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IEEE spectrum

features

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THE INSTITUTE OF ELECTRICAL AND ELECTRONICS ENGINEERS, INC.

departments

the cover

Leonardo da Vinci's anatomical sketch reproduced on the cover attests to two sides of his universal genius. Today, the attempt to design implantable artificial organs for humans raises the question of universality in a new context—just how much of a doctor must an engineer be to engage in artificial-organ research? Some eminent men answer this question. See p. 67

Spectral lines

Information Systems and the IEEE. With the development of new methods of transferring and retrieving scientific and technical information, the question arises, "Are there more efficient and effectual ways of disseminating technical information than by publication of periodicals and their distribution to subscribers?" It is clear that some of the new techniques of information transfer presently under discussion could have a profound effect on the operations of the IEEE. It is therefore of utmost importance that the Institute keep abreast of, and contribute positively to, these developments.

Activity by the Institute in this area started in 1959, when a subcommittee on information retrieval was organized by AIEE. It continued to function after the merger as the Information Retrieval Committee. Under the dynamic leadership of Prof. Morris Rubinoff of the University of Pennsylvania, this committee has written a preliminary internal report entitled "The IEEE Recommended Program for the Improvement of Information Dissemination and Retrieval." This report recommends both a short-term and a long-term program.

Some of the steps that are presently being undertaken include the development of index terms and procedures, standards for authors in writing titles and abstracts, and a document-numbering system. Additions have been made to the Headquarters staff to provide assistance in this field and to keep members alerted to the developing program. Because many of these steps will require the active participation of the TRANSACTIONS Editors, a subcommittee of editors has been formed under the chairmanship of Gustave Shapiro, Editor of the TRANSACTIONS ON COMPONENT PARTS.

The longer-range recommendations of the Information Retrieval Committee that are being studied by the Editorial Board include machine compilation of indexes, selective dissemination of information on the basis of an indicated-interest profile, and interconnection of IEEE specialized information centers with the larger information systems presently under discussion.

Since the information needs of engineers and scientists are not compartmentalized in separate categories, it is essential that any systems developed by the IEEE be compatible with those evolved by other engineering and scientific societies. The Engineers Joint Council (EJC), of which IEEE is a member, is coordinating an overall plan for such a system and has laid down some basic guidelines. As a first step, a Thesaurus, or word list, of some 11 000 terms derived from many engineering disciplines has been developed. This document, which is already undergoing revision and expansion, seeks to provide a meeting ground for the words describing IEEE intellectual activity and those used by others. The EJC Thesaurus must be supplemented with word lists prepared by the IEEE Groups before it will be possible to file documents so that all those, but only those, we desire are retrieved on command.

About two years ago, EJC initiated discussions with the Engineering Index (EI) regarding the performance of an indexing test of its initial methods and plans. Beginning this year, EI is publishing separate bulletins containing an index and abstracts of current articles in the electrical/electronics and also the plastics fields. The index items are printed out from magnetic tape storage that has been organized by a computer. The body of index terms, compatible in form with those of the EJC Thesaurus, grows as new documents are added.

The EI is dependent upon the Engineering Societies Library (ESL), which is in the United Engineering Center, the same building in which IEEE Headquarters is located. This library currently receives about 1500 periodicals a month from all the countries of the world in all branches of engineering. A member of the IEEE, Robert M. Bowie, is Chairman of the ESL Committee on Information Handling; he also heads a committee that is studying the possibility of locating an information center in the United Engineering Center.

In addition to these activities, Dr. Bowie has been appointed liaison representative of the IEEE to a task force of the Committee on Scientific and Technical Information (COSATI). This group, established in the Executive Branch of the United States Government, is an interdepartmental committee comprised of agency representatives who are responsible for the Government's scientific and technical information activities. COSATI makes recommendations to the Federal Council for Science and Technology for Executive Branch actions designed to improve the effectiveness of these information systems. A report of the President's Science Advisory Committee, entitled "Science, Government, and Information" and dated January 10, 1963, which is popularly known as the Weinberg report, has had a significant influence on the thinking of those United States governmental agencies that support research and development. It is recognized by COSATI that professional societies have a significant role to play in the development of new information systems but it is also clear that such systems as are developed should be compatible across the various scientific and social disciplines. From the IEEE standpoint, it is also essential that compatibility be maintained across national boundaries.

The IEEE Executive Committee recently assigned to the Editorial Board the responsibility for coordinating and supervising IEEE activities in the information processing field. There is much work ahead in enabling the Institute to play a creative role in this area and to improve its services to the members.

F. Karl Willenbrock

From physics to function

Electronics may be approaching a plateau. To ensure a renewed growth, a new philosphy of engineering is needed. In such a philosophy, systems engineering and the physical sciences will provide complementary and lasting disciplines for our future innovators.

J. A. Morton *Bell Telephone Laboratories*

To many experienced observers in industry, government, and education, the electronics industry looks young and vigorous with a bright and unlimited future. The spark of transistor science and the power of large financial support by industry and government have brought electronics rapidly to major industry status. If its growth continues, it promises to pervade all aspects of our socioeconomic lives.

Where are we?

As transistor technology has developed, our electronic systems have grown in size, complexity, and diversity of function. In about two decades, the capability of electronic systems, as measured by numbers of discrete components, has grown by four to five orders of magnitude. Some systems today require hundreds of thousands, even millions, of discrete separate elements. Each element must be made, tested, packed, shipped, unpacked, retested, and interconnected, *one at a time*, to produce a whole system. And each element and connection of the millions must continue to operate reliably if the system is to function as a whole.

Such large systems have become economically possible only because of great advances in the science and technology of electronic components, particularly semiconductors. Today, transistors and related components are approaching apparently intrinsic limits of performance, reliability, and cost.

The cost of such transistors has been decreasing exponentially with time. Through the application of batch diffusion techniques, thousands of devices now are processed as one slice before they are finally cut apart and finished as discrete elements. The cost per discrete element is indeed approaching a minimum. Remember, it costs a few cents for an operator or a machine just to pick up a single item without doing much to it.

In a like manner, the failure rate of such elements has improved by many decades and is approaching a practical minimum. At from one to ten failures per 10^9 device hours, the cost of establishing the failure rate becomes comparable to the cost of making the device.

Finally, the speed or frequency response of germanium and silicon transistors is approaching the intrinsic limitation set by the materials and the fabrication methods based upon diffusion and visible-light resolution techniques. Here too, performance range has been increased by several orders of magnitudes well into the microwave transmission or nanosecond switching speed regions.

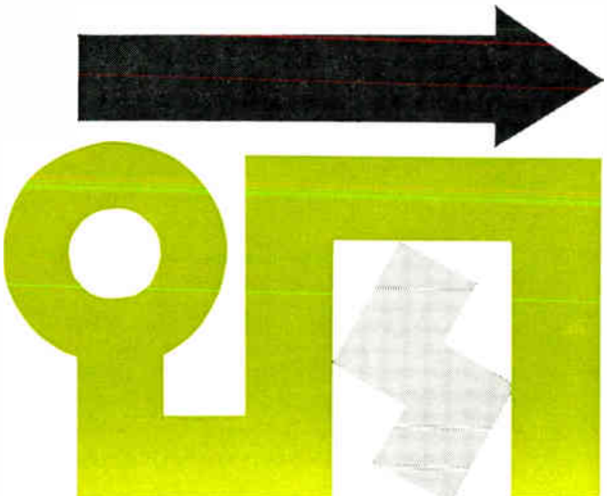
Some progress in each of these limiting factors can be expected, but certainly nothing like the orders of magnitude improvement that has occurred in the last 15 years.

Thus, the tyranny of large systems sets up a "numbers barrier" to future advances if we continue to rely on individual components for producing large systems.

Until recently, we have been deeply concerned with this component numbers barrier. Today, however, we believe that it can be penetrated by one or several of the current approaches to solid-state integrated circuits. For example, by using batch oxide-masking, diffusion, and epitaxial techniques, which brought discrete devices to their present limits, entire functional circuits are manufactured—hundreds at one time—along with their intraconnections.

In principle, the numbers barrier can be moved up to the circuit level rather than letting it remain, as it is today, at the component level.

To be sure, better basic understanding and control of our material systems and processes are needed. But the road to significant progress is well mapped. While there is a great deal of challenging scientific development ahead, we do not foresee the need for basically new inventions to



perfect such integrated circuits. We have every right to expect another major surge forward in system capability and industry growth.

On the other hand, mixed with this confidence in the future is an uneasy feeling among some thoughtful people that somehow our industry is approaching a plateau—at least a plateau of challenge to the new young people that any industry needs for continued technological growth.

In a recent article H. B. G. Casimir[1] observes that:

"Yet today there is a certain undertone of disappointment; it is there among management personnel as well as among scientists and engineers. No new phenomena have been found that vie in importance with minority carrier survival or with an older phenomenon like ferromagnetism. The tunnel diode did not entirely live up to expectations. Paramagnetic masers are beautiful low-noise amplifiers but of limited applicability. Lasers have so far hardly found really profitable applications, *at least not in circuitry*, and superconductive circuits are still 'round the corner' and may remain there."

Casimir continues:

"There is a moral to all of this. Although in the long run most (physical) phenomena play some role in technical applications, we should recognize that not every new physical phenomenon—and not even every beautiful and striking phenomenon—leads directly to an important new device . . ."

"Regret it or not, the frontier of science is moving away from solid-state physics. Electronics is no longer directly following the advances of fundamental science. It is in a way losing its privileged position . . ."

"Someone has remarked that for electronics the honeymoon is over. My answer is yes, perhaps, but it is after the honeymoon that one starts raising a family."

I believe that Casimir is right in some of his observations, and I share his feeling of unease. I further accept his mature advice about settling down to raise a family; indeed this is precisely what the industry is now doing in trying to perfect solid-state integrated circuits. But if we do nothing else, then electronics may well go the way of many other major industries that are based on only one or two basic discoveries or inventions.

An industry does not have to be analogous to a single individual or family in its morphological development. It can be a dynasty spanning many generations—if it has the good fortune or good sense to seek repeated renewal. Within its epoch it can have many honeymoons, many families, and long dynamic survival if it plans for renewal through repeated trips back to the "fountain of youth" of basic science. It must consciously seek to translate basic science into a new technology that is economically more powerful than the old.

Therein lies the core of our problem. We must have continuing renewal to answer the question over and over: What area of science is *relevant* to *what functions* to achieve increasing economic strength in our technology?

How did we get here?

In the broadest sense, electronics is not a young industry. Chronologically it ranks with the older of our technologies. And yet, despite its age, it is still seen as a precocious youngster, full of surprises and rapid growth; it has too-frequent periods of immaturity, and yet is full of promise for the future. How can this be so?

Electronics is different from many of our industries in the nature of its birth and its subsequent growth periods. Communications, a part of electronics today, had its beginnings in the early work of Maxwell and Hertz; telegraphy, telephony, and radio were direct outgrowths of the electric oscillations and waves that were being studied at the frontiers of classical physical science in the 19th century.

Following closely on the heels of the basic discovery and theory of the electron by Thomson and Lorentz, the audion was invented by DeForest in 1907. Its technological development was insured by the already pressing need for amplification in long-distance communications. By 1914, it was developed and used commercially in the first American transcontinental telephone line and radio-broadcasting.

World War I supplied additional needs and financial backing for its development and application to acoustic detection, radio, and carrier telephony. With industry support, by the mid-thirties electronics had grown steadily to a yearly level of some $1 billion. (It was then about fortieth in size among American industries.) By this time the mathematical theory of circuits, feedback, and modulation was being put to work in communications and the physics and equivalent circuit theory of the grid-type tube were reaching a high state of perfection and application. Indeed, it was possible to predict with some confidence the frequency limits of such tubes at a few hundred megacycles—the first performance barrier of electronics, which stood between us and the tantalizing field of microwaves.

During the early 1940s, workers in the field went back to basic classical physics to study in more detail the interactions of free electrons and electromagnetic waves. As a result, new useful interactions between electron space-charge and electromagnetic waves were discovered and new tube inventions such as magnetrons, klystrons, and traveling-wave tubes succeeded in extending the frequency spectrum well into the microwave region and beyond. The development of these new concepts into useful technology was greatly accelerated by the critical need for radar, weapons control, and communications during World War II.

After the war, intensified industrial effort led to a great expansion of tube electronics in microwave and broad-band cable telephony, radio navigation, television, and the early generations of electronic computers and experimental switching systems. However, some of these new systems, particularly the digital systems, because of their larger size and complexity, proved to be difficult to justify economically. The large amounts of power wasted by electron tubes, and their limited life, size, and fragility, led to high manufacturing, operating power, and maintenance costs. The further expansion of electronics was halted in all but the few cases where the high costs could be tolerated, if not desired.

In the meantime, beginning in the 1920s, the frontiers of science had moved far away from classical physics into the realm of atomic physics and quantum mechanics. In 1928 Sommerfeld applied quantum mechanics to the understanding of metallic conduction, and in 1931–32 Wilson made a similar application to semiconductors, thus establishing the energy band theory of such materials and the concept of conduction by means of holes and electrons. Only a small number of workers were applying these basic theories to semiconductor device technology. Wilson and Mott in England; Schottky and Spenke in Germany; Frenkel, Davydov, and Joffé in Russia; and Seitz, Lark-Horowitz, and Becker in the United States were attempting to understand the empirically discovered and developed semiconductor rectifiers with only limited degrees of success. They were severely hampered by the relatively crude state of their materials and techniques. Critical experiments to test their various hypotheses were most difficult to carry through.

Measured by today's yardsticks, the outlook for electronics in the mid-forties was modest. Basic science had been moving far away from the classical physics of vacuum-tube electronics for almost 20 years, and little financial support, either industry or government, was available for translating solid-state science into a useful electronic technology. The outlook for continued expansion for electron-tube technology was limited; it was mainly a matter of improving what we had.

In short, just such a situation existed then as Casimir described for today: the frontiers of science had moved far away from electronics and no new promising physical phenomena loomed on the horizon that had obvious large-scale technological potential.

However, by the late thirties, M. J. Kelly of Bell Telephone Laboratories had become sharply aware of the intrinsic limitations of electron-tube science and technology. He realized that if we had to rely on tubes we would not be able to make and operate the more capable future electronic communications systems needed at costs that anyone could afford. What was necessary was a new device, one that could amplify as did a vacuum tube, but without the vacuum tube's intrinsic limitations. A number of fields of basic physical phenomena were considered and measured against these requirements. The field of semiconductor physics was selected as the most relevant and promising one in which to seek better understanding. Work was started on a modest level prior to World War II. After the war, a more intensive program with these objectives of basic understanding and application was initiated.

The subsequent discovery by Bardeen, Brattain, and Shockley of "the transistor effect" based upon minority carrier injection and survival opened up a new set of technical, economic possibilities for large, complex electronic systems. Information processing, switching systems, and highly reliable mobile systems of a kind just not possible with tubes became economically possible in principle.

Heavy industrial and government support stimulated the rapid translation of these new phenomena into useful technology and the industry took another impressive leap forward in size and diversity of function. Indeed the gap between electronic technology and science was so effectively closed for a while that new solid-state science was stimulated by the technology.

The new solid-state science in turn led to new materials, new physical phenomena, and new devices such as gyrators, isolators, masers, cryotrons, and lasers, which have greatly enriched and extended our electronics capabilities. However, as Casimir pointed out, none of these new devices has yet equalled the technological impact of "the transistor effect," and fundamental research has again moved away from electronics.

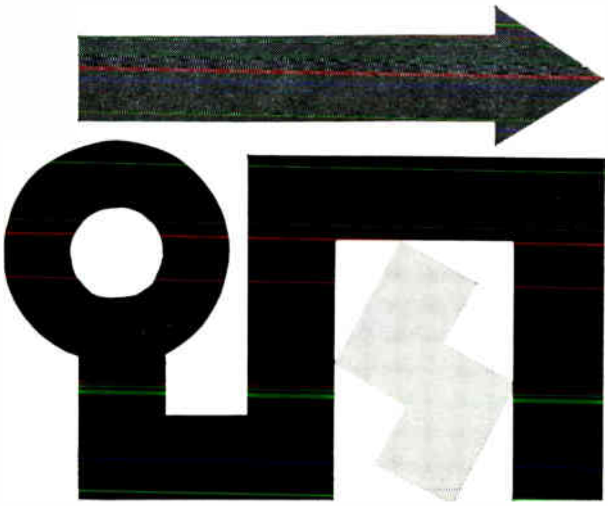
What this brief history tells us is that electronics was not continuously in touch with the frontiers of basic science. Indeed it has only been close to these frontiers twice in its long and checkered career—once in its beginning at the turn of the century and again at mid-century with the beginning of transistor electronics.

It is true that electronics has always stayed close to basic science and has used this knowledge to invent and develop new technology, but it was not always the frontier research knowledge of the day that had greatest technological importance. An important example is the situation in the late 1930s when electronics rejuvenated itself with a better understanding of the classical physics of electron space-charge waves and thus provided the key to much needed expansion into the microwave field.

Another case in point is the improved understanding and control of ferrite materials, which found rapid acceptance and development at a time when low-cost high-performance magnetic elements were sorely needed in transmission and in computer memory.

In short, the important lesson to be learned from the vigorous past of electronics is not that it was always close to the *new frontiers* of basic science. Rather, it was the conscious or unconscious recognition of *relevant* physical phenomena and materials, *old or new*, which could fulfill a critical need or break an anticipated technological barrier.

Renewal and technological growth occurred whenever a critical need and a highly relevant area of science came together in someone's mind. Whenever such a synapse occurred, the necessary financial support for technological



development was quickly forthcoming and significant growth took place.

At times the event resembled a "solution looking for a problem"—and this was certainly true of the original audion. Since it had no electronic competitors, it was developed and applied rapidly to communications. The laser is a similar case, an elegant solution looking for a problem, but in a well-developed field of economically strong and versatile competitors. It is having rougher going despite strong industrial and federal support for research and development. Perhaps we have been too prosaic in our consideration of the range of problems that the laser can solve. We have been strongly conditioned by its resemblance to microwave devices used only for transmission and perhaps should be looking more broadly at its unique properties in switching and memory; i.e., in the broad field of information processing.

More rarely, but particularly illustrated by the transistor episode, the synapse between need and relevant physics occurred as the result of a "problem looking for a solution." In such a case, a clear idea of the limitations of the old technology clarifies the economic as well as the technical requirements for the new technology. It greatly aids in the selection of the most relevant area of science in which to seek a solution, and insures a large area of application when the technological solution is found.

Where are we going?

From these lessons of the past and appraisal of the present, what can we say about the future? What should we be doing for the short- and long-term future to insure that electronics will continue to be a growing dynasty and not become an aging family?

The invariant problem, with us today and tomorrow, is the numbers barrier in its many disguises. The major short-term attack on this problem is through the technology of integrated circuits, as pointed out previously. But what are the specific problems? Success in this approach depends upon great improvement in the manufacturing yields or in the costs per circuit, and in the reliability or failure rate per circuit without sacrifice of circuit performance capability.

Underlying all of these objectives is the need for better understanding and control of the metal-oxide–semiconductor (MOS) system comprising the key parts of many integrated circuits. At the present time we are using a great deal of empirical technology in this area. It is fair to say that we do not understand the basic physics and chemistry of this complex three-phase material system in its simplest form. Until we have a quantitative theory, well verified by critical experiment, we will not be able to raise yields and reliability except by costly and lengthy empiricism. Even when the silicon–silicon dioxide–aluminum system is understood, much basic research is required on other MOS systems for optimizing cost, reliability, and performance.

The need for electrical isolation between elements in monolithic circuits and the increasing number and kind of elements desired per circuit have significantly multiplied the number of serial process steps necessary to construct such a circuit. This is another disguise for the numbers barrier and it results in reduced yields and lower reliability per circuit. We have simply pushed the numbers problem back into the material-process area. Reduction of the number of process steps per circuit will occur if the number and kind of elements per circuit are reduced and a better solution to the isolation problem, which currently adds many process steps, can be found. In this area also, better understanding of the MOS system will help, not only in better control of our existing device processes but in the use of more MOS unipolar devices. Such devices require fewer kinds of elements and process steps per function.

The "beam lead" technique also promises simplification and reduction in the number of process steps required for isolation, intraconnection, and protection. It too depends upon applied research in the MOS material system and gives promise of greatly improved manufacturing yield and reliability while at the same time permitting full capability in performance. For the short-term future, therefore, research on the physics and chemistry of MOS systems is essential for greatly improving the power of the integrated circuit attack on the numbers barrier.

Now let us look to the longer-term future. One feature common to all the integrated circuit approaches is their reliance on classical circuit concepts. In the final integrated circuit, every simple element and the intraconnection pattern of the equivalent circuit must be reproduced. Even after these circuits have been optimized and the number of elements pared down to an irreducible minimum, the total number of process steps per circuit function will always be larger than desired.

Let us remember that classical circuit equations are, after all, just mathematical approximations for describing the more general physical properties of electrical matter.

For example, today we would not use classical network equations to describe the behavior of waveguide devices or elastic delay lines. Certainly, we would not attempt to fabricate such structures with a great many lumped circuit elements. Substantial inroads might be expected by abandoning entirely classical circuit concepts and going directly to the basic interactions between energy and matter to perform desired system functions as simply as possible. Devices conceived in this manner have been called by various names, such as molecular or functional devices. A characteristic of such devices is that nowhere within one can we identify the separate elements of an equivalent circuit—in fact, there are functional devices such as the gyrator, maser, and laser for which there exists no classical physically realizable equivalent circuit that will produce the same functions.

A fair number of such truly functional devices already exists. Some, like the piezoelectric and magnetostrictive resonators and delay lines, were invented long before the numbers barrier was recognized. Such simple structures replace tens, and sometimes hundreds, of lumped circuit elements at great savings in performance, size, and cost. Others, more recently invented, are the p-n-p-n diode and counter, the Esaki diode, the maser, the laser, the phonon–magnon isolator, and the phonon–electron traveling-wave amplifier. Most of these recent devices have not yet reached high application levels. Some are not fully developed and others have not yet found their place in our technology in competition with the existing art. As previously mentioned, this could well be because we have seen them as replacing older similar devices rather than as providing other functions in a new and more powerful way.

One thing is certain, they promise to reduce greatly the number of elements and process steps per function when their capabilities are properly matched to an old or new system function. Part of the difficulty at present is a lack of compatibility with older devices and the fact that none represents a complete line of functions for a whole system. There is a natural reluctance on the part of the system designer to gamble on such incomplete technologies. (It is reminiscent of the early days of transistors when their functions also were too limited for a complete system synthesis.) Nevertheless, I am confident (as I was in the early transistor days) that the functional-device concept holds great promise for the long-term future.

At first sight, this concept might be seen as a naive demand for scheduled invention, and everyone knows that invention cannot be programmed. It could be and is argued that there is no methodical procedure for implementing a synthesis of function from basic physics, such as exists for the circuit approach.

However, I believe that the same opportunities exist in the functional physics approach as have existed in the circuit method. Actually, the functional physics concept will require for its realization no more invention than that required for the circuit approach. The major difference is that the latter is primarily behind us whereas the former is primarily yet to be done; *therein lies the exciting challenge for the next generation.*

In both cases, we start with statements of the needed system subfunctions. In the classical circuit case, we postulate a circuit model in terms of classical circuit elements as building blocks. We then analyze and predict its behavior, fabricate it, and measure its performance against that desired. If the results are not satisfactory, we change the circuit and the requirements on the devices until an economically realizable result is achieved.

In the functional physics approach, we skip the circuit model. Instead, we postulate a physical model directly from the interactions of the elementary material and energy particles; e.g., the maser and laser models are described in terms of the energy levels, transition probabilities, and lifetimes of the electronically active particles.

In each of these approaches, invention is present in the conceptual model for producing the function. The approaches differ in the level at which synthesis begins—be it classical circuit elements or the basic particles of matter and energy.

The electronic engineer of today has some 50 years of circuit invention to draw upon for circuit function synthesis. Once the new electronic engineer becomes as familiar with electrons, holes, phonons, magnons, and photons as today's engineer is with classical circuit elements, the process will seem more natural and straightforward.

Since the functional devices, by definition, will form a larger portion of the overall system than does the circuit element, they will represent a larger fraction of the total system cost. Decisions made at the interface between the new "device" and "system" engineers will therefore be of greater economic significance than in the past.

To achieve this higher level interaction, re-education will be required for electronic engineers. The system designer must start at a new level of synthesis, specifying his needs only in terms of basic system functions with properly weighted figures of merit. This, in turn, will free his imagination and effort for higher levels of elegance in logical design and system organization.

At the same time, the range of possible solutions open to the device engineer will be greatly enhanced in terms of such functional requirements. The response to the request, "Give us associative memory," can be much broader and more imaginative in seeking relevant physics than to the request, "Give us better magnetic cores and logic diodes."

If we are to make wise requests for new functions and to develop meaningful measures of technical–economic effectiveness for evaluating alternative solutions, electronic engineers, and particularly the system engineer, must be more highly educated and skilled in the use of the "systems engineering" method.

Conversely, if a broader range of physical phenomena is to be explored for relevant functional physics solutions, the electronic engineer, and particularly the device engineer, must have a broader and deeper education in the basic physical and material sciences.

Indeed each must have more grounding in both fundamental disciplines than today's engineers possess, so that they will be able to communicate adequately across the interface.

To ensure the challenge and growth of electronics, our educators must have the courage to synthesize a new philosophy of engineering and the confidence to strip away the old overspecialized technologies. In such a new synthesis, systems engineering and physical science will provide complementary and lasting disciplines for our future innovators. The one discipline helps to identify and evaluate our most pressing, generic problems; the other provides the knowledge and techniques for converting the most relevant science into more powerful technological solutions.

After all, the aim of electronics should be not simply to reproduce physically the narrow elegance of classical circuit theory; rather, it should be to perform needed systems functions as directly, as simply, and as economically as possible from the most relevant knowledge of energy–matter interactions.

This article is based on a talk given at the Recognition Seminar in honor of Prof. William G. Dow at the University of Michigan, Ann Arbor, Mich., Dec. 3–4, 1964.

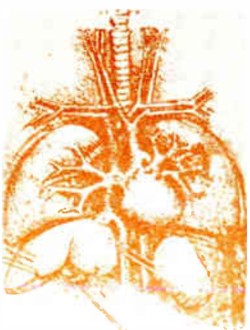
REFERENCE

1. Casimir, H. B. G., "Physical phenomena in new devices," *Proc. IEEE*, vol. 52, pp. 882–883; Aug. 1964.

The artificial heart—exemplar of medical–engineering enterprise

A survey of a dramatic field of endeavor: in which the role of engineers is assessed, and in which eminent doctors and engineers voice their views on the many problems involved—medical, technical, and otherwise

Nilo Lindgren *Staff Writer*



There is no doubt that engineers can and do play an important role in the development of artificial organs for humans, just as there is little doubt now in the minds of most of the major investigators in this field that, as in the case of the total artificial heart, such developments are completely feasible, and will, in fact, come about.

For the presently uncommitted engineer, then, there is here an area of endeavor—in the development of artificial organs—to which he might usefully bring his skills and his knowledge. It is a field in which his disciplinary outlooks are needed, in which his efforts would be worthwhile, and which could bring him some happy moral reinforcement; namely, he would know that he was trying to do something that really could help people in a direct tangible way.

The hard questions are: *what* can he do, and how might he go about it? Clearly, he first needs to know what has been done and what the problems are. To this technical side of the task, the following pages are in part addressed. In addition, we have asked a number of researchers eminent in the field of artificial organs—both doctors and engineers—for their advice on the first question. Their generous responses appear in the text that follows and in the special editorial boxes (see box, p. 69).

The line of attack

In surveying the field of biomedical engineering, we find ourselves looking over a seemingly limitless horizon of activities and potentialities. It is not an old field, this intimate conjunction of medicine and engineering, and yet a lot has happened in a short time. As in every other sphere of life, the impact of modern technology has lifted the lid on human limitations, and has brought revolutionary fantasies into the realm of the possible. And perhaps nowhere is this more startlingly evident than in the present efforts to make artificial devices to assist (orthotics) or to replace (prosthetics) internal human parts that are diseased or that have failed. Doctors, whom legend has it are a conservative breed, are in the forefront of these efforts.

In this article, we shall be quite drastically and arbitrarily selective. We shall not seek to paint a balanced picture, but shall concentrate on the research and development centering on the heart—on the cardiovascular system—but even here mainly on the efforts to build an internal artificial heart. Thus, for instance, we will not pretend to do justice to the development of pacemakers, a field which is already well advanced, but shall brush it out with a few unfair strokes. And we shall do the same with the efforts at developing artificial kidneys, artificial lungs, external prosthetics, sensory aids, and so forth.

What we will consider are some factors of heart functioning; we will look at them from the point of view of an engineer who is trying to design an artificial heart, weigh some of the major problems as they are presently seen, and then consider a few of the specific efforts to solve these problems.

What will emerge from this line of attack, hopefully, is a kind of "typical" case, an *exemplar* of the kinds of medical–engineering problems involved in the broad-scale development of many different types of artificial organs. That is, although each organ, from the point of view of its replacement or assistance, presents its unique problems, there are also the common problems involved in working in the "internal" environment—high temperature, a liquid (100 percent humid) atmosphere that is both corrosive and conductive, a soft environment that undergoes constant motion so that erosion and breakage are serious problems, and the physiological defenses of the living system, that is, its very capabilities of attacking and rejecting what is alien to itself. At the very least, the

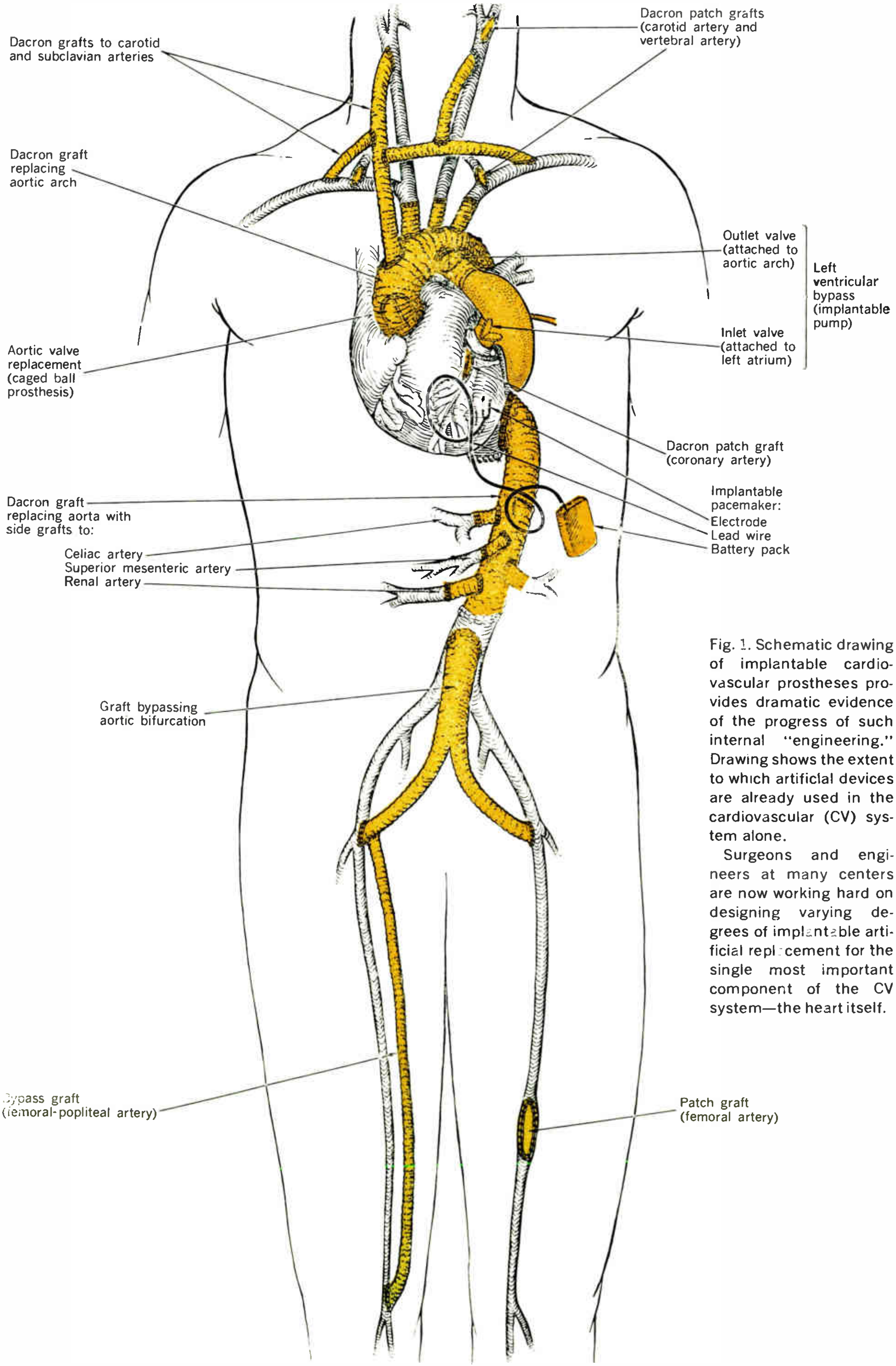


Fig. 1. Schematic drawing of implantable cardiovascular prostheses provides dramatic evidence of the progress of such internal "engineering." Drawing shows the extent to which artificial devices are already used in the cardiovascular (CV) system alone.

Surgeons and engineers at many centers are now working hard on designing varying degrees of implantable artificial replacement for the single most important component of the CV system—the heart itself.

artificial heart serves as the most dramatic point of focus on the subject.

To indicate just how narrow our line is, we should glance at the amplitude of the field we are neglecting. The extent of prosthetics now employed in the cardiovascular system alone is indicated in Fig. 1, which was prepared for SPECTRUM under the direction of Dr. C. William Hall of the Baylor University College of Medicine. Dr. Hall, one of the principal contributors to the nation's first multidisciplinary approach to the development of an implantable artificial heart launched at Baylor and at Rice University, points out that Fig. 1 does not show the various orthopedic and plastic surgery prosthetics because it would look too cluttered.

A measure of the "clutter" comes from the Dow Corning Center for Aid to Medical Research, a nonprofit center set up five years ago to provide information and technical assistance relating, among other things, to the medical applications of the important silicone rubbers. During this period, the Dow Center has been involved in a great many aspects of artificial internal organ development. Dr. Silas Braley, Director of the Center, recounts some of the artificial internal organs they have worked on: "the esophagus, trachea, bile ducts, ureters, bladders, ear ossicles, urethras, noses, cheeks, chins, jaws, ears, dura mater, hearts, heart valves, breasts, testicles, joints, tendons, blood vessels, corneas, lenses, and nerve and tendon sheaths. We have also worked on such ancillary areas as

The need for engineers in the medical field

The testimony to the need for engineers varies in tone, and although there is occasionally some slight question of just how the doctor–engineer cooperation should be brought about, the conclusion is uniform: engineers *are* needed. Here are a few statements from men well known in the field.

From Kenneth E. Woodward, Research and Development Supervisor at the Harry Diamond Laboratories in Washington, where engineering interest in artificial hearts dates back to 1960, comes this statement: "In general, because the educational background of medical people is usually lacking in mathematics, the physical sciences, systems analyses, etc., the language of the man of medicine necessarily lacks precision and descriptive depth. For the most part he must rely upon empirical techniques in the solution of medical problems. In my opinion the engineer will, in the future, give to medicine the language and tools necessary to understand and define the most complex and best engineered system of all, the human body."[47]

From Silas Braley, Director of the Dow Corning Center for Aid to Medical Research, a center that since its founding in August 1959 has been of tremendous service to the medical field, there comes something similar, though in different words: "We are not medically-trained, but rather we are chemists or chemical engineers working intimately with the medical field. Over the past five years, we have had a rather broad experience as para-medical operators. In this time, we have developed some ideas as to the problems and potentialities of the engineer–medical technician. First, we feel that the engineer is needed very badly in the medical field. The dogma of medical education is such that one must learn an incredibly large amount of information. As a consequence, the doctors do not usually have sufficient knowledge of the other fields to enable them to do the things that they want to do. They end up doing a job inadequately, or they spend an inordinate amount of time reinventing the wheel, as one disillusioned researcher picturesquely put it. The necessity of engineering specialists is recognized by many investigators, however, and quite a number of Bioengineering specialists are now at work."[1]

From an eminent surgeon, Dr. C. William Hall, Assistant Professor of Surgery at Baylor University in Houston, Tex., where the largest professional artificial-heart program is now well under way, there comes a somewhat different view: "It is difficult to say what contributions could be made by professional engineers in this field. I would doubt that a significant contribution could be made directly by an engineer in this field without close liaison with a person or group of persons trained in medicine. I say this from sad experience because I've reviewed many engineering attempts to build an artificial heart and most all of them come out looking something like a fuel pump for a '34 V-8 Ford. However, an engineer who is serious enough to seek out and work with medical personnel can and does contribute a great deal. The converse is also true, i.e., a medical person who tries to build an artificial heart without engineering back-up is simply spinning his wheels. The problems are too broad based and numerous to be solved by an individual. That is the reason we have selected a multidisciplinary approach to the problem and have incorporated several departments in these two institutions (Rice and Baylor) to help solve the problems associated with the development of an artificial heart."[40]

This theme of intimate cooperation is struck again and again. Engineers are urged not to work in their own basements, but to become involved with a solid medical team. Too often, it is said, both the engineer working alone, and the single doctor working with him, have been stung. And, they say, once a doctor, hoping to get help from an engineer, becomes disillusioned by the results, he develops a powerful immunity to trusting engineers again, or being interested in working with them. And apparently the same thing happens in reverse.

hydrocephalus drains, detached retina repair, antifoam for heart–lung machines, implants for velopharyngeal insufficiencies, silicone foam enemas, antifoam for flatulence, pacemaker encapsulations and many other applications."[1]

Electric pacing of organs

Electric stimulation or pacing of various organs that fail to function properly on their own is already a technique that is well advanced into the clinical stage. There are pacers now for the gastrointestinal tract, urinary bladder, paralyzed muscles in limbs, and many others. Electric pacing, Dr. George Myers of Bell Telephone Laboratories says, has reached "almost incredible proportions."[2]

The best-known pacer, of course, is the electric pacemaker for the heart, which is used in the treatment of Stokes–Adams disease. While the fact that a slow heart rate could bring about fits and death has been known since at least 1789, the therapy for it is only five years old. Pacemaking devices supply periodic electric pulses to the heart muscle, thus initiating contractions and restoring a normal cardiac rate. Dr. Yukihiko Nosé, Graduate Fellow in the Department of Artificial Organs of the Cleveland Clinic Foundation, estimates that pacemakers have been placed in more than 2000 patients who otherwise might not be alive today. Dr. William Chardack (who in 1960 reported treatments with totally implanted pacers) and his associates, Wilson Greatbatch and Andrew Gage, reported this year[3] that nearly 6000 pacemakers of their design have already been manufactured by Medtronics, Inc.

Although Wiggers studied electric stimulation of the heart in 1925, the use of such stimulus to treat heart block was first suggested by Callaghan and Bigelow in 1951, and by Zoll in 1952; in 1957, Weirich, Gott, and Lillehei described a method of implanting electrodes in the heart muscle.[4] If the reader re-examines Fig. 1, he will see that two electrodes are attached directly to the heart. These are stitched into place much as one might sew a button on a garment.

The literature in the pacemaker field is already vast. There are many different designs, and many well-known engineer–doctor teams and organizations involved—Kantrowitz, Raillard, Glenn, Mauro, Eisenberg, Parsonnet, Myers, Schuder, Kennedy, Enger, Weinberg, Sessions, all in the United States; Siddons, Davies, Abrams, Lightwood, in England; Camilli in Italy; Senning in Sweden. There is no need to cite specific references to the works of these well-known investigators; a few representative and easily obtainable articles will put the interested reader well on his way.[5–7]

Methods of powering pacers include implanted batteries (see Fig. 1), transcutaneous inductive coupling, and RF transmission. Most pacemakers thus far have had a fixed rate; recently, however, Nathan and Keller devised a synchronous pacemaker that locks in with the heart's natural pacemaker.[3] Two engineer–doctor teams have independently developed piezoelectrically powered pacemakers—G. H. Myers and V. Parsonnet[7] (Newark Beth Israel Hospital), and C. C. Enger, Jr., and J. H. Kennedy[8] (Cleveland Metropolitan General Hospital). The latter group has devised a piezoelectric-powered implantable cardiac pacemaker that derives its electric energy from the force of ventricular contraction—in one sense, the heart paces itself. Just this April, it was announced that two graduate students in biomedical engineering at Drexel Institute of Technology (P. Racine and H. Massie) had developed a self-energizing device to pace the heart without supplementary batteries or wires.

Reliability of existing implantable cardiac pacemakers for use in patients has been a serious problem—breakage of electrodes, permeability of materials, battery failure, and so forth, have led to a rather high incidence of pacemaker failure.[3] For this reason, the development of a self-generating pacemaker has been an important step.

"It's just a pump"

It is probably true for every layman that his mind holds such a web of associated imagery, his body such levels of feeling, his intuition such convincing impressions, about the nature of the human heart that it is both oppressive and difficult for him to imagine the heart being totally replaced by an artificial device. How could any

The problem of understanding

The biggest problem in this area is the understanding of the other specialist's field and language. We have not found the medical technical terms to be difficult, but we have found a great deal of difficulty where there are different meanings for the same word. "Compatibility," for instance, can mean complete reaction or solubility, complete nonreaction or absolute insolubility. Even the terms "soft" and "smooth" can be used as synonyms by the uninitiated. It takes a lot of cooperative work to get around such seemingly simple problems.

I can see another problem looming up on the horizon—one that has not yet been widely recognized. We have known quite a number of very fine professional engineers who have been of extreme value to their medical colleagues and who have voluntarily taken the relatively poor-paying medical jobs because of their dedication; yet these same engineers have left the medical field to return to their own specialty because they were not accepted on a professional level by the medical profession. If the latter wish to recruit and hold good engineers, they must realize that these engineers are as much specialists in their field, with as extensive a training, as the doctor himself, and they should be certain to treat these engineers as professional personnel and not as second-class citizens. I'm afraid that many of the present trainees in Bio-Medical Engineering are in for a disappointment when they find themselves relegated to the positions of technicians and not treated as the professional men they are.[1]

Dr. Silas Braley, Director
Dow Corning Center for Aid to Medical Research

artificial device, any artifact, successfully sustain the weight of so much subjective "evidence" as to its true nature? Obviously, if that layman is an engineer (it is probably not far from the mark to say that engineers are laymen with respect to body functioning) who wishes to make the journey into bioengineering, he must undo some of this implicit imagery, replace it, or bypass it, by starting the assembly of a more informed and sophisticated picture, and he must modify his feelings. This will cost him some effort.

It seems worthwhile to pay some attention to such subjective phenomena, at least in the first instance, because, as everyone knows, when a man uses words, their meanings are shaped and shadowed by his whole subjective history, and by his special training. And yet, as many people in this cooperative field of medicine and engineering point out, one of their biggest problems in this area is understanding the other specialist's field and language, *and* each other (see box, p. 70). For instance, it may come as a relief, and a liberating idea, for the engineer to hear a doctor say of the heart, "It's just a pump," or, really, that it's not just one pump but two pumps operating in series. But the way the doctor and the engineer understand this "pump," at least in the first instance, are worlds apart. It is the beginning of the engineer's getting a handle on the problem, but what an extraordinary pump it is! Capable of self-repair, it pumps one to two gallons per minute, and in an average lifetime beats between two to three billion times. And what an extraordinary, and often tortuous, system it sustains and feeds and drains of wastes, and what an extraordinary fluid it pumps. The hydraulics of blood, which is a "particulate suspension" of cells of various kinds in a solution of proteins, lipids, carbohydrates, and electrolytes,[9] does not involve the kind of hydraulics yet worked out by engineers although, it should be said, such studies have been begun by researchers seeking to understand the effects on cells of laminar shear fields, pressure gradients, turbulence, grinding action, and so on.[9]

Putting aside its electrical and chemical activity for the time, let us consider the double-pump action of the heart and the circulatory system it serves.

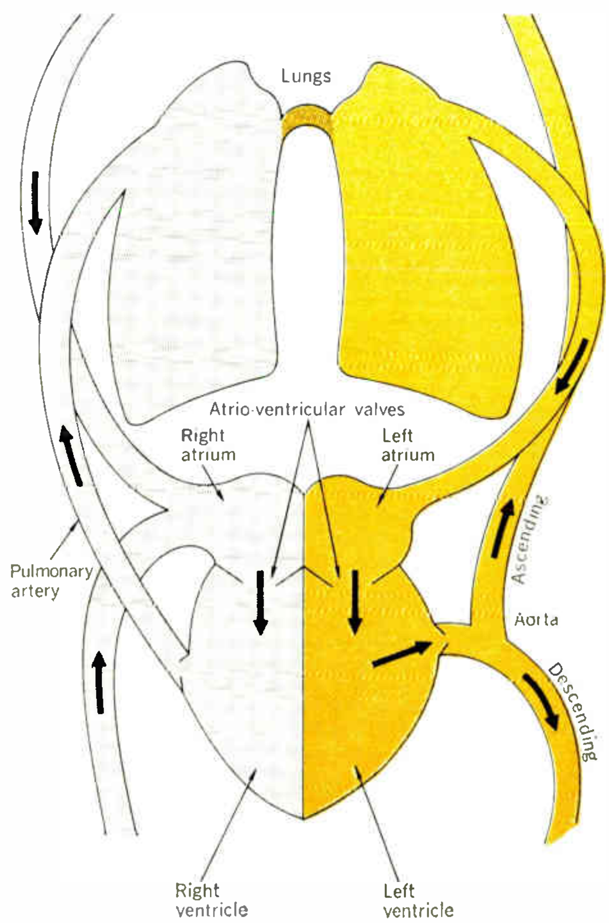
Figure 2 shows a simplified schematic view of the heart elements, with which we can easily follow this straightforward account of the heart–lung action: "Blood containing a fresh supply of oxygen leaves the left side of the heart in a large elastic pipe called the aorta. Branches (arteries) carry blood to the heart itself, the head, arms, internal organs, and to the legs and feet. The blood flows from the arteries into a network of capillaries. All exchange of materials between the blood and the body cells takes place thru the very thin walls of these capillaries. The capillaries unite to form veins which make up a return piping system that carries the blood to the inlet port on the right side of the heart. The right side discharges the blood to the lungs (at a much lower pressure than that prevailing at the entrance to the aorta). In the lungs, carbon dioxide is adsorbed and oxygen is absorbed. The blood flows from the lungs to the intake port of the left side of the heart to begin again its trip thru the body."[10]

Each side of the heart, or each pump, "has a required inlet and outlet pressure which is flow dependent and both must pump exactly the same volume of blood over a finite time. The pumping action of both sides of the heart is similar. Blood enters the pumping chamber (the ventricle) thru a check valve from an accumulator (atrium). When the ventricle is filled, it contracts rapidly, squirting blood out into the artery. A second check valve prevents the blood from the artery from flowing back into the ventricle when it relaxes for refilling. This contracting is what accounts for the beat of the heart and of the pulse. The arteries have thick, elastic walls that expand with each discharge from the heart. By the time the blood reaches the capillaries, the flow is steady. The major portion of the work of the heart is done by the left side. And, as might be expected, more malfunctioning of the heart occurs on the left side. In fact, there have been instances in which the total pumping load has been done by the left ventricle."[10]

An engineer's view of the cardiovascular system

Although the foregoing description gives us only a fairly simple, linear picture of the events in the closed-loop cardiovascular system, it does begin to suggest the complex interrelated parameters—mechanical, neural, and chemical—that control the stroke volume, pulse rate, and strength of muscular contraction in the heart. These are the parameters that an engineer would need to know in undertaking a design of a device that is to duplicate heart functions. For example, the engineer asks what

Fig. 2. The heart and the system it serves shown schematically. Conceptually, a simple-minded approach to the heart is to view it as two pumps operating in series.



kind of stresses, pressures, forces, flows, and energies prevail in the circulatory system, and what the nature of the pumping action is.

An interesting engineering analogy of the functioning of the cardiovascular system has been suggested by Kenneth E. Woodward and his associates of the Harry Diamond Laboratories, Washington, D.C.[11] The model, and the argument Woodward pursues in its development, is instructive, for it is posed in terms with which an engineer is more comfortable while leading him to a sharper view of the complexities of the natural system.

Woodward reasons that damped resonant principles govern the operation of the cardiovascular system. Only because resonant principles are employed, he suggests, can the heart and circulatory system meet the engineering design requirements and restrictions imposed on them. He enumerates some of these:

1. The compactness of a man's body and his active life in the environment suggest the need for a closed, forced circulation, cardiovascular system. Both in engineered devices and in living organisms, compactness is achieved by obligating functional elements to perform multiple tasks. Blood flowing in a closed circulatory system is such a multifunctional element. It carries the materials needed for respiration, nutrition, and excretion; it can be called upon to make rapid redistributions; in short, it can defend and regulate the body in the myriad contingencies of life.

2. However, the highly complex fluid needed to perform this multifunctional role is fragile and easily damaged, so that stringent requirements are imposed on the organ propelling it through the circulatory system. For instance, it has been found from the use of extracorporeal pumps (pumps used outside the body which do the work of circulating the blood during heart surgery) that this blood damage limits the pump run to one or two hours.

3. Thus, the heart must be designed to pump blood gently; it must squeeze the blood with minimal force. Forces may be minimized both by having variable resistive loads (blood vessels are highly elastic so that increases in flow cause them to distend) that help regulate the flows from a relatively constant pressure pump (the heart) and by employing resonant principles.

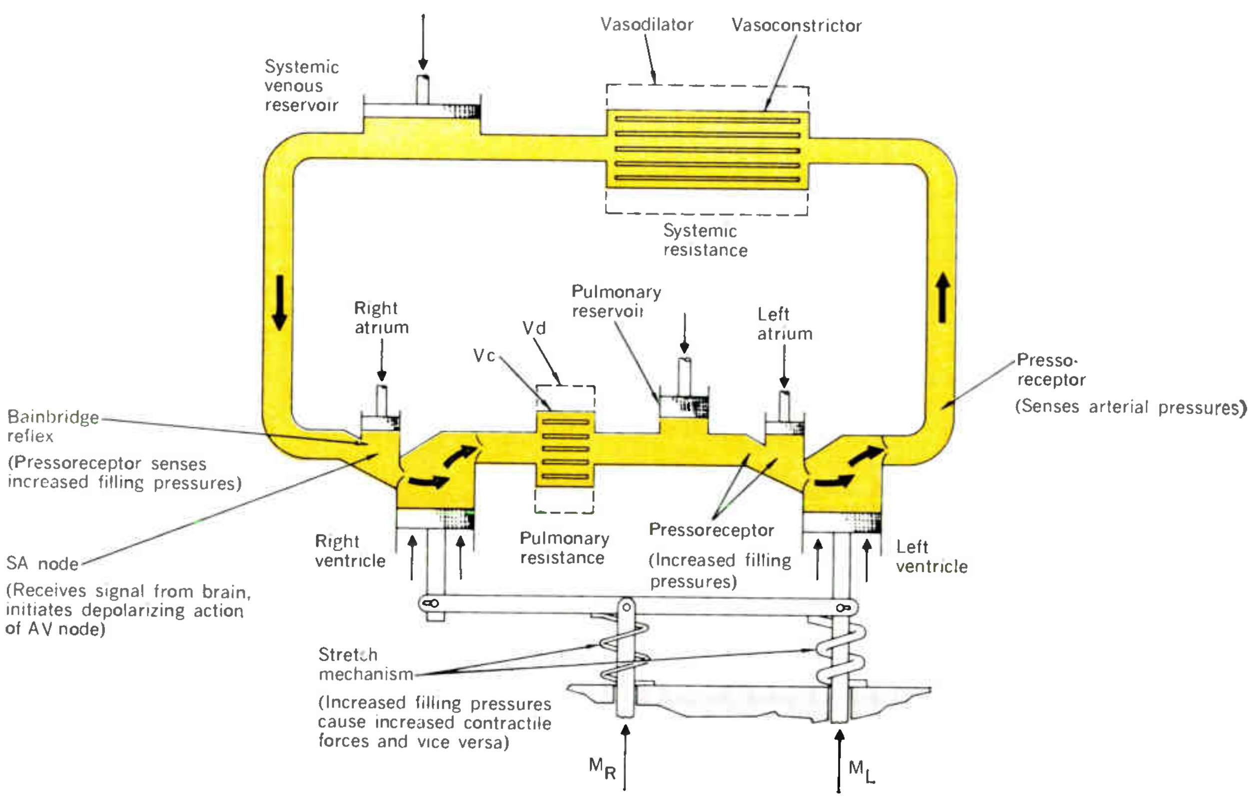
4. Because of fatigue limits of cardiovascular materials, inefficiencies of heart and circulatory system, limited squeezing capabilities of myocardial muscles (middle muscle layer of the heart wall), and the finite energies available, the heart and circulatory system are designed to keep these limiting criteria within bounds.

5. These bounds are commensurate with the capabilities of the body to repair or replace materials damaged during normal functioning of the body.

6. Conceivably, only a rhythmically beating heart forcing blood into and through an elastic arterial system in which the natural or commanded responses are uniquely related to the pulsed blood flows could achieve forces and expend energies sufficiently great to realize the required vascular pressures and flows. Simultaneously these forces and the resulting pressure and flows must be compatible with the heart's limited ability to generate them, the vessel's ability to contain them, and the blood's ability to tolerate them.

Woodward's engineering analogy of the cardiovascular (CV) system, shown in Fig. 3, is interesting to compare

Fig. 3. Engineering-type diagram of the human cardiovascular system, which allows an engineer to think about the heart function in terms that are familiar to him.



with the more naturalistic rendering of Fig. 1, or, for that matter, with the sketch of Fig. 2. The two pumping sections of the heart are here depicted as consisting of a spring-lever-piston configuration that displays the degree of independence of each ventricle. The contractile forces M_L and M_R, which are governed by the endocrine system or the sympathetic nervous system, operate simultaneously (although not necessarily at constant relative magnitudes); M_R and M_L are augmented by the stretch mechanism, which is itself affected by the residual atrial pressures. Both the resistive and capacitive loads shown in the system are regulated by constriction or relaxation of the blood vessels (vasoconstriction and vasodilatation).

Woodward and his colleagues state that perhaps the most important message of this analogy relates to the roles of the two sides of the heart. It suggests, they say, "that the left heart is concerned primarily with maintaining a general level of flow in the system. This conclusion is based on the locations and functions of pressoreceptors (at right). Pressure fluctuations in the flow tracts before and after the left heart caused by variational flows are compensated by changes in systemic resistance and by pulse rate adjustment in the case of the outflow tract. The left heart does not possess a sensing element in the inflow tract, to increase its pulse rate in the presence of increased flows, as does the right heart. The left heart, therefore, might be described as the prime mover of the cardiovascular system whose outputs are governed by the activity levels enjoyed by the individual. The diagram and logic would suggest the system pressures are maintained by alterations in systemic resistance, since for relatively constant activity levels smaller forces operate. This has the added advantage that pulse rate can become less variable. On the other hand, the right heart would appear to play a somewhat subservient role to the left heart. The only sensing element affecting its flow apart from the control received through the *SA* node is the Bainbridge reflex. Increased flows to the right heart, as indicated by increased filling pressures, cause both sides to speed up simultaneously, but the right heart is not favored with load regulators. Consequently the right heart must adjust its pulse rate either through the operation of the Bainbridge reflex or the *SA* node to pass the flows it receives without change but with the addition of enough energy to meet pulmonary loads. The right heart, then, might be described as performing an additional role to the one of providing the motive power to propel blood through the pulmonary circuit. It might function as the basic mechanism for balancing flows between the left and right hearts, particularly in situations where the flows are fluctuating widely."[11]

If, as this dynamic model suggests, flow in the circulatory system is controlled chiefly by appropriate changes in the systemic resistance and pulse rate, the result is that the forces the heart exerts on the blood are minimized.

In weighing these and many other engineering aspects of the CV system, while they were in the process of developing a blood pump for extracorporeal applications (called the Army Artificial Heart Pump), Woodward and his associates began to note many similarities between the dynamic character of pulsed blood flows interacting with the arterial system and the more familiar characteristics of resonance in electric and mechanical systems. Thus, they were led to suggest that the CV system operates on principles that govern damped resonant systems generally.

To make the image of this system more concrete, Woodward recalls the operation of a spring-actuated pendulum clock. As the pendulum swings through its appointed arc, it gets a small kick (minimal input force) from the wound spring (potential energy) at precisely the right instant to keep it going, which it may do for long periods (days or even weeks) with a minute energy investment, so long as the input force is in tune with the natural frequency of the pendulum. If, however, the natural frequency of the pendulum or the periodicity of the input force are modified, they can, if great enough, bring the clock to a stop.

This image, though extremely simple, is also extremely suggestive. It is not difficult to imagine ways in which the responsiveness of the natural cardiovascular system is disturbed, thus bringing about turbulence and excessive forces on the heart and arterial structures.

The resonant model is developed in a more general fashion, and numerous interesting comparisons are made between it and the natural CV system that illustrate the engineering principles implicit in it. Although it is not possible to follow all these interesting considerations, we cannot refrain from citing one or two points, before going on to the more general conclusions.

If the model holds, it is said, the arterial system operates in precisely the frequency domain one would expect from a force-energy viewpoint. Above this region the heart would be expected to overwork rapidly, which it in fact does. For frequency ratios less than the lower limit, inadequate perfusion (blood flow into the system) is the consequence. Also, in a resonant system, the potential energy stored in the blood vessel walls, as they expand during systole, is given up to the main stream in phase with the pulsed flows within the main stream. (Systole is the heart's contracting phase during which the blood is forced onward through the system, whereas diastole is the passive rhythmical expansive phase when the chambers of the heart fill with blood.)

The interest in developing models of this sort, of course, lies in their potential power not only in the design of artificial hearts but also as diagnostic tools. As Woodward points out, changes in the elastic properties of the circulatory system or in rhythms of the heart could conceivably be used for evaluating the effects of such changes on the entire system performance.

From another point of view, this kind of modeling is instructive to the neophyte (whether or not the model is on the right track), because it reveals how an engineer goes about thinking out a complex system engineering problem in an extremely (for him, the engineer) novel environment. It confirms once again the potency of such analytic methods constantly redressed and corrected through the accumulation of experimental evidence; i.e., the scientific method taking hold in the world of physiology.

Confronted in an experimental surgery room with the scene of a doctor holding a dog's pulsating heart in his hand, an engineer might well be intimidated (at least the first time he witnesses this event). But given some kind of system diagram with which to think things out, and to play around with, his interest (in the "problem") and his hopes (that he might solve "it") may revive and overcome his apprehensions and doubts.

Philosophy of replacement

The idea of total replacement of defective human organs must, of course, be subject to a whole host of qualifications and questions. There are varying degrees of replacement. Dr. Adrian Kantrowitz of the Maimonides Hospital, Brooklyn, a vigorous researcher in this field, has insisted that wherever feasible as much as possible of the function of the original organ should be preserved and given assistance by artificial devices. In cases of severe heart attack or major heart surgery, for instance, a heart can be bypassed with an auxiliary device for a period of time while the natural heart recovers.

This concept of assisted circulation for cardiac failure was first applied by Dogliotti in 1951 to a patient undergoing cardiac surgery. In 1952, Helmsworth and coworkers reported the use of veno-venous perfusion with an extracorporeal pump to help a heart patient. Among others active in this field are Stuckey, Dennis, Hall, Connolly, Akers, Claus, Soroff, Spencer, and Kennedy.

Only as a limit might total replacement be required to sustain life. But, even at that, total replacement of the heart is a radical step. Thus, one of the important goals (for all prosthetic and orthotic devices) is not merely extension of life, but restoration of maximum function with the least physical and psychological hindrance.

Eventually, many of the problems may be solved through organ transplantation or by a deeper understanding of chemistry at the cellular level, but at the present time, the possibility of artificially influencing the regeneration of body parts seems extremely remote. For this reason, total replacement with artificial organs or portions of organs may be regarded as a necessary and highly important way station with very valuable byproducts (see box, p. 74). As Dr. John H. Kennedy of the Cleveland Metropolitan General Hospital says, "We put in the prosthetic devices, but we don't like it."[12]

From whatever level and degree the diseases of the heart are attacked, there is one sure result: increased knowledge and understanding of its functions. When Dr. Kennedy says, "We are in the Renaissance of cardiac surgery!" one catches a glimpse of the excitement.

The artificial heart: what kind of flow?

One of the major questions that has confronted artificial heart pump designers, and the basic question that the model we have been considering was attempting to answer, is whether or not the artificial heart should produce pulsating flows or steady flows. This question is still not conclusively answered. However, the fact that the natural heart produces a pulsating flow predisposes most investigators to lean toward such a system.[10,13]

There is, of course, the possibility that the autonomic nervous system (that controlling the automatic reflexes, such as breathing, of the intact circulatory system) could compensate for certain lacks in the artificial heart, and there is some slight evidence that this could happen. Nonetheless, as Woodward states in a recent paper, "It does not seem wise to add to the number of imponderables already present by introducing an unfamiliar kind of flow."[14]

The first proposals

Who, more than ten years ago, did more than dream about the total replacement of the heart by an artificial device? Only the Russians, it seems. In his book, *Experimental Transplantation of Vital Organs*, V. P. Demikhov stated that in 1937 an artificial heart device was constructed and placed in the chest of three different dogs. He also reports work on dogs in 1958.[13]

But the real impetus began only about ten years ago when a few papers began to appear that suggested total replacement of the heart. For instance, based on their experiments, two American scientists, William J. Fry and Francis J. Fry, filed for a patent on a mechanical heart as early as 1956. The pace since the mid-fifties has been such that hardly anyone, as we first said, doubts the ultimate feasibility. Dr. Willem Kolff of the Cleveland Clinic Foundation, one of the pioneers and leading authorities in the field of artificial hearts and the father of the modern artificial kidney, says, "I will be disappointed if we do not successfully replace the heart in a human within the next three to five years." But, he adds with a wry smile, "I must remind you that I said this same thing five years ago!"[15]

The potential of artificial hearts

I can foresee that the artificial heart might be implanted in humans within the next 10 to 15 years with some degree of success. But I rather doubt that this will be as lasting and as important an advance with adequate widespread application as the development of the technique of transplanting hearts. I say this for several reasons, the most important of which is the proper power source that can be incorporated into the human body so that one does not have wires or tubes transgressing the skin, which also leads invariably to infection. Secondly, the tolerance of valve mechanisms and pumping systems without fatigue of the material used. Thirdly is the ability to avoid coagulation of the blood.

In spite of this, the development of an artificial heart offers fantastic possibilities for further physiologic research into the response of the intact organism to a pumping system over which one has control. This would allow us to define much more accurately some of the responses of the peripheral vascular bed to pharmacologic agents and to various changes in flow and pulse contour and also to such things as changes in pressure and pulse rate. If one were to develop to an adequate degree of refinement an artificial heart over which one also had control of the four heart valves, one could also study with infinite detail conditions simulating damaged heart valves that we see in clinical practice today. The problem of artificial heart valves is a subject all in itself and, of course, this is an integral part of the manufacture of an artificial heart. The precise development of a heart model would allow for further study of valves under rather ideal conditions.[30]

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The Denver Clinic

The work begins

The history of the present serious effort to develop artificial hearts, as well as the efforts to develop many other implantable devices, is well documented, notably in the pages of the *Transactions of the American Society for Artificial Internal Organs*. In fact, it was in a presidential address to the third annual meeting of the ASAIO in 1957 that Dr. Peter Salisbury urged that a serious, protracted effort be undertaken.

The development and clinical use of physiological machines (heart, lung, and kidney machines), external to the body (extracorporeal), that simulated body functions during surgical operations and that brought fresh understanding of vital bodily functions, made it more reasonable to imagine the implantation of some such devices within the bodies of persons who would not otherwise survive.

Once the work on artificial intracorporeal devices began, it gained rapidly in pace, with the basic problems being attacked over a broadening terrain. *Some* of the influential developments, and the dates when they were reported, are as follows[1c]: Dr. Selwyn McCabe demonstrated a four-chambered plastic blood pump (not used experimentally) (1957); Dr. T. Akutsu and Dr. Willem Kolff removed the heart of a dog and replaced it with an air-driven device of polyvinyl plastic, which sustained the animal for 90 minutes (1958); Dr. Bert K. Kusserow developed a single-chambered motor-driven diaphragm pump, which was used to assist the right ventricle of a dog for 10½ hours (1958); Dr. Kolff and Dr. Akutsu described a solenoid-driven blood pump (1959); Drs. Houston, Akutsu, and Kolff developed a motor-driven pendulum pump that sustained a dog's circulation for more than five hours (1960); Dr. Frank Hastings and his colleagues developed a hydraulically activated biventricular pump, on which work had begun in 1959, with which a dog was kept alive for more than 30 hours (1961); Dr. J. C. Schuder developed a system for importing power for an artificial heart across the closed chest by means of inductive coupling between coils inside and outside the chest wall (1961); Dr. R. C. Eggleton, Dr. F. J. Fry, and Dr. W. J. Fry reported in vitro and in vivo tests of an artificial heart pump that in the preliminary phase of experimental work kept a dog alive for up to half a day (1961); Dr. Kolff and his colleagues developed an electronic control system with which they could produce pump pressure outputs having forms resembling those encountered physiologically, and with which they demonstrated the important result that the peripheral resistance was actually reduced (1962); Drs. Barila, Nunn, and Woodward developed a fluid amplification system for reliable long-term circulatory support (1962); Dr. R. G. Burney and his colleagues reported work on an artificial heart which utilized a servomechanism so that pump output was a function of venous inflow pressure (1963); Dr. Loehr and his colleagues reported on the construction of an artificial heart powered by piezoelectric materials (1964); Drs. DeBakey and Hall experimented with the use of skeletal muscle as a power source (1964); Drs. Kusserow and Clapp ran a small pump for eight hours through the power developed by electrically induced contractions of a dog's muscle (1964); and, finally, the feasibility of using an implanted nuclear power source to drive an artificial heart is reported (1965).

In addition to efforts at total heart replacement, there have been very important advances in heart assistive devices, pumping devices that only partially supplant the heart or act in parallel with it. Impressive work has been done in this area by Dr. Adrian Kantrowitz, Dr. Domingo Liotta, Dr. C. W. Hall, and their associates.

Most of the names mentioned above continue to dominate the news of advances in this field. Their preeminence, and the space we shall devote to some of their more recent efforts in what follows, should not, however, obscure the fact that now there are many researchers engaged in good basic work, the exclusion of whom can only reflect on the inadequacy of this survey. Before departing from this mood, we should recommend the fine, detailed survey of this early research written by Dr. Bert K. Kusserow,[16] a more sweeping review by Dr. Francis J. Fry,[13] and, for a most comprehensive and readable discussion of the broad problems and specifications involved thus far in the development of artificial hearts, the report of K. E. Woodward.[14]

Artificial heart programs

As is probably evident from even the brief foregoing sketch, there are many different types of artificial hearts and power sources under development. Dr. DeBakey reported last year that there were already about eight basic designs, which relied on three sources of power—electric, hydraulic (fluid and gas), and skeletal. And since that time, atomic energy has been added. Each type of pump has presented unique problems, but as Dr. DeBakey pointed out, some problems were common to all. These included "the complex problems of blood destruction and clotting, wear and fatigue of the fabricating material, interruption of certain necessary physiological feedback (reflex) mechanisms, and biochemical acceptance of material by the host."[17]

Some hearts are designed to be totally implantable—that is, power supply and all—while others rely on wires or tubes passing through the wall of the body to the power supply outside. Some partial heart supports (auxiliary ventricles) are also totally implantable, while others are powered from outside. The various programs of heart development described below should bring many of these differences into relief. We shall start with a system that attempts to avoid breaking the "skin barrier," and that deals with an aspect of the artificial heart problem that should strike the electrical engineer with most immediacy.

Electromagnetic energy transport

Intensive investigations of the various ways in which high levels of electromagnetic energy can be transmitted across the intact chest wall, for the stimulation of biological organs and the powering of artificial units, have been made by Dr. John C. Schuder, who is with the Department of Surgery at the University of Missouri.[18,19] His approach involves basically the use of inductive coupling between a flat coil on the outside of the chest and a similar coil attached to the inner surface of the chest wall. With this general system, Dr. Schuder visualizes that an ambulatory patient could, during the day, carry the source of energy (batteries) on the surface of his body, and that the energy transported through the chest wall would be converted to some mechanical form that is suitable for the heart pump. At night, the patient's

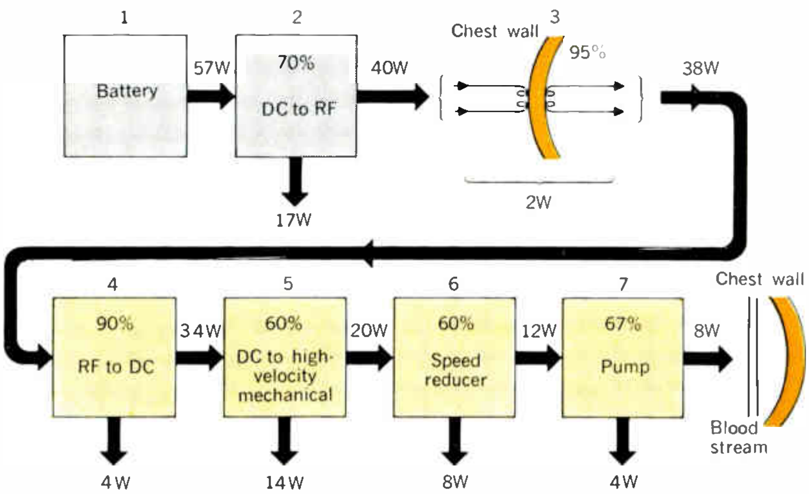


Fig. 4. System for powering an artificial heart without destroying the integrity of the chest wall. Coupling of energy is between coil on surface of the chest and another coil inside the body. This method might be used by an ambulatory patient.

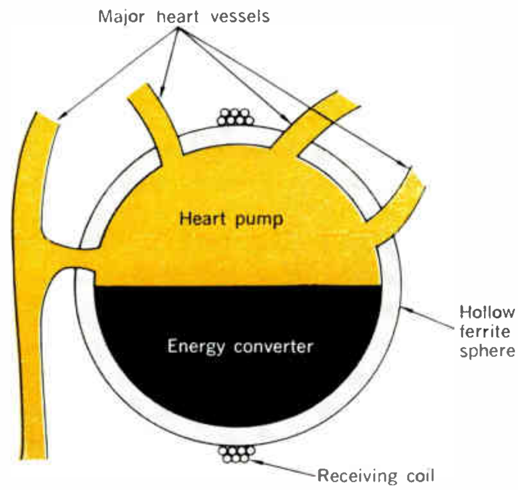


Fig. 5. Schematic of method of incorporating an artificial heart within a hollow ferrite sphere so as to increase efficiency of energy transport. Inside diameter of sphere is 7 cm. During experimental implants, ferrite vessel was covered with Silastic.

bed could be located in a very large time-varying electromagnetic field, so that he could remove the surface energy source.

It is estimated that the maximum power input required by an artificial heart is about 35 watts. A schematic of a proposed system to carry this kind of input is shown in Fig. 4. Dr. Schuder points out that although this complete system has not been used experimentally, he has made extensive and detailed studies of portions of it, and other portions are well understood from their use in other applications. Efficiency levels for the system components are within the range of the state of the art.

As it is visualized, the system consists of the following blocks: (1) rechargeable batteries; (2) a lightweight transistor inverter with suitable provision for heat dissipation: (3) flat pancake coils of 9-cm diameter and with 3-cm separation (in surgically acceptable geometries) that yield 95 percent efficiency; (4) a lightweight solid-state diode converter. In addition, (5) a really satisfactory solution to the electrical-to-mechanical converter problem is required—Dr. Schuder states that while most of his efforts thus far have concentrated on the problem of energy transport through tissue, he anticipates that during the next few years he will be involved in "an intensive investigation of electrical to mechanical energy conversion devices for actually powering an artificial heart";[20] (6) it is possible that block 6 can be eliminated by developing an energy converter for the previous stage that supplies mechanical energy at low speeds, or by finding ways to utilize high speeds in the heart pump; and (7) although Dr. Schuder has not been deeply involved in the engineering and biophysical problems involved in the heart pump itself and in its control, he stresses that its design must not overlook considerations of efficiency. In Fig. 4, he has arbitrarily assumed a pump efficiency of 67 percent, but he has also given serious consideration to methods of using less efficient pumps.[21] Though the details cannot be gone into here, he concludes that if necessary it may be possible to exchange efficiency for reduced size and increased longevity of the electrical-to-mechanical energy converter.

One method that he has recently devised for improving the efficiency of energy transport (e.g., when the patient is in the low-efficiency, large time-varying field) is to use a suitable ferrite spherical core for the receiving coil. The heart pump and energy converter would be located within the sphere as in Fig. 5. A detailed description and theoretical analysis of this design is scheduled to appear in the IEEE Transactions on Bio-Medical Engineering.[22]

Dr. Schuder has noted that other methods for powering an implantable heart—wires and tubes through the chest wall, mechanical forces transmitted through tissue, and energy from various muscles—are at the present time either unattractive for chronic utilization (unacceptable psychologically or because of dangers of infection) or have not been shown to have sufficient power capabilities, although some of them may eventually prove to be suitable.[20] One of the major concerns with his system is the possibility of tissue damage owing to the continuous exposure to an electromagnetic field. This question is currently being studied. For instance, dogs have been exposed to electromagnetic fields (equivalent to that required to transport 50 watts across the chest wall), one dog on a nearly continuous basis for approximately three years with, thus far, substantially negative effect.

In addition to this work on artificial heart systems, Dr. Schuder and his associates have developed a micromodule pacemaker that can be sutured directly to the heart ventricle and powered by inductive coupling with an external coil.[23,24]

An acknowledged authority in the field of artificial heart research, Dr. Schuder is also an electrical engineer. It is interesting, therefore, from the point of view of our original question about how engineers might relate to this work, to know how he entered this field. He received his Ph.D. in Electrical Engineering and in 1957 joined the open heart surgery group at the University of Pennsyl-

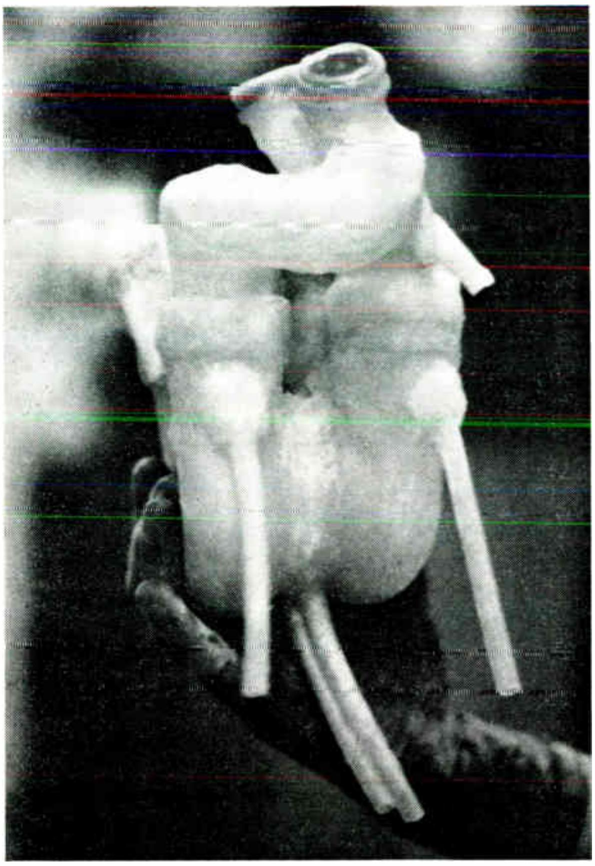


Fig. 6. Single-piece implantable heart fabricated from Silastic, which has been used experimentally in calves at the Cleveland Clinic Foundation. This natural-seeming artificial heart approximates the size and form of the calf's real heart.

vania, where for three years he was heavily involved in both the clinical and research activities of that group. In 1960 he went to the University of Missouri, where he has since been involved almost entirely in the application of electrophysics to cardiac problems. A couple of years ago, Dr. Bert Kusserow remarked of him, "I'm sure that when the ideal artificial internal heart is once constructed, Dr. Schuder will be there with an energy transport system to make it work."[25]

To engineers, Dr. Schuder comments: "There are numerous problems associated with artificial organ development which can only be solved with creative engineering effort. Engineers must move into this field if rapid progress is to be achieved. One way for an engineer with a B.S. degree to enter the field is to take graduate work in the biomedical engineering area. Work of this nature is available at a number of universities and typically combines elements of both engineering and biological science. Engineers with advanced degrees could enter the field by joining one of the many research groups which are actively involved in artificial organ work."[20]

In fact, a group that has been actively seeking engineers to join them (for help in developing telemetering systems, pressure transducers, compact pumping systems, and the like)[15] is the now-famous Department of Artificial Organs at the Cleveland Clinic Foundation, where the principal investigator is Dr. Willem J. Kolff, who was one of the very first to advocate seriously and to pursue the development of the artificial heart.

It is to their most recent work, and to another principal method of powering an artificial heart, that we shall next turn our attention.

Artifacts that resemble hearts

Although artificial heart researchers are careful to point out that they are attempting to duplicate function rather than anatomical structure, it is curious what persuasive power the artifacts convey when they look less like machines and more like their living counterparts. As if then, with the "proper" marriage of form and function, one's intuitive apperception of the evidence can harden into conviction.

Everyone has seen pictures and diagrams of hearts (and even eaten cooked ones!), so that the fabricated heart shown in Fig. 6 is perhaps shocking only because it is white. This is the single-piece heart that has been most recently developed by Dr. Kolff, Dr. Yukihiko Nosé, and their colleagues at the Cleveland Clinic Foundation.[26] It is being used in experiments with calves.

These hearts employ air-driven Silastic ventricles with inlet and outlet valves. Two types of ventricles are used: a diaphragm type, which is commercially produced by the Holter Company in cooperation with the Cleveland Clinic; and sac-type ventricles developed by K. E. Woodward.

These single-piece hearts are about 4½ inches high, 6½ inches long, and 3½ inches wide, designed to approximate the space of the pericardial compartment (the membrane sac that encloses the heart and the roots of the great blood vessels).

Figure 7 shows in cross section how the sac-type ventricles function. The right ventricle is shown in the systolic phase (with air pressure between the outer firm form and the inner collapsible sac causing the blood to flow out past the opened teardrop-shaped valve), while the left ventricle is in the diastolic phase. These ventricles may be pumped simultaneously, alternatingly, or independently of one another. The diaphragm type of ventricle differs from the sac type in that only one side of the ventricle moves like a diaphragm (and is more likely to rupture). Theoretically, the sac type will survive 300 million cycles, or from five to six years of life. (However, the search for new more satisfactory materials with which to make these hearts goes on.)

Compressed air applied to the air chambers of each ventricle is the driving force of this heart. A number of control systems have been employed to simulate the physiological pressure curve. One system is the NASA servomechanism, which is a sophisticated driving system with multiple electronic feedback mechanisms. It varies pulse rate, ratio between systole and diastole, degree of suction for diastolic filling, and slopes of the pressure curves.

Another driving system is the fluid amplification technique developed by K. E. Woodward's group at the Harry Diamond Laboratories. The basic principles of this system were first demonstrated in an extracorporeal pump in 1961 (the Army Artificial Heart Pump), and its design is now well advanced. Functionally, it mimics the human heart while requiring only four moving parts—two heart valves, one ventricle, and one suction control flapper. In June 1964, work was begun on an implantable heart based on the same design principles. Figure 8 shows the heart. The lucite shell houses both ventricles. A stainless steel retaining plate secures the ventricles in place, and also serves as a housing for four bicuspid heart valves. Two bistable fluid amplifiers (only one is shown in Fig. 8) control the ventricles. Eventually, the amplifiers will be packaged as an integral part of the ventricle housing.[14]

H. H. Straub (who was responsible for packaging this first heart) and K. E. Woodward of the Harry Diamond Laboratories conclude that much more effort and development are needed to achieve a practical artificial heart of any design. The fluid amplifier, however, seems to them to offer the ultimate in simplicity, life, and reliability because of the minimum of moving parts and the absence of electronics.[14]

Of these kinds of driving systems, where tubes must permanently penetrate the chest wall, Dr. Kolff has at one time said: "Should the only other alternative be death, one might prefer to have an artificial heart in the chest, even if some wires or thin tubes would have to come out of the chest wall to provide the necessary power."[27] But, to avoid any misconceptions, he goes on: "The air-driven pump seems to offer a solution that may be of practical use before other solutions become available—which does not imply that this is the all-time ideal."[27] He also mentions that it is known that Dr. N. M. Amosov, head of the department of thoracic surgery, Kiev Institute for Advance Training of Physicians, in Kiev, U.S.S.R., was working on the replacement of the heart by a pump driven by compressed air.

To bring home the reality of these efforts even more forcibly, Fig. 9 shows one of the calves used in the implantation experiments mounted on a special suspension system, alive, and with an artificial heart in his chest. The longest survival time thus far has been 31 hours. The calf reportedly jumped when the photo flashbulb went off, and in many other ways exhibited normal functions. Dr. Nosé says that he believes it will not be long before they will achieve more spectacular survival times of up to two weeks.[28]

Polyurethane heart

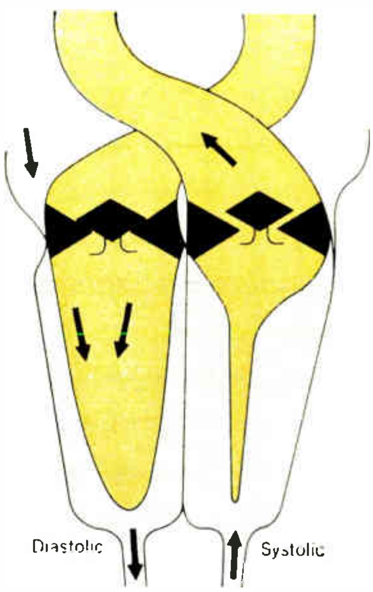
Among the compressed-air-driven artificial hearts is one designed by Dr. W. Gerald Rainer and his associates at The Denver Clinic, shown in Fig. 10(A). This prosthetic device, discussed in detail two years ago,[29] has an inner working part consisting of two polyurethane ventricles contained within the common "pericardial" chamber, also of polyurethane. This heart was designed to produce a pulsatile flow, which was deemed necessary in the prolonged pumping of blood. Of the use of polyurethane, these authors said, "We are impressed with its kindness to blood, its durability and its versatility of application." Between 1961 and 1963, the device was implanted in 21 animals. Figure 10(B) shows the method of heart insertion.

Rainer writes that they are still working on the artificial heart, and are investigating the use of Silastic. However, he says, "We have had practically no significant problems with clotting of blood on the polyurethane surface. This is in contradistinction to some other people's findings, but may be more related to flow through the heart rather than to the material used."[30]

This remark recalls one made by Dr. F. J. Fry. He

Fig. 7. Cross section of the artificial heart with sac-type ventricles. The four valves have a newly designed teardrop shape that permits greater flow with less excursion than a ball valve. Valve housing is made of stainless steel; valve itself is made of Silastic. The small black lines on the valves represent stainless steel retaining feet.

Fig. 8. Fluid-amplifier-controlled heart being developed at the Harry Diamond Laboratories. In this first model, only the ventricle package (lower left) is implanted in the chest of the animal. Compressed gases flow through plastic tubes from the two amplifiers (only one shown here) located externally. To the left is shown one of the Silastic ventricle sacs. This artificial heart has been tested in at least two calves at the Cleveland Clinic Foundation.



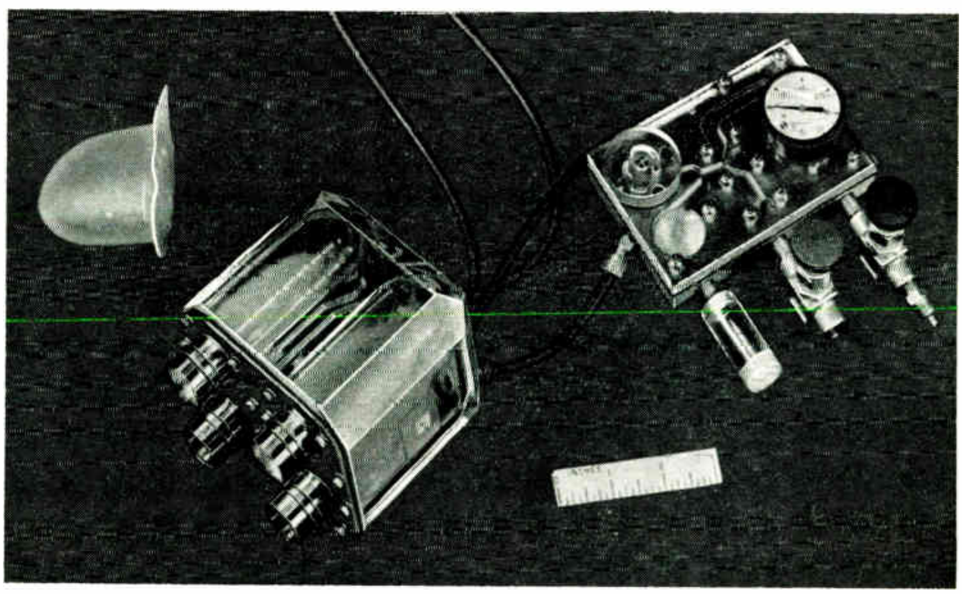
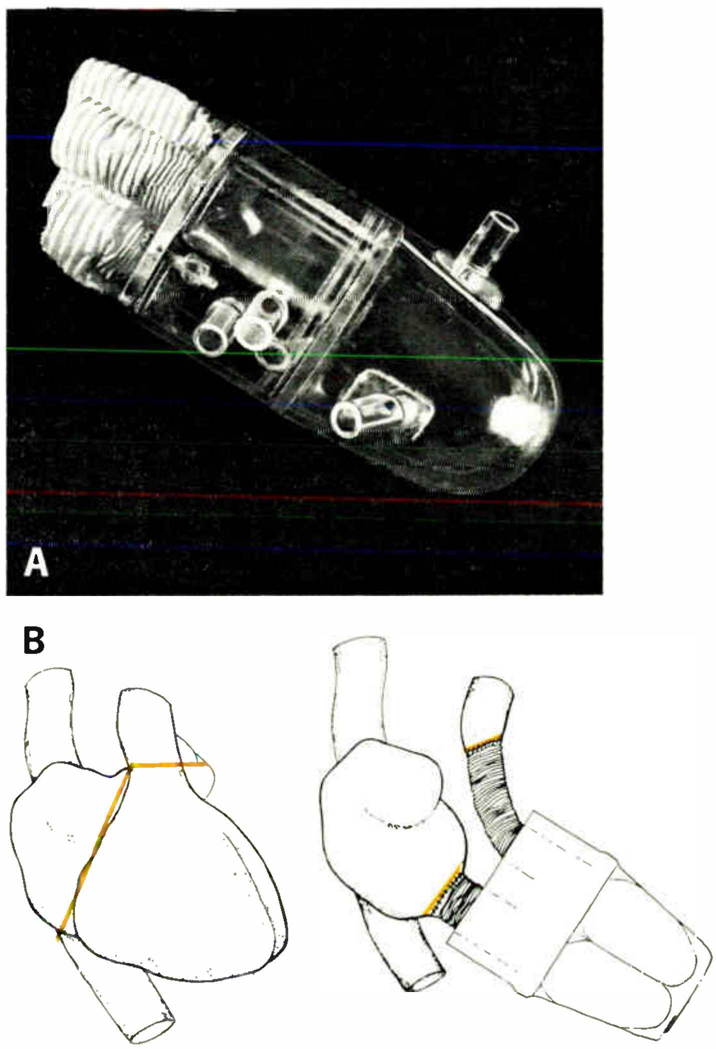


Fig. 9. Calf completely sustained by an artificial heart. Longest survival time to date is 31 hours. Experiments are carried out at the Cleveland Clinic Foundation.

Fig. 10. A—Air-driven polyurethane artificial heart designed by W. G. Rainer and his associates; it has partitioned ventricles for separate pumping and control. B—Schematic of how the heart is inserted, with the heart viewed from the right. The colored line shows the line of excision of the natural heart (to left), and the points of union (anastamoses) of the natural and artificial systems.



found that despite the generally rejected use of glass tubing for maintaining blood flow owing to clotting, he and his colleagues did not encounter this problem so long as the glass had been cleansed properly and the entry areas designed properly. From this and other experiences, he suggests that investigation of long-known materials should not be closed.[13] And he suggests further that this might be one of the important roles of scientists and engineers—that they will not take someone else's unquantified experiences for granted; that, in fact, they will reopen many closed questions in the medical-research area.[31]

Automatic control of artificial hearts

It has been said that those who have attempted to design artificial hearts have largely ignored the neural (and chemical) factors of control, except as they are reflected in the venous pressures in the atria through operation of the autonomic nervous system.[14] However, a sophisticated approach to this complex problem is now being included in a comprehensive artificial heart program that has been carried on in Japan since 1958 by a multidisciplinary team at the University of Tokyo headed by Professor Kazuhiko Atsumi. Details of their most recent work, in which they automatically control artificial hearts by digital computer, are reported at the sixth International Conference of Medical Electronics and Biological Engineering.[32]

Their system consists of the blood-handling parts, driving mechanism, and control system. They have adopted the air-driven method for use with sac-type artificial hearts. A block diagram of their control system is shown in Fig. 11. The digital computer was used as the pulse generator, the control procedures being so programmed that the optimum pattern of response to alterations in the circulatory system is selected and the venous pressure is kept at normal level.

Professor Atsumi points out that as the artificial heart is separated from the neural and humoral regulation of the organism, it must possess a control system that will maintain the circulation in a physiological state. In the near future, he says, the analysis of the multiple loop of the circulatory regulation mechanism will be begun. These data will be integrated into the present control system, and then, he concludes, the artificial heart will become a true substitute for the natural heart.[32]

Nuclear power source

Probably one of the most promising power sources for use as an implanted power source for an artificial heart, at least from an engineering standpoint, is one that uses a radioisotope fuel. Such a system has been under extensive development at the Thermo Electron Engineering Corporation in Waltham, Mass., for the past 18 months. The development there is under the direction of Robert Harvey, who several years ago, on his own, began thinking about the power source problem. He thought then of using a nuclear heat source with a thermionic or thermoelectric system, and the electric power would then drive the pump. His early calculations, however, showed that the method had an efficiency of only about 4 or 5 percent and, besides, produced an amount of heat that would have been intolerable in the human body. In addition, the resultant device would have been too large and heavy. However, an independent program had begun about two or three years ago at Thermo Electron to develop a miniature Rankine-cycle reciprocating engine, one that mainly could serve as a compact source of electric power, have high efficiency, be quiet and reliable, and operate as a hermetically sealed system with low maintenance requirements. A number of prototypes of this system were developed. When Harvey heard of this development, he again analyzed his system in relation to this engine, and found that it was feasible to go directly from heat to mechanical power with an efficiency of 10 to 15 percent, an improvement that "made all the difference" in view of his proposed usage.

At this time, T. R. Johnson (TE's vice president), R. Harvey, and their associates are sure that the power source can be built, that it will have an acceptable energy-to-weight ratio, that it will be long-lived, and that it is well within the present state of the art.[33] As presently designed, the power source (excluding the blood pump itself) would fit in a cylinder roughly 6 inches long and 3 inches in diameter, and, including shielding, would weigh between 2½ and 4 pounds. Such an isotopic source package and converter might be surgically anchored to the hip bone, with internal pneumatic cables going up to the artificial heart.

A key aspect of the device is that it needs a good mechanism for rejecting heat. The method proposed is to dump the heat into a major artery (possibly the iliac artery). Calculations indicate that this would raise the temperature of the blood very slightly—measurable in tenths of a degree F—and medical opinion seems to be that this amount of heat might not be intolerable or lead to excessive damage to the blood. (Not all medical aspects of the possible use of this kind of system have yet been taken into account.)

The device has not yet been used in a living creature. In the next several months, T. R. Johnson says, experiments with animals are likely to begin.[33] The work is being carried on in association with Dr. William Bernhardt, who is Director of the Surgical Research Laboratory at the Children's Hospital in Boston.

The way this device has been conceived and developed is illustrative of what kinds of imaginative things can result when two or three different disciplines come together.

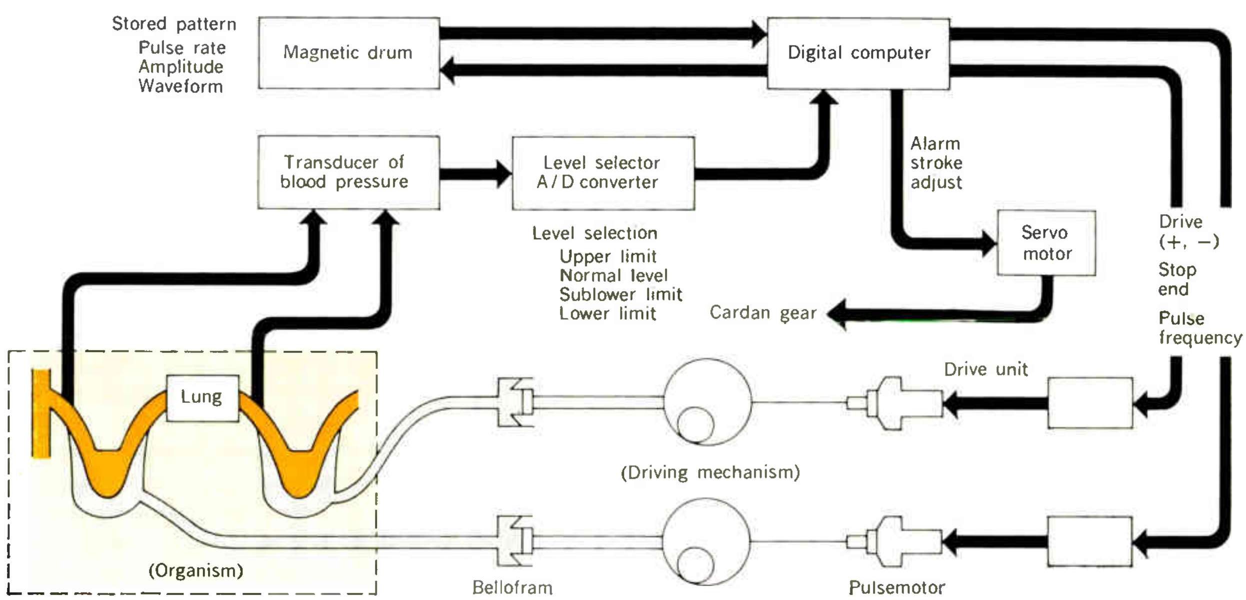
Auxiliary heart devices

To round out this picture of artificial heart research, we should also consider briefly the nature of devices that have been designed to assist failing hearts, rather than to replace them.

Figure 12 shows one such device, an auxiliary ventricle, which Drs. A. Kantrowitz, F. O. Grädel, and T. Akutsu (formerly with Dr. Kolff's group in Cleveland) have been developing for some time at Maimonides Hospital, Brooklyn. This device, fitted into the aortic arch ("the seat of the soul," quips Kantrowitz), and attached in series with the left ventricle, assists it by decreasing systolic pressure and thus reducing this chamber's work.[34]

Dr. B. K. Kusserow and J. F. Clapp, III, have designed a ventricle or pumping chamber consisting of a straight flexible tube residing within a fluid-filled hydraulic chamber. Periodic compression in the outer fluid pumps the inner tube. This type of pump is designed to retard thrombus formation and blood damage during prolonged pump runs.[35] The same paper reports

Fig. 11. Diagram of the control system for an artificial heart that makes use of a digital computer



Kusserow's experiments at powering a pump by harnessing skeletal muscle.

Professor E. S. Bücherl writes from Berlin that he also has been working on a device that might temporarily replace the left ventricle by a one-chamber pump.[36] The bypass device, shown schematically in Fig. 13, has a blood chamber (upper right, "not bigger than an egg") that contains a saclike plastic membrane filled with glucose. The blood chamber has two nozzles, each with a valve, one connected to the left auricle and the other to the aorta. The pump operates with compressed gas. The control signal is indicated at the right. Dr. Bücherl has also done research on the total replacement of the heart by a two-chamber pump.

Many experiments with different types of heart bypass pumps have been carried out by Dr. Hall, Dr. Domingo Liotta, Dr. M. E. DeBakey, and others at Baylor University.[37,38] (Dr. Liotta succeeded in 1960, the same year as Kolff, at replacing hearts in dogs with artificial devices.) In late 1963, these surgeons implanted a left ventricular bypass, a tubular device driven by air pressure. Currently, they are working on a right ventricular bypass based on the same principle. A combination of the two would provide a complete bypass of the biologic heart.[39]

Another recent and apparently simple method for total heart replacement, which does not require the removal of the biologic heart, is shown in Fig. 14. Molded double-walled Dacron-reinforced Silastic sacs are dropped into the left and right ventricle chambers. Air pressure drives these "intraventricular" pumps.[37]

The unresolved problems

About some of the major problems still unsolved in the development of artificial organs, there appears to be substantial agreement—the "materials" problem heads most lists—although in some areas there are differences in outlook and emphasis (see box, p. 82).

Dr. C. William Hall of Baylor University lists the problems quite simply. They are "in the area of materials, blood plastic interface, implantable power, proper valving, types of blood pumps, blood trauma, and certain physiological studies of animals having implanted artificial blood pumps."[40]

Dr. R. I. Leininger, Chief of Polymer Research at the Battelle Memorial Institute, writes that their work on materials is primarily directed toward the development of plastic materials that will be compatible with blood and so be useful for artificial hearts and arteries.[41] Another phase of Battelle's work is concerned with the development of improved membranes for artificial kidneys.

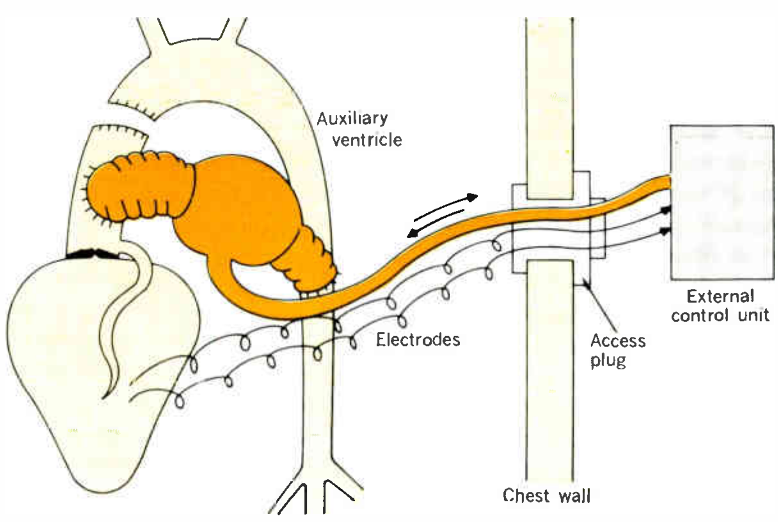
Dr. Silas Braley, Director of the Dow Corning Center for Aid to Medical Research, points out that although surgical techniques and knowledge have been available for some time, the engineering aspects of artificial internal organs have been unavailable. "The greatest problem in the engineering area has been the lack of proper materials. Even the artificial organs that are designed to operate outside the body, such as the current artificial kidneys, have been beset with the problem of finding materials that are acceptable."[1]

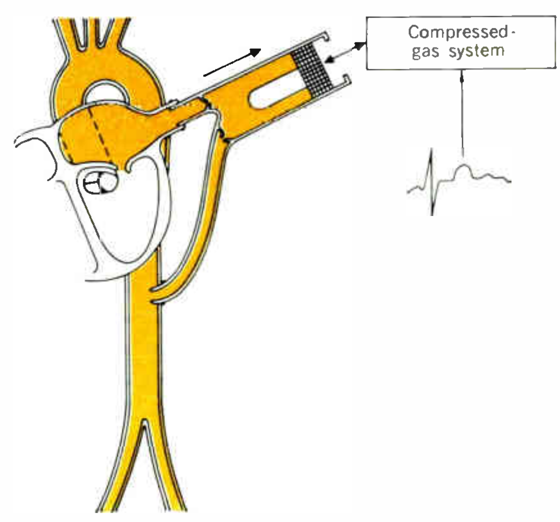
"Certain of the silicones have been found to satisfy [certain] criteria.[42] The major lack of knowledge at the present time is simply the effect of these materials over very extended periods; they have been used for only ten years."[1]

Another outlook on the problem of tissue reaction to foreign body intrusion is taken by Dr. Eugene F. Murphy of the Veterans Administration, New York. He urges that fundamental studies be made on ways of maintaining infection-resistant passages of inert materials through the skin barrier on a permanent basis,[43] an idea that, he says, is typically rejected as an impossible dream by many people with biological training. So-called temporary passages, he points out, are now used for very long pe-

Fig. 12 (below). Auxiliary ventricle consisting of a flexible silicone rubber bulb in a semirigid case. Two electrodes in left ventricle of the heart pick up the R wave of the ECG, which triggers a solenoid valve controlling the operation. The device is powered by compressed air from outside the body. The stitched break in the ascending aorta forces the blood flow through the artificial ventricle.

Fig. 13 (right). Schematic for a temporary bypass of the left ventricle designed by E. S. Bücherl, Director of the Surgical Experimental Laboratory, Department of Surgery, at the Berlin City Hospital.





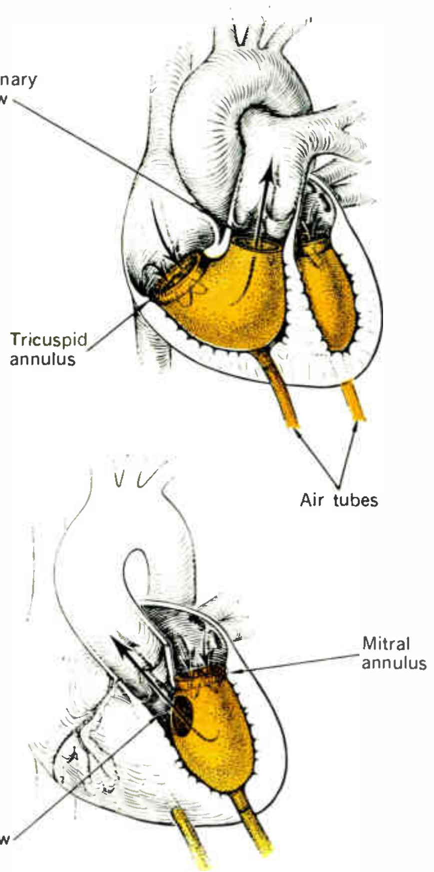


Fig. 14. Intraventricular pumps devised recently by surgeons at Baylor University College of Medicine, which are designed to replace heart function without removal of major heart structure. This drawing shows the air-driven pumps inside the left and right ventricles. Twelve-hour (animal) survival has been obtained with this model.

riods. If life-long infection-resistant passages could be realized, he foresees great developments for a wide variety of both external and internal prostheses.[44]

The multimillion multidisciplinary approach

Public recognition of the advanced state of development of artificial hearts, and a measure of their importance, probably came with the announcement that the Public Health Service had granted $653 324 to a multidisciplinary team of surgeons and engineers at Baylor University College of Medicine and Rice University to develop an implantable artificial heart. Over a five-year period, as much as $4.5 million will go to support this unique project (funded by a companion grant from the National Heart Institute). Heart disease is now the number one killer, so, at last, this kind of research is entering the "big time."

It is reported that the National Heart Institute of the National Institutes of Health is in the first phase of what may turn into a multimillion dollar program to develop an artificial heart. They are said to be currently evaluating more than 20 proposals for studies dealing with the problems of artificial heart technology. Dr. John R. Beem, associate director of NHI and head of the program, is quoted as saying that the effort would be mounted with all the systems development planning normally associated with a major defense or space-exploration project. Given perhaps $100 million, he thinks such a device could be in use by 1970.[45] Thus, there could be work for a lot of bright young men, and, as we have now seen, the fathers of the field have been laying the groundwork for the past decade and are ready to teach and lead the new recruits. Perhaps typically, Dr. Tetsuzo Akutsu says, "I am devoting my life to this effort."[46]

The multidisciplinary Rice–Baylor team will be directed at Baylor by Dr. Michael E. DeBakey, professor and Chairman of the Department of Surgery, and an internationally known pioneer in cardiovascular research. The engineering research part of the program at Rice

An M.D. advises an engineer about what he should know

An engineer should be aware of the reaction of biological tissue and biological tissue fluids upon the various prostheses. Although an organ such as a heart might be construed to be nothing more than a simple mechanical pump, and as such could be devised accordingly, there is a great deal of complexity in the response to pumping such as the feedback from peripheral vascular constriction or reflexes. One has to be aware of the many biologic variables in addition to the fundamental hydraulic and other engineering principles. Other typical problems that an engineer might encounter include the amount of reaction that foreign materials might produce when implanted in tissues. The long term response of these materials such as the gradual absorption of water, deformation by change in physical characteristics and deposition of calcium over a long period of time might be typical problems. Especially concerning organs that deal with blood flow, one has to be aware of the clotting potential of blood on any given surface. Also, for a tubular graft to be incorporated securely into an organism, one must be aware of the size of the interstices to prevent leakage but yet to encourage fibrous ingrowth. One certainly has to have some fundamental awareness of the anatomy involved, and the various flows through different chambers at different pressures and the rather highy critical problem of timing of ejection relative to valve opening.[30]

W. Gerald Rainer, M.D.
The Denver Clinic

will be headed by Dr. W. W. Akers, professor and Chairman of the Chemical Engineering Department. The first artificial heart to be a common effort of both institutions was implanted in a dog this spring.

The Baylor program of articifical heart research was started in 1962, and joined by Rice in 1964. Dr. Hall, one of the principal contributors to Baylor's efforts, writes that four major areas of research are underway. "These are: (1) the mechanics of blood traumatization; (2) the mechanical design of pumping devices and valves; (3) the evaluation of materials with suitable mechanical as well as biological properties; and (4) the development of required instrumentation and of methods of power and control of the artificial heart."[10]

The Baylor surgeons hope to attain total heart replocement in humans within the next three to five years.[39]

As Dr. Adrian Kantrowitz said at the March IEEE Convention, "The field has grown to the point where it is not possible to have half-baked engineers or doctors trying to perform each other's functions." Each must stick to his last, but know what the other is doing.

What remains?

The only deep unanswered question, after the technical problems are cleared away, is the question that will be posed by the man who is living only by the grace of an artificial heart, and whose "every second of life might be totally dependent on his local power company,"[10] namely, "*Who* am I?" Well may he ask. The question of subjective identity, long the private domain of artists and philosophers, may suffer new incursions and alarms. However, we may console ourselves with the realization that one thing leads to another, one step to the next, and the effort to answer that poignant question in new terms may be one of the interesting problems of research for the *next* generation.

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Widening energy horizons in the Pacific Northwest

Interconnections recently completed and under way represent a big step toward the electrical integration of three vast areas: the Southwest, the Pacific Northwest, and British Columbia. Of particular significance is the use of dc transmission for two of the projected four ties between the Northwest and the Southwest

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Power progress in the Pacific Northwest

Charles F. Luce *Bonneville Power Administration*

> *"I am convinced an adequate supply of energy is far more important to the security of our country than an adequate supply of gold. . ."*
>
> *W. A. Lewis*
> *Illinois Institute of Technology*

The day is drawing near when three vast areas—the Southwest and the Pacific Northwest of the United States and British Columbia in Canada—will be integrated electrically, and a power system composed of many separately owned and managed utilities will extend from Alaska through northern British Columbia to the Mexican border.

Before we describe progress in the Pacific Northwest, some facts about the Bonneville Power Administration, other utilities serving this region, and the area's geography are in order.

The Bonneville Power Administration, a bureau of the Department of the Interior, was created by the Congress in 1937 to act as the marketing agent for power from Bonneville Dam. It since has been designated to market the power from 20 other Federal dams in the region, and six more dams under construction. To accomplish its mission BPA has designed and built one of the nation's largest networks of long-distance, high-voltage transmission lines. The grid, adding capacity rapidly, is the main grid for the Pacific Northwest. The dams themselves are built and operated by the Corps of Engineers and the Bureau of Reclamation.

The BPA now has 9310 circuit miles of high-voltage lines and 261 substations. Of the existing lines, 58 percent are 230 kV or higher voltage, while 1056 miles of 500-kV or higher voltage lines are under construction. The grid is connected at more than 100 points with 14 other transmission systems. Besides scheduling and dispatching power from the 21 existing United States dams, with a capacity of 6.7 million kW, BPA wheels or exchanges over its grid about 4 million kW for nonfederal utilities. Its sales are at the wholesale level, except for large electrochemical loads that are sold directly.

The BPA serves the entire Pacific Northwest, an area bounded on the west by the Pacific Ocean, on the north by the International Boundary, on the east by the Continental Divide and the eastern border of Idaho, and on the south by the state lines that separate Idaho and Oregon from California and Nevada. This market area consists mainly of the states of Washington, Oregon, and Idaho, and that part of Montana west of the Continental Divide. It contains 290 000 square miles and has a population of 5½ million persons. In total, BPA supplies approximately 50 percent of the electric generation and 80 percent of the high-voltage transmission for the region.

The Pacific Northwest is also served by more than 100 electric distributors—private utilities, municipal systems, rural electric cooperatives, and public utility districts. Twenty-nine of these distributors have their own generating plants, nearly all of which are hydro. All but one of these generating utilities buy some power from BPA. A few distributors have small steam plants; they operate on a stand-by basis. The generating capacity of the non-federal utilities totals about 7.4 million kW. Their resources supply the other half of the region's power requirements.

In the Pacific Northwest the central geographic fact, strongly influencing the electric utility industry, is the Columbia River—the fourth largest river on the continent. Only the Mississippi, the Mackenzie, and the St. Lawrence travel farther or carry more water. The Columbia's flow is ten times that of the Colorado, twice that of the Nile. It has one third the hydroelectric potential of the United States, including Alaska. A large part of the river's potential is yet to be harnessed by man. This great river and its tributaries provide the indigenous energy base of the region.

The Columbia rises in the Canadian Rockies. It swings north, then south, and 500 miles later and 1360 feet nearer sea level, the river crosses the International Boundary into the United States. Approximately 15 percent of the river basin lies in Canada. About 28 percent of the Columbia's flow originates there. Between the boundary and the sea the Columbia flows another 740 miles and drops another 1290 feet.

Like the river itself, the Columbia's tributaries rise in the mountains and are fed by rains and melting snows. The flows of these rivers fluctuate sharply from season to season and from year to year. At the International Boundary the Columbia's largest flow on record is 550 000 cubic feet per second, and its smallest is 14 000 cubic feet per second. At Revelstoke, 130 miles north of the border, the highest measured flow is 99 times greater than the lowest.

The "308" report

The story of electricity in the Northwest is largely the story of the Columbia River. The first real efforts to promote the construction of Grand Coulee Dam began in 1918. These early efforts culminated in 1928, when Major John S. Butler, Seattle district engineer for the Army Engineers, was assigned to conduct a reconnaissance of the Columbia above the mouth of the Snake River. Butler recommended a detailed survey, completed July 31, 1931, which became known as the "308" report.

The 308 report was the first comprehensive plan for development of the Columbia River. It went beyond the wildest dreams of the proponents of Grand Coulee. The report recommended not only construction of Grand Coulee, but it also called for other dams: Foster Creek, which became Chief Joseph Dam; Chelan, which became Wells Dam; Rocky Reach, Rock Island; and Priest Rapids, which became two dams, Priest Rapids and Wanapum. The soundness of Major Butler's report is borne out by history, for all of the dams have been built. All but one are generating power. Wells, the last of the set, will begin producing power in 1967.

Not until 1933 did we begin to harness the river and transform it from a wild, untamed source of energy to one that would work for mankind. In that year, private capital built the first dam on the Columbia—Rock Island, a comparatively small run-of-the-river project near Wenatchee, Wash. That same year Bonneville Dam was started, and five years later began to sell its power.

Grand Coulee, the giant on the river, was finished in 1941. During World War II, power from these two projects was put to work building ships and bombers, and producing aluminum, lumber, food, and, finally, the atom bomb which ended the conflict.

After the war, large Federal dams envisaged in the first 308 report on the Columbia and its tributaries came along more rapidly—notably Albeni Falls, which was called Pend Oreille Lake in the report; Hungry Horse; McNary; Chief Joseph; and The Dalles. The original 308 report did not study Snake River dam sites. However, in 1947, during a revision of the report, the Corps' Portland district engineer in an interim report recommended construction of a high dam in Hells Canyon on the Snake, 111 miles upstream from Lewiston, Idaho. The revised report, issued in 1948, described Hells Canyon site as one of the more advantageous sites on the Snake River above Lewiston. In 1953 the Administration in office adopted a policy of "no new starts" on the Columbia. Hell's Canyon site on the Snake River, with 3 880 000 acre-feet of potential storage, was given to a privately

The North Shore fish ladder at the dam on the Snake River. Divided by baffles ten feet apart, each pool one foot higher than the other, the ladder allows the upstream-bound salmon to climb, either over the baffles or through openings below the water surface, the 100 feet from the downstream level to the forebay behind the dam.

owned utility for the development of three low-head dams with combined storage of 980 200 acre-feet. Federally authorized Priest Rapids was deauthorized, and Grant County and Chelan County public utility districts started three big projects on the mid-Columbia in central Washington—Priest Rapids, Rocky Reach, and Wanapum—all completed by 1963. Late in the 1950s, the Federal government re-entered the hydroelectric development program when Congress, without executive request, appropriated funds to start three new major dams—John Day on the main stem, and Ice Harbor and Lower Monumental on the lower Snake River.

This, then, was the status of electric power development in the Northwest when President Kennedy took office in 1961. Development of the Columbia's hydro potential had progressed a long way from the 308 report in 1931. But the development program was becoming disorganized. The dams started in the 1950s were basically run-of-the-river dams, and there was a crying need for more headwater storage projects to regulate stream flows. A treaty had been signed with Canada on January 17, 1961, to provide for three headwater dams, but its ratification by Canada was doubtful. Northwest utilities that had purchased shares of Rocky Reach, Wanapum, and Priest Rapids Dams were insistent upon a long-term coordination agreement assuring them benefits from proposed Canadian dams. Because of imbalance between headwater storage and installed capacity, the Columbia River plants were producing great quantities of secondary or dump power for which there was no market in the Northwest. A proposal for a 230-kV California intertie to market a tiny fraction of this spilled energy was stalled in the Congress. Looming ahead, in water year 1965–66, was a firm power shortage that could not be met by any project except the 860 000-kW Hanford dual-purpose atomic power plant. But Hanford had not been authorized, and there was strong political opposition to it.

In the past four years our solutions to these problems have been the Hanford atomic steam plant, the Joint Development of the Columbia River Treaty with Canada, a long-term hydraulic and electric coordination agreement among the generating utilities in the Northwest, and the Pacific Northwest–Pacific Southwest Intertie.

The threat of a Northwest firm power shortage ended in September 1962, when Congress authorized nonfederal financing, construction, and operation of the Hanford atomic steam plant by the Washington Public Power Supply System. The first 430 000-kW unit of this project will come on the line late this fall. The Washington Public Power Supply System, known as the Supply System, is an entity formed under state law by 16 public utility districts in the state of Washington. Congress authorized the AEC to sell the Supply System the by-product steam from the New Production Reactor at Hanford for use in two steam turbine–generators being built by WPPSS adjacent to the reactor. When and if NPR is not needed to produce plutonium, it will be leased to WPPSS and operated to produce steam specifically for power production rather than as a by-product. The steam will turn two 430 000-kW generating units in what will be, for a time at least, the world's largest nuclear power generating plant.

Hanford will add more than 900 000 kW of firm power to the region's supply. The power will go to market over BPA's grid under unique tripartite agreements between BPA, the Supply System, and 76 purchasers of fractional shares of Hanford's output. The power has been sold with 50 percent allocated to public power and 50 percent to private utilities.

Treaty with Canada

The Joint Development of the Columbia River Treaty with Canada was concluded last September when President Johnson and Prime Minister Pearson met at the International Peace Arch at Blaine, Wash., to sign the final treaty documents.

Under the treaty, Canada will build three large storage dams on the upper reaches of the Columbia, which originates in Canada, and the United States is entitled to build Libby Dam in Montana. Libby will back water 42 miles into Canada.

The three Canadian storage dams are Duncan, which was started last summer and is scheduled to be completed in 1968; Arrow Lakes, on which contracts have been let, to be completed in 1969; and Mica, to be completed in 1973.

The three Canadian dams will store up to 15.5 million acre-feet of water, leveling out the flow of the Columbia and enabling downstream United States dams to produce 2.8 million kW of additional firm power. Each country is to share this power equally. However, Canada has sold her share to 41 Northwest public and private utilities for 30 years.

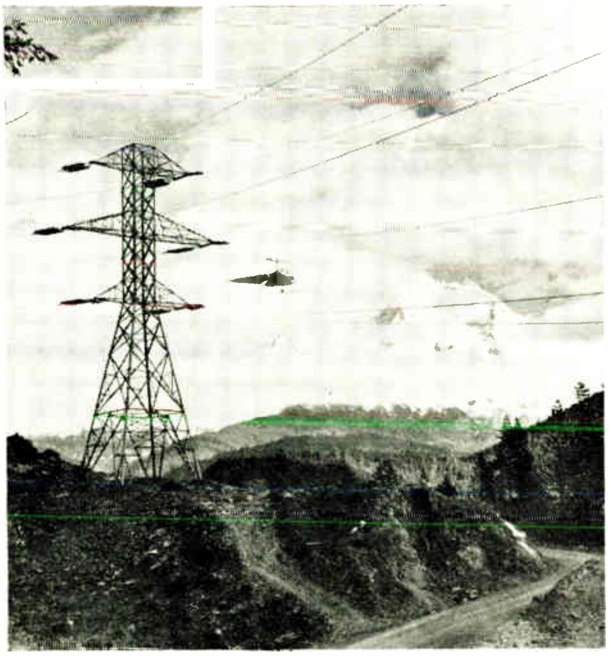
Libby Dam, with an additional 5 million acre-feet of storage, will add about 750 000 kW of firm power at site and downstream, bringing total treaty power benefits to about 3.5 million kW.

Besides power, the United States derives another important benefit from the treaty—flood control. The treaty projects will end the threat of major floods on both the Columbia and Kootenai Rivers.

The coordination agreement is the product of many years of cooperation. Optimum power production from Northwest hydroelectric projects has always required a high degree of coordination. For many years this was accomplished by the voluntary cooperation of the area's utilities working through the Northwest Power Pool. However, the development of nonfederal projects on the main stem of the Columbia River heightened interest in coordination on a contractual basis. Then with the advent of the Canadian treaty, a coordination contract became a must. The long-term obligation of the United States to return to Canada its half of the downstream benefits was predicated on full coordination of the hydro projects on the Columbia River in the United States.

Negotiation of a coordination agreement commenced in 1961 and a one-year agreement was signed in the fall of that year. A similar one-year contract was signed in 1962 followed by a 10-year agreement in 1963. During this time, engineers and lawyers of the area's utilities and the Bonneville Power Administration, the Bureau of Reclamation, and the Corps of Engineers, worked hard on the complex engineering and legal problems that had to be resolved before a long-term agreement could be signed. These negotiations were completed in 1964, and in August of that year, a 39-year coordination contract was signed between the Government and 14 of the area's generating utilities.

Under the coordination agreement, the various public and private utilities and the Federal government agree to operate their projects much as if all were owned by a



'Copter patrols key double-circuit high-voltage transmission line of the Bonneville Power Administration. Line carries power down the Columbia Gorge to coastal load centers. Mount Hood can be seen in background.

single entity. For example, water releases from storage projects are carefully timed so they will produce the maximum power at all downstream dams through which they flow. Thus, the owner of an upstream reservoir who might otherwise release stored water to produce power to meet his own loads at a time when the owners of downstream dams could not use the additional water agrees to hold his storage for release at the time that it will produce the most power on an overall basis. In the meantime, the owner of the upstream reservoir is supplied power from a downstream dam that has a surplus.

Owners of downstream dams agree to pay owners of upstream storage for the benefits they receive from the storage. Nonfederal owners pay each other and BPA in cash; BPA makes its payments in kWh. As the U.S. Government owns most of the upstream storage, BPA nets about $1.1 million annually from this arrangement.

Most important, the power consumers of the region are assured that all of the region's utilities are cooperating to produce the most power at the lowest cost possible.

Huge intertie under way

The Pacific Northwest–Pacific Southwest Intertie, approved by Congress last year, is the largest single transmission program ever undertaken in the United States.

It will be used to sell surplus Northwest secondary energy and peaking capacity in the Southwest, to exchange capacity between the two regions to take advantage of seasonal diversities, and to exchange surplus Northwest capacity for off-peak Southwest steam energy. The last use will enable the Northwest to firm up about 700 000 kW of secondary energy by importing small average amounts of off-peak steam energy from the Southwest to fill in low periods in Columbia stream flows. It also will be used to sell in California a portion of Canada's share of treaty power which, for a few years, will be surplus to the needs of the Northwest utilities that have purchased it. The BPA expects to net from $12 to $20 million annually from the intertie.

The intertie consists of four major transmission lines from large Federal dams on the Columbia River to Los Angeles and Hoover Dam. They will be built by a combination of public and private utilities and the Federal government.

Two of the lines will be 500-kV ac, each with a capacity of 1 million kW. Two will be 750-kV dc, each with a capacity of 1.35 million kW. The ac lines will run from John Day Dam, which is under construction, to Los Angeles. One dc line will go to Los Angeles and the other to Hoover Dam, both from The Dalles Dam. Other transmission lines will be added between Hoover Dam and Los Angeles and between Hoover Dam and Phoenix.

Utilities involved in the construction include BPA, the Bureau of Reclamation, Pacific Gas and Electric and Southern California Edison, the City of Los Angeles, Portland General Electric, Pacific Power and Light, and the Arizona Public Service Company.

The total investment for the intertie is estimated at $700 million. Private utilities will put up $330 million, the Federal government $300 million, and the City of Los Angeles $70 million.

The first ac line is scheduled to be energized in May 1967, and the second one in 1968. The first dc line is to be energized in 1969, and the second in 1971.

To sum up the past five years, since 1960 enough Federal dams, including Dworshak and Little Goose, combined with the Hanford atomic steam plant, have been started to add 50 percent to the generating capacity of the Federal system. Enough new lines, including a 500-kV backbone grid, are under construction to double BPA's transmission capacity. We have provided the base for orderly additions of generators to supply the region's power needs for at least the next ten years.

The coming decade

What of the next decade, 1965–1975? We estimate that the Northwest's energy loads will double in the next ten years. Except for Hanford, all of this load growth will probably be met by new hydroelectric capacity.

The rate of increase anticipated is no greater than that of the past ten years. What will make the next decade different, however, is that about 80 percent of the new generation will be installed at existing projects, both Federal and nonfederal.

Dams have been built on most of the economical sites in the basin. However, at many of these dams additional generators may be installed. For example, Senators Henry M. Jackson and Warren G. Magnuson of Washington have introduced a bill in the Senate to authorize a third powerhouse for Grand Coulee. The third powerhouse would have 3.6 million kW of capacity. Adding to the 2 million kW of capacity in the two existing powerhouses will boost Grand Coulee's total to about 5.6 million kW, or more than is presently installed at any dam in the world.

There is space at Bonneville Dam for a second powerhouse with six units with a total capacity of 324 000 kW. The second powerhouse will be needed at Bonneville Dam by about 1975.

The third powerhouse at Grand Coulee and the second powerhouse at Bonneville Dam are essential if we are to make full use of the improved stream flows resulting from the Canadian treaty.

There are 11 empty slots awaiting generators at Chief Joseph Dam; these will add 704 000 kW of capacity. Eight more generators and a total of 624 000 kW of capacity may be added at The Dalles Dam.

Sixteen generators have been scheduled for installation at John Day Dam, and four more will be added later. When completed the project will have a total capacity of 2.7 million kW. The first units at John Day will begin producing power in 1968.

Nonfederal capacity at existing dams also will be increased. Generators will be added at Rocky Reach, Priest Rapids, and Wanapum Dams.

In the decade ahead, there will also be new dams. The President's budget this year requested funds to start Libby and Lower Granite Dams; their combined capacity totals 720 000 kW. Asotin Dam is to be built in the 1965–75 period. Initially, it will have two units and 270 000 kW of capacity. A third unit will be added later.

New nonfederal dams will include Wells, under construction below Chief Joseph Dam, and Boundary Dam, which is being built on the Cowlitz River by Tacoma City Light. Still another dam, High Mountain Sheep, presently in litigation, will add about 900 000 kW when it is built.

We estimate that the Pacific Northwest will require about 12.5 million kW of new capacity in the next decade, or slightly more than one million kW new capacity per year. Approximately 4.7 million kW of this new capacity is now under construction at Federal and nonfederal plants in the Northwest.

On the basis of existing schedules, for the next decade, Federal installed capacity will increase by some 8.2 million kW. This would raise the present total from 6.7 million kW to 14.9 million kW by 1975. Nonfederal capacity will increase by 3.5 million kW from the present total, 7.4 million kW, to 10.8 million kW by 1975.

The fact that much of this power will move to load centers over BPA transmission lines is the reason why the 500-kV grid mentioned earlier is being built. It will overlay BPA's present 230-kV and 345-kV grids. The first 1056 miles of 500-kV lines are under construction. Congress has been asked to authorize another 207 miles. By 1974, BPA will require 1600 miles of 500-kV lines, exclusive of the intertie.

So far this article has been devoted almost exclusively to the Pacific Northwest. Let us look now at the trend in the United States in general, which is toward EHV transmission and larger steam-electric generating units. This trend was reaffirmed by the recent national power survey of the Federal Power Commission, which envisioned sizable savings in costs by the use of larger generating units of up to 2 million kW each. With advancing EHV technology the FPC sees as becoming economically attractive the construction of large mine-mouth generating plants at coal fields in Arizona, Wyoming, Utah, Colorado, and Montana.

The survey also foresees construction of large nuclear plants to supply loads in northern and southern California. It indicates that coordinated planning could bring about an $11.7 billion saving in plant investment by 1980, with almost equivalent savings to the consumer.

Another basic finding of the survey was that the nation's power systems can cut generation and transmission costs by participating in fully coordinated power networks covering broad areas of the country.

Such a network, the Northwest Power Pool, has existed in the Northwest since World War II. A similar power pool formed last year in the Southwest is called the Western Energy Supply and Transmission Associates—or WEST Associates. It is a group of southwestern power utilities formed to plan and carry out regional joint power development programs. One or more of the members of WEST may undertake to build and operate a large, coal-fired, oil-fired gas-fired, or nuclear plant. By joining together, these utilities can build larger units with smaller unit costs. Savings are also realized through the utilization of transmission lines and other common-use facilities.

The electric industry of the United States may be facing a quiet crisis: Can it utilize the economies offered by new technology and, at the same time, maintain its traditional pattern of organization? I believe the answer is yes, but it will require a higher degree of cooperation among all segments of the industry as well as far-reaching legislation.

In the United States today there are approximately 3600 individual utility systems, of which 480 are privately owned and more than 3100 are publicly or cooperatively owned. Of the privately owned utilities, about 57½ percent have installed generation of 50 000 kW or less. Of the public and cooperative systems, about 98½ percent have installed generation of 50 000 kW or less. Clearly, therefore, a substantial part of the electric utility industry cannot, as individual systems, take advantage of the new technology in electric generation and transmission. In the least advantageous position are the public and cooperative systems.

The implications of the situation are that if the United States is to have the most efficient electric system that engineers can devise, there must be either (1) close cooperation among public and private utility concerns in financing, construction, and operation of their systems—for example, new generating units, new transmission grids, and integration of operations—or (2) a consolidation of ownerships resulting in a relatively few utility systems, each large enough to finance and use on its own system the most efficient generation and transmission facilities that can be built. One may even question whether the concentration of the power industry into a few large utility systems would result in the optimum use of the improved technology. Such systems might have the size and financial resources to do so, but the absence of competition or other stimulus might perpetuate older methods of generation and transmission.

In other nations, the trend has been toward consolidation of ownerships in the national government, or subdivisions thereof. In the United States there has been some increase in cooperative arrangements between private utilities, and between public and private utilities. But a more significant trend has been toward the consolidation or merger of private ownerships into larger privately owned utilities.

It can be argued that the present pattern of organization is inherently inefficient—that consolidation of ownerships is the better way to achieve efficiency. The telephone industry here, or the nationally owned electric systems of other nations, can be cited as examples. I cannot accept this approach as sound national policy, although there will be cases where mergers are desirable. My reasons are:

1. The conditions for liberty are more favorable in an economy not dominated by huge aggregates of capital under single management, whether that management be private or public.

2. Efficiency can be achieved in the electric industry without the widespread consolidation of ownerships. The electric industry embraces three separate functions: generation, transmission, and distribution. Only in the first two functions is large size of unit facilities an important prerequisite of efficiency. In distribution, the same size units can be used, and ordinarily are used, by both large and small electric utilities. Among those Bonneville power distributors that have no generating facilities, the small ones have demonstrated their ability to be as efficient as the large ones.

If cooperative, joint-use arrangements between utility systems are the better way to utilize new techniques of generation and transmission, how can they be achieved?

The utility industry needs a legal vehicle whereby its members may pool their generation and transmission, or portions thereof. As the law now stands, the holding company act appears a serious obstacle to formation of utility-owned corporate subsidiaries for this purpose.

Such subsidiaries should be permitted to finance a very high ratio of debt capital. Investors in bonds of generation and transmission corporations would be adequately protected, through contracts between the G&T corporation and its participants, by the equity capital and earnings capabilities of the participants. Because interest, unlike dividends, is treated as a business expense, G&T corporations financed with 90 percent or even 100 percent debt would pay much less income tax than a utility with the traditional 60–40 ratio of debt to equity capital. Therefore they could charge less for electricity.

To guard against G&T corporations becoming a vehicle for further mergers and consolidations, I believe that no single utility should be allowed to own a controlling interest in the G&T. Participation of electric utilities in the formation and operation of these G&Ts should be subject to FPC surveillance to assure protection for investors and the public, and to assure that the G&T is not used to promote mergers or acquisitions of, or by, any participants. With FPC surveillance, the participants and the G&Ts would be exempted from the holding company act.

The G&T corporation would not, of course, be the whole answer to the problem of reconciling modern technology to our desire to keep the American way of independently managed electric utilities. Very probably other remedies, voluntary and legislative, state and federal, are required. But might it not be a constructive starting point?

Energy for the growing WEST

T. A. Phillips *Arizona Public Service Company*

The members of Western Energy Supply and Transmission (WEST) Associates probably meet no problems that are not typical of those met by the vast majority of utility companies in providing energy services for their areas. Utilities all serve the same types of customers: residential, commercial, industrial, and agricultural. However, some are combination companies and others are electric only. Some serve fairly dense population areas and others are spread across tremendous expanses of territory.

WEST Associates, however, is set apart from most other companies by this fact: it serves the nation's fastest growing region. It is anticipated that the population of the nine-state region encompassed by WEST will triple by the year 1985, which means that this organization must do far more than triple its capacity to serve.

Historical background

Before examining the organization itself, a brief historical review of its founding might be appropriate. This organization dates its genesis from the inception of the utility industry, which was of course launched by the discoveries of Thomas Edison in 1879. Looking back over the history of the industry, one can see the forces coming into play that gave rise to WEST Associates and other similar groups throughout the country.

Most organizations represented in WEST Associates have several corporate ancestors. Small utilities that served isolated areas have seen the advantages of mergers and poolings and have, as a result, combined operations over the years to the mutual advantage of suppliers and customers. Today, nearly all major electric power systems in the United States, providing nearly 97 percent of the nation's electric energy requirements, are members of one of several major interconnected operating groups.

The Association has established the following objectives:

1. To integrate area and regional planning of generation and transmission facilities based on the latest technological developments in generating facilities, fuel sources, and high-voltage transmission.
2. To work with member systems and other power suppliers for the maximum mutual advantage of systems members and the public.
3. To recognize the right and obligation of each member to own or otherwise provide for generation, transmission, and other facilities to meet the electric power requirements of its own customers.
4. To work toward the utilization of peak load diversity and the reduction of generating reserve margins to insure the lowest-cost power, while retaining and expanding the benefits of local control and responsibility.

WEST Associates was formed in September 1964 and at the present time already has 17 electric systems as members (see Appendix). These organizations serve in the states of Arizona, California, Colorado, Idaho, Nevada, New Mexico, Utah, Texas, and Wyoming.

Membership is open, now and in the future, to other utilities in the area. However, if the group is to plan productively and do an effective job of coordinating the generating and transmission facilities of the area, there must be a functional limitation to the number of power suppliers who are members and to the size of the geographical area that can be administered.

For these reasons, membership is limited to those systems that own generating and transmission facilities and have local utility responsibility for meeting the electric power requirement of their customers.

Such a membership requirement, however, does not preclude other power suppliers in and adjacent to the nine-state area from participating in the benefits to be derived from the activities of WEST Associates. It is the group's desire to cooperate with and to work with other power suppliers in the area so that they might derive all possible benefits for their systems and their customers.

Let us return to an important fact mentioned earlier: the expected tripling of population in this nine-state region by 1985. This means that WEST members will have to add 36 million kW of generating capacity to take care of this growth and to serve adequately the expected per-customer increase in kilowatthour consumption. Compare this kilowatt increase with the 15 884 000 kW of generating capacity in service at the end of 1964.

Most of this new capacity will be in units of 750 MW each, although it is contemplated that a limited number of peaking plants of 250 000 kW each will be placed where needed throughout the region.

Several of the 750-MW units will be coal-fired plants located at mine mouths. Use of coal as a fuel in some units will be of substantial economic benefit to several areas that have tremendous deposits of coal. However, we will not be limited to coal, but instead will utilize the best available fuel source, whether it be coal, oil, natural gas, or the atom.

In addition to building 36 million kW of new generation, WEST's program calls for the construction of a transmission grid of high-voltage lines tying together the load centers throughout the nine states. We are hopeful that such a system will eventually be interconnected with planned transmission grids in adjacent areas for additional benefits. (See Fig. 1.)

The initial construction under the WEST program is expected to begin next year. This project calls for the construction by Southern California Edison Company of two 750 000-kW units at the Arizona Public Service Company's Four Corners Power Plant near Farmington, N. Mex. Arizona Public Service will build a 500 000-volt transmission line from the plant site to connect with Edison's system at the Arizona–California border.

Arrangements similar to this will be followed down through the years as additional new generating units and transmission lines are required. Two or more individual companies will join together on projects since WEST Associates itself will not construct or own any facilities.

An integral part of the WEST program is an investigation into the feasibility of dual-purpose nuclear plants for the desalination of sea water. The program is of such magnitude that it is hoped it can be tied economically and technically to the long-range solution of the water problems in the Southwest.

The 20-year program will require an investment of $10.5 billion. However, this will be substantially less than what would otherwise be required if each WEST member were to "go it alone" in the future.

Preliminary studies show that by 1986 the program will create 34 000 new jobs and a payroll of $207 million annually. (These figures are based on data relating only to the ten founding companies; as the organization grows, figures will increase accordingly.)

In addition, by 1986, annual retail sales in the region

Fig. 1. WEST Associates transmission plans.

and local taxes (paid on new facilities built by member companies) are each expected to increase by $75 million.

Factors in recommendations of organizational structure

The WEST Associates group was formed following a study by Stone and Webster. Some of the considerations that Stone and Webster included in their recommendations might be of interest:

- Each member of WEST has winter peaks, except for the Arizona Public Service Company and the El Paso Electric Company. Under these conditions there is a modest amount of diversity interchange of both kilowatts and energy possible which will permit deferring generating units in the area.
- For study purposes, fossil fuel costs were developed as a result of discussions with coal suppliers, railroads, and other interested parties and were inflated 2 percent per year. Costs differ for each proposed plant site; this is one of the economic factors that will influence the sequence of plant site development.
- Nuclear fuel cost equivalent was estimated at 1.8 mills per kWh and decreased one percent per year, on the assumption that further progress will be made in the reduction of nuclear production costs.
- Loads of the participating utilities were assumed to be concentrated at specific points where bulk substations are planned. At these points, individual companies' subtransmission facilities would take delivery. This bulk delivery of power and energy at a few points yields economic advantages favoring 500-kV transmission. A preliminary analysis of 345-kV, 500-kV, and a combination of 345-kV and 500-kV systems favored the 500-kV selection by several million dollars. However, further studies with more detailed load analyses might dictate another voltage.

The projected 500-kV system will interconnect the generating stations with all major load centers. The ultimate system is expected to provide for the peak load of each participant on a double contingency basis, with its largest unit and heaviest loaded line out of service. The 500-kV line that Arizona Public Service is scheduled to build will go into service in 1968. A second east–west line will be needed to provide 1000 MW of firm power to the West with one line out of service.

WEST Associates operates with a board of directors composed of one representative from each organization. The "home" office of WEST is in Albuquerque, N. Mex.

Four major committees have been appointed by the board of directors and are at work on studies expanding the scope of our original study. They will submit recommendations to the directors from time to time as to the courses WEST should be following. These committees are management, engineering and planning, public relations, and legal.

Appendix

Members of WEST as of August 1965:
Arizona Public Service Company
City of Burbank, Public Service Department
City of Colorado Springs, Dept. of Public Utilities
El Paso Electric Company
City of Glendale, Public Service Department
Imperial Irrigation District, Operation Headquarters
City of Los Angeles, Department of Water and Power
Nevada Power Company
City of Pasadena, Municipal Light and Power Department
Public Service Company of Colorado
Public Service Company of New Mexico
Salt River Project, Phoenix, Ariz.
San Diego Gas & Electric Company
Sierra Pacific Power Company
Southern California Edison Company
Tucson Gas & Electric Company
Utah Power and Light Company

Canadian aspects of the Columbia Treaty

H. L. Keenleyside *British Columbia Hydro Electric and Power Authority*

On January 17, 1961, the United States and Canada signed the Columbia River Treaty. This comprised an agreement between the two governments for the cooperative development of power, and the mutual provision of flood control benefits, in the basin of the magnificent river whose name has been in our headlines for so many years. The treaty was supplemented by a codicil signed three years later on January 22, 1964, which spelled out and clarified certain of its terms. At the same time agreement was reached on the terms of sale under which the United States would be entitled to use the Canadian share of the downstream benefits resulting from dam construction in British Columbia for a period of 30 years.

To understand the full significance of the treaty, the codicil, and the terms of sale, it is essential to know something of the background against which these agreements must be judged.

In British Columbia we have been lavishly endowed by nature with a hydroelectric potential that is probably unmatched in any comparable area anywhere else in the world. The minimum estimate of the power that can still be developed on our rivers is 30 million kW while some calculations put it as high as 100 million. Only 2.5 million kW have so far been harnessed for our use.

The provincial requirement for electric energy is increasing at a compound rate of about 8 percent per year. There is good evidence to suggest that this rate may rise substantially in the near future when large amounts of low-cost power become available.

As everyone engaged in the industry is aware, planning for any kind of power supply, except for those relatively insignificant amounts that can be provided by diesels or small thermal plants, has to be undertaken well in advance of the time of need. It should be done at least five years, and preferably ten or more years, ahead.

In the circumstances existing in British Columbia today, falling water provides the cheapest source of electric energy.

The advent of nuclear techniques has brought a new element into all power calculations, and this must now be considered by every agency that is engaged in the generation of electric energy. There is a warm and increasingly pertinent argument as to the date at which nuclear power will become commercially competitive with other thermal or hydroelectric installations. What many engineers and economists consider to be somewhat extravagant claims have been made by some of the more enthusiastic partisans of the new source of power. In certain cases it has even been claimed that a really competitive position has already been reached. Most objective observers, however, would agree that the low costs that are now sometimes quoted turn out on examination to involve elements of subsidy or the acceptance of certain limited conditions of size and load factor that make such comparisons of limited validity. On the basis of reports at the World Power Conference two years ago and in recent publications, it is now generally conceded by most competent observers that, except under very special conditions, nuclear plants are not yet in serious economic competition with the better examples of hydro and thermal installations.

There is sound reason to believe, however, that the cost of nuclear energy will continue to decline and that at some period, variously estimated at from 10 to 25 years, nuclear power will make most other new installations uneconomic.

Hydro development pushed

In view of these facts it became clear some time ago that in British Columbia it would be desirable to develop just as rapidly as possible every hydroelectric project for the output of which a profitable market could be found. Once developed and the capital costs paid, hydro plants can produce power for approximately 100 to 200 years, with no cost for fuel, with a minimum expenditure on maintenance and operation, and at a price that no nuclear installation could ever rival.

Our provincial authorities studied this situation carefully in order to decide which of the major hydro projects could be developed at the lowest cost and with the maximum output in the time still available to us. There were two British Columbia rivers from which it was obvious that large quantities of power could be obtained at a very low cost and without creating any great controversy over other issues, such as damage to the fishing industry; these were the Columbia and Peace Rivers. It was obvious that we would not be able to use the full power of these two rivers immediately and at the same time; yet if development of either was postponed its tremendous latent power might be lost forever to the people of British Columbia.

It was essential, therefore, to study the markets to see if some part of the energy that could be generated by the Columbia and the Peace could be sold outside the province. When this was done it became clear at once that the only large external market during the next 10 to 15 years would be in the northwestern part of the United States. This conclusion was accepted by the two firms of outstanding British consultants who were brought in by the British Columbia Energy Board to review the situation.

If developed independently and the power used exclusively for provincial purposes, the cost of energy from the Columbia and the Peace would be roughly comparable. The Columbia, however, had one great advantage that the Peace did not share. By establishing works in Canada to control the flow of the Columbia waters across the boundary into the United States, American plants could produce a large increase in output at a comparatively small cost. This offered us an attractive opportunity for a mutually profitable agreement with the United States. Such an arrangement would also result in collateral advantages through the establishment of flood control on a river notorious for variations in flow. In its natural condition the Columbia varies in proportion of one to 100, and has a sad record of damage from flood. With the growth of industry and settlement in its basin the effect of floods was becoming increasingly disastrous.

As a result of negotiations carried on in the International Joint Commission, it was finally agreed that Canada would be entitled to one half of any benefits in additional power that would be created downstream in the United States by the construction of regulatory dams north of the International Boundary.

It was also agreed that the United States should pay for the flood control benefits that would result below the boundary from Canadian management of the waters above the boundary.

When it became apparent that an agreement with the United States could probably be negotiated, the Government of British Columbia decided that the prudent and profitable course to follow would be to develop the potential of both the Columbia and the Peace, and to do it at once. The energy from the Peace could be used to meet the province's load growth for from seven to ten years, while the energy resulting in the United States from the Columbia storage reservoirs could be sold in the United States until it was needed in Canada. The proceeds from this sale could be applied to reducing the cost of additional generation on the Columbia in Canada and thus bring further advantages to the British Columbia consumer.

This was the original purpose of the provincial government's "two-river policy" and the wisdom of that policy will become more and more apparent as time goes on.

British Columbia takes exception

The original treaty providing for the cooperative development of the Columbia resources was signed by Prime Minister Diefenbaker and President Eisenhower in January 1961. But that treaty, while it permitted the sale of Canada's downstream power entitlement to the United States, was not fully acceptable to British Columbia because it was not accompanied by a definite arrangement for such a sale. The British Columbia Government argued that if the treaty were ratified, the province would be committed to proceed with the building of the dams but would have no assurance of a purchaser for the downstream power.

The Government took the position that ratification could only be accepted if accompanied at the same time by a specific undertaking on the part of the United States to purchase the Canadian entitlement at an agreed price, and for an agreed term.

The logic of the British Columbia position in relation to the treaty was soon recognized and gained the support of the national government in Ottawa. Negotiations were renewed and for two years they dragged slowly forward.

In the course of the renewed and prolonged negotiations that followed, two major changes were introduced and finally accepted by both sides.

Perhaps the most important single change in the Canadian negotiating position was the decision to abandon the original idea of demanding a certain number of mills per kilowatthour for British Columbia's share of the downstream electrical benefits. The essence of the idea that was now developed was the sale by Canada and the purchase by the United States, or by public utilities in the United States, not of a certain number of kilowatthours but of a service—the controlled flow of Columbia River water across the boundary in accordance with an agreed plan of operation. British Columbia contended that the payment by the United States for this service should cover at least the costs of the three storage dams at Duncan, Arrow, and Mica. Such an arrangement was made the more acceptable because of a vigorous disagreement between the two sides on the actual number of kilowatthours to which Canada would become entitled during the period of 30 years for which the sale was being contemplated. There was no way of telling in advance exactly how many kilowatthours Canada's entitlement would provide. In the end a compromise figure was established and accepted by both parties which was used in all subsequent computations of mills per kilowatthour; however, the sale was not based on this computation but on the value to the United States of the regulatory service.

The second major step to facilitate agreement was the decision in the United States to establish a consortium of public utility districts and private power companies to act as a single purchaser for the Canadian entitlement.

In the final agreement the Government of Canada undertook to ensure that British Columbia will build three major dams on the Columbia River, and to use them to regulate the flow of water into the United States in accordance with an agreed plan of operation. For 30 years the United States will have the use of the Canadian half as well as its own half of the extra power generated in the United States plants. Canada also agreed that the United States may build a dam at Libby on the Kootenai River in Montana in spite of the fact that this will flood some 40 miles of the southern Kootenay Valley in British Columbia.

In return for these services the United States agreed to pay Canada—and Canada agreed, by domestic agreement, to transfer instantly to British Columbia—the sum of $274.8 million on October 1, 1964. An additional total amount of $69.6 million will be paid in 1968, 1969, and 1973 as three Canadian dams come into operation at Duncan, Arrow, and Mica. The payment was in fact made on September 16, 1964.

What advantages do these payments bring to Canada and to British Columbia? They can be quickly summarized:

1. The total amounts received from the United States will: (a) pay all the capital costs of the storage dams as they occur; (b) pay about half the capital cost of the generators at Mica; (c) enable a 1.8 million kW installation at Mica to produce 6.6 billion kWh of energy annually for less than 1.5 mills per kWh. The corresponding cost under development without the treaty would be nearly 4 mills per kWh. The savings at Mica at full production will be about $16 million a year.

2. An alternative way of stating the advantages accruing to Canada and to British Columbia would be to say that the United States payments during the 30-year periods of sale would: (a) pay off all the capital costs of the dams and reservoirs at Duncan, Arrow, and Mica; (b) pay all the operating expenses of these storage projects; and (c) leave a surplus of approximately $40 million at the end of the sales contract period.

3. The arrangements ensure that the storage projects in Canada will be debt-free as they are constructed. This compares with a normal amortization period for such projects of 50 to 100 years.

4. Construction of the treaty projects on this basis with all costs paid will make possible enormous economic advantages to Canada and British Columbia, which could only be attained, if at all, at much higher cost through development without the treaty. These advantages make possible:

a. The installation of over 4 million kW at points on the Columbia River in Canada which will produce energy at a cost of about 2 mills per kWh. (This installed capacity will be more than 1½ times the total present hydroelectric installation in British Columbia and about one fifth of the total for all of Canada.)

b. Reduction in the British Columbia hydro system cost of generation from just over 5 mills today to approximately 2½ mills by the time the Columbia River in Canada is fully developed.

c. Delivery of this power to centers throughout the southern half of the province at about 3 mills per kWh.

d. Prevention of floods in settled areas on the Kootenay and Columbia Rivers in Canada.

e. Receipt at the end of the 30-year contract of payments from the still-continuing downstream benefits of from $5 to $10 million annually.

f. Additional payments of up to $8 million by the United States for extra flood control if it is required during the treaty period as well as special flood control compensation for any emergency requirements of the United States during and after the life of the treaty.

g. Creation of a Columbia–Peace high-voltage transmission network that will bring the full resources of the two great rivers within reach of all major communities in the province.

h. Construction of the Libby reservoir by the United States which will make possible the additional annual generation of more than 200 000 kW-years of low-cost energy in Canada, energy essential for the continuing development of the Kootenays. These benefits do not have to be shared with the United States. The Libby Dam will also provide additional flood control in the industrial and farming areas of the West Kootenays.

In addition to providing an abundant supply of low-cost power, the Columbia projects will be a major stimulant for the British Columbia economy.

These are the chief reasons behind the decision of British Columbia and Canada to enter into the treaty and associated agreements with the United States. That the results will be profitable also to the United States is now clear. This is one of those happy occasions upon which each participant in an international agreement knows that his own objectives have been attained at the same time that he has behaved as a good neighbor.

This article is based on three papers presented at the American Power Conference, Chicago, Ill., Apr. 27–29, 1965.

Atmospheric research and electromagnetic telecommunication—Part II

The concluding portion of this two-part article presents an analysis of telecommunication-oriented atmospheric research in the United States for the fiscal year 1964

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Telecommunication-oriented research programs in fiscal year 1964

For a research program to be considered an atmospheric science program, we have required that physical information about the atmosphere, rather than just the electrical channel characteristics of the transmission medium, be obtained. Propagation studies that do not give physical information about the atmosphere have therefore been excluded. Examples of studies excluded are compilations of statistics of transmission loss, phase, or bandwidth, unless these are used to deduce physical information about the atmosphere. In addition, for a research program to qualify for inclusion in this analysis it must be, in the view of the reporting organization, directed toward understanding atmospheric effects on electromagnetic propagation rather than toward one of the other objectives of the Interdepartmental Committee for Atmospheric Sciences (ICAS), such as "scientific understanding."

The fiscal figure used for current programs is the funding committed by sponsoring agencies to laboratories in the fiscal year 1964. Information was obtained from sponsoring organizations and working laboratories by mail, telephone, or visit. A short description of the objectives of each program enabled categorization of each program, or portions of it, according to research area, estimated relevance to a particular propagation mechanism, and portion of the electromagnetic spectrum.

Part I of this article appeared in the August issue, pp. 44–52.

Research areas. Two major categories of atmospheric research related to electromagnetic transmission are *aeronomy*, the science of the upper region of the atmosphere where dissociation and ionization are important, and *radio meteorology*, the science of the neutral lower atmosphere as it affects electromagnetic waves.

The following subcategories of aeronomy have been used from the list of ICAS research areas, with some modifications:

Physics of the ionosphere and exosphere, which includes the properties and constitution of the ionosphere, exosphere, and magnetosphere, from a lower height of about 30 km to an upper height of several earth radii; electron and ion density, temperature, and collision frequency; electromagnetic properties of the medium (refraction, scattering, absorption, emission and polarization effects) at radio frequencies; magnetic field; and ionization processes, diffusion, irregularities, and perturbations of medium.

Laboratory aeronomy, which includes theoretical and laboratory studies of dissociation, chemical reaction, recombination rate coefficients, ionizing rates, and molecular and atomic absorption cross sections; and laboratory studies of electromagnetic wave–plasma interaction. For convenience, controlled atmospheric chemistry studies such as seeding of the ionosphere have been included, but study of natural luminous emission of the atmosphere is covered in the subcategory on aurora and airglow.

Solar–terrestrial relationships, which encompasses studies of solar emission at all wavelengths relevant to

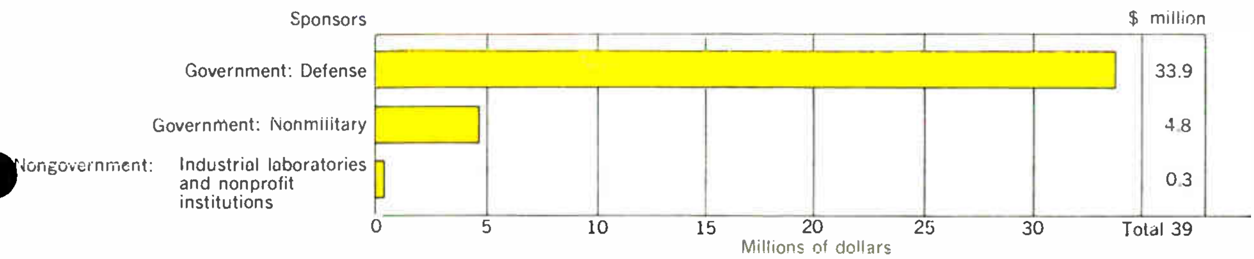
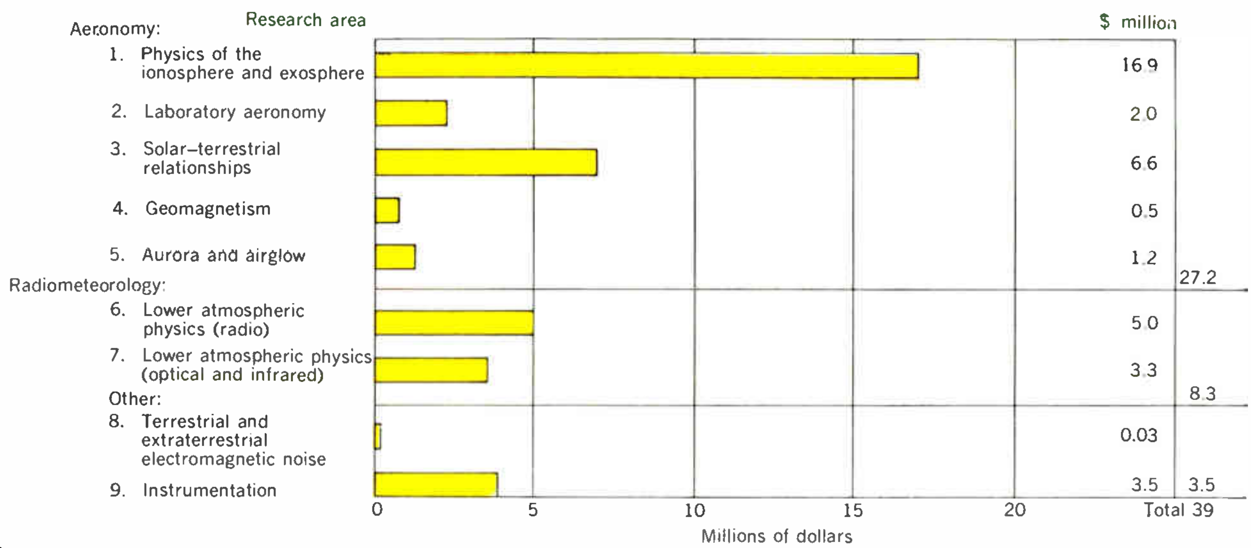


Fig. 5. Distribution of atmospheric research, by type of sponsor.

Fig. 6. Distribution of atmospheric research, by research area.



ionospheric processes, including ultraviolet and X-ray radiation, radio and corpuscular emissions; studies of the sun's photosphere and chromosphere, including the solar corona, sunspots, flares, and magnetic field effects; and studies of the relationship of ionospheric disturbances to solar emissions, including magnetic storm theory.

Geomagnetism, which is the study of the temporal and spatial variations in the earth's magnetic and electric fields; it also includes magnetotelluric and micropulsation investigations.

Aurora and airglow, which includes studies of the intrinsic and chemical luminosity of the upper atmosphere; spectrum, polarization, intensity, temporal variations, morphology, altitude, and excitation processes of nightglow, twilight glow, dayglow; aurora, auroral forms, geographical distributions, radio scattering from aurora, relationship with other geophysical phenomena.

Radio meteorology encompasses two subcategories:

Lower atmospheric physics (radio), which includes studies of the properties and composition of the neutral atmosphere affecting electromagnetic wave propagation, absorption, refraction, scattering, emission, and atmospheric irregularities and motions.

Lower atmospheric physics (optical/infrared), which has the same scope as the preceding subcategory except that it is related to the optical/infrared and the near-ultraviolet portions of the electromagnetic spectrum.

Two additional subcategories of research are related to both aeronomy and meteorology:

Terrestrial and extraterrestrial electromagnetic noise, which includes studies of atmospheric noise from lightning discharges, and solar and galactic noise as a limitation to terrestrial electromagnetic wave propagation. It excludes other natural emission of the earth's atmosphere or ionosphere, which are covered in categories above.

Instrumentation, which covers the development of instrumentation for atmospheric research directed toward electromagnetic propagation problems.

Propagation mechanisms. Categories of propagation mechanisms are similar to those introduced in the preceding section except that tropospheric line-of-sight propagation and earth–space propagation are here subdivided into radio and optical/infrared propagation. The propagation mechanisms used are:

1. Tropospheric line of sight
   a. Radio
   b. Optical/infrared
2. Tropospheric ducting and reflection
3. Tropospheric scattering
4. Earth–space
   a. Radio
   b. Optical/infrared
5. Earth–ionosphere reflection and ducting
6. Ionospheric forward scatter
7. Meteor scatter

Portion of the electromagnetic spectrum. The third categorization is by portion of the electromagnetic spectrum. Band designations that are used here correspond to the band numbers of the International Telecommunication Union.* The lowest portion of the spectrum used is regarded as including all frequencies below 3×10^4 c/s.

Analysis of the program. The total fiscal year 1964 program amounted to approximately $39 million. Apportionment of this total—by type of sponsor, research area, propagation mechanism, and portion of the electromagnetic spectrum—is shown by means of bar graphs in Figs. 5 through 8.

It is possible that total funding reported here may be in error by 25 percent or more. There are several reasons for discrepancies between fiscal year 1964 funds indicated by funding agencies and those indicated by laboratories. First, the funds may be committed or obligated by sponsors in fiscal years prior to that in which the laboratory experiments are made; often such commitments cover several years' activity at the laboratory. Fiscal information available from the source funding agency, from intermediate laboratory levels, and from working laboratories are not equivalent. An effort was made to obtain homogeneous data on the basis of committed funds, but figures had to be approximated in some cases. Second, some atmospheric research may be but a portion of a larger program in communication electronics. In these cases rough estimates were required, at the laboratory, of the amount devoted to atmospheric science. It is apparent that much atmospheric research is done as part of communication electronics research programs rather than as part of an atmospheric or environmental science program. Such programs may not be included completely in programs normally reported to ICAS. Although an effort has been made to include these programs here, it is likely that omissions have occurred, or that programs were included which the agency might not regard as atmospheric science.

From the information obtained from sponsors and laboratories, approximately 500 project cards were prepared. About 100 were excluded because the projects were judged not to meet the strict criteria for atmospheric research in support of electromagnetic telecommunication. Many laboratory projects were then matched and consolidated with cards representing sponsors' major programs. Finally, 250 programs were tabulated and classified.

It must be emphasized that these figures do not by any means include all of the U.S. aeronomy and meteorology programs relevant to electromagnetic transmission. Indeed, it might be argued that *all* atmospheric research programs are relevant to electromagnetic propagation through the atmosphere. We have here attempted to identify only those *directed toward* facilitating electromagnetic telecommunication.

Distribution by type of sponsoring agency. As shown in Fig. 5, defense agencies account for $33.8 million of the total $39 million, which amounts to about 87 percent. Of the remaining 13 percent, about 12.3 percent is spent by the government in nonmilitary applications, and about 0.7 percent by industrial laboratories and nonprofit institutions.

Distribution by research area. Figure 6 shows the apportionment of the program by research area. About three quarters of the work is in aeronomy and one quarter in radiometeorology, assuming proportionate distribution of the instrumentation. Perhaps the most significant feature of the analysis is the 43 percent devoted to ionospheric and exospheric physics. Lower atmospheric physics accounts for 13 percent at radio wavelengths and 8 percent at optical/infrared wavelengths.

Distribution by relevant propagation mechanism. It is found that 72 percent of the total program relates to propagation by earth–ionosphere reflection and ducting (see Fig. 7). A surprisingly small amount is found related directly to tropospheric scatter, though it is clear that much of the tropospheric line-of-sight work is applicable to the tropospheric scatter mechanism. Included in the line-of-sight work are studies of atmospheric clutter and refractive limitations to radar, among other topics. There were no indications of research in ionospheric forward scatter or meteor scatter in the fiscal year 1964 program, though some meteor astronomy or meteor physics work is being carried out in connection with re-entry problems. It is interesting to note in categories 1 and 4, involving tropospheric and earth–space line-of-sight transmission through the lower atmosphere, that somewhat over 40 percent of the effort is directed toward optical/infrared transmission.

Distribution by relevant portion of electromagnetic spectrum. Figure 8 shows the apportionment of the total program by frequency band, using the band numbers of the International Telecommunication Union. Research relevant to high-frequency propagation (ITU band 7) accounts for 26 percent of the total. The portion of the spectrum that includes high frequencies and below accounts for two thirds of the total funding. The figure for the VHF band is probably the least accurate one; it includes a portion of the work on ionospheric and exospheric physics, as well as a portion of the work on aurora and airglow. The principal telecommunication usage of the VHF band is for tropospheric line-of-sight and tropospheric scatter systems, while the VHF ionospheric forward scatter and meteor scatter mechanisms are relatively little used. For this reason it may be that the figure for the VHF band should be reduced. Such a reduction would accentuate the disparity between the large amount of atmospheric research in support of ionospheric telecommunication frequencies and the relatively small amount spent in supporting the tropospheric telecommunication bands.

Relative magnitude of the research program. The fiscal year 1964 current atmospheric research program in support of telecommunication is estimated as about $39 million, which is only about 0.2 percent of the national expenditures on atmospheric telecommunication, outlined in Part I. It must of course be recognized that the huge telecommunication industry is supported by larger research efforts on such activities as the design of materials, components, devices, antennas, etc.; nevertheless, it would appear that the fraction spent on the propagation limitations of the medium is unexpectedly small.

As described in the following section, failure to give adequate consideration to propagation-induced limitations has frequently resulted in expensive failures of telecommunication systems. These unfortunate errors are likely to become increasingly frequent and increasingly expensive as telecommunication systems become more and more sophisticated. Such systems typically place increasingly severe limitations upon the propagation; an

*Band N covers 0.3×10^N to 3×10^N c/s, or nominally 10^N c/s.

expanded research program is required to obtain the propagation information in a timely and efficient manner.

Balance of the research program. In reviewing the balance of the atmospheric research program in support of telecommunication, it is important to recognize the unity of the electromagnetic spectrum. That is, atmospheric information obtained via the propagation of electromagnetic waves of one frequency can often be used to predict the propagation at other frequencies. Nevertheless, it is appropriate to consider the balance of the research effort in broad spectral categories, such as 10^4 to 3×10^7 c/s (ground-wave and ionospheric propagation), 3×10^7 to 10^9 c/s (mainly tropospheric line-of-sight radio propagation), 10^9 to 3×10^{12} c/s (line-of-sight and beyond-the-horizon tropospheric propagation), and above 3×10^{12} c/s (infrared and optical propagation).

A combination of various data given in Parts I and II of this article permits the preparation of Table X, in which the fifth column gives the atmospheric research as a percentage of the telecommunication usage for each broad region of the spectrum. One might expect that the highest ratio of research to usage would be found in the newer bands of spectrum utilization, and that the earlier and more developed parts of the telecommunication spectrum would show large telecommunication usage figures with relatively low research percentage. The latter is, in fact, the case for the most easily used part of the spectrum (3×10^7 c/s to 10^9 c/s, line 2). However, it is surprising to find that the highest research ratio (relative to telecommunication usage) lies in the oldest part of the spectrum (line 1, 10^4 to 3×10^7 c/s—ionospheric propagation). This is in part due to the large amount spent by DOD agencies on special types of atmospheric research pertaining to their unique missions. However, even after correcting for this fact, the ratio of ionospheric telecommunication research to usage is much higher than for the higher radio-frequency bands of Table X. Although the atmosphere plays a dominant role at ionospheric frequencies, it does seem that the balance of atmospheric research effort between ionospheric and tropospheric radio telecommunication studies is inappropriate. Further research on ionospheric propagation is undoubtedly needed, but the telecommunication benefits of such research appear to be relatively limited compared to the greater opportunities for further growth that lie at frequencies above 10^9 c/s. It is noteworthy that about 80 percent of the research lies in the frequency range below 10^9 c/s (which may be rather crudely identified as the range where further atmospheric research is not likely to have the greatest telecommunication benefits) and only 20 percent in the range of higher frequencies, where the lack of knowledge and the potential economic benefit are probably greatest.

The need for atmospheric research

The electromagnetic spectrum is a natural resource, analogous in many ways to such great natural resources as land, water, and air. Like land, it can be used, or left unexplored and virgin; the different areas of the spectrum can be "farmed," but with varying degrees of difficulty; different telecommunication "crops" grow best in different regions of the spectrum. Unlike timber or mineral resources, it is not depleted by use; like land it is plagued by "weeds" (electromagnetic noise) or may be contaminated by man-made "poisons" (interference from nontelecommunication radiations such as from automobile ignitions and diathermy machines).

Until about 50 years ago this huge natural resource was largely unused. But since World War I, scientists and engineers have learned to farm this spectrum at an ever-accelerating pace. Year by year and decade by decade they have discovered new uses—broadcast (AM, FM, and television), radar, space telecommunication, and a score of others—until by 1962 this nation alone made some $17 billion use of the spectrum each year for electromagnetic telecommunication. The impact of these crops on the economy is much greater than is implied by the size of the industry itself. Without this exploitation of the spectrum the way of life of every citizen would be significantly and even dramatically affected. For instance, the very existence of such activities as the aviation industry is dependent upon telecommunication.

The huge magnitude of this resource makes it essential that we farm it efficiently. Analysis of the present usage of the VHF mobile, TV, and FM bands shows that the spectrum can be farmed in VHF–UHF bands at yearly rates of up to about $50 million per megacycle of bandwidth. The potential crop for the first 1000 Mc/s of the spectrum is therefore of the order of $50 billion; the present crop is about $12 billion. It is estimated that the long-range yield of the next 9000 Mc/s (now about $4 billion per annum) can be increased to roughly the same figure of $50 billion, and that the usage of the remainder of the radio spectrum plus the infrared and optical part of the spectrum could also eventually increase from the present $1 billion to about $50 billion.

Compared with such figures it is clear that we are making only limited usage of this great resource. Perhaps it will be argued that a potential long-range future crop of $150 billion per year is a gross overestimate; however, since the crop has grown by at least three orders of magnitude in the last 50 years and is still growing rapidly, it seems not unreasonable to anticipate a tenfold growth in the next 40 years. Such a growth factor would be achieved in 40 years with a 5 percent (compound) growth per year.

The present rate of growth will only continue, however, if there is continued increase in demand for telecommunication and if this demand can be met. We are convinced that the demand for telecommunication services will continue to grow. Future demands for automatic data collection, mobile installations, and educational and closed-circuit television are expected to rise rapidly. Data transmission systems for connecting together computer centers, for automatic retrieval of information from central files and libraries, and for military command and control are only in their infancy, and are expected to make rapidly increasing demands upon the nation's telecommunication capabilities. Even consumer expenditures for telephone services and color (rather than black-and-white) television are expected to rise faster than the GNP (about 5 percent per year in current dollars). We also believe that the increased demand for telecommunication can be met. For example, present technological advances, including satellites and lasers, offer possibilities for carrying much more than ten times the present traffic. It is important to recognize that the impact on the nation of these increased communication capabilities will extend far beyond the telecommunication industry alone. For example, the automatic collection and dissemination of geophysical data may be expected to have considerable impact on the geophysical services of the nation; similarly, the coupling together of computer centers, or the provision of remote access to computers, may be expected to have major impact on the computer industry and eventually on the technology of the nation.

The growing significance of atmospheric limitations. In Part I of this article the significance of atmospheric limitations to electromagnetic telecommunication was discussed. It is important to realize that these atmospheric limitations are not uniform across the spectrum. Also, we must recognize that certain telecommunication systems require especially favorable atmospheric propagation conditions and therefore are limited to certain parts of the spectrum, whereas others can make broader use of the spectrum.

Frequencies below about 5 × 10⁸ c/s are now being

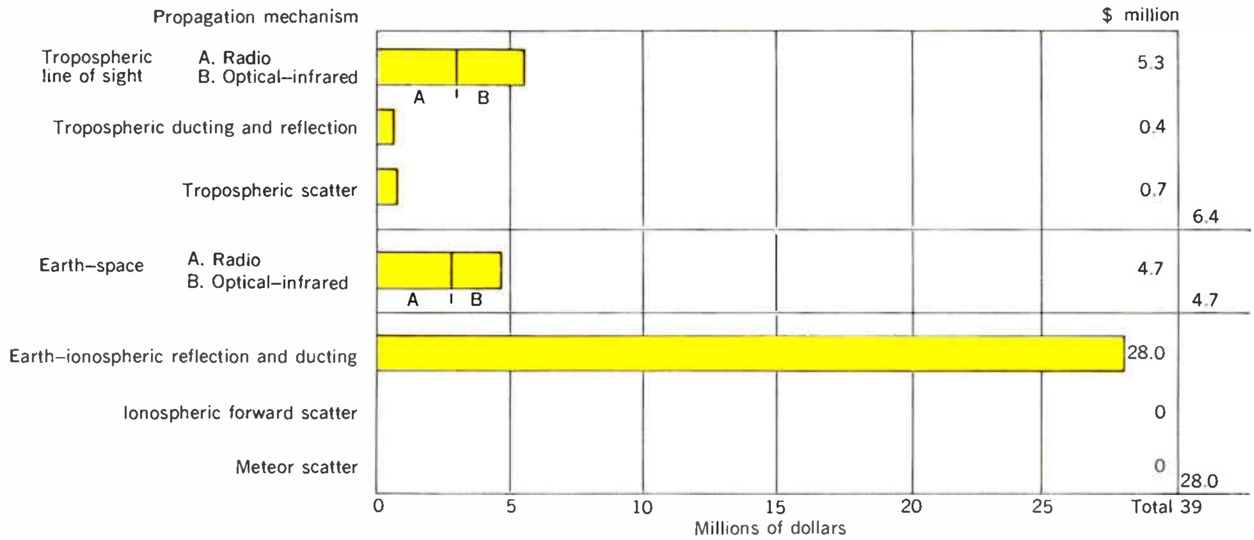
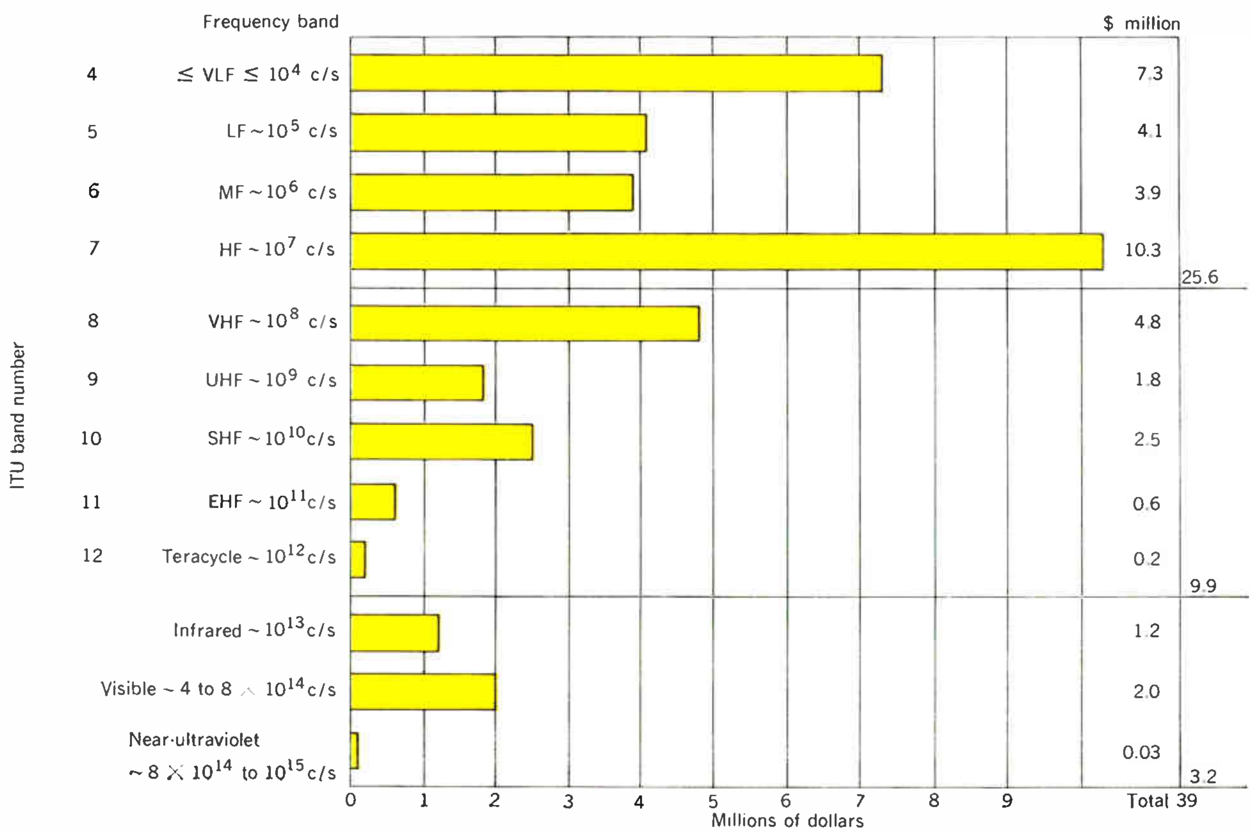


Fig. 7. Distribution of atmospheric research, by relevant propagation mechanism.

Fig. 8. Distribution of atmospheric research, by frequency band.



X. Atmospheric research relative to telecommunication usage

Spectral Region, cycles per second	Telecommunication Expenditures, millions	Propagation Medium	Relevant Atmospheric Research, millions	Research Percentage
10^4 to 3×10^7	$2940	Ionosphere	$25.6	0.87
3×10^7 to 10^9	8890	Troposphere	5.7	0.056
10^9 to 3×10^{12}	4370	Troposphere	4.2	0.096
3×10^{12} to 10^{15}	600	Troposphere	3.2	0.53

farmed very intensively, and it does not appear likely that the density of usage of this part of the spectrum can increase by a factor of more than two or three, except in certain narrow bands. Instead, we may expect that the main expansion in usage will come (as traditionally it has always come) by increased utilization of higher and higher frequencies, even though in many cases the atmospheric propagation difficulties become more and more serious as one moves to higher frequencies. The role of modern telecommunication scientists can therefore be likened to that of agriculturalists who try to increase their total crop both by improving the yield of existing fertile fields and also by opening up and finding ways to use virgin soils. Much of the spectrum (by far the largest fraction in terms of bandwidth) is essentially unexploited for telecommunication purposes; the task of optimizing the use of this spectrum is a huge and important one. While it is clear that many of the problems are related to the technology of transmitting and receiving devices, it is also clear that the atmospheric limitations will play an increasingly important role in further exploitation of the spectrum. It should be noted that the additional sophistication of modern telecommunication systems is placing ever more stringent demands on the telecommunication medium, and that this also accentuates the needs for atmospheric research in support of the telecommunication activities of the nation.

Specific reasons for atmospheric research. Atmospheric research to facilitate electromagnetic telecommunication is needed for at least two fundamental reasons:

To optimize the total use of the electromagnetic spectrum. Since the telecommunication capabilities of the atmosphere differ dramatically across the spectrum, it is clear that the use of the spectrum for telecommunication requires a full understanding of the electromagnetic properties of the atmosphere. There are a number of notable cases in which failure to understand the propagation medium led to costly mistakes. For example, during World War II the decision was made to design a number of radar systems to operate at a wavelength of 1¼ cm ($\sim 2.4 \times 10^{10}$ c/s). Only during the early field tests was it discovered that attenuation due to water vapor was so large as to render the radars useless—with a resultant need to design long-range radars using other frequencies. Similarly, it was only after the allocation of FM and TV channels to the frequency range 42–50 Mc/s that it was recognized that ionospheric propagation during sunspot maximum rendered these assignments unacceptable because of propagated interference, with the result that TV Channel 1 was dropped and the FM broadcast band moved from 42–44 Mc/s to 88–108 Mc/s. The freezing of television assignments within the United States from September 30, 1948, to April 11, 1952, resulted from the discovery of unexpectedly strong interference fields. This major delay was due to lack of understanding of the propagation difficulties, and could have been avoided if the propagation characteristics of the troposphere had been more completely understood.

To optimize the design of individual telecommunication systems. In the absence of accurate knowledge of the atmospheric limitations, telecommunication systems must be designed either by the expensive cut-and-try approach, or by building in an expensive reserve capability ("overdesign"). Only by these expensive means can the designer avoid the risk of an even more expensive "underdesign" of the system. Many cases of expensive overdesign and underdesign of telecommunication systems occur each year in the approximately $17 billion annual expenditures on telecommunication.

An important aspect of optimum system design is the avoidance of creating unnecessary interference. In many cases, interference levels have been found to be unexpectedly high because of propagation by inadequately predicted propagation mechanisms; atmospheric research can contribute greatly to the description of the unwanted, interfering received signal powers as well as the wanted received signal powers. Atmospheric research is also required to permit the design of optimum modulation systems—that is, systems of modulation designed to cope with the defects in the propagation while simultaneously making optimum use of the spectrum.

Some additional benefits of atmospheric research. It is perhaps appropriate to stress some of the extra benefits that are obtained from atmospheric telecommunication research. As in any field of research, the unforeseen benefits often outweigh those that were foreseen. Thus pulse and Doppler radars were first developed not by engineers to detect aircraft, but by physicists to measure the height of the ionosphere. The contribution of electromagnetic propagation studies to atmospheric research is huge, and still growing rapidly. Examples of such studies are Doppler studies of precipitation, and the many different radio techniques for the study of electron densities in the upper atmosphere. Remote electromagnetic probing studies of the atmosphere are playing an increasing role in atmospheric research, and may be expected to continue to do so as telecommunication usage moves to higher and higher frequencies. It is often difficult to differentiate between the role of atmospheric research in support of telecommunication, and telecommunication in support of atmospheric research; the two fields tend to overlap and certainly each supports and benefits from the other.

The authors wish to acknowledge the major contributions made to the preparation of this material, in its original form, by the other members of the Steering Committee, especially Mr. Stuart L. Bailey, Dr. W. H. Culver, and Mr. Harry Fine. Thanks are also due to Mr. R. C. Kirby, of the Central Radio Propagation Laboratory, who conducted the study of the fiscal year 1964 atmospheric science programs in support of electromagnetic telecommunication.

Science in and for space

Space technology has not changed the fundamental character of scientific development, but it has created many demands on science and has hastened many investigations that otherwise might not receive prompt attention

Richard W. Porter General Electric Company

A great deal is being said these days about the "impact" of space exploration on science. "Impact" is a harsh word, which perhaps explains the extent to which it has become fashionable in these harsh times. I have not consulted my dictionary because, having driven an automobile in heavy traffic for many years, I have direct physical experience with the word. I know what it means. In fact, all of us who have followed the accounts of the embryonic stages of lunar exploration in the form of the Ranger series obviously know what the commentator meant when he triumphantly shouted "Impact!" after an exciting sequence of pictures closer and closer to the surface of the moon.

In a way, I think this is an appropriate word to describe the relationship of space exploration to science, because I do not believe the ability of man to send his instruments into space or to go there himself will change the fundamental character of the development of science any more than Rangers VII, VIII, and IX have changed the surface of the moon.

The tools of experimental science

"Science," to quote Albert Einstein, "is the attempt to make the chaotic diversity of our sense-experience correspond to a logically uniform system of thought. In this system single experiences must be correlated with the theoretic structure in such a way that the resulting coordination is unique and convincing. The sense-experiences," he continues, "are the given subject matter, but the theory that shall interpret them is man made—hypothetical, never completely final, always subject to question and doubt."

The earthy old editor of the *Baltimore Evening Sun*, H. L. Mencken, seems to have understood the true nature of science better than many of our modern journalists, as is evidenced by this terse editorial of April 6, 1931:

> "In the sciences hypothesis always precedes law, which is to say, there is always a lot of tall guessing before a new fact is established. The guessers are often quite as important as the factfinders; in truth, it would not be difficult to argue that they are more important. New facts are seldom plucked from the clear sky; they have to be approached and smelled out by a process of trial and error, in which bold and shrewd guessing is an integral part. The Greeks were adepts at such guessing, and the scientists of the world have been following the leads they opened for more than two thousand years. Unluckily, the supply of Greek guesses is now running out, and so science begins to show a lack of imagination."

Science is not big rockets or manned space capsules or automated telemetric cameras crashing into the face of the moon, fascinating as these things may be, any more than it is giant atom smashers, electron microscopes, or telescopes. To state it even more simply, chemistry is not test tubes. But science can use these instruments and conveyances to extend the range of Dr. Einstein's sense-experience, thus doubtless adding to its chaotic diversity. This is my first main point. Second, the technological problems of building these instruments and conveyances frequently provide an incentive for scientific work that otherwise might not receive prompt attention.

In general, the tools of experimental science are the instruments used to extend the senses of the scientist, thus enabling him to observe phenomena more acutely, and also to extend the devices and systems that he uses to control or systematically modify the physical environments in which the phenomena are observed. In this latter category should be included, I believe, the means sometimes used to transport the scientist or his instruments to a place from which observations can be made more advantageously. Under some conditions, therefore, I suppose one would have to classify the jeep as a "tool of experimental science." I doubt if many experimental geophysicists would dare to disagree! It is essentially in this lowly category with the jeep that space vehicles belong, when related broadly to science. Why then do scientists consider them so important?

Science as a crossword puzzle

In order to answer this question, I would like to refer to an analogy which I happen to like. In this analogy, science is compared to a gigantic crossword puzzle, extending perhaps to infinity in all directions. What we can see, hear, feel, smell, and taste here on the surface of the earth shows us only a few squares of this puzzle and, although we can begin to fill these in with words that seem reasonable, we begin to be in trouble whenever we approach the boundary of this little region. The whole structure will be somewhat in doubt so long as any of the squares remain blank, although, of course, this doubt continues to decrease as word after word seems to fit in correctly. The microscope and the telescope have opened up large, new areas of this puzzle; electrical, magnetic, and thermal measurements have opened up still others. Particularly challenging parts of the puzzle were brought into view by the spectroscope, the ionization gauge, and the Wilson cloud chamber. Although our newly acquired ability to send instruments and people into space differs in many ways from these earlier examples, some of us feel that the ability to make observations and measurements from space vehicles will extend our view of the puzzle at least as much as any other technological advance in the history of the world.

The moon, Mars, and Venus

We have not yet reached the tenth anniversary of the first artificial earth satellite, yet already some scientific progress has been made, and the outlines of still more to come can be dimly foreseen. For example, we now have close-up photographs of several selected areas on the moon from the Ranger vehicles—photographs showing up to a thousand times more detail than those taken previously with the best earth-based telescopes. These pictures have not answered very many questions, but they have certainly raised a lot of new ones that we hadn't been aware of before.

A similar beginning is being made in the close-up study of Mars. The pictures recently sent back from Mariner IV, though not nearly so detailed as those from Ranger, still represent a great improvement over the view from earth through our best telescopes. They too probably will raise more questions than they answer, but eventually, perhaps by 1971 or 1973, we hope to land our instruments there as well, and as time goes on the new areas of the puzzle will be filled in. There is one peculiarly important question in this part of the puzzle—that is, whether anything that could be called a living organism exists or has ever existed on the surface or in the atmosphere of Mars. This planet seems capable of supporting some of the simpler forms of life that have developed on earth, and it is tempting to suppose that perhaps similar evolutionary processes have led to similar but not necessarily identical results on Mars. One of the obstacles to be overcome in trying to answer this question is the difficulty of avoiding the contamination of Mars with terrestrial microorganisms in the early phases of exploration.

Even more puzzling than either the moon or Mars is the planet Venus. To scientists it has become not the goddess of love, but a real "bag of worms." Using the tools of radio and radar astronomy, we have learned that its surface is very hot—hotter than the melting point of lead—and that it rotates very slowly in the wrong direction. It has a much thicker atmosphere than the earth, although we are not sure what gases it contains—only that there seems to be a lot of carbon dioxide and not much oxygen—and it is perpetually swathed in heavy clouds of what we are not yet sure. No single hypothesis yet advanced explains all the so-called facts we already know, or think we know, so the obvious requirement is for more facts. It is like a guessing game. When enough clues are given we hope to be able to find an answer that fits them all. Incidentally, it is the confidence that there exists a consistent answer to fit all the facts that makes this game called science possible at all.

The sun

The atomic furnace that supplies power for our solar system is the sun. Once held in awe as an object of religious adoration, it is still perhaps the most important object of nonterrestrial scientific research. Since it is obvious that spacecraft, manned or unmanned, are not ever likely to approach much closer than the outermost fringes of its corona, we shall have to be content with what we can learn by studying the electromagnetic energy that it radiates and the particles of matter that are driven away from it in a sort of solar wind. Since only a small part of the solar spectrum can penetrate our atmosphere—essentially only that part we call visible light plus some of the shorter radio wavelengths—and since much of the important scientific evidence is to be found in other parts of the spectrum, such as the X-ray, ultraviolet, and the longer radio-wavelength regions, it is clear that we must use rockets and satellites to carry our instruments above the atmosphere. In order to achieve any degree of completeness in the scientific picture of the solar wind and its occasional storms, we shall need not one but several spacecraft continually probing the plasma flow and magnetic fields in different regions of the solar system. Of course, until we began to launch scientific rockets and spacecraft, only the most courageous of scientific guessers had any idea that there was such a thing as solar wind, and we had only the vaguest of notions about the origin of terrestrial magnetic storms and ionospheric disturbances. Thus, in this area, space research has had the effect of expanding our view of the puzzle and has helped us to fill in some of the blanks closer to home.

The scientists who first began to use rockets and satellites to observe solar ultraviolet and X rays, being full of curiosity like all good scientists, were obviously tempted to look at other parts of the sky, especially in regions where astrophysical hypothesis indicated that these highly energetic radiations should be strongest. As a result, a new branch of astronomy, our oldest science, is emerging. Because it deals with the high-energy end of the spectrum, the scientific information that will be obtained is likely to be extremely useful in answering fundamental questions about galactic and intergalactic phenomena. Again, however, the results of the first crude experiments seem to be raising more questions than they answer.

Atmospheric studies

As one last example, I would like to mention the scientific study of the earth's atmosphere. Application of the results of this area of science are well known in the practice of weather forecasting. Observations from rockets and satellites are adding to our store of meteorological information in two ways. First, the use of many small, inexpensive rocket sondes for measuring wind, temperature, and pressure or density in the upper atmosphere—that is, above the normal limits of balloon sondes—is beginning to give a coherent picture of the major features of the circulation in this hitherto relatively unstudied region of the atmosphere, where some of our weather apparently begins. Second, the use of artificial earth satellites to photograph clouds and to measure the energy radiated outward from the earth in different spectral regions is providing a means to fill in the large geographical gaps where conventional weather stations are not available. This technique is giving us, for the first time, something that approaches global coverage of the tropospheric circulation. An additional contribution from space research to meteorological science that now seems certain to come in the near future is the use of satellites in data-gathering systems involving free-flying constant-altitude balloon sondes, and free-floating instrumented buoys in the oceans. By this means, it appears possible to obtain detailed three-dimensional data about the tropospheric circulation on an almost continuous global basis. Anticipation of the availability of some such data-collection system is already providing the incentive to develop fantastically extensive mathematical models of the lower atmosphere, covering at least an entire hemisphere, and also superhigh-speed computers capable of handling such models.

There are many other examples of this kind. However, rather than spend more time elaborating this half of my subject, "Science *in* Space," I should like to turn now to the other half—"Science *for* Space." By this I mean scientific work stimulated by the demands of new or improved technology required for space explanation.

There is no absolute division between the nature of the work involved in these two categories; however the ultimate objective is clearly different. The astrophysicist wants to observe and to try to understand the sun because it is our nearest star and because it is a complex of physical pnenomena that fascinate him intellectually. The spacecraft engineer, on the other hand, is interested in knowing the intensity and energy spectrum of the different kinds of radiation from the sun under various conditions in order to design appropriate shielding. The same relationship holds for many kinds of space environmental data, such as the micrometeorite environment, magnetically trapped radiation, the characteristics of planetary surfaces and atmospheres, astronomical constants, and so on. The capability to explore space not only provides us with an opportunity to learn more about such things, but also demands that we learn enough about them to make correct and meaningful evaluations and predictions.

Demands on science by space technology

On the other hand, there are some kinds of scientific work that are strongly stimulated by the needs of space technology, but which would not otherwise result from the exploration of space. These have to do principally with the physics and chemistry of materials, with combustion and high-temperature high-pressure plasmas, and with certain biological, physiological, and psychological phenomena. One would not normally find it either necessary or desirable to go out into space to study photosynthesis, for example; however, the technological interest in photosynthesis for use in a closed ecological system for space exploration has led to considerable laboratory work on this subject which might not have been done at all, or at least not so soon. I shall try to give a few more examples of this kind of scientific work.

Lubrication, for instance, is a rather old area of technology. Oils and greases have been used for a long time to reduce bearing friction. However, these common lubricants tend to evaporate in the vacuum of space, and to be polymerized or changed chemically by the radiation levels encountered during some space missions. Lamellar solid lubricants, that is, crystalline materials having layer lattice structures, seem to be one answer to this problem. Finding the best material for this purpose and the best method to apply it requires a detailed understanding of the internal forces in such crystals and the role of occluded gas molecules, both of which involve rather fundamental scientific research, despite the fact that the work has a definite technological objective.

In a similar way, the demand for lightweight materials that are strong, stiff, and able to retain their strength up to very high temperatures has led to a re-examination of the theoretical strength of small, perfect crystals of alumina and boron, and to the phenomenon of adhesion between such crystals in the form of long, thin fibers and metallic or plastic matrix materials. The re-examination has stimulated some basic work in solid-state physics which might not have been done on the same time scale without the pressing requirements of space technology.

The problem of micrometeorite penetration of spacecraft structures and the need to minimize the probability of damage through optimum design and selection of materials has led to careful experimental and analytical studies of the phenomena involved in hypervelocity impact. This, in turn, has required extension of the equations of state for various materials far beyond the regions that were previously of concern to engineers. The need for lightweight high-temperature energy-conversion devices has inspired new scientific interest in the characteristics of thermionic emitting surfaces and space-charge phenomena, on the one hand, and in nonequilibrium ionization phenomena for MHD generators on the other.

As a last example of the demands on science by space technology, I should like to mention the solid electrolyte ion-exchange fuel cell. Conceived in 1954 by General Electric scientists, this type of fuel cell seemed ideally suited for space applications because of its inherent promise of light weight, low volume, long life, and the ability to work in a zero-gravity environment and to produce potable drinking water along with electric power. However, it was discovered early in the course of development that the ion-exchange membranes, which were produced by incorporating polystyrene sulfonic acid into a fluorinated hydrocarbon matrix, were subject to rapid degradation and subsequent leaching out of the active material under some operating conditions. This caused early failure of the cells and impaired the potability of the water produced. Basic chemical research was urgently needed to develop an understanding of the oxidative degradation of styrene polymers so that appropriate steps could be taken to eliminate or at least to minimize this source of trouble. I am happy to state that the research was done and that corrective steps have been successfully taken.

None of these examples has yet led to any major scientific discovery, that is, one that would fundamentally change our ideas about mass, energy, space, or time. None of them has brought a Nobel prize to any of the scientists involved. But each in its own way represents a striving after truth—an expanding of the part of the crossword puzzle we are privileged to see. "It is open to every man," Einstein says, "to choose the direction of his striving" and "the search for truth is more precious than its possession."

Condensed and updated text of a talk presented at the St. Louis Bicentennial Space Symposium, Fifth National Conference on the Peaceful Uses of Space, May 27, 1965.

Present-day solid-state power switches

New static components and devices, many of which are characterized by decreasing cost with time, are being developed at a rapid rate. A review of their properties and applications, at this time, is in order

J. D. Harnden, Jr. *General Electric Company*

Although the SCR is only seven years old,[1] many of the original types are either obsolescent or already obsolete in view of the apparent ability of present-day power semiconductor technology to develop "ultimate" devices (see Fig. 1).

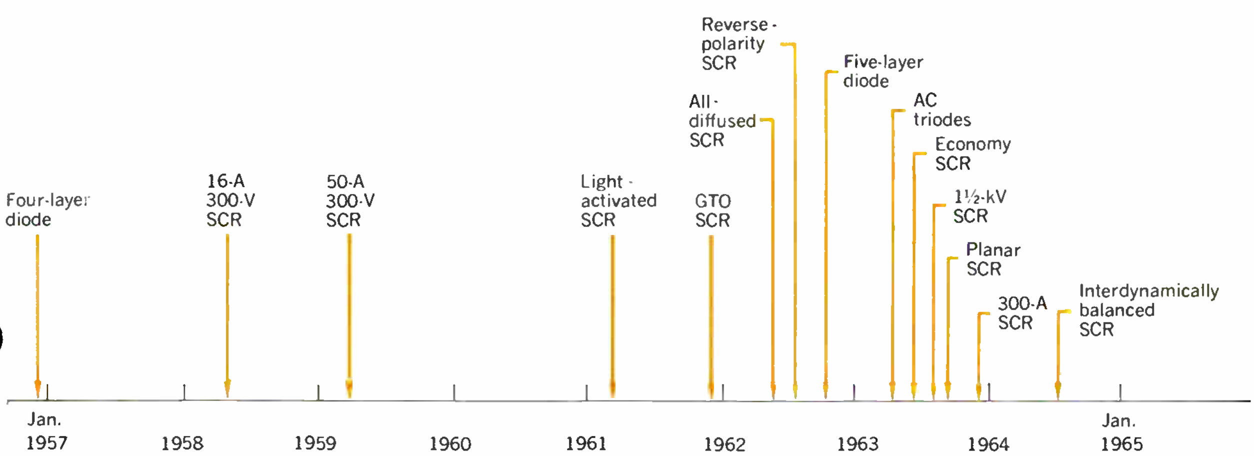
The popularity of the SCR is growing at a rapid rate. In 1959, approximately 40 000 SCR devices were sold; in 1962, 1.4 million; in 1963, 3.5 million; and by 1966, power semiconductor switches should account for half of all power semiconductor sales. As for the immediate future, 50 million SCR devices are anticipated within the next few years.[2-7]

Electrical properties

The largest group of bistable devices is made up of SCRs, usually with three terminals, although several with four terminals have been marketed. The most common structure is the p-n-p-n. The connections are most commonly referred to as gate, cathode, and anode, while in some cases, base, collector, and emitter is the terminology used. SCR is most commonly used as the device name; other names include Thyrode, Thyristor, Trinistor, Pylistor, Dynistor, Binistor, Dynaquad, Transwitch, Trigistor, and Controlled Switch. Some of these names have been used by more than a single manufacturer to refer to different devices. The name Thyristor was adopted by IEC Technical Committee Number 47 on Semiconductor Devices at its October 1962 meeting in Copenhagen, Denmark, as a general name to take the place of p-n-p-n type switch.

A great many process improvements have been utilized in SCR manufacture as they have become available. All-diffused devices are now available, as are epitaxial units and units made by planar passivated methods. In

Fig. 1. Time chart of important bistable switch developments.



most cases improved stability has been achieved, and in some, improved electrical properties have resulted. Small structures have also been fabricated as part of microelectronic and molecular fabrication developments. Ring counters based on these methods have been built with as many as 24 p-n-p-n devices in the same chip, along with associated resistors and diodes.

In general such devices have three important properties: (1) a high-resistance high-voltage blocking state in the forward and reverse states; (2) a low-resistance low-voltage conducting state; and (3) the ability to remain on after the application of the triggering signal.

Gate turn-off (GTO) and multigate operation are featured in other related bistable devices. The GTO is sometimes also called a gate-controlled switch or GCS. Turn-off units are currently available up to about 7.5 A at 700 volts, and about 10 A at lower voltages, with gains of about 10. In some cases normal SCRs can be used in the turn-off mode, but at very much reduced current levels. The GTO device is presently receiving consideration for automotive ignition, and for television sweep applications. If these should prove feasible, many other control and medium-power applications would directly benefit. The GTO, by nature of its design and processing, is inherently faster than the SCR and cheaper than the transistor; thus it may win favor for medium to low powers. Judging from the rate of product introduction, appreciably higher current and higher voltage GTO units do not appear to be 'just around the corner.'"[8,9] In lieu of high-power "turn-off" devices, much effort has gone into developing commutation techniques whereby the SCR can be "turned off" by means of external circuit components.[10] During the last seven years, a great deal has been learned about the SCR in this mode, particularly its lack of conformity to the ideal device characteristics. In addition to the early recognized "turn-on" and "turn-off" limitations, careful designers now are concerned about the additional problems of dv/dt and di/dt; i.e., the dynamic voltage and current properties.[11,12] Several manufacturers now provide a series of selected units with guaranteed turn-off times, while several have begun to treat dv/dt similarly. It is to be hoped that some degree of uniformity in rating and standardization can be instituted.

Until this past year, SCR devices exhibited high-frequency capability that was little improved over the

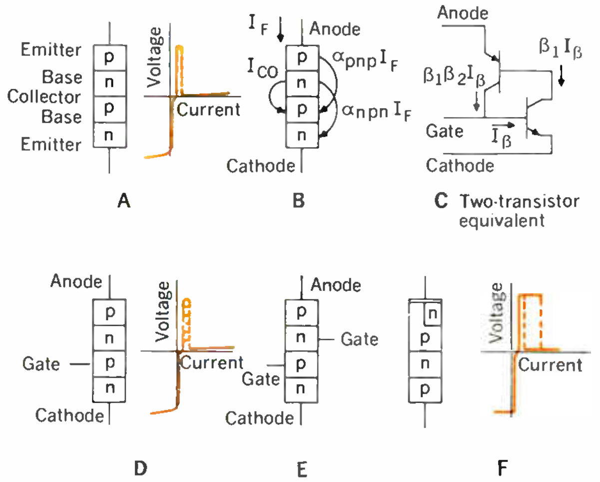


Fig. 2. Basic p-n-p-n switch structures.

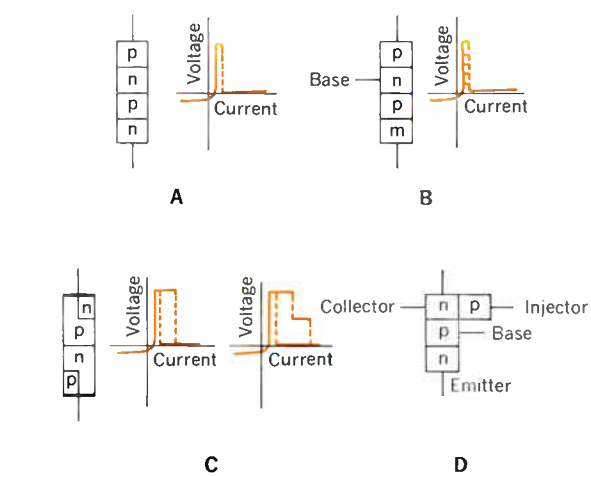


Fig. 3. Modern switch structures.

Fig. 4. AC (bilateral) power switches.

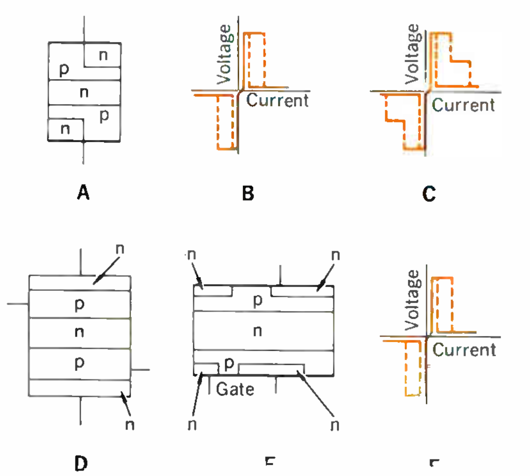
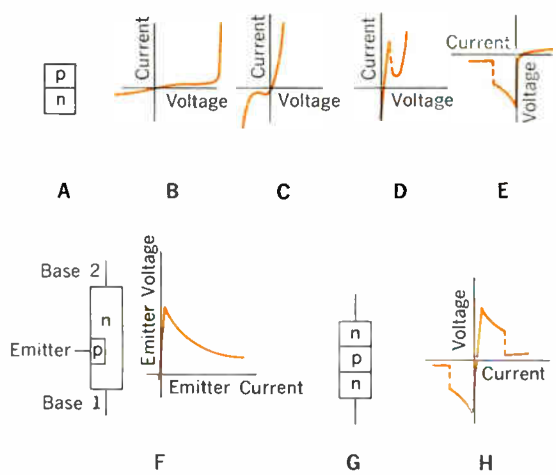


Fig. 5. Fundamental structures.



1958 devices. The new devices attempt to balance the dynamic properties to achieve the highest frequency of operation.[13] Efficient operation at 10 kc/s is now practicable with effective operation at several times this figure possible. Rates of voltage in excess of 200 volts per microsecond and turn-on current build-up greater than 200 A per microsecond are now available.

A number of low-cost SCRs in the current range from 1 to 30 A have found wide application. Voltage ratings at present are normally less than 400 volts. The 110-volt rms unit of lowest current rating (1 A) costs less than $0.50. Economy units use soft solders in order to achieve maximum price advantage.

Device configurations

Figures 2 to 5 show a variety of structures and typical electrical characteristics for bistable switching devices, while Fig. 6 shows the familiar transistor characteristics. Included in the bistable category are both power arrangements and "signal devices" such as avalanche diodes and unijunctions. In the great majority of bistable switches silicon is utilized for fabrication, but about three manufacturers of small devices are using germanium. The breakover voltage for two-terminal units is often quite different than for three, as a result of the applications. Since the diodes are intended to be "turned" on by anode switching, consistency between units with regard to temperature and life are very important. Diode voltage ranges presently available are from 2 to 200 volts and up to approximately 10 A, although the technology would allow ratings as found in SCRs.[14] Three-lead switches are most often gate controlled so that the minimum blocking voltage to be expected under all conditions is specified. While SCRs are capable of anode firing, some manufacturers have placed restrictions on this mode of operation. Improvement in this direction is to be expected, with the development of better surface control and controlled avalanche techniques.

The fact that a unit consists of a p-n-p-n structure does not uniquely describe its electrical properties. There are two main classes of devices, depending on whether the sum of the alphas is greater or less than unity, where the alphas are for the equivalent p-n-p and n-p-n transistors as shown in Figs. 2(B) and 2(C). If the sum of the two alphas is greater than unity, a small voltage between anode and cathode will cause both transistors to go into saturation and the device is switched on. To keep the device "off," it is necessary to reverse-bias the control electrode. If the alpha sum is less than unity, the transistors will not saturate and only amplified leakage current will flow. If the supply voltage applied to such a device is increased, alpha multiplication at the junctions will begin to take place, causing switching, as in a four-layer diode. The most common and useful method is through the introduction of current at a gate connection. In most silicon devices alpha is quite low at low emitter currents, but increases rapidly with increases in current. In germanium, on the other hand, high alphas at low currents are encountered unless one of the bases is reversed-biased. If a metallic or M-type junction is used for one of the emitters, as shown in Fig. 3(B), the injection efficiency will increase with current, causing a variation in the alphas. (The p-n-p-m nomenclature is used to identify this type of device of which the RCA Thyristor is an example.) A light beam falling on a junction can also cause triggering. Five manufacturers are presently marketing diodes and triodes featuring light triggering with ratings to about 2 A and 400 volts.[15]

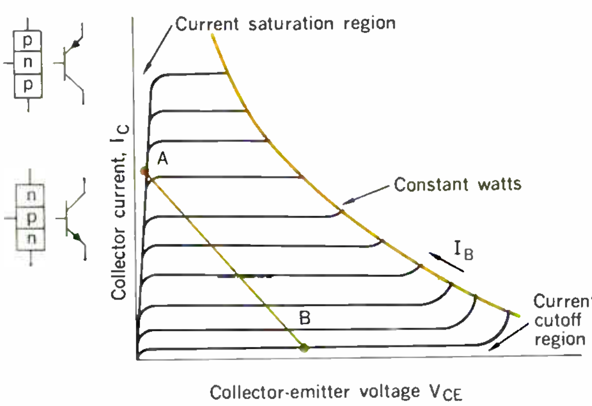
There are about three common reverse characteristics, including full blocking (p-n-p-n) as in a normal reverse-biased rectifier [Figs. 2(A), (D), and (F)], fully conducting (p-n-p-m) as in an ordinary forward-biased rectifier [Figs. 3(A) and 3(B)], and a switching characteristic similar to the forward characteristics (as illustrated in Fig. 4).[16]

The gate requirements consist of voltage, current, and time information, including minimum values to fire and maximum allowable values. Very often excessive gate drive is useful to speed up the switching action. A steep wavefront for the gate trigger is desirable to insure most symmetrical turn-on action of a number of units. The direct ohmic relationship of the three terminals at all times poses some problems. SCRs of larger current rating are now using separate cathode leads for the gate signal to help minimize false triggering. To insure stable characteristics with temperature, some smaller units require the use of a negative gate bias, either in the form of a resistor connected from gate to cathode, or of a negative voltage.

The most sensitive gate turn-on presently available is about 1 μA at 0.5 volt, while for larger units 150 mA might be required. Extremely high gains and great trigger sensitivity are thus evident, surpassing the sensitivity of moving coil meter relays. Units in this category are usually marketed as "switches." However, even though basic SCR sensitivity of 1 μA is not uncommon, practical unit values greater by several orders of magnitude insure adequate device protection for dynamic conditions, temperature effects, etc.

Table I indicates performance of SCRs over a four-year period, with some improvement in most cases. Under actual operating conditions, lower values will result, taking into consideration normal device variations and the particular circuit utilized. The ratio of average forward conduction current to average leakage current will usually be about 10 000 to 1 at a maximum operating temperature for a well-designed device. Ratios that are one to three decades greater in magnitude are possible, depending on temperature, device quality, and method of fabrication. The maximum load current and maximum

Fig. 6. Simplified collector characteristics of common-emitter transistor showing operating regions.



continuous voltage shown as the first two items in Table I may not necessarily occur in the same device.

AC switches

The ac switches, as shown in Fig. 4, are becoming important; these include two-, three-, and four-terminal devices. Terminology such as Diac, Triac, and Quadrac is beginning to be applied to a variety of ac switches as they become available. Most of these devices make use of the short-circuited emitter structure, as indicated by the heavier line segments. Normally the devices have complete turn-on, with a drop of about one volt in either direction.[17] Ratings up to 20 A at 400 volts are currently available. At present only two or three companies are producing ac power switch devices. It would appear as though the range of current and voltage increases might continue at a slower rate than occurred with SCRs.

The main virtues of the ac devices are somewhat economic—there are fewer components to mount, install, cool, etc.; the devices are largely self-protecting from transients; there are simpler or no gate circuits, etc. The smaller 5 A devices do offer cost advantage in some applications. It is a little too soon for much significant cost information on the higher wattage devices to be available, although it appears that some savings may be possible.

I. SCR electrical properties

	Jan. 1961	Jan. 1963	Jan. 1965
Max. load current (average current) per device	150	300	300
Max. continuous voltage (peak)	500	800	1300
Max. current gain	50×10^{1}	10^{6}	10^{6}
Max. voltage gain	400	500	1500
Max. power gain	80×10^{6}	120×10^{6}	120×10^{6}
Max. power per device (peak voltage × average current)	60×10^{3}	90×10^{3}	200×10^{3}

Dynamic properties of ac devices have not been explored in depth as yet. Indications are that di/dt and dv/dt may pose problems in certain circuits. Power-frequency operation accounts for the major application areas at present.

Diodes

The simple p-n junction electrical characteristics take many forms. A few are shown in Fig. 5: the rectifier or diode in (B), back diode in (C), tunnel diode in (D), and avalanche diode in (E). Snap, hot-carrier, light-emitting, breakdown (or Zener), and varactor diodes are other forms of importance.

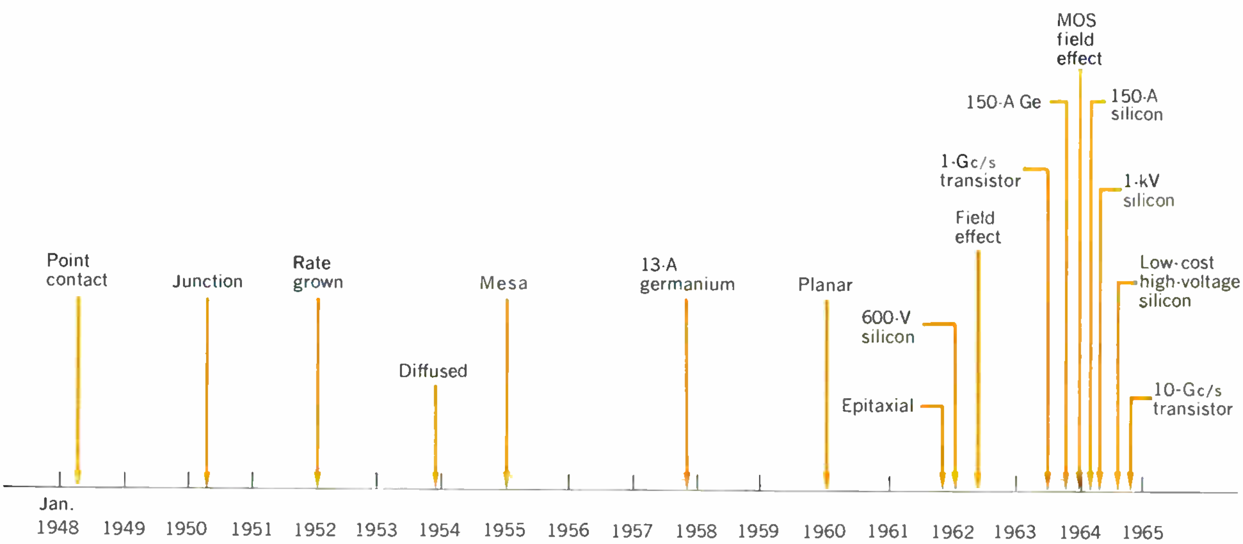
The simple junction rectifier device has progressed to a status of 3 kV for a 3 A junction and 2 kV for a 500 A junction. Prices of power rectifiers are in some cases around 20 cents per kW, which is partially a result of the development of the press fit rectifier for automotive alternator applications. The newer controlled avalanche and high-speed units needed for fast switching applications are more expensive per kW and are manufactured by fewer companies.

Tunnel diodes are double valued over a portion of the characteristic, with the device voltage alternating between two discrete levels. The "peak-point" current is usually held fairly accurately by the etching process employed, and is often used as a reference. The voltage operating points are all less than a volt, and will depend on the material used, such as Si, Ge, or GaAs. Devices with current ratings from a few hundred microamperes to several thousand amperes have been built. Thus, while high currents are possible, high voltages and power are not.

Breakdown diodes are available from a few volts to over 200 volts, in power ratings from a few milliwatts to about 50 watts (at which point they might more correctly be called rectifiers). Temperature coefficient of voltage ranges from almost standard cell values to about 0.1 percent per degree centigrade.

The varactor diode is becoming important in high-frequency work. It is a junction rectifier in which ca-

Fig. 7. Time chart of important transistor developments.



pacitance variation with voltage is maximized and minimum series resistance is desired. Groups of such diodes are used at the few-hundred-watt level to provide harmonic outputs at a few hundred megacycles. Operation to 300 Gc/s has been reported.

Junction devices can also emit light, and are often referred to as light-emitting diodes (LED). Although LEDs have been commercially available for only about two years, rapid progress is being made in the area of light-coupled circuits for control and switching. LEDs are available in several wavelengths of light emission and are relatively efficient, highly reliable, extremely fast, and potentially inexpensive.

The n-p-n and p-n-p transistor devices

In Fig. 7 some of the more important transistor developments are noted. The intense activity in the past few years is evident. Certain process techniques provide important bench marks since new device characteristics can be achieved. A very good illustration is the field effect transistor, which was known well before the junction device, but which could not become a controlled, stable product until better processes based on diffusion and other advanced methods were devised.

The transistor is an important power switch. In the diode form of Fig. 5(H), negative impedance properties are employed in what is known as the "avalanche" or trigger diode. Since the power loss in the device is high, other modes of operation must be utilized if efficient operation is to result. Figure 6 indicates a typical collector characteristic, in which the switching operating points *A* and *B* are indicated. Typical transistor characteristics usually include input, output, current transfer, and transconductance. These will be an aid to switching applications, but more specific testing is usually required to define the safe limits of the switching mode. To the conduction and blocking losses of points *A* and *B*, one must also add the switching losses. These depend on the speed, load line, load reactance, etc. Mechanisms of breakdown and punch-through are numerous, and have often been troublesome in successful applications of transistors as switches.

Power transistors are fabricated from both germanium and silicon material. In general the germanium devices are characterized by lower saturated voltage drop, modest collector ratings, higher betas (current gain), and, to date, by lower cost. Ultralow-voltage-drop p-n-p units, made by the alloy process, feature 50-mV drop at 100 A. Such units are intended for high-efficiency converters and low-drop rectifiers. The frequency performance of germanium alloy transistors falls off above 10 kc/s. Diffused base units are good to approximately 1-μs switching speed at a few amperes. Transistors require control power (base drive), to keep them in the saturated region of the collector characteristic, whereas bistable devices do not. The base drive is of course a factor in the rating and efficiency of the transistor. Germanium alloy ratings are roughly 200 volts at 25 °C case, with a junction-to-case thermal impedance of about 0.5 °C per watt and a junction time constant of about 50 ms. The power rating is usually derated to zero at about 100 °C. Recent advances in geometry and passivation methods have caused some renewed activity in germanium. High-voltage applications require silicon, with low-current devices to around 1 kV and 5 A units up to about 600 volts, while germanium appears to be limited to about 200 volts. Approximately the same currents are commercially offered (150 A), while 400 A devices in germanium are reported.[18] At the present time all silicon units over 10 A are n-p-n structures.

Higher transistor speeds are being rapidly achieved. Interdigitated and epitaxial methods are commonplace. Power outputs of 8 watts at 500 Mc/s are reported, while 3.5 watts at 1 Gc/s, 1.5 watts at 1.5 Gc/s, and $^1/_3$ watt at 2 Gc/s have also been reported. The single-crystal metal base transistor and surface-controlled avalanche transistor (SCAT) have been proposed within the last year as answers to providing higher powers up to 10 Gc/s or possibly 20 Gc/s.[19]

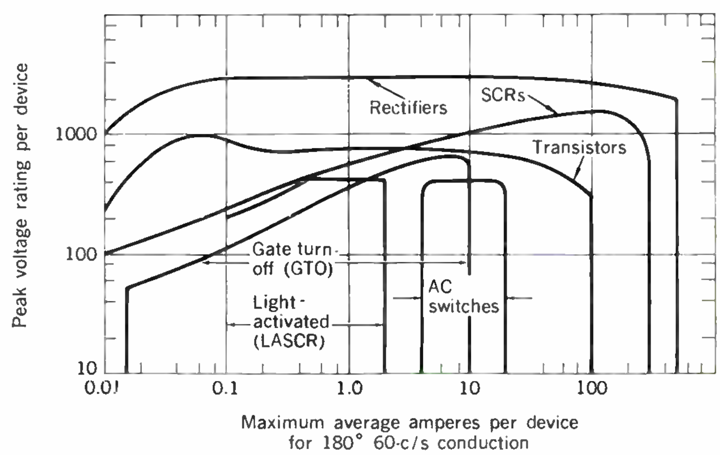
Until about mid-1964, transistors with voltage ratings in excess of about 100 volts were more expensive than SCRs (or bistable switches) of the same power rating. However, as a result of the market opportunities in line-operated radio, high-fidelity, and television equipment, several manufacturers introduced silicon transistors rated at approximately 2 to 3 A, priced at 1 cent a volt, with voltage ratings to 400 volts. It is too early yet to appraise adequately the influence, if any, that this development might have on low-cost low-power SCR applications.

The rapid spread of planar technology to the consumer market has been spearheaded by the development of adequate epoxy sealing or potting systems. The extent to which cost improvements in other products will be made via the epoxy route will depend on improvements in passivation methods, understanding of channeling, development of field relief electrodes, etc.

Power capacity

Figure 8 plots the locus of peak voltage and average current ratings for bistable switches and transistors presently available. There are very few situations in which the full rating can be realized since circuits will impose utility restrictions, designers will require safety margins, etc. It will be noted that p-n-p-n devices inherently provide high-voltage and high-current capabilities. This is unlike the transistor in which the base must be made thin to obtain high current gain and a high cutoff fre-

Fig. 8. Limits of voltage and current for presently available bistable switches, transistors, and rectifiers.



quency, thus limiting voltage because of punch-through and other effects. With a p-n-p-n unit, the alphas do not have to be high, so that the base regions can be wide, and greater geometric flexibility is possible. Individual units can be connected in series and parallel to provide greater output or to allow circuit requirements to be met. While power rectifiers have been paralleled for many years with success, certain additional precautions are necessary with SCRs. Mounting of rectifiers to experience common cooling conditions is recommended. Parallel matching of forward characteristics can be helpful, but gates may still be mismatched. Ample firing signal, in both magnitude and duration, is essential. The development of diffused devices has permitted the achievement of better gate characteristics, among others, to make for easier paralleling. The introduction of beryllium oxide (BeO) insulators has been a help in providing electrically isolated, yet thermally efficient, heat sinks, particularly in lieu of many reverse polarity power units. In addition, direct wafer attachment to the BeO using silicon pellets is being used in certain products.

The allowable forward current is governed by the thermal impedance of the device, the frequency, the duty cycle, and the junction's thermal capacity. The peak current rating is determined by the last characteristic and can be an order of magnitude times the normal current. A few manufacturers provide I^2t information to allow proper choice of protection devices.

Series operation requires the use of voltage dividers consisting of resistors and capacitors, since sharing transiently as well as in steady state is required. Slaving techniques have been developed so that it is only necessary to control a single gate.[20]

Packaging

At least five dozen different cases and methods of mounting are used, including completely isolated units, lead-mounted units, stud-mounted units, and flat-flange units. One manufacturer provides a stud-mounted unit with an auxiliary lug on the header end so that all connections can be made at one end of the device without attaching an extra connection to the stud end. Some TO-18 packages are available, with a greater variety of smaller packages beginning to appear, but the power capabilities are limited. Transistor-basing arrangements appear to be consistently used for SCRs, anode (collector), gate (base), cathode (emitter) for normal p-n-p-n units and vice versa for complementary n-p-n-p units. All of the grounded stud-mounted SCRs have the anode connected to the case. One area which has yet to receive much attention is that of acoustical noise. This is sometimes a problem at 60 c/s, but more often appears as the frequency is increased. It is particulrly troublesome in inverter circuits.

Summary

Literally thousands of semiconductor switches are available to choose from for a given application.[21] The trend is more and more to silicon as prices of silicon products are reduced.[22-24] In many applications, it is not the cost of the power switch that is the controlling or major factor, but rather that of the "brain" and logic circuit. Integrated circuit techniques are expected to be a big factor in providing lower cost, more reliable input circuits.

The extent to which new structures, such as power field-effect devices, will be important cannot be evaluated as yet.[25] However, it is clear that low-level FETs, especially of the MOS type, will be widely used in controls.

The figures that have been presented must be changed as newer techniques and processes are developed. It is impossible to outline the direction and extent of changes which might be expected for all of the devices considered in this article. However, a safe guess might be that a two-to-one change in any parameter could easily take place in the next few years.

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Rise of the engineer–executive

A recent survey by Scientific American *reveals some dramatic trends in the top management structure of 600 of our largest nonfinancial corporations*

Education—particularly in the scientific and engineering disciplines—holds more weight today in the corporate industrial community than a wealthy and influential father. In short, the rags-to-riches theme of the popular dime-novel hero, as portrayed by Horatio Alger more than 60 years ago, is fast becoming a reality as an ever-increasing percentage of professional men from humble origins make their mark in the top slots of American industry.

Since the turn of the century there has been a steady shift in the social and educational backgrounds of the top corporate officials (chairman of the board, president, and executive vice president) of major American industrial corporations.

In 1964, a comprehensive survey of approximately 1000 of these top officers of 600 of the largest nonfinancial corporations, entitled "The Big Business Executive," sponsored by *Scientific American* and conducted by Market Statistics, Inc., in collaboration with Dr. Mabel Newcomer, was updated from 1950 to present a compendium of facts and figures that reveal definite and dramatic changes in the top management structure. According to the survey, one such significant change is indicated by the statistics that in 1964, 34.8 percent of the business executives in the top three categories had technical backgrounds—degrees in engineering, natural science, or equivalent on-the-job experience—as compared with 19.3 percent in 1950, and 12.5 percent in 1900 (see Table I).

Bridging the gap

Apparently this trend is gathering so much momentum that, within the next 10 or 20 years, most of our "captains of industry" will be men with the interdisciplinary ability to close the gulf between the business–financial and the science–engineering cultures. Thus these industrial leaders will be better equipped to meet the challenge of the spiraling advance of our contemporary technology.

Methodology of the survey

Dr. Newcomer had studied biographical data for three generations of business leaders—the top brass of the largest corporations in industrial manufacture, trade, public utilities, and railroads—keyed to the milestone years of 1900, 1925, and 1950. In 1900, there were 214 in the category of the largest corporations. The number increased to 238 in 1925, 428 in 1950, and to approximately 600 in 1964. The corporations on this list accounted for at least one third of the total corporate assets in the United States.

The median assets per corporation increased from $45 million in 1900 to $97 million in 1925, and to $147 million in 1950. In the 1964 sampling, the corresponding list of corporations had a median asset value of $150 million, and accounted for over one half of the nation's total corporate assets.

The social implications

In 1900, nepotism in American industry seemed to be fairly rampant. About two thirds of the business executives of that generation had fathers who were either heads of the same corporation or independent businessmen (see Fig. 1). And, at that time, less than 10 percent of the total group had fathers who were employees. But in 1964, only 10.5 percent of the present generation of big business executives were the sons of wealthy families, and the percentage of father–employees increased to almost 30 percent.

This striking change in patterns clearly indicates that contemporary industrial leadership has largely slipped from the hands of the rich and well-born to those of the educated middle class. The survey shows that, in 64 years, the evident trend toward management by professionals has been accompanied by increased vertical mobility in the selective processes by which the leaders of top management evolve (see Fig. 2). Further, the extension of formal education through graduate studies now furnishes

I. Principal occupational experience of big business executives

Occupation	Number of Executives 1900	1925	1950	1964	Percentage of Executives 1900	1925	1950	1964
Entrepreneur	97	66	86	24	31.0	20.2	9.9	2.6
Capitalist	39	20	43	4	12.5	6.1	4.9	0.4
Banker or broker	24	12	43	7	7.7	3.7	4.9	0.8
Engineer or scientist	39	51	168	319	12.5	15.6	19.3	34.8
Lawyer	41	45	104	101	13.1	13.8	11.9	11.0
Other professions	12	9	69	105	3.8	2.7	7.9	11.5
Management	61	123	358	357	19.5	37.7	41.1	38.9
Total	313	326	871	917	100.0	100.0	100.0	100.0

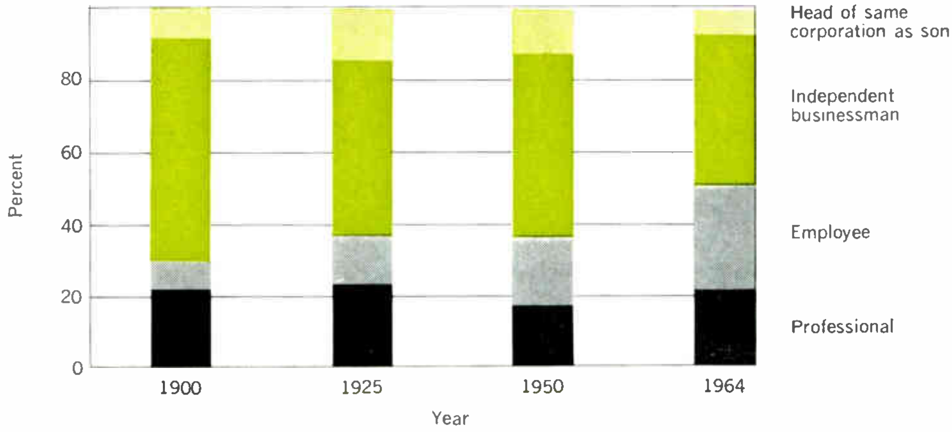


Fig. 1. Occupations of fathers of big business executives. The chart indicates that top executives in industry have been coming in increasing numbers from families headed by employees and professional men, rather than from families of businessmen and company heads.

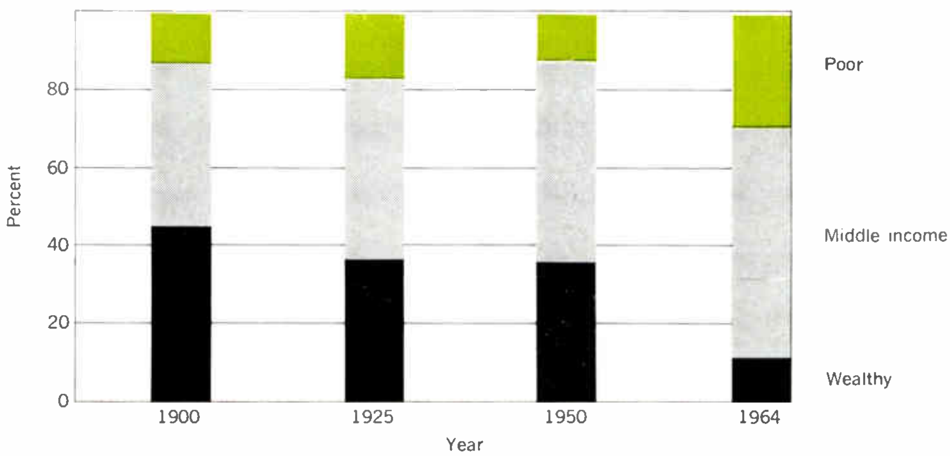


Fig. 2. Family background of big business executives. Comparative bar graphs show that the top management executives in industry have been coming from families in modest circumstances, poor or middle income, in recent years.

the basic qualifications for promotion to first-echelon executive responsibility.

Success and the Ivy League

One of the most interesting aspects is the broadening of the base of the colleges and universities from which successive generations of top executives were educated.

Back in 1900, the preponderant majority of this group who attended college went to Harvard. Yale ran second, Columbia third; and relatively few were from M.I.T. and the University of Michigan.

But, in 1925, Columbia had moved to the top of the list, with M.I.T. a close second. The descending order next included Harvard, Yale, and Princeton. And, by that time, Lehigh, Michigan, and Amherst were advancing on the list.

By mid-century, Harvard was far in the lead, with Yale second. The remainder of the significant list included Princeton, Cornell, Michigan, Columbia, and M.I.T.; with Wisconsin, the University of Pennsylvania, and the University of California coming up fast (see Table II).

In 1964, this list had expanded tremendously to include 45 colleges and universities. Table III lists these institutions and the numbers of executives in the survey who completed either the undergraduate curricula or graduate studies. Note that Harvard and Yale are still in the first and second positions, while M.I.T. has come up from seventh position in 1950 to the third spot in 1964.

II. Principal universities and number of executives attending each (1900–1950)

Year: 1900		1925		1950	
Institution	No. of Executives	Institution	No. of Executives	Institution	No. of Executives
Harvard	22	Columbia	18	Harvard	74
Yale	12	M.I.T.	14	Yale	62
Columbia	10	Harvard	13	Princeton	34
M.I.T.	5	Yale	12	Cornell	33
Michigan	4	Princeton	10	Michigan	31
		Lehigh	8	Columbia	29
		Michigan	6	M.I.T.	23
		Amherst	5	Wisconsin	17
				Pennsylvania	15
				California	14

III. Principal institutions as of 1964

Institution	Number of Executives: Total	Under-graduate	Gradu-ate
Harvard	98	46	52
Yale	78	66	12
M.I.T.	46	30	16
Princeton	40	39	1
Cornell	36	24	12
University of Illinois	32	27	5
Stanford	29	23	6
Columbia	26	11	15
University of Michigan	26	13	13
University of Pennsylvania	20	19	1
University of Wisconsin	20	18	2
University of California	18	14	4
Dartmouth	18	18	0
University of Missouri	14	11	3
U.S. Naval Academy	14	14	0
University of Chicago	13	8	5
University of Minnesota	13	10	3
Lehigh	12	11	1
Northwestern	12	10	2
Ohio State	12	6	6
New York University	12	10	2
University of Texas	11	8	3
University of Kansas	9	9	0

Institution	Number of Executives: Total	Under-graduate	Gradu-ate
Virginia Polytechnic	9	8	1
George Washington	9	3	6
Williams	9	9	0
Carnegie institute of Techn.	8	5	3
Purdue	8	7	1
Pennsylvania State	7	6	1
Iowa State	7	7	0
Texas A. & M.	7	7	0
Virginia Military	7	7	0
Clemson	6	6	0
University of Colorado	6	4	2
University of Maryland	6	4	2
Rensselaer Polytechnic	6	5	1
Vanderbilt	6	5	1
University of Virginia	6	5	1
Emory University	5	4	1
Georgia Institute of Tech.	5	5	0
Illinois Institute of Tech.	5	5	0
University of Oklahoma	5	4	1
Oxford	5	3	?
Stevens Institute of Tech.	5	5	0
Syracuse	5	4	1

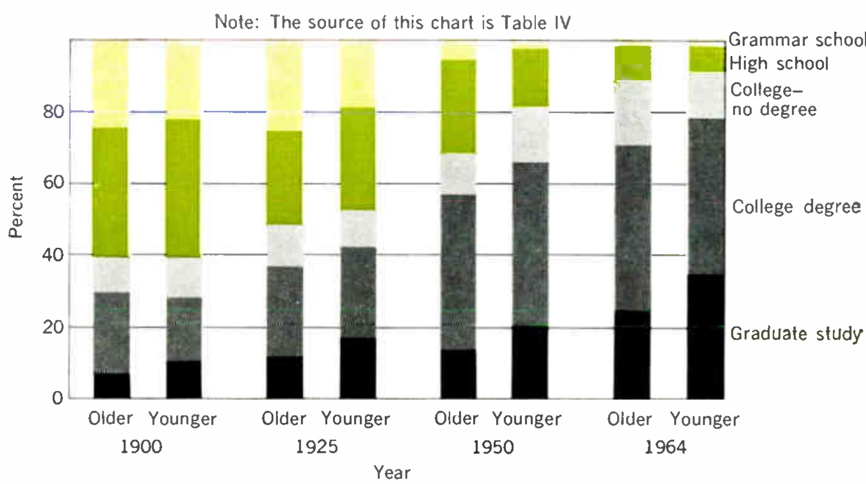


Fig. 3. Education of top management executives. A significant index of the "professionalization" of the big business executive is the doubling of the percentage of those with some higher education. In 1900, the figure was just under 40 percent; in 1964, it was more than 90 percent. The percentages with college degrees and graduate training among younger executives consistently exceeded the corresponding percentages among older executives in each year studied after the turn of the century.

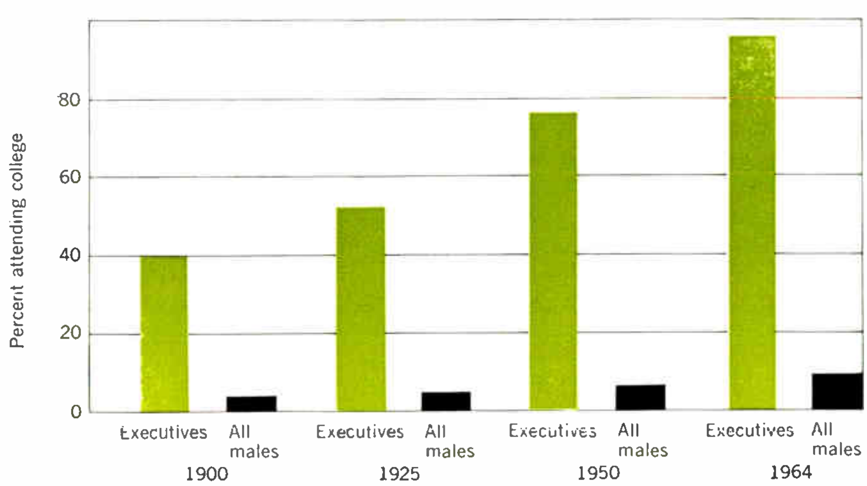


Fig. 4. Education of big business executives as compared with their contemporaries. While the percentage of all males with some college education has approximately doubled since 1900 to 8.7 percent, the percentage of big business executives with some college education has increased from 39.4 percent in 1900 to the point where, in 1964, more than 90 percent have at least some higher education.

IV. Education of big business executives—percentage distribution

Highest Level of Education Reached	1900 Older	1900 Younger	1925 Older	1925 Younger	1950 Older	1950 Younger	1964 Older	1964 Younger
Grammar school	25.3	22.7	26.0	19.8	6.5	2.5	0.3	0.2
High school	35.4	38.0	24.4	27.5	24.3	16.8	10.5	7.6
College: no degree	10.1	11.4	12.6	10.6	11.8	14.8	17.6	14.3
College: 1st degree	24.0	17.9	26.0	25.1	44.8	45.8	47.2	43.4
Graduate study	5.1	10.0	11.0	17.0	12.6	20.1	24.4	34.5
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Number of cases included	79	231	119	207	382	487	324	525
Education or years in position unknown	1	5	0	4	6	7	152	

Note: The distinction between "younger" and "older" executives used here is based on the length of time in present position; in general, "older" executives have served for more than 7 years.

Total education of big business executives

A significant index of the "professionalization" of the top corporate executive is the more than doubling of the percentage, between 1900 and 1964 (from about 40 to more than 90 percent), of those with some higher education. As may be seen in Fig. 3 and Table IV, the percentages with college degrees and graduate training among younger executives has consistently exceeded the corresponding percentages among older executives in each year studied after 1900.

Another fascinating statistic is that while the percentage of all males with some college education in the adult generation has roughly doubled since 1900 to 8.7 percent (see Fig. 4), the percentage of big business executives with at least some college education has increased from 39.4 percent in 1900 to more than 90 percent in 1964.

Comment by respondents

In addition to the statistical data summarized by charts, the *Scientific American* study sought and obtained informal comment from most of the 600 executives to whom its questionnaire was directed. The comments, which were solicited at the end of the two-page questionnaire, generally concerned two topics, "Professional Training" and "Pivotal Factors in Career."

It is interesting to note, in a number of instances, that the respondents' replies tend to bear out what many engineering educators have long suspected—that deficiencies in humanities courses in the engineering curricula often become apparent in the business community.

A sampling of these comments on professional training, with the respondents' degrees indicated in parentheses, include:

(B.A. and M.B.A.) "I feel my lack of technical knowledge is a distinct handicap. To help overcome this, we have had a full-time senior corporate executive to advise me on the long-range implications of technological change."

(B.S. in Engineering and M.B.A.) "Engineering education should provide wider exposure in the arts and humanities."

(B.S. in Engineering) "Technical training was adequate, but most fortunately, I had a sound secondary education emphasizing the 'humanities'—Latin, Greek, History, English. I am not sure but that this secondary academic course was not *more valuable* in the long pull, than my engineering degree."

(B. S. in Engineering) "Training in expression, both speaking and writing was lacking in my formal education... its importance to business is greatly overlooked."

(B.S. in Civil and Mechanical Engineering) "Would have benefited from a more thorough course in languages. A course in investment banking techniques would have been valuable..."

On the subject of pivotal factors, a sampling of observations include:

"I was the first trained engineer to enter the business. Because of my family position, I was able to introduce improved technical procedures faster than would otherwise have been the case. In general, I rate inherent ability very highly—much higher than many do—also, the good fortune to fall into a niche you fit."

"Constant technical reading to keep up to date..."

"Working in a business having a high technological content, I had the benefit of a technical education and the experience of growing up with the business essentially from its beginning. My motivation has been to translate pioneering technical accomplishments into practical realities."

"Without question the pivotal factor in my career was the availability of scholarship funds at both the prep school and college level. After the war, of course, I was able to use G. I. Bill funds to finish college and to finance law training at night."

"I feel that such minor success as I have attained is due to a *combination* of adequate technical and classical education... that tends to produce a *balanced* man. This is a prerequisite to the 'learned' professions—law and medicine—and I feel most strongly... should be a requisite to the *professional* engineer or scientist."

The corporate cross section

Among the 600 major firms selected for the survey were: American Electric Power Company, Aluminum Company of America, Baldwin-Lima-Hamilton Corporation, Consolidated Edison Company of New York, Southern Railway, Dow Chemical Company, E. I. du Pont de Nemours, General Electric, General Motors, International Telephone & Telegraph, Kaiser Industries, McGraw-Hill, Inc., and the Standard Oil Company of New Jersey.

Apparently the corporate search for the best of two worlds—technology and the humanities—continues, but it is evident from this survey that the scientist and engineer are finding their place in the corporate sun.

G. D. Friedlander

Special Conference Report

1965 Rural Electrification Conference

Frank C. Miramontes
Pacific Gas and Electric Company

The Ninth Annual Rural Electrification Conference of the IEEE was held at the St. Francis Hotel, San Francisco, California, on May 24–25, 1965. The conference was sponsored by the Rural Electric Committee of the IEEE Industry and General Applications Group with the effective cooperation of San Francisco and Sacramento Sections. Total registration was 126. Ten papers were presented covering overhead and underground lines, motors, motor overcurrent protection, sponsored research, some specific uses of electricity on the farm, and foreign developments in rural electrification. Three presentations were not accompanied by papers.

One of the highlights of the meeting was the awarding of a certificate and a $100 prize to Dr. Naim N. Abou-Taleb, UNESCO Expert in Mexico, for his paper, "Problems Facing Developing Countries in Their Planning for Rural Electrification."

The Monday morning session was devoted entirely to underground distribution.

At Monday evening's banquet Robert R. Gros, vice president, Pacific Gas and Electric Company, delivered an excellent address on "The Fifth Freedom," comparing the American way with that of other countries he has visited.

Kern Yee Loo, Pacific Telephone and Telegraph Company, presented a delightful account of "Old Chinatown Customs" at the Monday luncheon. Charles A. Powel, retired executive of Westinghouse Electric Corporation and past president of AIEE, took the group back into the early history of electricity with "Early Days of AC Transmission" at Tuesday's luncheon.

Two of the participants in the annual banquet were: Frank C. Miramontes (above), conference chairman; and D. M. Pritchett (right), vice president and secretary, California Pacific Utilities Company, San Francisco, Calif., who was master of ceremonies.

Technical program highlights

Problems facing developing countries in their planning for rural electrification. (Dr. Naim M. Abou-Taleb, UNESCO Expert in Mexico.) Eighty percent of the population of the developing countries live in rural areas, and domestic water, roads, and electricity are a prerequisite to raising the standard of living. These countries have to import all their electric equipment, much of this being negotiated as a foreign loan or help. As compared with 4251 kWh per capita in the U.S.A. in 1960, figures in the Asian and Far East countries vary from 0.8 for Nepal and 9.3 for Indonesia to 37 for India.

The rate of growth of electric generation in Afghanistan has averaged about 35 percent per year. Most of these countries have good natural resources for power development, but lack basic data and technical personnel. Standardization of frequency and voltage is essential. A power system developed for only five years ahead is usually outmoded before completion. The use of small, isolated generating plants is limited and diesel plants serving a group of villages generally compare unfavorably with grid connections. Besides advantages, however, there are some integrated high-voltage-grid disadvantages: some rural areas may wait a long time for service while local generators would provide it much earlier. A very high capital investment and foreign currency allocation is needed at the start. Technology is moving so fast that too much time may go by before the integrated system is fully utilized and by that time it may become somewhat outmoded.

Phase converters: their application and current demand. (George H. Huber, System Analyzer Corp., Nokomis, Ill.) The use of the electric motor in the integral hp sizes has increased considerably in most rural areas, and this

Mr. Miramontes was conference chairman for the 1965 Rural Electrification Conference and is director, agriculture sales, Commercial Sales Dept., for Pacific Gas and Electric Co. in San Francisco, Calif.

creates problems where three-phase power is not readily available. Phase converters have allowed the operation of sizable three-phase electric motors from single-phase power lines.

A capacitor-type phase converter consists essentially of starting capacitance, running capacitance, the necessary relay, and an autotransformer. Practically all the losses in the converter unit are in the autotransformer and amount to approximately 2 percent. The three-phase currents are balanced at full load, with unbalance resulting at reduced load, although not exceeding name plate amperage by more than a small amount. Use of two or more motors from the same converter is not recommended unless 75 percent or more of the load is started and stopped simultaneously.

Underground residential distribution and the total electric subdivision. (Perry W. Reams, Clark County PUD, No. 1, Vancouver, Wash.) The Clark County district will now install an underground residential distribution system in a platted and recorded subdivision at no initial cost to the developer.

A typical system consists of direct burial primary and secondary cables, pad-mounted transformers, and secondary pedestals, all located inside the street property line with delivery point on the property line. At no cost to the developer aluminum light standards are installed. The developer must require the homeowner to provide a 200-ampere service panel and to install and maintain the service conductors to the delivery point. The subdivision developer must reimburse the district $250 for each subdivision home not totally electric and share the increased investment cost of underground distribution when unsupported by sufficient revenue.

Following adoption of this policy in July 1964, 112 residential lots have received underground service, and planned are four subdivisions of 67 lots and two subdivisions of 117 lots each.

Underground residential distribution in northern California. (J. H. Lawson, Pacific Gas and Electric Company, San Francisco, Calif.) Pacific Gas and Electric Company now provides underground service to about 20 000 single-family residential customers and about 20 000 apartment dwelling units. The primary distribution system is three-wire 12-kV with the neutral grounded at the substation. Transformers are predominately pad-mounted.

A "partial" underground system, called "streamlined," was offered in 1963 as an intermediary between standard overhead construction and pad-mounted underground installation. In the streamlined system all secondary mains and services are underground. Primaries and streamlined transformers through 50 kVA remain overhead, supported on tapered steel poles which also support street lights. The transformer secondary leads run down inside the pole to a small underground system usually supplying approximately six homes. Span lengths are long and normally no guying is used. Poles, transformers, street light brackets, primary bushings, and insulators are of a silver-gray blending with the sky. As of December 1964, 12 600 single-family dwelling units and 1800 apartment units were served by this streamlined system.

Mr. Lawson also discussed the P.G.&E. Co.'s latest developments in "total underground."

Rural electrification problems and situation in Latin America. (Chris L. Schultz, Bureau for Latin America, Agency for International Development, Washington, D. C.) It is tempting to apply the experience in the U.S., where rural electrification has advanced so far in 35 or 40 years, to rural areas of Latin America; however, there are differences and similarities between the two areas. Other factors than engineering must be given consideration and the engineer must understand these other problems and be sympathetic toward them before he can approach them objectively.

The individually owned and operated farm of small and medium size and economic worth, typical in the U.S., is seldom seen in Latin America. Rural electrification then becomes a matter of taking electricity to each village and serving a few isolated customers between villages.

People must be developed as regards their health, education, and purpose if the economic status of the country is to be improved. The burden for success must be carried primarily by the Latin American countries themselves. Private utilities as we know them are relatively few in Latin America, and rural electrification becomes the job of government agencies.

American farmers were and are able to operate many types of machinery and can visualize their advantages. They also understand commercial farm management, but most of these conditions do not exist today in Latin America. In summary, we find four interdependent conditions affecting rural electrification in Latin America: economic, market projections, technical personnel, and the availability of materials and equipment.

Overcurrent protection in each conductor of isolated three-phase motors. (Frank C. Miramontes, Pacific Gas and Electric Company, San Francisco, Calif.) It has long been known that an "open" in a primary conductor of a wye-delta or delta-wye transformer connection with the neutral isolated supplying a three-phase motor would produce in one motor conductor, a current two or three times the normal current, with the current in each other conductor, however, increasing to perhaps only 15 percent above normal. Hence with overload (overcurrent) protection in only two motor conductors there is a one-in-three chance that the heavy current will occur in an unprotected conductor and damage the motor.

Because of the great number of customer-owned, three-phase irrigation pumping motors on its system (a present total of about 1 800 000 hp), plus a desire to reduce customers' motor burnouts to a minimum, Pacific Gas and Electric in 1947 initiated a program to encourage overcurrent protection in each conductor of the three-phase irrigation pump motors of its customers, as well as for other applications. Three-phase 220-volt demonstration equipment was constructed consisting of wye-delta-connected transformers, switch, motor starter and a small three-phase motor to demonstrate the above principle. Thirty-one demonstrations were made to a total of 1050 employees and 61 demonstrations were provided for 1300 pump and motor dealers.

The dealers recommended to customers the addition of a third relay and/or time-delay, thermal-type fuses, and manufacturers altered pumping panels to accommodate the third relay with a common reset. For over ten years now, almost all new pumping panels installed in P.G.&E.'s service area have overcurrent protection in each motor conductor. While motors are damaged and do burn out for a variety of reasons, it often being difficult to determine the cause, there is no question but that this program has provided better motor protection and better power company customer and dealer satisfaction.

Electric control of automatic egg gathering, processing, and handling systems. (W. B. Crawford, Seymour Foods Company, Topeka, Kans.) Mr. Crawford pointed out that a high degree of practical automation must be made available to egg producers because of low egg prices, rising labor costs, and larger production facilities. He described a new concept in egg handling involving a completely automatic system that gathers and processes eggs at the producer level for flocks of 100 000 birds and up. Several systems are available to transport eggs from the birds to the egg room or from a number of production houses to a central processing point. Seymour Foods has introduced a new piece of equipment, "Trans-link," to convert masses of eggs from conveyor belts to organized rows for processing. The Trans-link involves limit switches and indicating lights to adjust the flow of eggs to the capacity of the processing system. Other egg processing operations are washing, cooling, electronic blood spot detection, sizing and cartoning. Human visual inspection is still required in the candling section during egg grading. Mr. Crawford provided figures on power requirements and cost of the value of labor saved.

Changing aspects of rural underground distribution. (J. E. O'Brien and J. N. Thompson, R.E.A., Washington, D.C.) The changing pattern of rural life is resulting in a demand for underground electric distribution. New materials and techniques have lowered costs and improved reliability so this may be possible. These developments have helped to bring down the cost ratio between overhead and underground construction from 10–1 to somewhere between 2–1 and 1.25–1. Further reductions are anticipated but we can expect considerable application at the present ratio.

Research on farm applications of electricity. (M. C. Ahrens, U.S.D.A., Washington, D.C.) The Farm Electrification Branch, Agricultural Engineering Division, Agricultural Research Service of U.S.D.A., at locations in 18 states, studies the development of electric controls and equipment for labor saving; development and application of electric equipment for modification and control of environment; application of electromagnetic radiation to plants, animals, their products and to insects; performance characteristics and requirements of farm electric equipment; development of technical instruments and measuring techniques for research in farm production; and electric energy distribution and demand studies on farms. Typical examples of research are the testing of the suitability of certain types of electric motors for specific requirements, research on blacklight traps for controlling insects attacking vegetables, the use of soil-heating cable to increase blue grass turf vigor during unfavorable weather, and environmental studies with poultry.

The code takes a look at farm wiring. (H. H. Watson, Burndy Corporation, Norwalk, Conn.) Mr. Watson discussed new developments in the proposed 1965 National Electric Code. Two apply to farm wiring. One is, *where diversity exists* the sizing of feeders supplying farm buildings (excluding dwellings) would be determined by various percentages of the total connected load (in steps) rather than by 100 percent of this load. A similar procedure is proposed for farm services. If adopted, these changes will allow more electric equipment to be installed for a given size of wire and size of switch where diversity exists, but the changes will not apply where experience indicates that there is no diversity.

New developments in lamp sources for rural indoor and outdoor lighting. (Leonard A. Komor, Sylvania Electric Products, Inc., Burlingame, Calif.) Mr. Komor demonstrated and explained many of the newer forms of lighting, including the 400- and 1000-watt metalarc lamps primarily used in parking areas and general roadway lighting. These include color rendition. Also shown was the 75-watt mercury lamp for general residential illumination such as post lanterns. He demonstrated the single-ended 250- and 500-watt quartz iodine lamps for sign, building, or flood lighting. These come with varicolored shields in a line of outdoor fixtures.

Improving services—through sponsored research. (Joseph Harbin, Bailey County Electric Cooperative Association, Muleshoe, Tex.) While the rest of the world spends 50 percent of its disposable income for food, Americans spend only 19 percent. Only about 8 percent of America's population produces this abundance, as compared to Russia's 43 percent.

In Muleshoe, Texas, good dry land sells for $100 to $150 per acre, but irrigated land sells for $750 to $1000 per acre. A depletion study was made on the High Plains of Texas involving water level data in a 4 000 000-acre area with 100 000 irrigation wells for the purpose of determining the pumping overdraft and the necessary long-range conservation measures so that the agriculture (and electric power supply) in this area could continue. Another research project near Lubbock, Texas, involved 6 000 000 acres of irrigated crop lands and about 200 000 pumps, nearly all delivering water from ground water supplies.

Service to electric motors in rural areas. (Lorne M. Holdaway, R.E.A., Washington, D.C.) Conventional methods for calculating voltage drops for existing and proposed rural electric circuits involving motors require so much time as to discourage their use. Machine calculating methods help but are not readily available to smaller utilities. The paper presents a fast simplified short-cut method having practical accuracy for motors up to at least 300 hp. Seven tables are provided in the paper which should be helpful in improving voltage conditions and increasing the capacity of distribution feeders. Motor starting currents, voltage drops, and flicker are discussed.

Air ion studies with swine. (Fred C. Jacob, Woodland High School, Woodland, Calif.) The influence of temperature, wind, and humidity on the growth rate, health and other physiological responses of swine was investigated under controlled conditions in a laboratory at the University of California, Davis. The pigs were raised from about 100 lb to market weight in a controlled-temperature laboratory at 70° and 90°F and also in a hog barn. Pigs were exposed to natural conditions, excess positive ions or excess negative ions for minimum periods of one week, with ion effects evaluated in terms of animal weight gains.

In three tests no effects of ion polarity were noticed. In four tests there were effects but all different. Excess positive ions were harmful in one test. Although no specific effects can be proved from these tests, some of the differences suggest the possibility that under certain conditions air ions can influence the growth rate of swine.

Authors

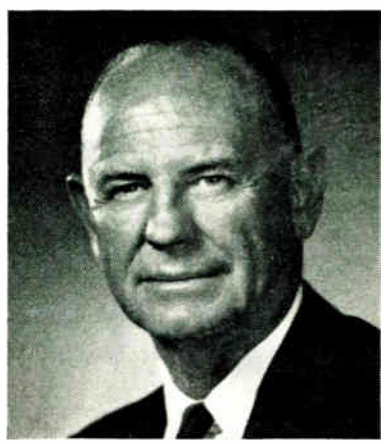
J. A. Morton (F) received the B.S. degree in electrical engineering from Wayne University in 1935 and the M.S. degree in engineering from the University of Michigan in 1936. He joined Bell Telephone Laboratories in 1936 and continued part-time graduate studies at Columbia University until 1941. He was named vice president of all electronic component development for Bell Laboratories in 1958. During World War II he concentrated on the development of radar receivers, which helped turn the tide in the Battle of the Pacific. After the war he invented and developed the microwave tube, which is the heart of the transcontinental radio relay system for telephone and television transmission. In the late 1940s he turned to research and development on the newly discovered scientific concept of the transistor.

Mr. Morton was awarded the honorary Doctor of Science degree by Ohio State University in 1954 and by Wayne University in 1956. In 1948 he received an honorable mention award from Eta Kappa Nu, and in 1951 a University Alumni Award from Wayne University for "distinguished service and accomplishment in science." He is the author of numerous technical articles and holds 14 patents. He also serves in an advisory capacity at Pennsylvania State University and in the graduate study program of Bell Telephone Laboratories.

H. G. Booker and C. G. Little. Biographical sketches of these authors appear on page 116 of the August issue.

Charles F. Luce attended Platteville (Wis.) Teachers College and received the B.A. and LL.B. degrees, both with honors, from the University of Wisconsin. He also did graduate work at Yale University Law School on a Sterling Fellowship. In 1942 he was an attorney for the Board of Economic Warfare, Washington, D.C., and from 1943 to 1944 was a law clerk for Mr. Justice Hugo L. Black, United States Supreme Court. In 1944 he joined the Bonneville Power Administration, U.S. Department of the Interior, Portland, Oreg., as an attorney. From 1946 to 1961 he engaged in general law practice in Walla Walla, Wash., and in February 1961 was appointed administrator of the Bonneville Power Administration, Portland.

Mr. Luce is a member of Phi Beta Kappa, Phi Delta Phi, the American Bar Association, American Judicature Society, and the State Bar Associations of Oregon, Washington, and Wisconsin.



T. A. Phillips (SM) was born in Globe, Ariz., in 1909 and attended the University of Arizona, from which he received the bachelor's degree in electrical engineering in 1936. Following graduation he joined the Central Arizona Light and Power Company as an electrical engineer. After four years of active duty during World War II in the United States Navy, in which he achieved the rank of lieutenant commander, he returned to public utility work with the Central Arizona Light and Power Company, now the Arizona Public Service Company, as superintendent of distribution. He subsequently became general superintendent, and then chief engineer, in charge of operation and engineering, before he was named vice president, with responsibilities for engineering, in 1954. He became vice president and manager, engineering, four years later.

Mr. Phillips is a member of the Pacific Coast Electric Association, Pacific Coast Gas Association, and Southwest Committee for Utilities Radio, vice chairman of the Arizona Atomic Energy Commission, and chairman of the Engineering and Planning Committee of Western Energy Supply and Transmission Associates.

H. L. Keenleyside is chairman of the British Columbia Hydro and Power Authority and adviser to the Government of British Columbia on resource development policies. His undergraduate work was done at the University of British Columbia, and he received the master's and doctor's degrees from Clark University in the general field of international relations and economic history. He spent 20 years in the Canadian diplomatic service, resigning his post of Canadian Ambassador to Mexico to become Deputy Minister of Mines and Resources, in Ottawa. In 1950 he was appointed director-general of the United Nations Technical Assistance Administration. He returned to Canada in 1959 to become chairman of the British Columbia Power Commission.

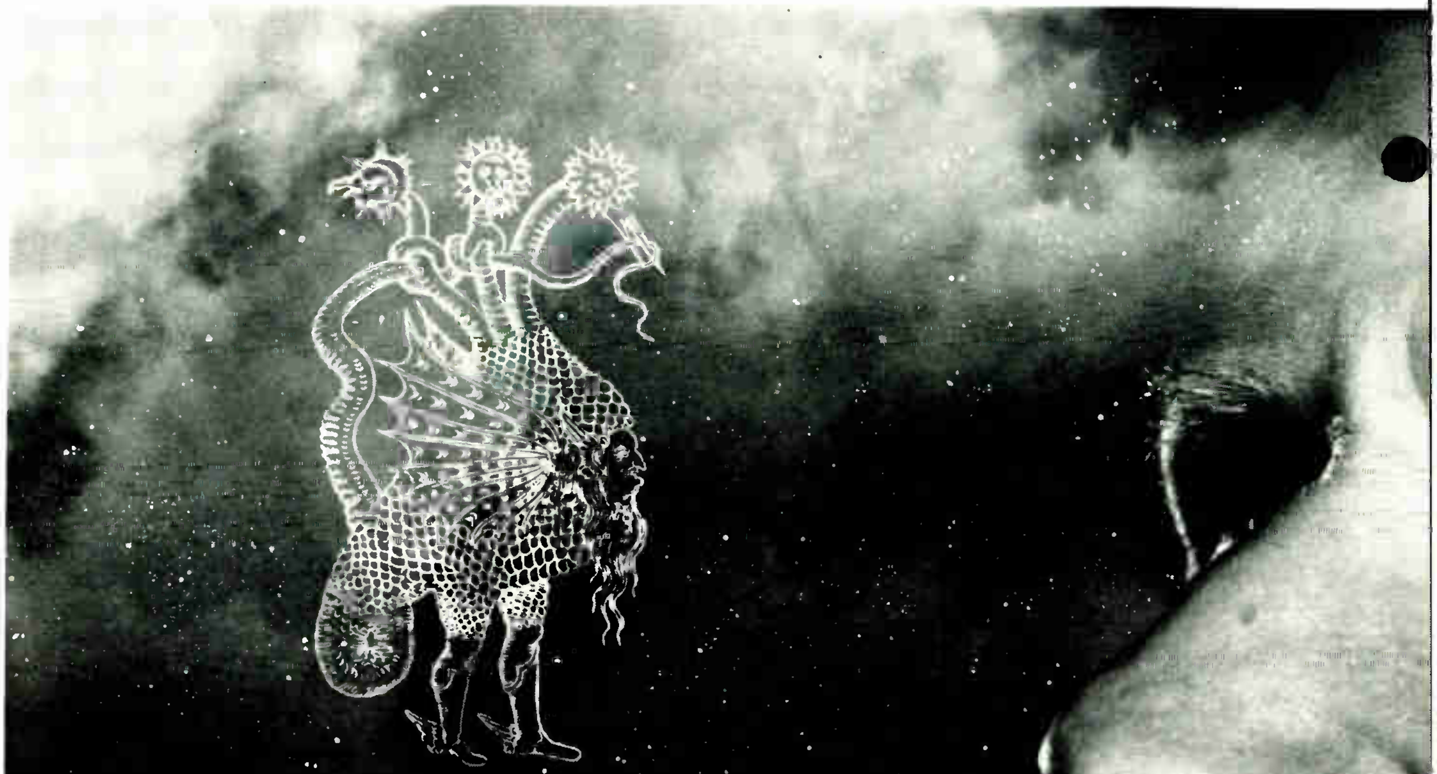
Dr. Keenleyside has served on many national and international committees in the general fields of scientific and economic development. He is a member of a number of learned societies and is the author of three books. He has received honorary degrees from several universities in Canada and the United States and was the first recipient of the Vanier Medal, awarded by the Institute of Public Administration of Canada. He also received the Haldane Medal of the Royal Institute of Public Administration of the United Kingdom.

Richard W. Porter (SM) received the B.S. degree in electrical engineering from the University of Kansas in 1934 and the Ph.D. degree in electrical engineering from Yale University in 1937. After working for two summers with the General Electric Company, he joined the staff on a permanent basis in 1937. He worked in the laboratory of Dr. E. F. W. Alexanderson in 1938, and in voltage-regulator engineering in 1939. He developed and designed the first military and commercial applications of amplidyne generators. From 1941 to 1944 he was in charge of aircraft equipment development. He was responsible for the GE fire control system used in the B 29 and other aircraft, as well as automatic tracking equipment for early fire control radar. From 1945 to 1953 he was a project engineer in guided missiles. He was manager of the Guided Missiles Department from 1953 to 1955 and a consultant in advanced technology for Engineering Services until 1963. Since then he has been on special assignment as a consultant to the Aerospace Science and Technology and Aerospace and Defense Groups. He has been chairman or member of many national and international advisory groups.

Dr. Porter is the recipient of an honorary Sc.D. degree from Yale University, the Alumni Award from the University of Kansas, and the Outstanding Young Electrical Engineer Award from Eta Kappa Nu.

J. D. Harnden, Jr. (SM) received the bachelor's degree in electrical engineering from Union College in 1950. Immediately after graduation he joined the General Electric Company as a member of the Engineering Test Program. After completion of this program in 1952 he joined the Advanced Technology Laboratories, General Electric's corporate advanced technology center in Schenectady, N.Y., as a development engineer. For over a decade he has been responsible for the application of new semiconductor components to electric power systems for amplification, modulation, interruption, control, and conversion. He has had extended experience in the design and application of switching circuits and has pioneered in the use of semiconductors to handle high currents and high voltages. From 1962 to 1963 he had technical responsibility for the company's efforts in support of the NEAR program, and acted in a consulting capacity for the company's NEAR contracts. He received a Management Award in 1963 for contributions in connection with this assignment. At present he is engaged in developing and proving feasibility of a wide variety of next-generation semiconductor devices, including monolithic and integrated structures.

Mr. Harnden has published more than 28 technical papers and has coauthored three books in the general field of solid-state electronics.



A microwave link by space creatures?

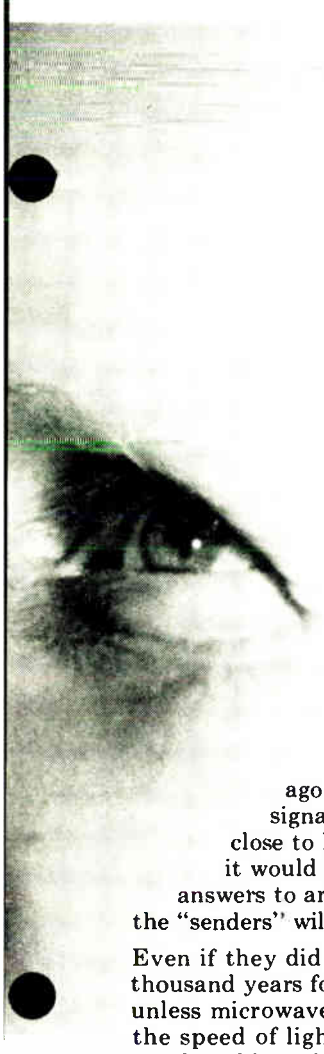
Henry Magnuski, Motorola's internationally recognized leader in microwave research, ponders the possibility that intelligent creatures in outer space, a thousand or so years ago, may have sent Earth some mysterious microwave signals. But he doesn't let that stop him from luring down-to-earth engineers and scientists to join Motorola's advanced microwave team.

Recently, a segment of the scientific community has been knee-deep in confusion, if not controversy, about CTA-21 and CTA-102, mysterious points in outer space which emit strong, short microwave signals.

As of publication time, no one knows exactly what is causing these signals... but a lot of people have strong opinions. Some say planets; some say they are gaseous disturbances like other "radio" stars; some say they were sent by space-creatures of a super intelligence!

Don't laugh. Some well-respected astronomers take the "super-intelligence" theory quite seriously (but don't take that medieval "monster" I'm pictured with seriously). The Russians even laid claim to detecting an "intelligent" 100-day pattern to the signals. In my opinion they laid an egg and most British and American astronomers agree.

So, the controversy rages. Although I accept only the "gaseous disturbance" theory, I'll never be able to prove it, unfortunately. Why not? It's simply a matter of time and distance. Best estimates put CTA-21 and CTA-102 about 1,000 light-years away, so the microwaves



our radio telescopes are picking up now were sent about 1,000 years ago. Thus, even if we could answer these signals today (and Earth engineers aren't close to having the power or technology yet), it would take another thousand years for our answers to arrive at the CTA's; and who is to say the "senders" will still be there?

Even if they did read us, it would take still another thousand years for any "intelligence" to answer us... unless microwaves can be made to travel faster than the speed of light. Who has the time to wait? And another thing—if these creatures are so blasted intelligent, why didn't they send us a more readily decipherable signal in the first place?

Maybe I'm skeptical simply because I don't like the idea of anyone being a thousand years ahead of Earth's technology... without my being able to slip him a Motorola application blank.

However, if you are a scientist or engineer with only your head in the clouds, and have a penchant for designing advanced microwave systems, we can offer you the rare opportunity to join some of the world's outstanding microwave systems engineers in work on projects like these:

ONE MAN BAND

A solid, down-to-earth microwave development is the Motorola MP-7... truly a portable one-man field terminal. It can be used for high-speed data, high-density voice, multi-channel remote control and telemetry, closed-circuit TV, radar relaying, troposcatter trunking, portable command post trunking, downhill radio transmission... *you name it, MP-7's got it!* This solid-state equipment also fits readily into existing shelters for radio-remoting of many outputs from other electronic equipment. Developed on company funds, currently in production, and operating in the field as a finalized system terminal, the MP-7 fulfills a present-day communications need... *on this planet, of course.*

KEEPING AN EYE ON EDWARDS

The Air Force Flight Test Center and NASA's Flight Research Center at Edwards AFB has to keep a close eye on a variety of test activities over hundreds of miles of their high-speed test range. Motorola designed, engineered, installed, and maintains the microwave and multiplex system (a "turnkey" job). It allows several control centers to continuously communicate with, receive, record, and display flight test data from test vehicles in *real time* as they proceed over any point of the flight range. Data may include four 500 kc telemetry composite signals, one timing and five intercom signals, one wideband search radar and 60 control and monitoring signals.

Complex data transfer system installed at Edwards AFB high speed test range.

Portable MP-7 microwave unit for tactical use.

BACK IN THE IVORY TOWER

Our special "ever-advancing-the-state-of-the-art" group (the quotes mean I know it's a cliché, but at least you know what I'm talking about) is feverishly applying the latest thinking in advanced microminiaturized circuitry... much of it their own... to the design of microwave components and systems. In their own words, they are placing "particular emphasis upon the integration of devices such as tunnel and back diodes, varactors, microwave transistors, and ferrite devices, into miniaturized assemblies offering improved performance". They are working in these four general categories of microminiature circuitry:

THIN FILMS—deposited layers of semiconductors, or metal, on a suitable substrate.

HYBRIDS—a combination of thin film, semiconductor, and microminiaturization techniques.

MONOLITHIC—totally integrated semiconductor circuits.

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News of the IEEE

calendar
people
obituaries

Summer Power Conference attended by 1200 registrants; 25 technical sessions held

The first Summer Power Conference, sponsored by the IEEE Power Group, was held at the Statler Hilton Hotel in Detroit from June 27 to July 1. More than 1200 registrants attended, including representatives from Canada and 15 foreign countries in Western Europe, the Orient, and Central and South America.

Participating were the Committees on Rotating Machinery, Transmission and Distribution, Switchgear, Power System Instrumentation and Measurements, Power Engineering Education, Insulated Conductors, Power System Communication, Safety, and Power Generation. About 100 technical papers were presented. Symposia on the topics of Underground Distribution in Medium Load-Density Areas, EHV Cable, and Issues in Power Engineering Education were conducted.

Field trips were conducted to Detroit Edison Company's transmission and distribution substations, the Cadillac motorcar assembly plant, the 80-inch hot strip mill of the Great Lakes Steel Corporation, and the Detroit Edison St. Clair Power Plant.

M. W. Balfour of Consumers Power Company, Jackson, Mich., was general chairman of the conference.

At the Recognition Luncheon on June 29, retiring Chairman C. A. Woodrow introduced R. W. Gillette, the new chairman of the IEEE Power Group, who assumed office as of July 1. Hendley Blackmon, a vice president of IEEE, reported on the membership and general status of the IEEE. Current IEEE membership stands at about 149 000, an increase of approximately 3500 during the last year. Mr. Blackmon anticipated that the membership would increase steadily at the rate of about 3½ percent per year over the next few years. He also mentioned that the new IEEE Membership Directory will be published in December. Recognition certificates were presented to the retiring Power Group members-at-large, Bradley Cozzens, C. T. Hatcher, Luke Kennedy, and C. T. Pearce, and to T. E. Marburger, the power Group secretary, who is also concluding his term of office. The keynote speaker at the luncheon was Seymour Marshak, manager of marketing research for the Ford Division of the Ford Motor Company, who discussed "Knowing Your Market—The Key to Innovation in Automotive Engineering and Design." Dr. Marshak spoke on the planning, development, and marketing of the new Ford "Mustang."

At the Council meeting on June 29, Chairman Woodrow gave his report on the Power Group's first year of activities. Although the membership drive has fallen short of expectations (8000 instead of 10 000), the Group membership is increasing at the rate of about 150 per month. At present, there are 55 Chapters throughout the United States and Canada.

The officers and members-at-large of the 1965–1966 Power Group Administrative Committee were introduced. They are: R. W. Gillette, chairman; E. J. Linde, vice chairman; D. T. Michael, secretary; J. T. Lusignan, Jr., treasurer; H. M. Hess, Organizations Department; W. F. Fee, Meetings Department; E. L. Kanouse, Technical Operations Department; J. D. Robinson, Publications Department; and E. W. Greenfield, G. E. Heberlein, J. H. Kinghorn, and F. L. Lawton, members-at-large. C. A. Woodrow becomes the junior past chairman.

An unscheduled but noteworthy event was the participation of three Power Group members in the Radio Station WWJ Newsline Program. C. A. Woodrow discussed the aims and purposes of the IEEE Power Group, the reason for the Summer Power Conference, and future plans of the Group. R. D. Nevison, of the Hydro-Electric Power Commission of Ontario, gave a brief description of the theory and function of pumped-storage generation for peaking power. L. J. Weed, of the Boston Edison Company, chairman of the Committee on Underground Distribution in connection with the President's White House Conference on Beautification, discussed the necessity for esthetic considerations in connection with new and existing power transmission and distribution systems.

Highlighting the social activities was a five-hour cruise on the Detroit River and Lake St. Clair.

IEEE Power Group officers include: (left to right) R. W. Gillette, the new chairman; A. P. Fugill and B. Cozzens, members-at-large; T. E. Marburger, secretary; and C. A. Woodrow, the first chairman of the Group.