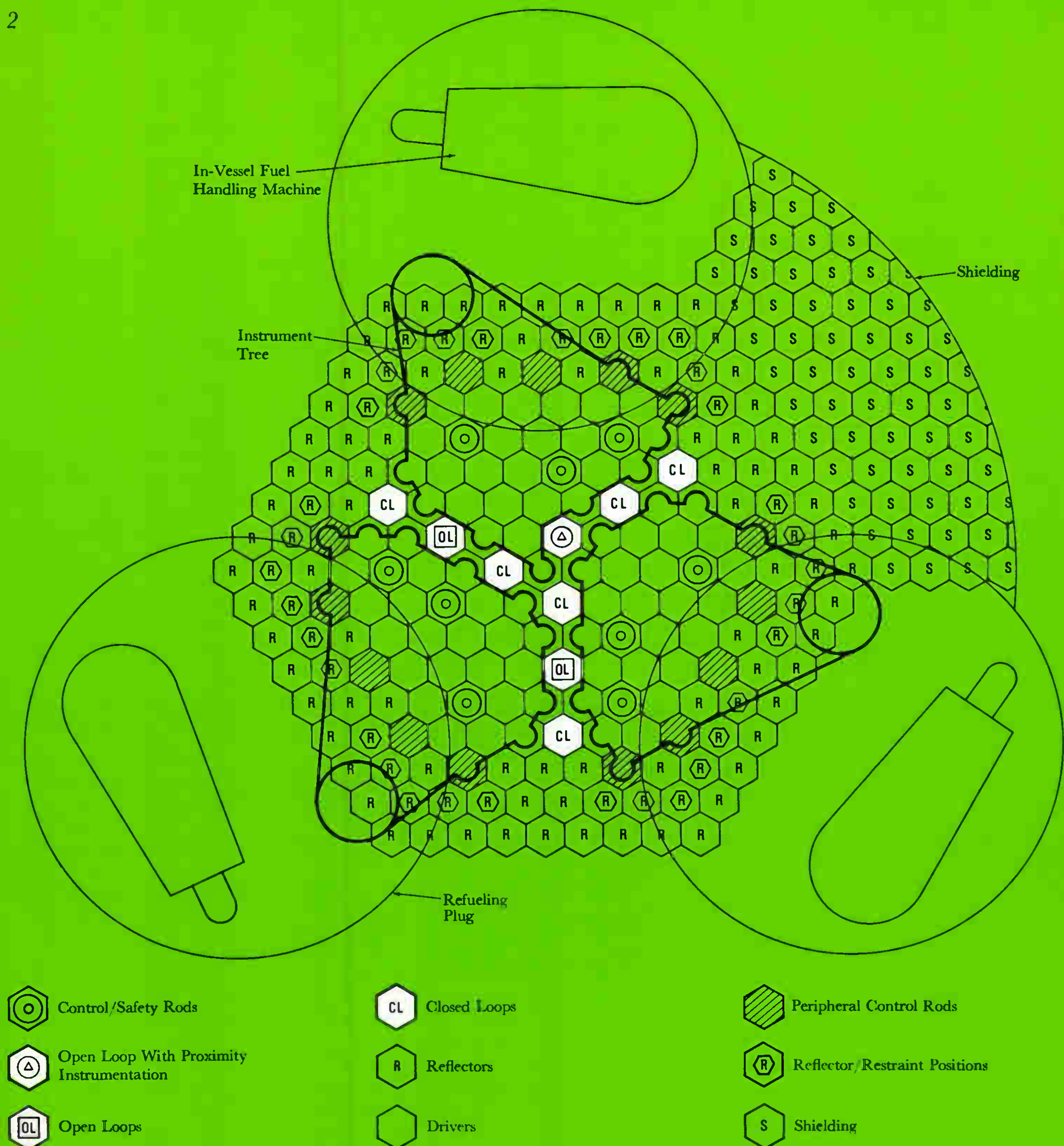
Of the fast breeders, only the sodium-cooled and gas-cooled reactors appear to offer the potential of less than 10-year doubling times. The sodium-cooled breeder was chosen by the AEC for its priority LMFBR program because of several inherent advantages of a liquid metal coolant for a breeder plant: the high boiling point of sodium will permit high-temperature, low-pressure coolant operation and thereby provide high thermal efficiency for the plant; and sodium has excellent heat transfer capability and high heat capacity, thereby minimizing pumping power requirements because a relatively low volume of coolant circulation is required. Furthermore, the large heat capacity of sodium provides good emergency cooling in the event of a power transient or loss of coolant pumping.

Breeding Ratios and Achievable Doubling Times

	Breeding Ratio	*Doubling Time*
Plutonium-Uranium Fast Breeders		
Sodium-Cooled (near term)	1.2	12-20 years
Sodium-Cooled (ultimate)	1.4–1.5	5-8 years
Steam-Cooled	1.1–1.3	20-40 years
Gas-Cooled (ultimate)	1.4–1.5	6-8 years
Uranium-Thorium Thermal Breeders		
Molten-Salt	1.05	9-14 years
Light-Water	~1.04	—

2—Reference core map illustrates the Y-shaped pattern of the test loop area, an arrangement that permits access to the core for refueling without disturbing test loops.

2



In-Vessel Fuel Handling Machine
Shielding
Instrument Tree
Refueling Plug
Control/Safety Rods
Open Loop With Proximity Instrumentation
Open Loops
Closed Loops
Reflectors
Drivers
Peripheral Control Rods
Reflector/Restraint Positions
Shielding

machine (IVFHM) and each servicing a one-third sector of the core. The refueling plugs and IVFHMs are removable for maintenance operations.

The IVFHM (Fig. 3) is used to transfer driver fuel assemblies and other core elements between a reactor core sector and an in-vessel storage facility. The IVFHM is operated from a remote control console outside the reactor shield.

Each IVFHM contains a grapple that can be positioned over any location in its sector. The grapple is operable only in the down position, where it picks up or releases a fuel subassembly or other core component in either the core or the in-vessel storage facility. Three in-vessel storage facilities (IVSF) are provided, one for each one-third sector of the core. Each storage facility has several positions which will accept a fuel subassembly or other core component.

To transfer a driver subassembly or other core component out of the reactor vessel, the component is positioned in a finned pot under a small transfer port in the reactor head so that the subassembly or core component can be withdrawn through the port within the pot filled with sodium. This assures cooling of the item even if the lifting device becomes stuck in a partially withdrawn position.

Handling of fuel elements and core components outside the reactor vessel is accomplished with shielded handling equipment.

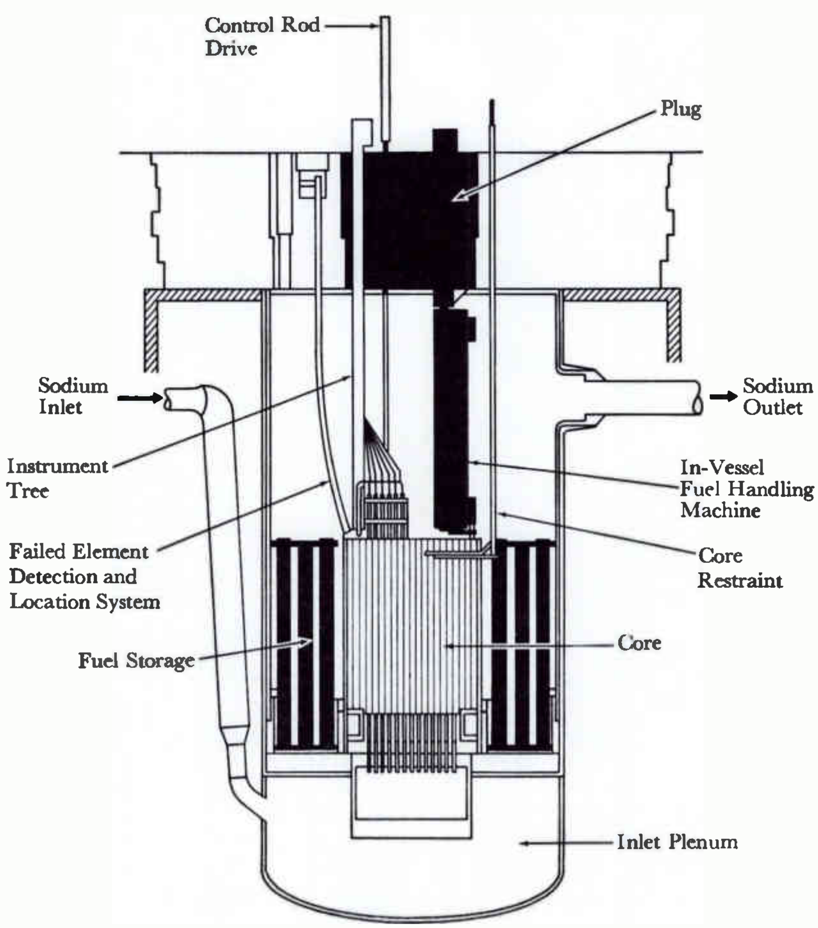
Reactor Core Instrumentation

Instrumentation probes are provided to each fuel subassembly in the core. Instrumentation consists of removable sensor packages that monitor subassembly coolant flow and temperature. The instrument probes are mounted on three instrumentation trees, one for each core sector. A column supports and positions the instrumentation tree over the core sector. During fuel handling, the instrument tree is raised (after control system hanger rods have been disconnected) and the tree is rotated away from the core. Maintenance access ports in the reactor cover provide capability for replacing the sensor packages at periodic intervals.

In-Vessel Out-of-Core Instrumentation—Coolant level is sensed with an inductance probe, and inlet coolant temperature is measured with thermocouples installed through thimbles that penetrate the vessel. Inlet coolant plenum pressure and cover gas pressure are monitored.

Failed Element Detection and Location—The primary failed element detection system is based on monitoring of reactor vessel cover gas. Each closed loop has an independent failed fuel detection system. Of the various failed element location systems considered, one based upon detection of released fission gases was chosen for the reference concept. This system has the potential for locating a failed element from which gas is released, either continuously or in a burst. It also has the potential for locating a failed element with the reactor shut down and for identifying and locating simultaneous

3



3—Elevation view of the reactor vessel shows the basic arrangement of internal components.

4—In operation, the top of the reactor vessel is covered by the inner barrier, shown as a dome. For refueling or reloading of test loops, the inner barrier is removed so that test specimens or core components can be moved from reactor vessel with shielded handling equipment.

element failures in different subassemblies.

A sodium sample is gathered at the top of each fuel subassembly position. To ensure that the sodium sample stream can obtain gas from any fuel pin in the subassembly and that the amount of gas in the sample stream is maximized, a vortex generator is located above the fuel pins in the fuel subassembly. Centrifugal action forces gas bubbles to the center of the vortex, where a tube collects the sodium and gas mixture.

Sodium samples are pumped to shielded cells where gas is separated from the sodium by distillation. The separated gas is delivered to a shielded location where radiation detectors monitor for an increase in gas activity.

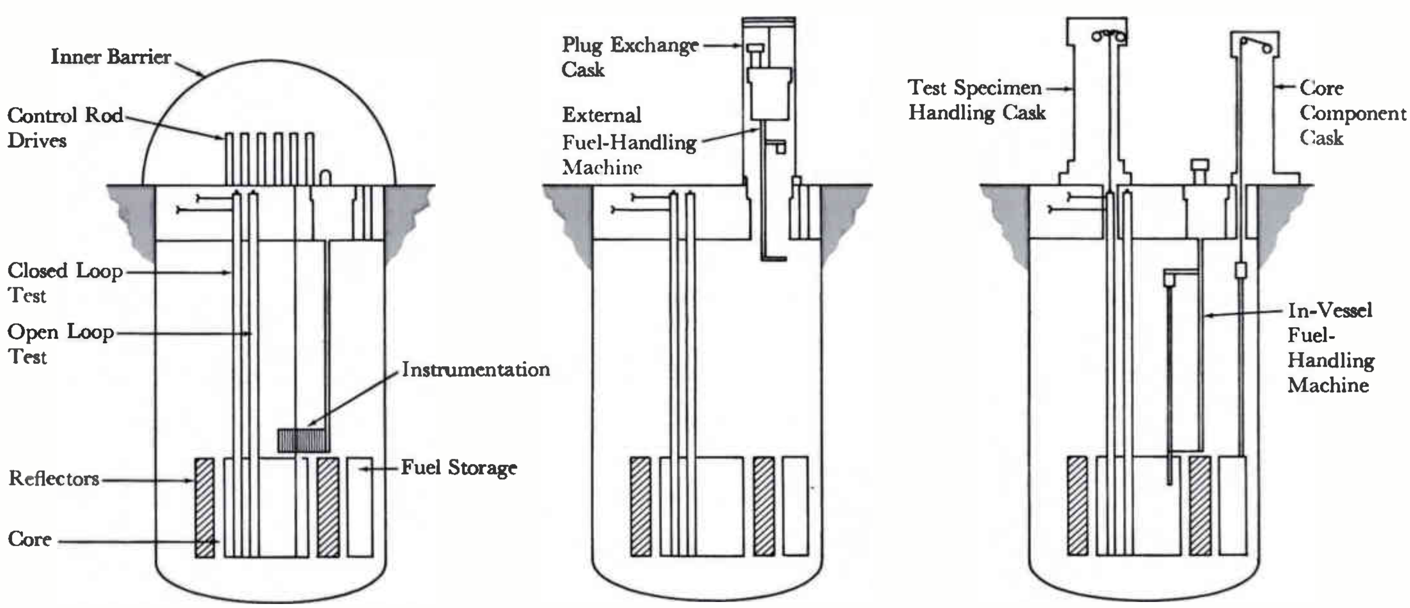
Irradiation Test Facilities

The reactor core provides nine test spaces along the 120-degree trisecting axes of the core. These are identified in Fig. 2 by CL (closed loop), OL (open loop), and Δ. However, the position adjacent to the central core position can only have proximity instrumentation to permit refueling access to the central position. This position is identified by the symbol Δ. The remaining eight positions can accommodate closed or open test loops. A maximum of six closed test loops are possible because each piping trench will accommodate only one closed loop located at the edge of the active core with piping running radially outward and one inside closed-loop position with piping extending along one side of the outboard position. Open test loops can be substituted for closed loops if desired.

All open and closed loop positions are accessible through independent ports that penetrate the vessel cover. Any other test position in the core is reached with the in-vessel handling machine.

There are two kinds of closed-loop instrumentation. One type is used for process surveillance and the other is used

4



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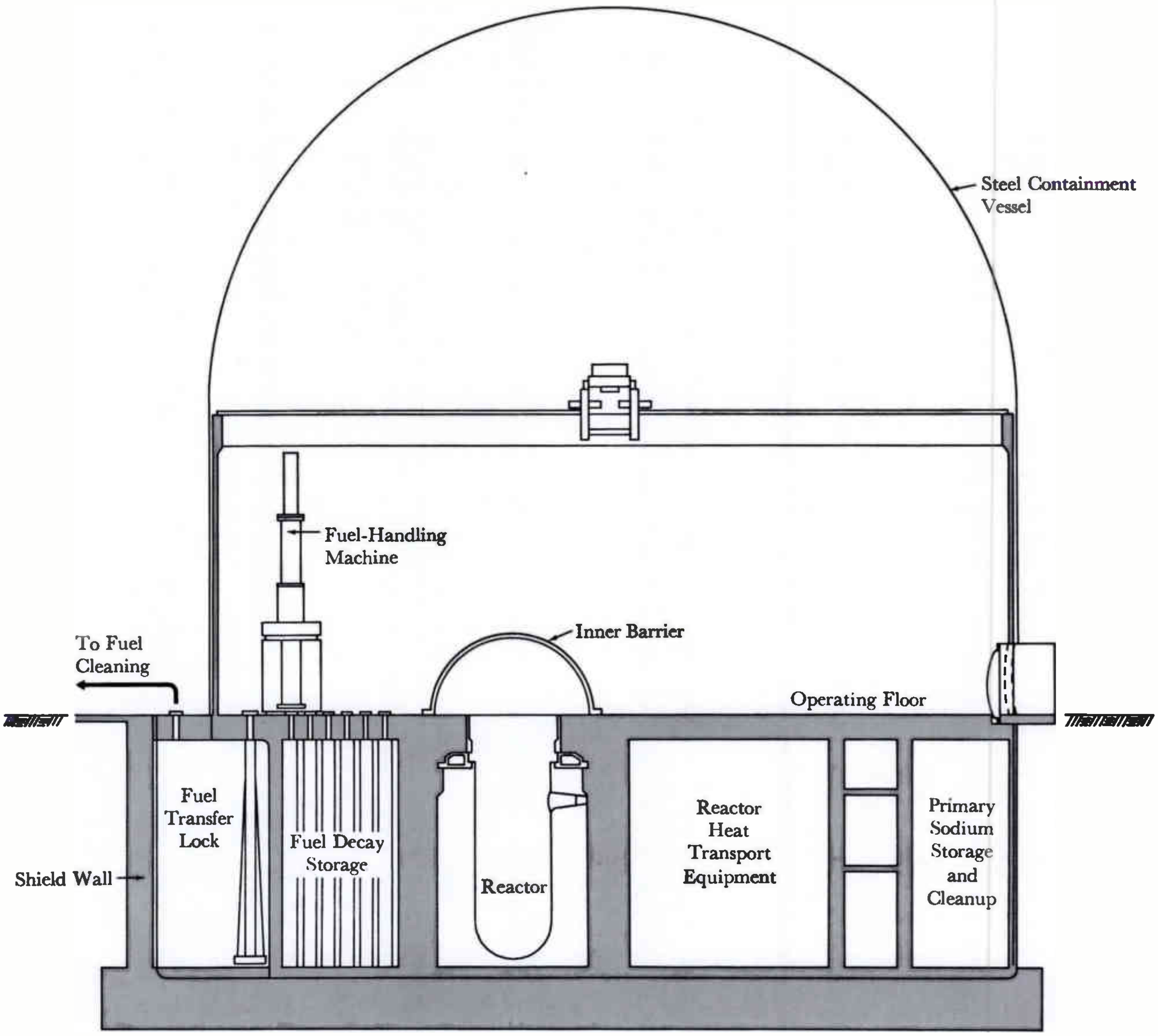
Steel Containment Vessel
Fuel-Handling Machine
Inner Barrier
To Fuel Cleaning
Operating Floor
Fuel Transfer Lock
Fuel Decay Storage
Reactor
Reactor Heat Transport Equipment
Primary Sodium Storage and Cleanup
Shield Wall

to obtain experimental information.

Process surveillance provides for measurement of inlet coolant temperature, outlet coolant temperature, coolant flow, and prompt fuel failure detection. Differential pressure across the test section is measured and neutron flux is monitored.

Experimenter's instrumentation for a fuel test may include provisions for measurement of such variables as fuel pin internal pressure and temperature, and fuel pin cladding temperature. For material tests, instrument lines are available for specimen temperature and strain gage measurements when appropriate sensors are developed.

The reactor core layout also provides locations for driver-fuel-size test assemblies at positions other than the nine central core positions. Proximity instrumentation can be provided for these positions in a manner similar to that for instrumenting driver fuel.

Open- and Closed-Loop Experiment Handling

The open and closed test loop nozzles in the reactor cover have a welded closure with a shielded seal plug. When the plug is removed, the opening through the nozzle allows withdrawal of a driver-size test assembly.

A *loop preparation cask* is used to prepare open and closed loops for experiment insertion or removal. The loop preparation cask contains a weld cutter, a vacuum cleaning system to pick up chips formed during cutting, a grapple for removing the loop shield seal-plug, and a welding head for rewelding the seal plug to the loop nozzle.

A shielded *loop handling machine* (LHM) is used for handling closed and open loop test assemblies. The LHM is used to move test assemblies from the reactor to either interim storage or the transfer cell. The machine is sodium cooled, with a cooling system utilizing NaK as the secondary coolant.

5—The FFTF reactor containment consists of an inner steel barrier positioned over the reactor vessel cover, an outer steel pressure vessel, and a steel lined reactor cavity vault.

Reactor Vessel

The reactor vessel and arrangement of internals is shown in Fig. 3. Sodium primary coolant enters the vessel through inlet lines near the lower end. Inlet flow is mixed in a large plenum below the core to provide smooth flow of coolant to the core. Sodium exits from three large main coolant lines above the core.

Since it is not considered feasible to operate the vessel wall at a temperature of 1200 degrees F, a bypass flow of inlet sodium is used to cool the barrel and outlet nozzles to a maximum of approximately 1000 degrees F and to suppress the scram transients.

The reactor vessel is about 17 feet in diameter and 54 feet high. Barrel thickness is about two inches, a relatively thin-walled construction made possible because of the low vapor pressure of liquid sodium at the 1100-degree bulk driver-core outlet temperature.

The vessel head is of low-alloy steel, clad with type 304 stainless steel. Overall diameter of the head is about 22 feet, with a structural depth of about 3 feet.

The vessel is top-mounted by suspension from an upper ring flange, which rests on a support skirt, an arrangement that accommodates radial ring flange expansion.

Double-Barrier Containment

The overall FFTF reactor containment provides a double barrier to restrict radionuclide leakage to the atmosphere to acceptable levels (Fig. 5). The outer and final barrier to the environs is a steel pressure vessel, with a leakage rate of less than one volume percent per day at design pressure. It is designed in accordance with the ASME Nuclear Pressure Vessel Code and will be tested to determine its leak rate initially and at periodic intervals thereafter.

The inner containment barrier is the reactor machinery dome. This is a steel pressure vessel positioned over the reactor vessel cover during reactor operation. It has an air atmosphere. The reactor machinery dome is elliptical, about 30 feet in diameter and 10 feet high. It is removed during shutdown for maintenance and refueling operations.

The reactor cavity vault, a cylindrical concrete structure that surrounds the reactor vessel, is steel lined to prevent leakage and designed to withstand high pressure. An argon atmosphere in the reactor cavity vault minimizes the possibility of a sodium-air reaction. The concrete is thermally insulated and will have embedded cooling coils to supplement the nitrogen cooling and limit temperatures within the structural concrete.

FFTF and Demonstration LMFBRs

Because the FFTF reactor and the LMFBR demonstration plants will be similar in several respects, much of the experience gained in designing and building the FFTF will be valuable to developers of the demonstration plants.

The first demonstration plant[4] will lag the FFTF by about two years. This means that some fuel tests and test results or operating experiences from the FFTF will be available before the design of this demonstration plant is completed. The task of designing the FFTF reactor plant system will clearly pinpoint areas in which knowledge is lacking and where additional emphasis must be placed on research and development work. Designing a real plant brings out practicalities that no amount of conceptual studies can produce, so demonstration plant designers will be made aware of potential problems that could affect plant design much sooner than these problems would otherwise have come to the surface.

Thus, the greatest benefit to the first LMFBR demonstration plant design is expected to come from the early cross fertilization of ideas, which will permit both FFTF designers and the LMFBR prototype plant designers to borrow the best from each other.

Westinghouse ENGINEER **November 1969**

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The Apollo Color Television Camera

L. L. Niemyer, Jr.

A proven low-light-level monochrome camera design using the sensitive and versatile SEC camera tube was converted to a field-sequential color camera to provide earth-bound viewers their first color TV spectacular from space.

During the Apollo 10 and 11 flights, a compact color television camera provided real-time color scenes of the earth, the moon, spacecraft maneuvers, and the interior of the command module. The excellent performance of the camera under these abnormal and adverse conditions was witnessed by millions of viewers.

The camera was designed and developed for the NASA Manned Spacecraft Center by the Westinghouse Aerospace Division. The camera is unique in its concept, both for its role in NASA's total color TV system and for its configuration and performance as a television camera. The camera generates a field-sequential color signal using a single image tube and a rotating filter wheel. A ground station color converter changes the sequential color signal to the standard NTSC color signal for broadcasting. (See *Television Lines, Fields, and Frames*, page 176.) This approach permits a simple and reliable camera aboard the spacecraft and relegates the complexity of generating the compatible broadcast signal to the ground station where the complex signal processing required for color broadcasting is more readily handled. A conventional NTSC compatible color camera, with its three image tubes and associated signal-processing circuitry, could not have satisfied either the low weight and power requirements or the low-light-level performance requirements for the Apollo camera.

Developing the Camera

The field-sequential color camera is basically a black-and-white camera, synchronized with a three-color filter wheel in front of the camera tube. This filter wheel design made it possible to utilize the basic electronics and packaging from a Westinghouse monochrome camera that had already been developed. This existing family of compact cameras (WTC-13 and WTC-14) has been used for televising rocket shots, for underseas imaging tasks, and for other military applications where a low-power, lightweight camera with low-light-level capability is required. These cameras use the Westinghouse SEC (secondary electron conduction) camera tube, which provides the low-lag imaging sensitivity required for a color camera. Also, since the field rate of the WTC-13 camera conforms to the desired EIA standard (525-line scan, 60 fields per second, 2:1 interlace), the electronic package of the WTC-13 camera could be readily adapted for use in the field-sequential color camera.

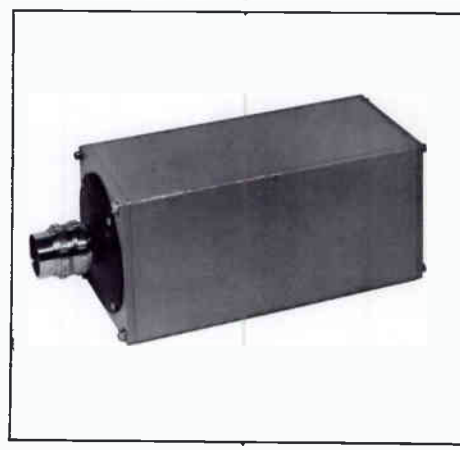
The Apollo color camera and its predecessor (WTC-13) are shown in Fig. 1. The color camera is 17 inches long, including the zoom lens, weighs only 13 pounds, and is completely self contained. (The WTC-13 camera weighs 8 pounds.) A small four-wire cable carrying a single dc input voltage and a composite video output suitable for modulating the transmitter is the only connection required.

A small viewfinder monitor occupying a volume of only 85 cubic inches and using 2.5 watts of power is used to assist the astronaut in aiming and focusing the camera. Thus, the astronaut does not have to depend on ground control for instructions.

The Total System

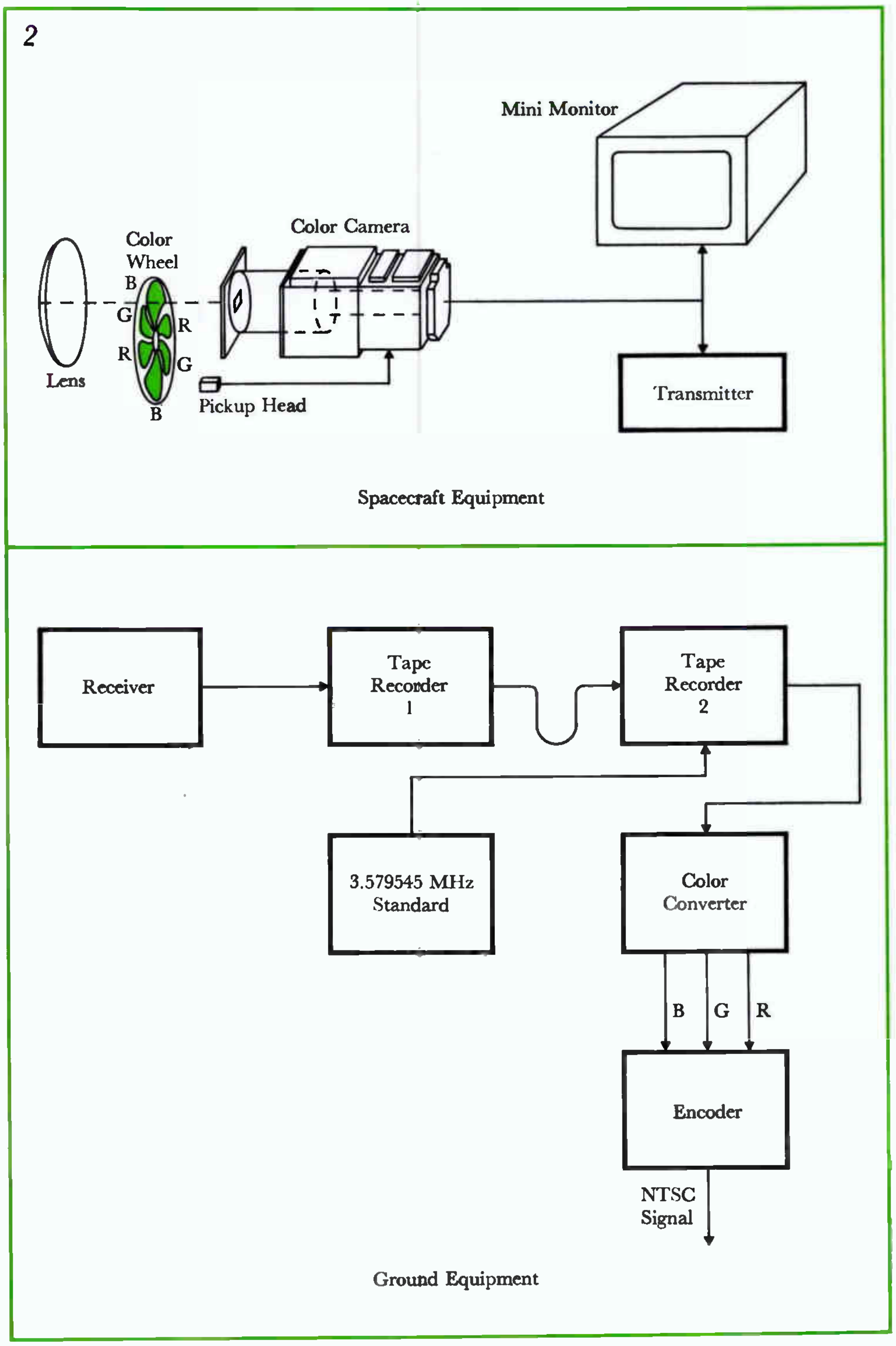
A general layout of NASA's Apollo color television system is shown in Fig. 2. The image is focused by the lens through the filter wheel onto the faceplate of the image tube. As the wheel positions a red filter in the field, the image tube stores the red information of the scene being viewed and then reads it out. This information is processed by the electronics of the camera and is fed to the "Mini Monitor" and to the 20-watt transmitter. The green and blue signals are generated in the same fashion and, since the color wheel is changing filters at a field rate of 60 fields per second, color information is generated at the standard field-sequential rate.

The field-sequential color signals, transmitted to the earth in the S-band region, are picked up by two receiving stations—one at Madrid and the other at Goldstone, California—and relayed to Houston. Here, the received signal is fed to two tape recorders in series to compensate the signal for doppler frequency shift. The



1—The Westinghouse-built components of NASA's Apollo color television system are the field-sequential color camera and a miniature monitor that aids the astronaut in aiming and focusing the camera. The camera (above) and its monochrome predecessor (below) use essentially the same electronic package. The color wheel assembly and synchronizing and driving circuitry were the primary adaptations required to convert the monochrome camera to a field-sequential color camera.

L. L. Niemyer, Jr. is a design engineer at the Aerospace Division, Westinghouse Defense and Space Center, Baltimore, Maryland.



2—The Apollo color television system uses a simple and reliable field sequential color camera to generate the signal transmitted to earth.

Ground processing equipment corrects the signal for doppler shift and converts the field-sequential signal to a standard NTSC video signal for broadcasting.

information is recorded as received by the first unit, and the second unit is driven with the subcarrier standard frequency, which adjusts tape speed to correct frequency errors introduced by doppler shift. A single tape recorder could have been used but the transmission would have had to be completely recorded before performing the second operation, thereby delaying the presentation at least that long. With two recorders in series, the delay is only about 10 seconds from input to output.

The sequential color information is fed from the second recorder to a color converter, a storage and read-out device that holds six fields in memory (red, blue, green, red, blue, green) and presents three fields in parallel at the output. (See *Television Lines, Fields, and Frames*, page 176.) As a new field is placed into memory, the oldest field is erased so that the information is updated at the field-sequential rate.

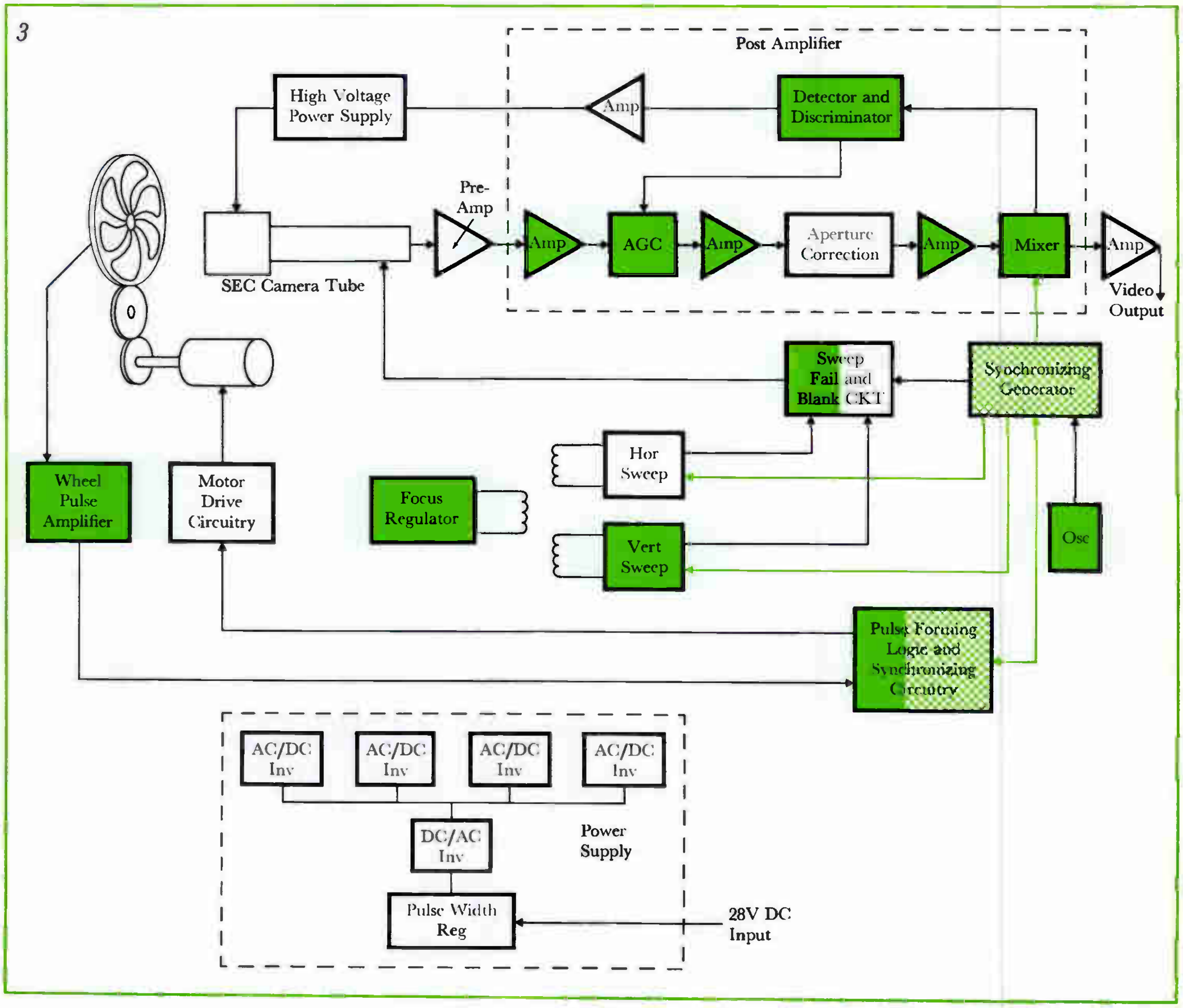
And finally, the color encoder transforms the color converter output to an NTSC signal for commercial broadcasting. The quality of the original color signal from the camera can be appreciated from the fact that the video signal, when viewed from the vicinity of the moon, may be degraded by as much as 105 dBm (1 milliwatt reference power) between the camera output and the input to home television receivers.

The Apollo Color Camera Design

A block diagram of the color camera is shown in Fig. 3. Almost 70 percent of the functional blocks are integrated circuits, not including the power supplies. The extent of medium scale integration employed is indicated by cross hatch.

The color camera with case removed is shown in Fig. 4a. It consists of three sections: the basic chassis is the monochrome camera with synchronization, pulse-forming, and drive circuitry added for the color adaptation; the second section is attached under the camera and forms the housing for the transformer and motor; and the third section, attached to the front of the camera chassis, contains the motor, gearing, and filter-wheel assembly and also serves as the lens mount.

3



3—The basic circuit components of the Apollo color television camera are shown in this block diagram. The colored portions represent integrated circuitry.

The video signal from the SEC camera tube is fed to the *preamplifier*. The preamplifier is made up of discrete components, primarily to provide low-noise performance. The input is a field-effect-transistor stage with a tube-load resistor of 300 kilohms. This is followed by a feed-back pair. The equivalent input noise current is approximately 1 nanoampere for 2 megahertz.

The *post amplifier* includes all the circuitry from the preamplifier to the high-voltage driver. Most of this circuitry is made up of hybrid integrated circuits. The output is a current source, which delivers a 3.5-volt swing into 100 ohms.

The *vertical deflection circuit* is of the Miller run-up variety, and it uses two integrated circuits and a dual transistor for the active components. The size of the scan is varied by adjusting the feedback resistor and the centering adjusted by offsetting the input operational amplifier.

The *horizontal deflection circuit* is a high efficiency reaction type with one percent linearity.

The *two power* supplies in the color camera are the high-voltage supply, driven by the ALC loop, and the low-voltage supply receiving 28-volt primary power from the spacecraft. The low-voltage power supply develops all the voltages for operating the camera circuitry and the image tube with the exception of high voltage for the camera tube photocathode. Its efficiency is approximately 60 percent at the nominal input voltage.

An internal view of the predecessor to the color camera, the WTC-13 monochrome camera, is shown in Fig. 4b. The open circuit board is the sync/sweep board, and it displays the three techniques of packaging: modules, medium scale integration, and conventional printed circuit wiring. The large flat package in the center of the board is the synchronizer, which delivers horizontal drive, vertical drive, mixed blank and mixed sync at its outputs. Fig. 4c shows the interior of this 1-inch square by ⅛-inch package, which contains 22 integrated circuit chips—14 dual bistable multivibrators and 8 gate circuits. The synchronizing generator is completely bistable, has no adjustments, and therefore is ideally suited for medium scale integration.

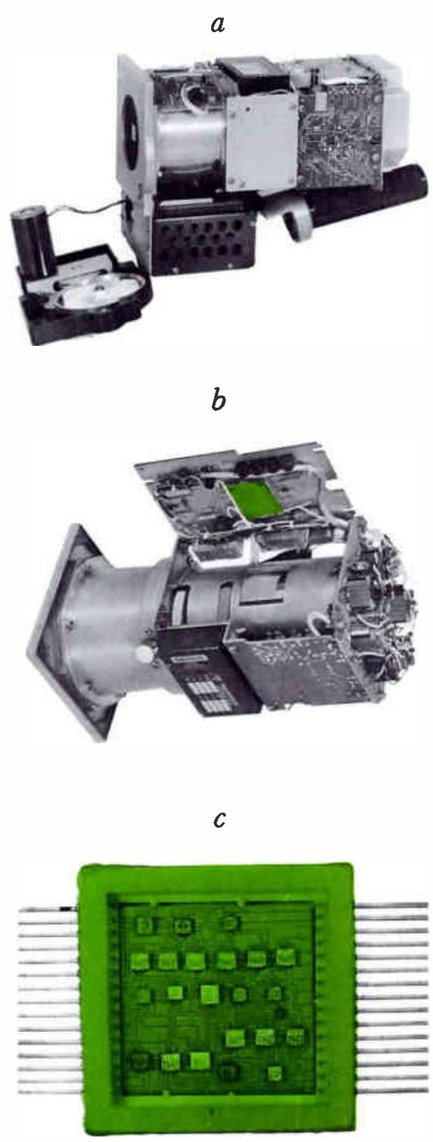
To conserve space, the printed-circuit boards are mounted with the printed circuit tracks outside and the modules and components projected inward around the cylindrical housing that contains the deflection assembly.

The input voltage to the camera is 28 ± 4 volts dc, and power consumption is 20 watts nominally. Camera output is a standard EIA format at color standard frequencies with the exception that it does not carry the 3.58 MHz color reference burst, which is added at the ground station. It is a black negative signal from -0.75 to $+2.75$ volts (into 100 ohms), constrained within 20 percent to prevent over-deviation of the transmitter.

The bandpass of the camera is 4.5 megahertz with a 20 dB/octave roll off, which provides a theoretical limiting horizontal resolution of 360 TV lines/vertical dimension. Due to the fact that the signal-to-noise (S/N) ratio is high and that the roll off is finite, more extensive calculations and experience have shown the horizontal resolution to be in excess of 425 TV lines/vertical dimension.

The limiting vertical resolution fixed by the number of scan lines and their statistical positioning factor (Kell factor) is approximately 350 TV lines/vertical dimension.

The bandpass of the camera considerably exceeds the bandpass of the command module transmitter, which sets



4—The Apollo color television camera (*a*) with case removed to show the components added to the low-light-level military camera package (*b*). Medium scale integration techniques were used where applicable (*c*) to minimize size, weight, and power requirements.

the limiting horizontal resolution of the system. (Limiting horizontal resolution is often referred to as resolution or limiting resolution.) The theoretical limit set by the transmitter bandpass is 160 TV lines, but because of high S/N and some camera processing, the resolution is actually in excess of 200 TV lines.

The Apollo color camera controls are limited to one switch associated with the electronics and the common lens adjustments of focus, iris and zoom. The switch is used to change the automatic light control detector circuitry from an averaging type for "inside" scenes to a peak detector type for "outside" scenes. (A typical scene for the outside mode would be the earth subtending one third of the vertical field of view.)

The lens is a standard commercial cine lens that has been extensively modified. The most significant modifications were to the format, adjusting its diagonal from 12.7 mm to 25 mm and to the mechanical mechanism (zoom, focus, iris). The lens was totally disassembled, baked in a vacuum, space lubricated and rebuilt. The lens characteristics are listed in Table I.

Testing for Space Environment

The original WTC-13 monochrome camera was designed to rigid military specifications, and the color camera has been designed to these same specifications. However the short delivery schedule did not permit sufficient time to evaluate those efforts, so testing was limited to the command module environment. Although testing in other areas was limited, the camera, lens, monitor and cables were thoroughly tested for complete operation in the command module oxygen environment. Another requirement was that the camera be subjected, nonoperating, to a vacuum and operate after exposure to vacuum. Therefore, the equipment was completely tested for vacuum transition.

Shock and vibration at liftoff and splashdown was accommodated by testing to determine a safe level that the camera could stand and one that could be acquired by packing. This level was set as a limit and was achieved by appropriate packaging.

The thermal situation in the command module while it is in space is unusual. The atmosphere is oxygen, kept at 5 psia, which presents a question of convection cooling because of the low density. In addition, the oxygen atmosphere is weightless and convection would have to depend on forced flow. Since the amount of forced flow generated by movement of the astronauts and several cooling fans is also an unknown, the camera has to be passively cooled by radiation.

Evaluation of the thermal design indicated that the camera could be used indefinitely in the command module. This evaluation was borne out by the long uninterrupted transmissions from the Apollo 10 and 11 flights. Moreover, the existing camera is thermally suitable for operation in the lunar module (LEM), since the environment is the same in the two modules. However, the LEM transmitter poses much more severe bandpass restrictions than does the command module transmitter, and interface equipment will be required.

Use of the camera on the lunar surface poses both vacuum and thermal problems. Assuming that the camera could be operated in a vacuum, there are periods when the lunar surface thermal environment would be suitable for the existing camera. If desired, the camera could be modified to extend its thermal range of operation. However, no decision has been reached as to whether the mission objectives should be extended to include more extensive use of the color camera.

The SEC Camera Tube

The key element of the camera is the SEC camera tube (Westinghouse WL-30691). This image tube is ideally suited for space applications because of its size, weight, power requirements, ruggedness, stability and simplicity of operation. It has in addition the features of wide dynamic range, tolerance to high saturation levels, and an electrical gain mechanism. The SEC tube has a linear dynamic range of more than 1000 to 1 for a high S/N and will accommodate saturating bright areas without blooming. The lens extends this range by 100 to 1. These features are essential for a portable unit such as the Apollo camera because it must work with almost no operational controls to handle changing or uncontrolled scene lighting.

For the Apollo color camera, the two most desirable characteristics of the SEC camera tube are its low-light-level capability and its lack of lag (Fig. 5). The low-light-level capability comes from the noiseless gain mechanisms and generally noiseless performance of the tube. The lack of lag is due to the signal generating mechanism of the SEC target and its relatively low capacitance.

Lag is a problem when viewing a moving scene because it results in a loss of resolution in a monochrome system and, in addition, an edge color breakup in a field-sequential color system. With most image tubes, such as a vidicon or an image orthicon, resolution becomes especially poor at low light levels. However, the lag characteristic of the SEC camera tube at low light levels is quite good and therefore its performance remains useful in that region.

The need for good low-light-level capability for the Apollo camera arises from two basic conditions—low lighting in the command module and light losses in the color wheel mechanism. The command module has a wide spread of light levels from spectral reflections of the sun to shadow areas of less than one footcandle. Since special lighting for the purpose of television is not practicable because of power, space, weight and layout problems, the entire light range extending to the low levels must be detected by the image tube.

The color-wheel losses are not unusual for a color television camera. Light losses are usually experienced through lens systems and the color filters in studio cameras. Thus, although the losses are kept to a minimum for the Apollo color camera, some are unavoidable. The lens in the wide-open position has a T number of 5.1, which is a 104 to 1 light loss. The ratio of the photocathode area to the product of filter and photocathode area is approximately 5 to 1 for all filters. The ratio of field time to transmission time is 2.5 to 1. Therefore, the total light loss is the product of these individual losses, or about 1290 to 1. In other words, for a 1.3 footcandle scene illumination with unity reflectivity, the image tube would receive approximately 0.001 footcandle faceplate illumination, a level well below the capability of a standard vidicon. However, the SEC camera tube, with the 2 MHz bandpass of the color camera, provides a S/N of approximately 35 dB at this light level, a signal that is more than adequate.

Automatic Light Control—The gain mechanism of the SEC camera tube is controlled by varying photocathode voltage from -2.5 to -8 kV. Automatic gain control is accomplished by sampling the video signal at the mixer and deriving a signal to control the photocathode potential. This control enables the SEC camera tube to handle a light range greater than 1000 to 1 and deliver a video signal with a minimum S/N of 32 dB.

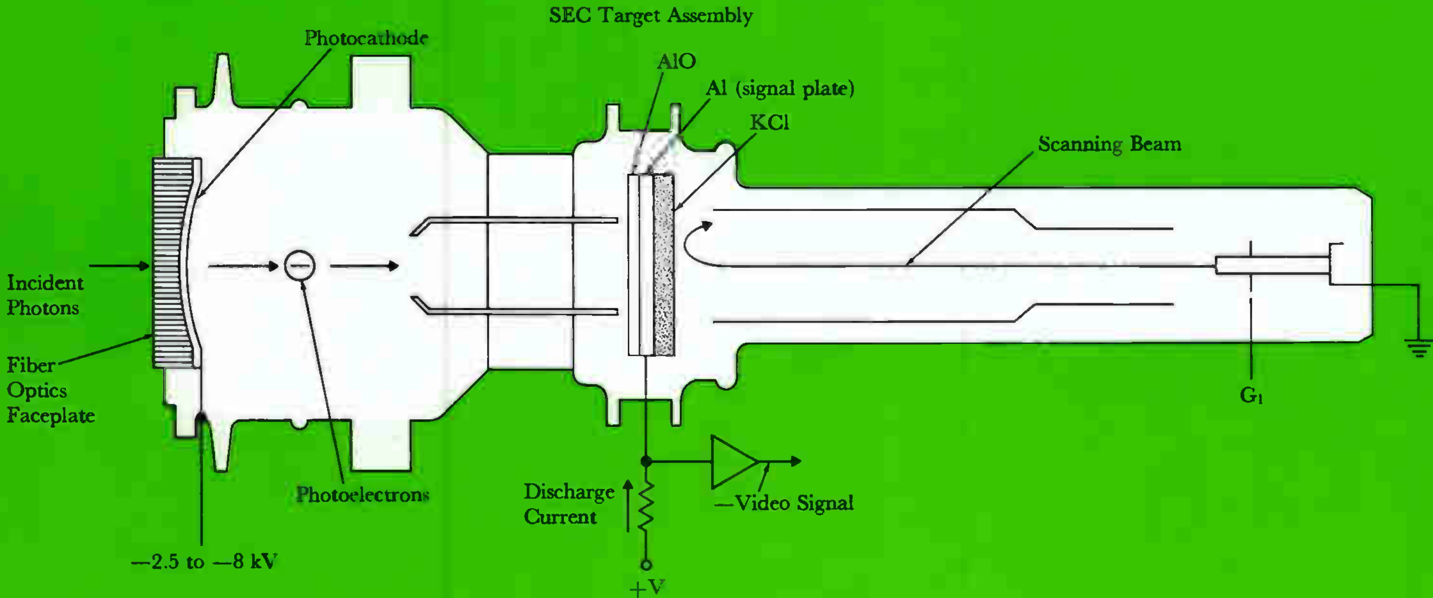
The gain curve of the SEC camera tube is nonlinear (Fig. 6), providing little additional gain for photocathode voltages greater than 5.5 kV. The color camera design takes advantage of this lack of gain above 5.5 kV to provide a safety factor for preventing the image tube from being damaged. (The damage level to an SEC camera tube is proportional to the exposure time for a given voltage.)

At very low light levels, photocathode voltage is allowed to rise to -8 kV to achieve maximum sensitivity. But when light level rises and the S/N output of the camera rises above 25 dB, photocathode potential is immediately limited to 5.5 kV. Although this results in a 20 percent decrease in S/N, this loss is hardly per-

Table I. Lens Characteristics

T Number		5.1 to 51
Zoom Ratio		6:1
Focal Length		25 to 150 mm
Field of View: Wide angle—43° horizontal Narrow angle—7° horizontal		
	Near Focus	*f Number*
Wide Angle	20"	4.4
Wide Angle	1"	44
Narrow Angle	3"	4.4
Narrow Angle	2"	44

5



5—The light image is focused by the lens on the image faceplate. This light image causes the S-20 photocathode to emit photoelectrons, which are focused and accelerated by the geometry and an electrostatic field on the SEC target. Target gain is controlled by adjusting the photocathode accelerating potential (—2.5 kV to —8 kV).

The high-energy photoelectrons penetrate the aluminum oxide and aluminum layers to the KCl, where they strike a particle causing secondary electrons. The positive potential of the aluminum layer causes the secondary electrons to migrate to it, where they position with respect to the positive particle in the KCl layer. The electron charge is held in place on the signal plate until the target is swept by the electron beam. The electron beam deposits on the positively charged areas, returning the KCl surface to gun-cathode potential. This charging current, which constitutes the video signal, is capacitively coupled to the signal plate and causes current flow to the signal plate, developing the video voltage signal across the load resistor. Electron gain of the SEC target can be as high as 100. The combined gain of the image section and the SEC target is typically 10,000 μA/lumen.

The low-lag characteristic of the SEC target makes possible the excellent dynamic performance of the camera tube. The signal generating mechanism of the SEC target is essentially without lag because when secondary electrons are released into the vacuum interstices in the highly porous KCl film, secondary electron conduction takes place in a vacuum rather than in a conduction band. Therefore, the persistence effect caused by trapping and subsequent release of charge carriers in a conduction band is avoided. Thus, when the electron beam scans the KCl surface, electrons are deposited on the positively charged areas and no delayed positive charges appear after the beam sweep.

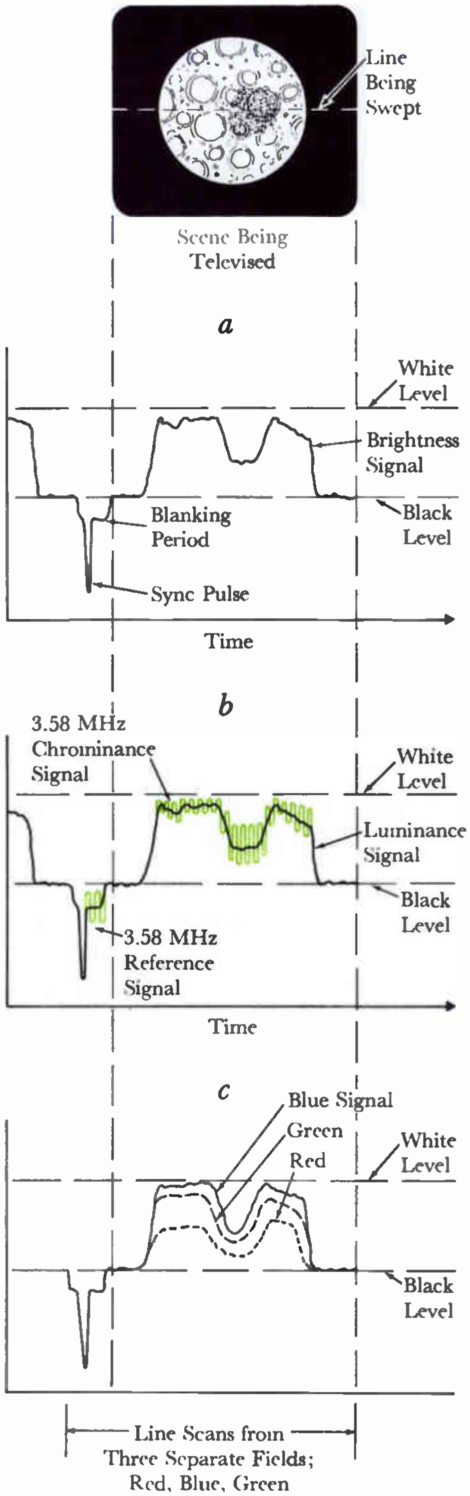
The relative freedom from lag in the SEC target makes possible a camera tube with a dynamic sensitivity that is only slightly less than its static sensitivity. For example, the SEC tube will develop resolution for a 20-second dynamic scene equal to that obtained with a static scene if the light level on the dynamic scene is increased by 2.5; under similar circumstances, an image orthicon requires an increase in light level of about 100.

Television Lines, Fields, and Frames

A black-and-white television broadcast signal for a single line scan (Fig. *a*) consists of a synchronizing pulse to lock the receiver's scanning beam to the broadcast scanning frequency, a blanking period that provides time for the scanning beam to return from the previous scan, and the video brightness signal that reproduces the brightness level of the scene being scanned. A complete frame (picture) of 525 lines is produced in 1/30 second, but, to reduce flicker, each frame actually consists of two interlaced fields, one field being the even numbered lines and the next field the odd lines. Thus, the standard TV vertical frequency is 60 fields per second. [To conserve bandwidth, the Westinghouse black-and-white TV camera[1] used for the moon-landing telecast transmits video information to earth at 10 frames per second (no interlacing) and 320 lines. From this information, signal processing at the ground station synthesizes a standard interlaced 60-field-per-second signal for broadcasting.]

The NTSC (National Television System Committee)[2] standard color signal (Fig. *b*) is fully compatible with the standard monochrome broadcast signal even though the color signal contains three different kinds of video information. A color camera uses three camera tubes to produce three separate video signals, one for each primary color. These color signals are electronically matrixed to provide two signals for broadcasting: the ***luminance*** signal is synthesized from the three primary color signals—59 percent green, 30 percent red, and 11 percent blue—but for all practical purposes is identical to a monochrome signal; the ***chrominance*** signal, also derived from the three primary color signals, is superimposed on the luminance signal and is both phase and amplitude modulated. The luminance and chrominance signals are reprocessed at the color television receiver to reproduce the three primary color signals. But to a black-and-white receiver, the chrominance signal frequency (3.58 MHz) is such that signals from consecutive fields are 180 degrees out of phase and the chrominance signal is blanked out.*

The mechanical field-sequential scheme used for the Apollo color camera uses a color wheel to insert color filters before a single camera tube so that red, blue, and green fields are transmitted sequentially at the standard color field rate (59.94 fields/second). Thus, a full-color field must be synthesized from three separate single-color fields (Fig. *c*). This is accomplished at the ground station with a magnetic disk recorder of the type used for instant replay. The color fields, transmitted from the camera in serial form, are switched and recorded on six separate tracks on a magnetic disk (red, blue, green, red, blue, green). Six tracks are used rather than three to provide time for erasure between recordings. Switching logic and delay circuits are used to develop synchronized red, blue, and green output fields in parallel. Since red, blue, and green fields are coming into the recorder at 59.94 fields per second in serial form, and are commutated out at 59.94 fields per second in parallel, each field transmitted from the camera must be used three times, yielding an effective color field rate of 20 fields per second. The three parallel output signals from the recorder are fed to a color encoder where they are converted to the standard NTSC signal (Fig. *b*) for broadcasting.



*Actually, this cancellation is due to the choice of the subcarrier frequency of 3.579545 MHz, which is an odd multiple of one half the line frequency. The line frequency chosen is 15734.264 Hz, and $(15734.264/2) \times 455 = 3.579545$ MHz. Since there are 252.5 lines per field, $15734.264 \div 252.5 = 59.94$ fields per second, the standard vertical frequency for color.

ceptible to the observer. The amplifier automatic gain control circuitry (AGC) limits photocathode voltage to 5.5 kV maximum over a light range, but permits the voltage to drop for higher light levels. The photocathode voltage reduction from this point is linear because the gain curve is reasonably linear below 5.5 kV.

The Color Wheel and Motor

The color wheel is a compromise in size, transmission efficiency, and uniformity. If it could have been large and rotated stably, its transmission could have approached 100 percent with no deviation in uniformity. However, size was a primary consideration for the Apollo camera and compromises were necessary, with some innovations to minimize losses.

The color wheel has six sections comprising two sets of red, green and blue filters (Fig. 2). This configuration is dictated by the speed of the motor (1798.2 r/min) and the gear ratio of 3 to 1. Thus, the color wheel rotates at 599.4 r/min (or 99.9 r/s) and yields six fields per revolution at the standard vertical color frequency of 59.94 hertz.

Between the filters are opaque regions, a compromise required by the small (three-inch) diameter of the color wheel. As the red filter rotates past the image tube faceplate, the red component of light information is integrated by the target. To prevent color mixing, this information must be read off the target by the scanning beam before the green filter arrives. Thus, the electron beam scan must follow the red filter and precede the green filter. With a large-diameter wheel and the filters positioned on the outer rim of the wheel, the dividing line between filters travels almost parallel with the scanning beam so that there is no problem in keeping the scanning beam operating within the confines of the desired filter. However, because of the small diameter of the wheel used in the color camera, it is necessary to use an opaque region between each filter, the size and shape of which is determined by wheel size and by the stability of the scanning beam and wheel rotation. Frictional load shifts and hunting in the motor cause some erratic motion in the filter wheel so the size of the opaque region allows for these irregularities.

Once the opaque region is sized, the scanning electron beam must be synchronized with the wheel to keep the beam within the confines of the opaque region. This is accomplished by sensing wheel position with a pickup device (Fig. 3). The wheel pulse signal is amplified and used to set the synchronizing generator that controls the sweep circuits, thus keeping the beam correctly positioned relative to color wheel position.

The ability of this system to keep the scanning beam in the opaque region depends to a large extent upon the stability of the synchronous motor, which is only as good as its input frequency. For that reason, the motor input is referenced to the camera's basic clock frequency, which has excellent stability. To minimize power consumption, the motor is driven with a pulse input, which results in a total power consumption of approximately 12 watts at nominal input voltage. (If a class A driver had been used to drive the motor, total power would have exceeded 30 watts.)

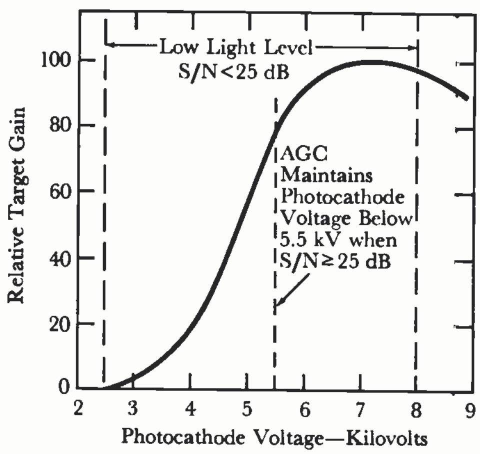
The filters are dichroic depositions selected for maximum transmission and spectral response. When modified by the spectral response of the S20 photocathode and a daylight source, their response closely matches that of the P22 phosphor. These filters are deposited on one piece of glass and sealed by another.

The Role of Color Television

The feasibility of using color television aboard a spacecraft has been proven and the public interest confirmed. The question now arises as to its practical application. The astronauts demonstrated some of these applications during the Apollo 10 and 11 flights when they televised the crew indicating their condition, the instrumentation, and the unusual condensation in the tunnel for ground support evaluation. In future missions, the color camera might also be used as a navigation aid by viewing the moon's surface with long focal length lenses and having ground support personnel determine spacecraft position by comparing the telecast picture with lunar maps.

There are many other potential applications, most of which can be classified as remote viewing; this classification includes viewing at points that are inaccessible because of position, or because of a hostile environment. For the present these are the most likely conditions for television applications in the space program because spacecraft by necessity have limited viewing positions and outer space is certainly an extremely hostile environment for man.

In addition to providing real-time communications useful to NASA ground personnel and the public, the Apollo color system has another scientific feature that should not be overlooked. The use of a calibrated color filter wheel permits true color information to be derived by data reduction from the recorded video transmission. This technique would provide a form of spectral analysis that might have useful applications in future space missions.



6—Gain of the SEC camera tube is controlled by adjusting photocathode voltage between −2.5 kV and −8 kV. For very low light level scenes, the image uses the full voltage; for scenes with S/N at 25 dB, the automatic light control reduces photocathode voltage to 5.5 kV to protect the camera tube with an imperceptible loss in S/N.

REFERENCES:
[1]E. L. Svensson, "The Lunar Television Camera," *Westinghouse ENGINEER*, March 1968, p 46-51.
[2]C. A. Scarlott, "Color Television," *Westinghouse ENGINEER*, May 1954, p 98-105.

Solid-State Relay Improves Control Capability and Reliability

John P. Conner

A new control device can be used interchangeably with electromechanical industrial control relays but is faster, has longer life, produces no acoustical noise, and withstands unfavorable environments without protection.

In the wide application area between manual machine control and electronic control, industrial control relays have traditionally provided most functions in arrays ranging from one to hundreds of relays. Although they have served well, these electromechanical relays have some inherent disadvantages; consequently, a new solid-state relay has been developed to provide a better answer to most machine control problems without going to the considerably greater expense of electronic logic systems.

The inherent disadvantages of electromechanical industrial control relays include limited cycling rate (less than 200 cycles a minute) and the tendency of the contacts to bounce on closing (for as long as 20 milliseconds). Contact bounce accelerates contact wear, and it also restricts relay applications because electronic devices in the circuit would follow the bounce and thus cycle improperly. Other disadvantages are the finite life expectancy of the contacts (generally of the order of 10 million mechanical operations) and, frequently, the difficulty of changing contacts in installed relays. Moreover, relays create considerable mechanical noise.

Electrical noise created by energizing or deenergizing the coils shows up as random voltage spikes superimposed on the normal line voltage, where it can cause problems with solid-state controls served by the line. Finally, relays are difficult to apply safely in explosive atmospheres, and their contacts suffer in such unfavorable environments as foundries, chemical plants, pulp and paper mills, and where salt spray is present.

The new Type SSR (solid-state relay) unit is a single-input multiple-output device made to be applied in the same manner as an electromechanical industrial control relay. Although completely solid state, it has all of the best features of the electromechanical type: complete isolation between input and output as well as between poles, pole units easily converted from normally open to normally closed, conveniently located terminals with captive wire clamps, interchangeable pole units of different ratings, and pole units replaceable without disturbing the wiring. This design enables panel builders and electricians to install, wire, and maintain a control installation with familiar procedures and techniques. In short, the solid-state relay can be used interchangeably with electromechanical relays.

Cyling rate of the Type SSR unit has been measured at up to 350 cycles per minute. That is not the limit but only the point at which the load could no longer follow. Life expectancy in number of operations is unlimited under normal ambient-temperature and load conditions.

Solid-State Relay Design

The solid-state relay has an operator section that is directly equivalent to the operating coil of an electromechanical relay (Fig. 1). When power is applied to it, opening or closing action is induced in the accessories being used with it. Those accessories are the pole units and delay timers listed in the accompanying table. All are rated for use in 120-volt 60-hertz service.

The pole units are plug-in, and each is marked with contact symbols. They function as normally open contacts when inserted into the operator in the upright position and, when inverted, as normally

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1—Solid-state relay is shown assembled at left and, at right, with its plug-in pole units removed from the operator section. The pole units function either as normally open or normally closed contacts, depending on their orientation when plugged in. At far right are the solid-state timers (on-delay and off-delay) that can be plugged into the operator section in place of pole units.

closed contacts. (See *Solid-State Relay Operation*, page 180.) The two types of pole unit are physically of the same size and can be used simultaneously on a common operator.

The timers plug into the operator in the same manner as the pole units except that each occupies the space of two pole units. Their adjustment potentiometers are so tapered that 20 percent of resistance value (and 20 percent of maximum time value) occurs at 50 percent rotation of the adjustment shaft, enabling the user to set timing intervals easily below 5 seconds as well as in the longer range (Fig. 2).

The Type SSR unit can operate over a ± 10 percent range of voltage and frequency variation. A built-in pilot light indicates when power is applied. The unit mounts in the same space and in the same manner as the new Westinghouse Type AR electromechanical control relay, and it can also go on adapter plates to replace other makes of relay.

Noise Suppression

Electromechanical relays are virtually immune to false operation by random noise because of their relatively slow operation (8 to 25 milliseconds). Electronic devices, however, (such as transistors, triacs, and SCR's) have extremely fast response and so can be keyed into conduction or cut off by random noise spikes generated by magnetically operated devices and transmitted over the power lines.

Therefore, suppression circuits are included in both the input and output sections of the Type SSR unit to counteract the types of electrical noise usually encountered in industrial installations. (See diagram on page 180.)

Rate of rise protection (also called dv/dt protection) is obtained with R-C combinations. The values of resistance and capacitance have been calculated to be most effective with a load similar to the coil of a machine-tool relay, although protection is effective over a wide range of coil sizes. Input noise is suppressed by converting the ac input to direct current, by using a generous filter, and by adding a second R-C circuit. A specially developed noise-rejection gate circuit is used for the SCR. Finally, a Zener diode is included to clip stray high-voltage noise spikes at a safe level and thus prevent damage to the SCR.

The suppression circuits also control any electrical noise that may be generated by the firing or cutoff of the SCR.

Construction

All components are of proven reliability. For example, input is by a transformer with multiple secondary windings. Taps on the primary winding can be arranged to accept different input voltages. Normal insulation between windings provides for isolation through the unit and between poles. The output switch is a reliable SCR-diode bridge.

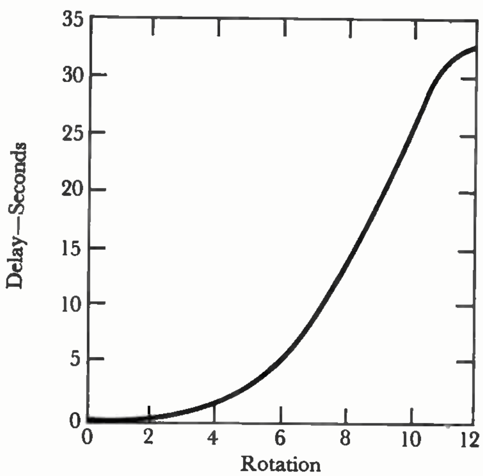
Good overload capacity is realized by applying the SCR well below the rating set by the manufacturer. The SCR used in the pole unit rated for 5-ampere inrush has a half-cycle surge rating of 80 amperes, while that in the 1.7-ampere-inrush pole unit has a one-cycle surge rating of 20 amperes.

All electronic components are assembled on printed circuit boards, which are potted in the housing with an epoxy resin. The potting material acts as a heat transfer agent to help assure that components will not be overheated under normal operating conditions. It also is a good electrical insulator, and it makes all components virtually immune to vibration, shock, and unfavorable atmosphere.

Application

Although only a four-pole unit is described in this article, there are no restrictions on the pole configuration of the solid-state relay. The four-pole structure was chosen for the initial development program because it is common to many industrial control relays and because it coincides with the space requirements for this particular design. Circuit requirements for less than four poles can be met by omitting unnecessary poles, and applications that require more than four poles can be served by paralleling two or more relays.

The provision of pole units in two ratings but of the same size results in a high degree of application flexibility. A single unit can handle information processing (such as determining control sequencing in response to switch inputs) and output functions (for example, inter-



2—Response curve for the timers illustrates why timing interval is easily set even at the low end of the range. Each increment on the *Rotation* scale is about 25 degrees.

Accessory Units for Solid-State Relay Operator Section

Unit	*Rating*	*Function*
Pole unit	1.7 A inrush, 0.6 A continuous	Intelligence processing. Also to actuate motor starters through Size 2.
Pole unit	5 A inrush, 1.5 A continuous	Driver stage for pilot solenoids. Also to actuate motor starters through Size 4.
Timer	1.7 A inrush, 0.6 A continuous	On delay. Adjustment range 0.1 to 30 sec.
Timer	1.7 A inrush, 0.6 A continuous	Off delay. Adjustment range 0.1 to 30 sec.

Solid-State Relay Operation

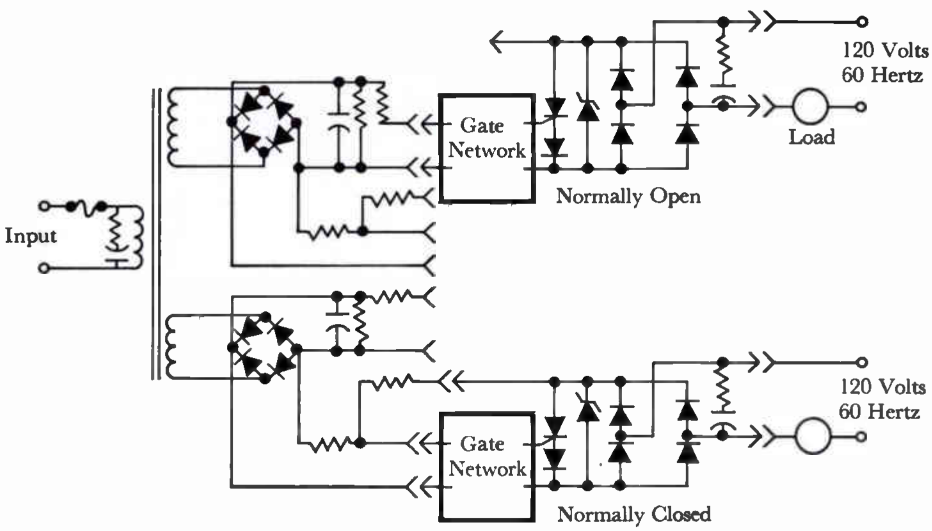
The solid-state relay is diagrammed schematically in the accompanying illustration. Only two poles are included—one normally open and one normally closed—because other poles would duplicate those shown.

The top branch of the circuit shows a pole unit as a normally open contact. Gate drive to the SCR is present, and the contact closed, only when the input transformer is energized. Removal of the input voltage to the transformer also removes the gate drive from the SCR. With no gate drive, the SCR conducts only until the next current zero. It then blocks, so turn-off time is of the order of one-half cycle. Turn-on time is set by the time constant of the overall gate circuit and is also of the order of one-half cycle.

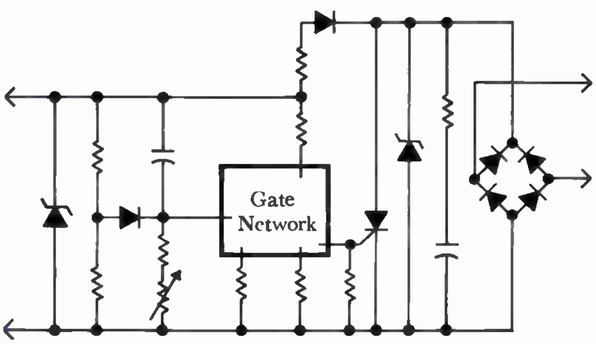
When the pole unit is positioned as shown in the lower circuit branch, it functions as a normally closed contact. Power applied to the series combination of electronic switch and load causes the voltage across the SCR to increase. Current flows through the series resistors in the gate circuit and turns the SCR on at each half cycle. However, energizing the input transformer impresses a blanking voltage on the SCR gate, and the normally closed electronic switch is then blocked open.

The special timers that can be applied are shown in the second illustration. They are designed to operate in the same position as the normally open pole. When power is applied to the input transformer and converted to direct current, a signal is generated by means of an R-C circuit, is amplified, and is used to gate the same type of SCR-diode bridge as that used in the poles. *On* delay is a function of charging time of a capacitor and is adjusted by changing the value of the resistance. *Off* delay is achieved by storing energy in a capacitor and discharging it through a variable resistance.

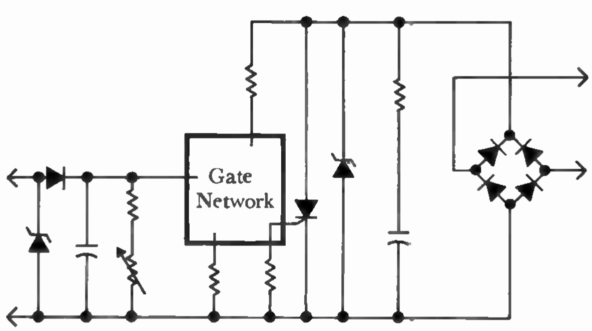
Reliable timing is realized over the adjustment range of 0.1 to 30 seconds. Timing accuracy is excellent—tests indicate that repeatability error is less than ±2 percent for shifts of ±10 percent in voltage and ±15 degrees C in temperature.



Solid-State Relay



On-Delay Timer



Off-Delay Timer

facing between information processing and such control devices as pilot solenoids, motor starters, and brakes).

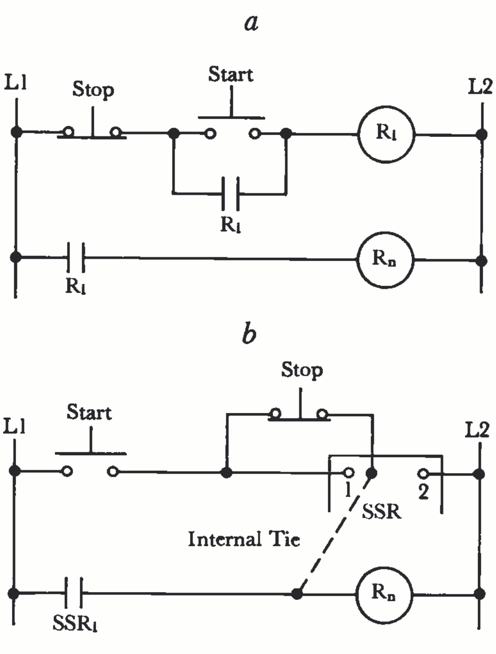
No special techniques are needed to apply the solid-state relay to a machine, because control circuit layout and contact arrangement follow the familiar patterns. Contacts on the solid-state relay can be connected in parallel in the same manner as those of an electromechanical relay.

Series connection is also possible, but the accumulated voltage drop across the series combination has to be taken into account. Each normally open electronic contact has a uniform closed-circuit voltage drop of about two volts, similar to the drop frequently encountered with conventional relay contacts.

This flexibility of connection, along with the fact that the solid-state relay is mechanically similar to a four-pole electromechanical relay, means that the two types of control device can be interchanged one for one. Existing circuits can be improved by simply substituting the solid-state relay for a conventional relay in areas where improvements are needed in reliability, life, cycling rate, or resistance to environment (Fig. 3). Builders of new control panels can intermix the two types to best meet their requirements and thus gain a degree of reliability and adaptability that has not been possible until now.

The solid-state relay can also be used to simplify circuits. For example, many relay control circuits have a combination of relay contact and start-stop pushbutton connected in a low-voltage-protection (LVP) arrangement (Fig. 4a). This connection requires use of the relay specifically in an interlock capacity. In an unplanned power dip, the control relay (R_1) drops out and stops the machine. Manual restarting is necessary, allowing the operator to first make sure that it is safe to restart. Such an LVP circuit is simplified by using an internal connection in the solid-state relay to effectively put the input to the operator section in parallel with the load controlled by one pole of the relay (Fig. 4b). Certain polarity relationships must be maintained in this approach. The arrangement is cited only

3—Type SSR unit is identical in mounting and connecting provisions to the Westinghouse Type AR electromechanical relay, and, with adapter plates, it can also be mounted in place of other relays. The two types are thus interchangeable in control circuits, so users can include the solid-state relay to upgrade selected parts of a circuit.



4—Relay control circuits can be simplified by use of the Type SSR unit. An example is the typical low-voltage-protection arrangement (*a*), in which R_1 is a conventional control relay and R_n represents any other relays in the circuit. The arrangement is simplified (*b*) by using a Type SSR unit and internally connecting a special terminal in it.

as an example of potential circuit simplification, as it would not be very practical where other normally open contacts are interposed between the control power line and the solid-state relay.

Established relay test procedures can be applied directly. Anyone capable of checking and modifying a circuit built with electromechanical relays can easily work with circuits that include the Type SSR unit because the same procedures apply across the board. Contacts are converted from normally open to normally closed by loosening the knurled knob at the top of the assembly, removing the cover bracket, pulling the pole free, and reversing it. Pole function corresponds to the contact symbol that is visible after the cover bracket has been replaced.

Cost is an important consideration with any control device. Control systems using electromechanical relays have been in use for many years, so their cost picture is well known. Systems employing electronic logic cost considerably more because, in addition to the logic processing equipment, the user needs special power supplies, input and output matching devices, and special construction techniques; the complete package cost can be as much as six times that of a comparable electromechanical relay panel.

An individual solid-state relay costs about four times that of an electromechanical relay, but availability of the new unit permits construction of hybrid control systems using both it and the conventional relays. Each such application can be arranged to take full advantage of the best features of both types, thus greatly improving system reliability and flexibility with only a small increase in total system cost. In addition, such an approach provides the benefits of solid-state equipment without special personnel training.

Extremely high reliability, long life, ability to serve in unfavorable atmosphere, total convertability, applicability of conventional circuit design techniques, suitability of well-known maintenance practices—those factors go a long way toward justifying the use of the new solid-state relay in machine control systems.

Planning Experiments for Efficient Information Gathering

Robert Hooke
John R. Van Horn

Profitmaking requires intelligent action, and intelligent action requires information. Information comes in many forms, some good, some bad, and nearly all expensive. The disciplines of statistics and design of experiments have been developed for the purpose of getting the kind of good information needed for as little money as possible.

Most of what we know comes from experience, and one way of gaining experience quickly is by experimentation. However, experimentation to find cause-and-effect relationships in real life usually reveals many causes for each effect, as well as many accompanying variables that may look like causes.

In other words, variability is associated with all experiments, so doing the same thing twice doesn't always produce the same answer. That being the case, we need to learn to interpret what we see. The need is not restricted to problems involving people, animals, or plants; much variability occurs in "standardized" manufactured products, as any worker in the reliability field knows.

Coping with Variability

Treating variability scientifically, as opposed to the usual seat-of-the-pants way, is the job of statistics. This scientific treatment is based on the ideas of *population* and *random sample*. When we want to know something about a population of things, and the population is too large to inspect completely, we look at a sample (a small subset of the population) and try to *infer* what we want to know about the population. If the sample is random (i.e., if the members of the population have equal chances of being in the sample and are selected independently), then mathematics can tell how good the answers are.

In general, testing a few items (light bulbs, transistors, or steel ingots, for example) isn't for the purpose of finding how those particular items behaved. (In fact, they are often destroyed in the test.) Rather, it is to be able to infer the characteristics of the population from which they came. Virtually any test, survey, experiment, or other data collection process can be regarded as producing a sample of numbers that should tell something about the population of interest.

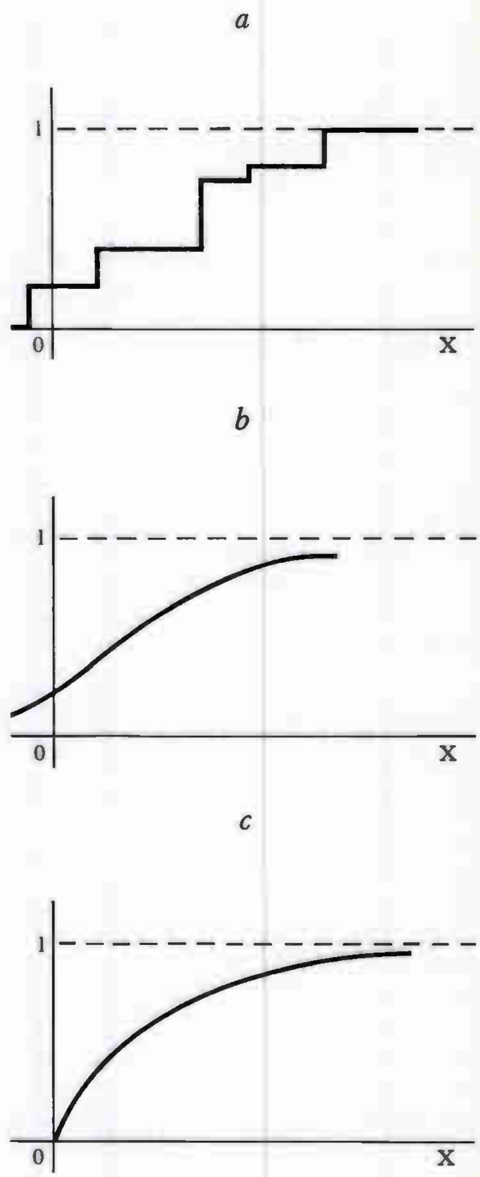
A single member of a population, selected at random and measured in some way, produces a number called a *random variable*. Examples are the hat size of a randomly selected man, the length of life of a randomly selected light bulb, and the tensile strength of a randomly selected piece of wire.

A random variable is described quantitatively by its *distribution function*. If R is a random variable and x is any real number, $Pr(R \leq x)$ means "the probability that R is less than or equal to x," and this probability is a number that depends on x. The number is written $F(x)$, and it is called the distribution function. When x is increased, $Pr(R \leq x)$ increases; since the probability must lie between 0 and 1, such functions often look like those in Fig. 1.

When the distribution function has a derivative, the derivative is called the probability density function, which is another way of describing a random variable.

Estimating Population Characteristics

Much of scientific and engineering work consists of taking some observations of a random variable and trying to infer its distribution. A common way of doing that is to select a family of distributions known to be appropriate to the type of situation being studied and then use observations to determine which one of the family most nearly describes the case under study. The procedure can be carried out by specifying the family in terms of one or more unknown constants, or *parameters*, and using the data to estimate the parameters. For example, a common one-parameter family used in reliability problems is the exponential distribution, described as follows. If L is the lifetime of a lamp, diode, or transistor, L is a random variable that can be described by a distribution function $F(t) = Pr(L \leq t)$,



1—Distribution functions are used to describe random variables quantitatively. The three distribution functions shown graphically here are for: (*a*) a discrete random variable, meaning one whose distribution function is a step function; (*b*) a continuous random variable; and (*c*) another continuous random variable that is always positive.

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where t instead of x is used for time. In many problems, this function takes the form:

$$F(t)=1-e^{-\gamma t},$$

where γ is an unknown parameter. For example, the lifetime distribution of a new device may be known, from experience with similar ones, to be (at least approximately) of the exponential form, but its particular γ isn't known until the device is tested. (Incidentally, γ is the failure rate, and $1/\gamma$ the mean time to failure of the device.)

Most processes of data collection and interpretation can be made more effective and meaningful by specifying the population of interest, observing a sample or samples to learn about it, and keeping the two carefully separated. Much confusion comes about because engineers and scientists often use the same word (e.g., "average") sometimes referring to a sample and sometimes to a population without ever distinguishing between the two. A characteristic of a population is called a *parameter*, while a function of a set of observations is called a *statistic*. For example, if one could test all the resistors made by a particular machine, their resistances might be R_1, R_2, . . . , R_N, where N would be a very large number. The mean of this population would be

$$\mu=(R_1+R_2+\ldots+R_N)/N,$$

μ being a common designation for a *population mean*. If we take only a sample of these R's, say n of them, where n is ordinarily much smaller than N, we can represent the members of the sample as r_1, r_2, . . . , r_n, and the *sample mean* is

$$m=(r_1+r_2+\ldots+r_n)/n.$$

(Some people use the word "average" exclusively for sample mean.) Note that when a parameter (μ) and a statistic (m) have analogous positions relative to the population and sample, they are often represented by corresponding Greek and Latin letters, respectively. Another common convention is to use the symbol $\hat{}$ for a statistic, so the sample mean is represented by $\hat{\mu}$. (The average of a set of numbers x_1, . . . , x_n is also frequently written as $\bar{x}$.)

Measuring the Variability

As pointed out earlier, the crux of the problem of interpreting experiments is variability. Two sets of numbers may have different averages, but to decide whether the difference is more than accidental we must measure the variability, for which we introduce the idea of *variance*. First we find out how much the individual numbers deviate from the mean of the group. We might be tempted to average these deviations, but some are positive and some are negative, and their average is zero. Instead, we square the deviations, average them, and call the result (mean square deviation from the mean) the variance. The positive square root of the variance is called the *standard deviation*. The variance is used mostly in mathematical and computational work, since it is easy to handle, while the standard deviation (sometimes called the scale parameter) is a convenient measure for making physical interpretations and stating conclusions because it is in the same units as the original numbers.

> **Design of Experiments Course**
>
> The principles of good experiment design, as outlined in this article, are applied by the Mathematics Department at the Westinghouse Research Laboratories to help other engineers and scientists throughout the Corporation develop better products, systems, and services economically.
>
> Moreover, the principles are taught in a Design of Experiments Course made available by the Westinghouse Training and Development Department. The course combines closely integrated film lectures, texts, and problem material into a flexible self-instruction program to enable working engineers or scientists to learn the theory and the practical application of applied statistics. Its author and lecturer is Dr. J. Stuart Hunter, Professor of Applied Statistics, School of Engineering and Applied Science, Princeton University.
>
> The course is divided into seven major units, each represented by a volume of text material. These units are, in turn, divided into 32 topics, with a topic presented in each of the 32 films. The seven major units are: Introduction to Statistics; Elements of Experimental Design and Analysis; The Balanced Block Designs; Factorial Designs; Fractional Factorial Designs; Least Squares, Introduction and Theory; and Response Surface Methodology.

The variance of a population or distribution is denoted by σ^2, the standard deviation by σ. If a sample consists of n numbers x_1, x_2, . . . , x_n, the sample variance is s^2, where

$$s^2=[(x_1-m)^2+\ldots+(x_n-m)^2]/(n-1)$$

and m is the mean. Note that we subtract m from each observation, square the results, and divide the sum not by n but by $n-1$. We use $n-1$ because subtracting the sample mean m, rather than the population mean μ, makes the result a little too small; division by $n-1$ just counteracts this, on the average. Those accustomed to the term in physics will note that we have lost one of our n "degrees of freedom" in estimating the mean by m, and it is the number of degrees of freedom that is used as the denominator.

Everyone knows that the average of several observations is usually better than a single one. Why is it better, and how can we state the principle more precisely? Since each of the observations that made up the average is a random variable, the average itself is a random variable. If m is the average of observations x_1, x_2, . . . , x_n, and if the x's come independently from a distribution with mean μ and variance σ^2, then m itself has mean μ (the same as the x's), but its variance is σ^2/n. The fact that σ^2/n is smaller than σ^2 gives quantitative meaning to the observed fact that an average tends to be better than a single observation. The standard deviation of an average thus goes down only as $\sqrt{n}$, an unfortunate fact since it means that to halve the error by averaging we must take four times as many observations.

Statistics and Design of Experiments

Statistical activities consist largely of designing investigations to learn about means (and other population characteristics) as efficiently as possible in the presence of variability. Although this article discusses only very simple examples, the physical world presents many complicated problems demanding a variety of techniques that may be quite complex. The techniques, however, are largely based on these simple ideas.

The approach to an actual problem depends on one's objectives, and there are various kinds of objectives for which procedures have been designed. The objective of the scientist is often to draw a *conclusion*, which may be expressed in the form of a confidence limit or limits. Thus he may say that the mean distance to the sun is, with 95 percent confidence, between 92.91 and 92.93 million miles. This means that, if many scientists measured the distance with the same method and computed confidence limits the same way, each would get a different pair of limits, but about 95 percent of the pairs would enclose the true value. Confidence limits are a way of making a statement about a population parameter (often the mean); the confidence level (95 percent in the example) measures the degree of confidence we can express by telling how often the precedure produces correct statements. (Some of the books in the bibliography tell how to produce such confidence statements.)

Engineers use confidence limits, too, and they have considerable use also for *tolerance limits*. After measuring the diameters of 100 ball bearings, for example, the engineer may not be so much interested in the population mean as in some population proportions. He might like to be able to say, for example, that 99 percent of the diameters are between 0.196 inch and 0.204 inch. No such statement based on sample observations can be made with total assurance of being correct, so statisticians have learned how to put a confidence level on it. A typical tolerance statement is, "With 95 percent confidence, 99 percent of the ball bearings lie between 0.196 and 0.204 inch."

Another area in which statistical tools can be used profitably is *decision*. Books have been written on decision theory, so the subject will not be gone into here, but it is important to know of its existence. For example, if I have to choose between two processes and can afford only three observations on each, I may not have enough data for a useful conclusion. But I can make a decision from virtually anything, and the important thing is to know (when I set up my test) what the costs of possible errors in decision will be and how I can minimize my total costs, taking costs of testing into account but also considering the costs of making an error from using too few tests.

In elementary cases, the idea of *significance* is often used in both conclusion and decision situations. A *null hypothesis* is set up, and when observations depart too far from it, significance is declared and the null hypothesis is abandoned. There are many troubles with this procedure: when the results are not significant, one is left with no particular conclusion or decision except to accept the null hypothesis from lack of choice; large samples usually produce significant results, whereas small samples tend to fail to do so, so in either case the outcome is fairly predictable from the sample size; and, finally, "significant" only means statistically evident, and a significant effect may or may not be of any importance physically. To summarize, significance tests receive a good deal of attention in textbooks because they are easy and provide a nice introduction to statistical ideas, but in practice there are usually better things to do.

In general, then, conclusions and decisions are the two main categories of objective. One might list also detection and persuasion, although not much has yet been done with them on the quantitative side. In greater detail, one can use the terms of G.E.P. Box as objectives of experiments: screening, empirical model building, response surface exploration, mechanistic model building, and mechanistic model fitting. The important thing is to remember that the proper way to carry out any data collection procedure depends on your objectives, so the proper time to determine your objectives is before, not after, collecting the data.

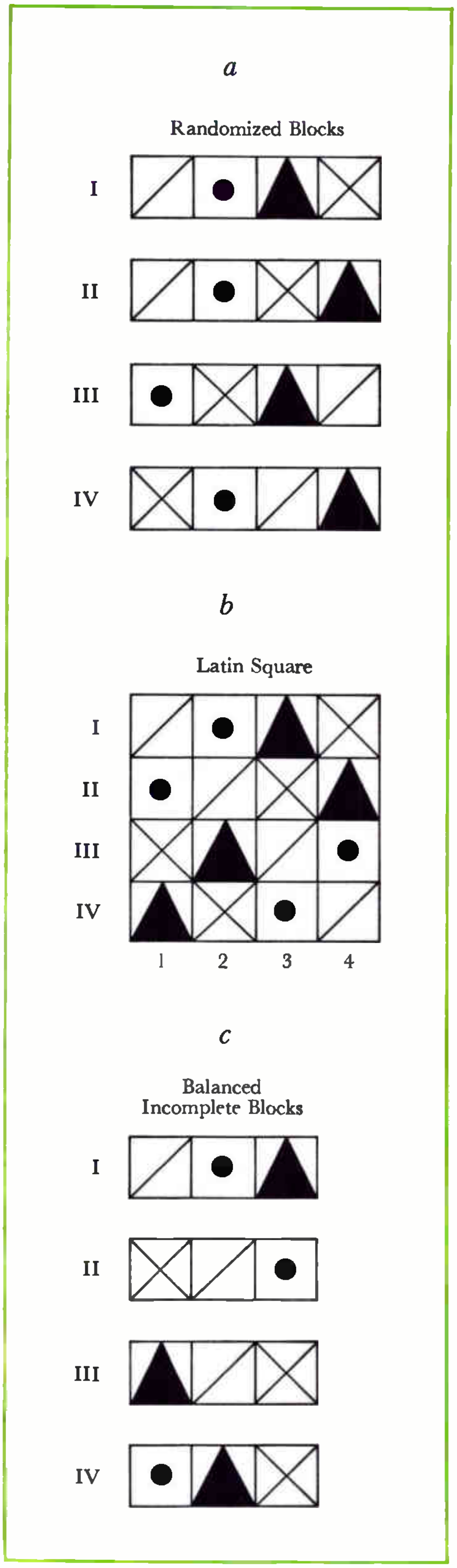
Experiments Are Samples

Returning now to the idea of sampling, experimental results (or any other kind of data) are regarded as a sample from a population of interest. Consideration of objectives is related to determining what population is the one we want to study. If our data are random samples, the rest is mathematics. In practice, however, random samples are difficult or impossible to get. So we must understand why they are difficult to get and what we can do about it.

The main difficulty is that real populations don't come to us all mixed up. If they did, say like a well-shuffled deck of cards, we could take the nearest (or easiest or cheapest) n members to observe and treat them as a random sample. Instead, populations (whether people or steel ingots) tend to come in clusters, or blocks, with members of a block tending to be more like each other than like members of other blocks. That is why a sample of 2000 people taken randomly around the country is more likely to predict correctly the result of a national election than is a sample of 1,000,000 all taken in New York City.

The principle so obviously true of people is equally true, though not so obviously, of other populations. Steel ingots made to the same specifications vary. However, if they are made on the same day, or at the same place, or from the same batch of ore, variation usually is less than if they were not so made. Examples can be produced by the dozen. The chemical analyst, for instance, appears to have a much more repeatable process if he runs two duplicate analyses together than if he does them several days apart. So he nearly always does run

2—Some experiment designs can be diagrammed as patterns in which treatments are assigned to experimental units that make up blocks in such a way as to permit comparing the results as efficiently as possible. The three examples illustrated are for an experiment involving four treatments; the blocks are marked I, II, III, and IV, and the treatments applied to units are shown as designs. In randomized blocks (*a*), each treatment occurs once and only once, in randomized order, in each block. The idea is to eliminate any block-to-block variation from the treatment comparisons. The latin square (*b*) is used when there are two systems of blocks and the experimenter wants each treatment to occur exactly once in each block (row) of one system and also exactly once in each block (column) of the other system. It might be used, for example, in testing four gasolines on four cars (I, II, III, IV) and four drivers (1, 2, 3, 4). Balanced incomplete blocks (*c*) may be used when the number of units in each block is smaller than the number of treatments.



them together because that may be cheaper and make him look better, whereas for most purposes his customer is (or should be) more interested in knowing about the larger variation.

What To Do About Clustering

The tendency of populations to cluster can be counteracted by introducing the mechanics necessary to produce a random sample. In practice, however, that is often not possible. For example, if the population of interest is all the ball bearings that will be produced by a given machine over a period of two years, a truly random sample would require two years, while the information may be needed now. What we must do in practice is reach a compromise, but, to do so, it is necessary to understand the problem.

Incidentally, the fact that a random sample may not be physically achievable does not mean that sampling theory is impractical. Lines without thickness are not physically achievable, either, but the Pythagorean theorem that assumes their existence has proved to be fairly useful.

The first necessity is to learn to recognize blocks in practical situations. It is helpful to remember that they are usually associated with place and time; that is, things that happen in about the same place or at about the same time tend to be more alike than similar things that happen at more widely separated places or times. For example, in an oven set for 200 degrees C, the temperature may deviate from the setting by different amounts in different places, but places close to each other differ from each other less on the average than do places farther apart. Similarly, if the oven is brought up to temperature every day for a year, the temperature on consecutive days tends to be more nearly the same than on days several months apart because of such effects as slow changes in ambient temperature and instrument drifts. This problem of clustering affects virtually every data-collection activity.

The solution of the problem has two parts. Part one is planning the sampling procedure so that it does not take place in too small a block. As pointed out earlier, it may not be feasible to sample randomly from the output of a machine over two years. However, if you have a week in which to do sampling, you should use the whole week and not do all the sampling in one hour just because that happens to be easy. The various small changes that occur in the machine's operation over two years may not manifest themselves in a week, but they have a much better chance to do so in a week than in an hour. In general, to have a good *range of validity* for the conclusions drawn from an experiment, sample randomly over the population about which you wish to draw conclusions. If such sampling is impossible, do it over as large a part (i.e., over as many different blocks) as is physically and economically possible.

The second thing to do about clustering is perhaps more important, because it is a very simple and usually almost cost-free way of making experimentation far more efficient. To explain it, we must go back a bit. In some data collection activities, such as measuring the distance to the sun or the political preference of a state, we simply take a sample and measure its members. In most experiments, however, we are interested in finding out what happens when we do certain things to members of the sample. That is, we select certain *experimental units* and apply certain *treatments* to them. The units may be children, apples, or quantities of steel, and the treatments may be toothpastes, insecticides, or annealing temperatures, respectively. The universal problem is that children, apples, and quantities of steel vary, so the ones that receive the "best" treatments will sometimes nevertheless give the "worst" response. Experiments must be so planned as to reduce to a minimum the probability that a wrong conclusion will be made. The existence of blocks (regarded as a nuisance to this point) now provides a way of saving time and money in doing such planning.

The rule, in brief, is to *make comparisons within blocks*. When comparing the results of two treatments, you want the units to which they are applied to be as much alike as possible beforehand. In any experiment, one naturally supposes that the units have the same specifications, but there remains some variability and you can reduce its effect by making comparisons within blocks. As mentioned earlier, if you have a week in which to sample units from a production, you use the whole week. If you apply treatments to the units, however, you should compare treatments on units that came off the line very close together to increase precision of comparison.

As another example, if you want to compare two toothpastes on 12-year-old boys, you can randomly assign 100 of them to one brand and 100 to the other, but if you first obtain some identical twins you can make comparisons within each block (pair of twins) much more efficiently; you still need several pairs for range of validity, but far less than 100 are needed to make the comparison with equal precision.

Experiment Designs

Starting from simple principles such as these, Sir Ronald Fisher and others in England and America developed the basis for the modern theory of design of experiments during the 1920's and 1930's. Today in the United States a few dozen PhD degrees are awarded each year in this specialty.

The early work consisted of invention of designs appropriate to a variety of situations. The designs are patterns according to which treatments are assigned to experimental units that make up the blocks, the idea being to compare the effects of treatments as efficiently as possible in the presence of within-block and block-to-block variations.

The designs were constructed largely for agricultural experimentation. Blocks were areas of land, the treatments were various fertilizers, for example, and the experimental units were plots (arbitrary pieces of the blocks).

During World War II, it became evident to scientists working on military and manufacturing problems that the designs could be used to speed up the experimental process in many nonagricultural fields. A block could be an ingot of metal, plots could be pieces cut from it, and treatments could be various annealing temperatures applied to the pieces. We now see that most experimentation consists of applying treatments to units to compare the responses obtained, and of trying to reduce the confusion caused by unit-to-unit variability by taking advantage of the existence of blocks with their greater homogeneity.

Some of the designs created for various purposes came to be known as randomized blocks, latin squares, and balanced incomplete blocks (Fig. 2). Many more complicated designs have been devised for various special purposes.

Sir Ronald Fisher also introduced the concept of the *factorial* experiment. For experiments where the purpose is to study the effect of two or more factors, each at two or more levels, he demonstrated the many advantages of studying all combinations of levels in one big experiment as opposed to the common practice of varying only one factor at a time.

A good design is of little use, however, unless the resulting data can be properly interpreted. A very general mathematical tool for interpreting data is the *analysis of variance*, sometimes shortened to *anova*. It can be applied to all of the designs mentioned as well as to many others such as the *fractional factorials*, which are pieces of full factorial designs especially tailored to produce usable results even when it may not be possible to carry out all the combinations of the full factorial. The analysis of variance enables us to separate treatment effects from block effects, estimate the interactions of the treatments, and provide confidence intervals and significance tests for all of the treatment effects and interactions.

An additional impetus to the application of statistical design of experiments to nonagricultural work was provided by the methods developed by Box in the 1950's and 1960's. Being mostly interested in relationships involving quantitative variables, he combined principles of good design with those of regression analysis (curve-fitting) to produce a theory for the investigation of response surfaces. A part of his work that is especially interesting to engineers is the technique of *evolutionary operation*, or *evop*, for improving manufacturing processes. The idea is that one cannot afford to do normal experimentation with a manufacturing process that is in profitable operation. *Evop* is a way of experimenting by making changes so small that they don't materially affect the process output. The effects of the changes are hard to see, but if enough observations are taken they begin to stand out, and the improvements they suggest can be permanently incorporated into the process.

Conclusion

As with other applications of mathematics, the use of good experimental design theory on real problems is not so easy as it appears when illustrated by textbook problems. Every real problem presents new types of constraints, but, nevertheless, the basic principles of good design can nearly always be used.

Professional instruction through a convenient film-and-text Design of Experiments Course was made available to Westinghouse personnel early this year for training and development at their locations. By September, 750 scientists and engineers at 17 locations had attended or were scheduled to attend the course.

Professional consultation in statistics and design of experiments has been available at Westinghouse since the early 1950's. The group at the Research Laboratories has, during the past year, applied this service in reactivity measurements, torpedo testing, elevator traffic studies, additive selection for mercury lamps, tests of steel plates for nuclear reactors, transformer core testing, lightning arrester testing, insulation breakdown tests, and many other areas.

Westinghouse ENGINEER **November 1969**

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High-Density Integrated Circuitry Produced by Electron Imaging

Integrated electronic circuitry much smaller than that now in use has been produced by using electron beams in place of the light employed in the conventional photoengraving processes that fabricate solid-state devices and integrated circuits on silicon slices. The resulting high packing density could pave the way for large-scale integration, the next generation of integrated circuitry, in which circuit components might be 100 times smaller than those available today.

Large-scale integration would produce arrays of integrated circuits (which consist of interconnected components) that would themselves be interconnected to form complete subsystems for complex electronic systems such as computers. It should provide products that are smaller, less expensive, more reliable, faster acting, and less power consuming.

Electrons are used in the new process because they are smaller than the wavelengths of light and can be projected on targets as small as a few millionths of an inch on a side. They are projected by an image tube that produces patterns with finer detail than such tubes have achieved in the past. The tube, about three inches long and three inches in diameter, is surrounded by electromagnets that focus the electrons in essentially perfectly parallel lines.

A series of light-sensitive masks are placed one after the other at the cathode of the image tube. When ultraviolet light is directed onto a mask, the mask ejects electrons along the parallel magnetic lines toward the anode of the tube.

The anode holds a silicon wafer with a sensitive coating that records the pattern in which the electrons strike it. (That pattern is identical to the pattern of the mask.) The pattern is etched into the wafer by an engraving process, and dopants are then diffused into the etched pattern to create elements of the circuitry. The steps are repeated with each mask until the wafer is covered with its complete interconnected circuitry.

The entire surface of a silicon wafer two inches in diameter is processed in each step, and larger surfaces could be processed by simply using larger image tubes. In contrast, the best optical systems can cover less than one square inch with the smallest circuits they are able to produce, thus requiring more manufacturing steps for a given number of circuits. A further advantage of electron beams is their large depth of focus compared with light beams; because of it, the silicon wafer does not have to be kept at near-perfect flatness to be an acceptable surface for making high-quality devices.

The technique was developed by the Westinghouse Research Laboratories, with early work supported in part by the U.S. Air Force Avionics Laboratory. The project is being continued under support of the U.S. Air Force Rome Air Development Center and the Westinghouse Aerospace Division.

The exceptionally detailed and precise masks used in the new process are made by "writing" patterns into sensitized metal surfaces by computer control. Essentially, a drawing of each mask is digitized and the information punched out on cards. The computer translates the information to magnetic tape, which controls an extremely thin electron beam that makes an exact tracing of the circuit drawing. (See photograph.) The tracing is done in a scanning electron microscope to the exact size of the required mask. The process is simpler, more exact, faster, and easier to control than the photographic methods that convert drawings to masks by light-projection systems.

The design displayed on the monitor is a detail from one of the electron-emitting masks used to form an interconnected array of ultra-small integrated circuits on a silicon wafer such as the one in the man's hand. The highly detailed masks are "written" by the scanning electron microscope at left, with the electron beam controlled by magnetic tapes prepared from drawings.

BART Train Control System Nears Operational Status

The automatic train control system for Bay Area Rapid Transit (BART) is now being programmed. Serving the San Francisco area, the rapid-transit system will be operated automatically from a train control room and adjacent computer center at BART's Lake Merritt headquarters building in Oakland.

The first ten cars are expected to start test runs next fall, and revenue service is scheduled for part of the East Bay leg by late 1971. Westinghouse designed and

Train operations control center for Bay Area Rapid Transit includes a display board that depicts various functions of the 75-mile system. Tight automatic control of the trains will permit safe operation at speeds to 80 miles an hour and spacing as close as 90 seconds.

supplied the automatic train control and communications system and, under a separate contract, will provide advanced propulsion and control equipment for the 250 cars that are being built by Rohr Corporation.

A system-wide display board 8 feet high and 88 feet long dominates the operations control center, located one floor below street level. The board depicts a map of the 75-mile system, including the 33 stations. It also shows the condition of the electric power network, ventilating fans, and all other critical equipment.

BART will be the world's first fully automatic transit system. When in full operation, its central supervisory system will automatically control the trains on aerial, underwater, underground, and surface tracks. The system will be automated because its operation will be too taxing for safe and efficient human control: trains will accelerate to 80 miles an hour and operate as close as 90 seconds apart.

In the event of an electric power interruption, emergency power sources in a room one floor below the control room can maintain the full supervisory system for two hours. Moreover, duplicate computer systems are provided, with either computer capable of supervising system operations. If necessary, independent automatic controls at each station can take over train control and operate the system safely.

The propulsion and control equipment to be supplied can accelerate BART trains from standstill to 50 miles an hour in 20 seconds and decelerate smoothly from 80-mile-an-hour top speed to full stop in 27 seconds. The contract also calls for friction brakes, air conditioning, trucks complete with wheels and axles, an auxiliary power system for each car, and diagnostic test equipment.

The propulsion and control system is essentially a 1000-volt solid state dc "chopper" control. It electronically connects and disconnects the four high-performance traction motors on each car with the third-rail electric power supply, providing both smooth acceleration and dynamic braking. The system has been tested on BART's four-mile test track near Concord, California, over a period of two years.

Mountain Models Aid Design of VLF Radio Antennas

Different sizes and shapes of mountain valleys have different effects on very-low-frequency (VLF) radio antennas, and, moreover, antennas for those frequencies have to be so long and so high that mountain crests can sometimes be used as towers. Consequently, the engineers studying antenna problems at the Westinghouse Georesearch Laboratory have made a detailed model of a mountain valley with its surrounding peaks and hills.

The model is made of wire mesh stretched over a wooden frame. A dugout beneath the model contains electronic testing equipment.

Stretching across the valley from peaks on either side are the wires of a working scale-model radio transmitting antenna. (A full-size version of the antenna would span a distance of well over a mile.)

The engineers are conducting the program to help the U.S. Navy select VLF transmitter sites for project Omega, a radio navigation system scheduled for full operation in several years. They have provided the Navy with charts and tables for predicting transmission power and bandwidth characteristics. An ideal valley for project Omega has been found to be one with parallel ridges rising sharply from the surrounding plain. It is U-shaped, about a mile and a half wide, and 2000 feet deep. The ridges are steep near the crests and extend only far enough to provide good anchorage at the desired height for the antenna.

The Georesearch Laboratory is a facility of the Westinghouse Research Laboratories. It is devoted to fundamental study of the earth and its electrical and magnetic fields, radio wave propagation, mineral resources, seismic phenomena, and design of related instruments and systems.

This model of a Trinidad mountain valley spanned by a working VLF radio antenna facilitates development of such antennas and selection of sites for them.

Welder Training Program Cuts Time and Cost

A welder training program developed by the Westinghouse Learning Corporation is reducing the time and costs associated with skills training. Whether used to train welders at a new plant or to upgrade an existing work force, the program enables a single instructor to teach four times as many students in about a third of the time required with previous techniques.

The needs and goals of the user determine what portions of the total program are used and the length of the training course. Educational institutions have used a two-week version to familiarize students with terminology and techniques; where welders are trained for industrial production purposes, the course lasts from four to nine weeks.

The complete course, including basic and advanced arc welding, consists of four student workbooks and 20 filmstrip lessons. Before trainees are introduced to the program, an intensive two-day workshop teaches experienced welders (picked by the user) how to be instructors in the program.

A trainee begins by taking a pretest to determine his entry level into the program, thus eliminating time wasted in teaching him what he already knows. Next, the instructor gives a lecture on safety practices. (It is the only scheduled formal lecture in the course.)

Then the student begins the self-instructional training phase, learning basic welding terminology by going through the programmed text in his workbook. If his answer to each question is correct, he continues to the next; if incorrect, he reviews the information to find his mistake.

Once the trainee has learned the terminology for a particular task, he enters the demonstration-application phase of the course. Each has his own audiovisual viewer and can recycle it as often as necessary to understand the material. The filmstrip lessons recreate as closely as possible the steps that should be followed; they include color pictures, narrated instructions and descriptions, and actual welding sounds. (The trainee sees and hears an arc before he strikes one.)

An instructor monitors each trainee's progress by checking test results after each workbook study unit and by observing the trainee's skills in his welding booth. The final test, tailored to meet a customer's particular needs or to meet ASME standards, qualifies a welder for his job. In early applications, 75 to 95 percent of the trainees passed the final test on their first try.

The speedup in learning possible with the welding training program is attributed to high motivation. In the workbook and filmstrip lessons, there are immediate rewards for progress: the trainee feels that he has achieved something worthwhile, and that feeling motivates him to seek further successes in the next lesson.

In one application, the welding training program cut training time from an estimated six months to nine weeks at the new Tampa plant of Westinghouse Nuclear Energy Systems. The initial 87 trainees, many with little or no previous welding experience, were recruited from the local labor pool.

All the trainees successfully completed the four-week basic portion of the arc-welding course, with 93 percent passing the final test on their first try. They then took courses in advanced arc welding, tandem arc welding, TIG welding, or tube welding, depending on the preference of the trainee and the needs of the plant. Those courses lasted as long as five weeks and used the same instruction procedures outlined above. Seventy-four percent of the trainees passed the advanced arc-welding final test on their first try, 90 percent the tandem arc-welding test, and 100 percent the TIG and tube-welding tests.

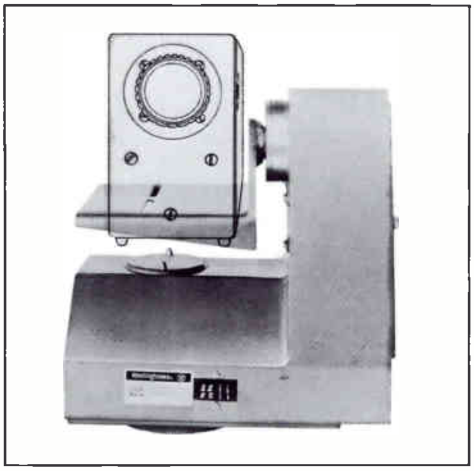
Products for Industry

High-voltage transistor for high-current industrial applications has switching speed of three million pulses per second, and it can operate at voltages up to 375 volts and peak current of 30 amperes. The No. 1823 transistor is a double epitaxial type. Applications include power supplies, voltage regulators, inverters, linear amplifiers, dc-to-dc converters, and various industrial control circuitry. *Westinghouse Semiconductor Division, Youngwood, Pennsylvania 15697.*

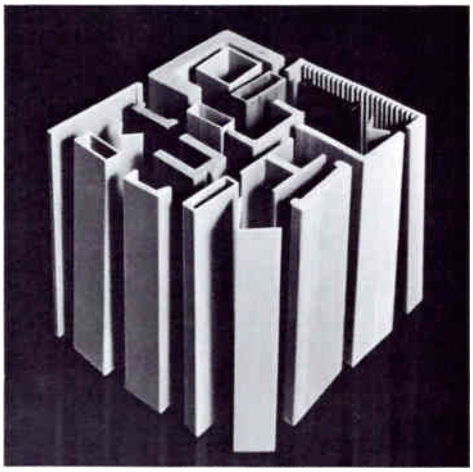
Camera mounts for remotely controlled closed-circuit television applications accept a wide variety of standard cameras. Lightweight model (illustrated) is suited for indoor applications. Pan and tilt motions up to 315 degrees and ±45 degrees respectively, with adjustable limit switches, are controlled by a four-way "joy-stick" unit. Larger medium-weight mount is for outdoor use, where it is required to support both the camera and its weatherproof housing. *Video Information Department, Westinghouse Specialty Electronics Division, 7800 Susquehanna Street, Pittsburgh, Pennsylvania 15221.*

Failure relay gives remote indication of failure of a semiconductor device in a system. Its applications include static inverter power supplies, high-frequency generators, and SCR power supplies for motor drives. The Type L-65 indicator employs a trigger fuse to actuate a single-pole set of contacts, which can be either normally open or normally closed. Operation provides visual or audible indication, or actuation of a shutdown relay or emergency circuitry. Dimensions are 4 inches long by ¾ inch wide by 2 1/16 inches deep. *Westinghouse General Control Division, 4454 Genesee Street, P.O. Box 225, Buffalo, New York 14240.*

Fiberglass-reinforced shapes in wide variety are produced by continuous resin molding process. In the "pultrusion" forming process used, a continuous length of reinforcement material is drawn through a bath of the resin system. It is then pulled from the bath through a precise die, where polymerization takes place. *Westinghouse Industrial Plastics Division 1575 Lebanon School Road, West Mifflin, Pennsylvania 15122.*



Camera Mount



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About the Authors

Eugene R. Astley received his BS in Physics from the University of Oregon in 1948 and his MS in Physics from Oregon State University in 1950. Astley's early experience included physics research and development at General Electric's General Engineering Laboratory. From 1951 to 1954, he was lead engineer in charge of some basic developments in support of the submarine *Seawolf* at the Knolls Atomic Power Laboratory. Acoustic gas analyzers, which he developed, are still in use at the gaseous diffusion plant at Oak Ridge.

Astley moved to Hanford in 1954, where he has had assignments in several phases of reactor design. He has held the positions of Supervisor of Reactor Design Analysis and Manager of Applied Reactor Engineering. In the Irradiation Processing Department, he developed programs to increase production, improve product costs, and enhance nuclear safety.

Astley transferred to the staff of Battelle-Northwest in January 1965 when it assumed operation of the Pacific Northwest Laboratory for the AEC. In March 1965, Astley was put in charge of Battelle's preliminary conceptual design studies for a Fast Flux Test Facility (FFTF) for the Atomic Energy Commission. He was appointed to his present position of Project Manager of FFTF in September 1965.

Dr. John C. R. Kelly, Jr., is General Manager of the Westinghouse Advanced Reactors Division. He joined Westinghouse after receiving his PhD degree in Physical Chemistry from Carnegie-Mellon University in 1949, and his first assignment was to the Westinghouse Central Research Laboratories as an intermediate research chemist. In 1950, Dr. Kelly moved to the Lamp Division to do research in metallurgy. He holds a number of patents in the fields of physical chemistry and extractive metallurgy of refractory materials.

Dr. Kelly returned to the Research Laboratories and advanced through a series of assignments to become Director of Materials Research and Development in 1964. He assumed his present position early in 1966. His Advanced Reactors Division has the responsibility for developing, designing, marketing, and supervising the erection and start-up of nuclear steam supply systems other than pressurized water reactors.

L. L. Niemyer, Jr., graduated from the Johns Hopkins University in 1959 with a BES. He is a registered professional engineer in the state of Maryland. Before joining Westinghouse, Niemyer worked on the design of specialized television circuitry, cameras, and systems—mostly low-light-level types employing unusual modes of operation. When he came with the Westinghouse Aerospace Division in 1964, he continued to specialize in unusual types of television cameras and systems.

Niemyer worked on the electrical design of the lunar television camera and the integration of the SEC lunar camera tube into the system. He designed and developed a compact low-light-level military camera to operate at standard rates and another system to operate at slow scan rates, which included new techniques for signal enhancement. This low-light-level camera was the basic component for the Apollo color television camera described in this issue.

Niemyer is currently a Fellow Engineer in the Electro-Optical Systems Section and Engineering Director for the Apollo Color Television Camera Project.

John P. Conner graduated from the University of Pittsburgh in 1943 with a BS in industrial engineering. He went into the Army and, after completing officer candidate school, was commissioned a second lieutenant. Conner took training in electronics and then served as a radar specialist, first with the Coast Artillery Corps, Antiaircraft Artillery, in the United States and then with the Air Force in Germany.

Conner returned to the University of Pittsburgh in 1946, earning his BS in electrical engineering in 1948. He joined Westinghouse on the graduate student training program and went to work in the former Standard Control Division. There he contributed to the development of the Type N control line, thermistor inherent motor protection, Cypak static control, the A/200 control line, and solid-state timers. He is now Engineering Section Manager in the Control Products Division, responsible for the engineering of open control devices.

Dr. Robert Hooke joined the Westinghouse Research Laboratories as a senior mathematician in 1954. His first assignment was to produce a control device that would work by automatic experimentation; the resulting OPCON device gained Westinghouse the AAAS Industrial Achievement Award in 1958. Dr. Hooke became Manager of the Statistics Section in 1956, and since 1963 he has been Manager of the Mathematics Department. His major fields of interest are statistical inference and design of experiments.

Dr. Hooke earned his AB and AM degrees in mathematics at the University of North Carolina in 1938 and 1939, and his PhD in mathematics at Princeton University in 1942. He taught mathematics at North Carolina and at the University of the South from 1941 to 1951. He then served on the staff of the Operations Evaluation Group, Department of the Navy, until 1952, when he went to Princeton University as a research associate.

Dr. Hooke's publications include the books *Introduction to Scientific Inference*, *The Science of Science* (with R. E. Fox and M. Garbuny), and *Math and Aftermath* (with D. H. Shaffer).

John R. Van Horn graduated from Oberlin College in 1943 with a BA in physics. He then worked in nuclear physics research in the Manhattan District (the atomic bomb project) and later at the Los Alamos Scientific Laboratory. In 1946, he joined the Physics Department at the University of Illinois as a teaching and research assistant, earning his MS in physics and mathematics there in 1948.

Van Horn joined the Westinghouse Atomic Power Division in 1950 as a staff assistant to the director of research and director of development, and in 1954 he was made staff assistant to the division manager; in both posts, he was responsible for patent activities, technical education and training programs, and special assignments. In 1955, he was made Manager of Education and Training, Bettis Atomic Power Laboratory.

Van Horn came to Company headquarters in 1961 as Manager, Professional Development. He originates and carries out programs for continuing development of professional personnel in all functions of the Company. He was project manager for the Design of Experiments Course mentioned in his article, with overall responsibility for conception and production of the course.

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