VOLUME 7 □ NUMBER 5 IEEE spectrum MAY 1970

IEEE spectrum

features

THE INSTITUTE OF ELECTRICAL AND ELECTRONICS ENGINEERS, INC.

Here's One Place Where Your Dollar Is Worth A Dollar

Two new HP oscillators are teaching the old standard new tricks in performance and value. Both the new HP 204C/D and HP 209A Oscillators have exceptional spectral purity (< 0.1% − 60dB). Both have FET's in the bridge for improved stability—balanced output—sync in/out. All this adds up to greatly improved performance. And, you get this extra value at only a modest increase in price over the old standard.

Both oscillators offer improvements that assure you of a consistent signal—test after test—time after time... whether you are testing on a production line, researching in a design lab, or instructing future engineers.

Portable, line or battery powered. The 204C is a clean, inexpensive oscillator with a frequency range of 5 Hz to 1.2 MHz. Output is 2.5 Vrms into 600 Ω, 5 Vrms into open circuit. Choose interchangeable power packs—line, rechargeable or mercury battery. Price HP 204C, $250 to $285.

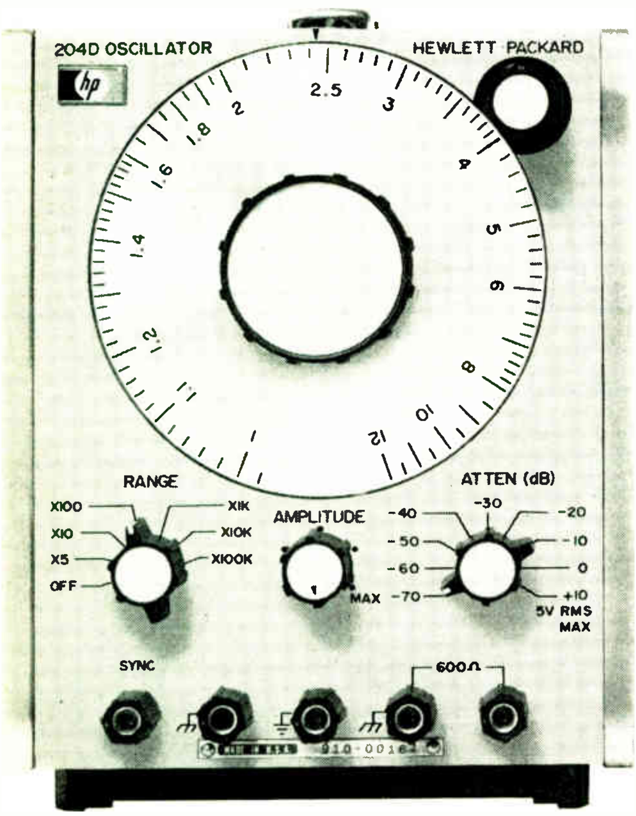
The 204D has the added convenience of a built-in 80 db attenuator. Eliminates using an outside attenuator when you need clean low-level signals. Price: HP 204D, $325.

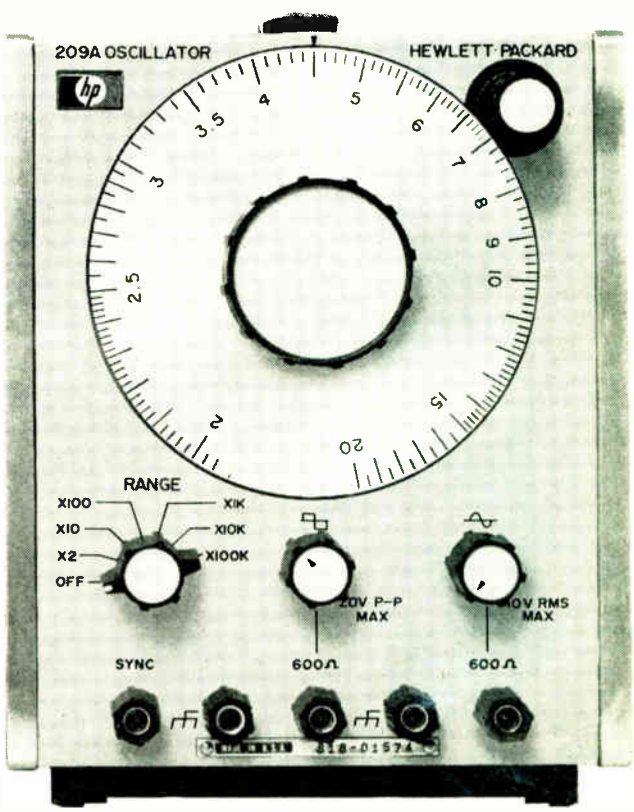
High power output, sine or square wave. The 209A generates simultaneous sine and square wave outputs over a frequency range of 4 Hz to 2 MHz. Amplitudes are independently adjustable. Voltage output for a sine wave is double that of the 204—5 Vrms into 600 Ω, 10 Vrms into open circuit. Square wave output is 20 V peak-to-peak. Price HP 209A, $345.

Get full value for your signal-source dollar. Consult your HP Instrumentation Catalog for full specifications and order your oscillator by calling your nearest HP telephone order desk. For additional data, write Hewlett-Packard, Palo Alto, California 94304. Europe: 1217 Meyrin-Geneva, Switzerland.

HEWLETT hp PACKARD

SIGNAL SOURCES





Circle No. 7 on Reader Service Card.

the cover

Large-scale integration has made tremendous strides in recent years because of its many inherent advantages. However, the dielectric development program described in the article beginning on page 50 was not without its share of problems. One problem encountered was oxide eruption caused by stresses within the film, as shown greatly magnified on this month's cover

departments

THE INSTITUTE OF ELECTRICAL AND ELECTRONICS ENGINEERS, INC.

IEEE SPECTRUM is published monthly by The Institute of Electrical and Electronics Engineers, Inc. Headquarters address: 345 East 47 Street, New York, N.Y. 10017. Cable address: ITRIPLEE. Telephone: 212—752-6800. Published at 20th and Northampton Sts., Easton, Pa. 18042. Change of address can be made effective with any particular issue if received by IEEE Headquarters by the 10th of the preceding month. Annual subscription: IEEE members, first subscription $3.00 included in dues. Single copies $1.50. Nonmember subscriptions and additional member subscriptions available in either microfiche or printed form. Prices obtainable on request. Editorial correspondence should be addressed to IEEE SPECTRUM at IEEE Headquarters. Advertising correspondence should be addressed to IEEE Advertising Department, at IEEE Headquarters. Telephone: 212—752-6800.

OTHER IEEE PUBLICATIONS: IEEE also publishes the PROCEEDINGS OF THE IEEE, the IEEE STUDENT JOURNAL, and more than 30 Transactions for IEEE Groups with specialized interests within the electrical and electronics field. Manuscripts for any IEEE publication should be sent to the editor of that publication whose name and address are shown on page 17 of the January 1970 issue. When in doubt, send the manuscript to E. K. Gannett, Editorial Services, at IEEE Headquarters, for forwarding to the correct party.

Forum

Readers are invited to comment in this department on material previously published in IEEE SPECTRUM; on the policies and operations of the IEEE; and on technical, economic, or social matters of interest to the electrical and electronics engineering profession.

Engineering registration

The several letters appearing in "Forum" during the past few months on the subject of engineering registration have made quite interesting reading. It has been enlightening to see the reasons given by some of the EEs, especially those in the electronics field, as to why they have never identified themselves as engineers through legal registration procedures.

The problems with registration—many of them mentioned in these columns—are known to many leaders in the engineering profession. The officers of the National Council of Engineering Examiners, recognizing many of these problems, appointed a 16-man committee in 1968 to work on the future of the identity (or recognition) of the engineer, and on engineering registration in particular. This group, balanced in geographic representation, in fields of practice, and in technical disciplines, has held a series of meetings to consider these problems and to propose some solutions. It is significant that only three members of the committee are members of state licensing boards, and that not all members of the committee are registered. A report of the committee findings and recommendations will be presented to the NCEE Annual Meeting in August in Chicago. Meanwhile, the committee is providing all interested engineering groups with its recommendations in the hope that this will stimulate thinking and action.

It seems to me that IEEE, as the largest engineering society, should take an active interest in this subject. If EIT exams, for example, are in fact inappropriate for the electrical engineers to take, then IEEE is the organization that should make its influence felt. By the silence of the officialdom of IEEE on the subject, it is assumed that the Institute does not really care—however, expressions of many members indicate that this is not really the case.

It is up to IEEE to begin to take an active interest in the subject to correct whatever may be wrong with registration and then to support the engineering profession in advancing sound registration procedures.

Rex A. Tynes, Chairman
NCEE Committee for the Future Recognition of Professional Engineers
Las Vegas, Nev.

The layoff problem

The current exodus of aerospace engineers and scientists from the industry as a result of layoffs is alarming. The unnecessary dissipation of this pool of creative brainpower is an irresponsible waste of a national and urgently needed resource.

Clearly, the emphasis of the military–industrial complex is experiencing a rapid and dramatic change. The emphasis is swinging away from a high level of production activity. If we can judge from experience, the interest and needs of the military will trend toward an increase in research and development. This is a slow and tedious process. Aside from questions of current fiscal policy, there are many justifiable reasons for this transition; for example, the cold wars of the coming generation will probably be concerned more with technological advantage and less with existing military arsenals.

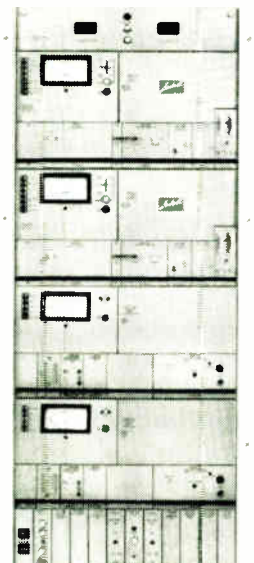
In the past, when the need for large pools of scientific talent decreased in one area, there always appeared another to take up the slack. Thus in the 1950s the aerospace engineers went from aircraft design to missile design. In the early 1960s they again changed, from missile into space vehicle design. The big change recently has been back to airframes and V/STOL aircraft design.

The layoffs due to the current cutbacks have nowhere to go. There is no up-and-coming sector on the horizons of the aerospace industry that can absorb the large number of engineers and scientists suddenly finding themselves without jobs. As a result, these people will find other activities and professions by means of which to support themselves and their families. The tragedy, of course, is that the many years of scientific education and experience that they represent will disappear with them. To compound this unfortunate set of circumstances, the next-generation student will avoid the physical science and engineering professions like the plague. This situation is already evident in the low level of enrollment on the engineering campuses throughout the country.

This does not imply a lack of challenging problems for our scientific community. On the contrary, the economic, environmental, and social problems arising from a rapidly changing, overpopulated world are staggering. In most cases, these problems are so severe that they will tax both the ingenuity and technological know-how of our most talented scientists and engineers. The need is greater than ever for the pool of creative talent now being abandoned by the aerospace industry. It does not make sense to sit idly by and allow its attrition.

When an agricultural or industrial resource is threatened by disaster, the government steps in with various emergency measures. This usually takes the form of agricultural subsidies, depletion allowances, tax-free loans, special tax credits, and the like. The potential attrition of part of our technological resource described in the foregoing has all the earmarks of a national emergency. Why, then, cannot our government treat it as such? A temporary government agency should be established to address the problem. The purpose and function of such an agency should be to facilitate the retraining of the aerospace talent pool, presently being laid off, to cope with the current problems of our society. It should provide the means in the form of short, intensive retraining programs at various academic institutions. It should provide interest-free loans, so that these people can maintain themselves and their families during this transition period.

The program suggested herein represents a small investment in time and effort. The major dividend from this investment is apparent. It will preserve a much-needed technical pool of creative brainpower to cope with the urgent and crucial problems



sponsorship of classified meetings or sessions, let it follow that policy honestly without deceit or subterfuge. The prime test of sponsorship is the expenditure of IEEE funds and the use of IEEE facilities such as mailing lists. Almost half the sessions described in the announcement sent at IEEE expense, and prepared at IEEE expense, were classified. Seven of the 17 pages in the advance program described classified sessions, and a clearance form was included in the mailing. Such a mailing represents clear, substantial support of a classified symposium by the IEEE.

Richard G. Gould
Washington, D. C.

Classified research

In R. M. Anderson's letter "Professors and Research" (*Spectrum*, February 1970), he presents his case as though the problem were simply, "Will professors undertake classified research or not?" Then he concedes that allowing a little may be a compromise solution.

I don't see the issue as quite that simple. Though one could take issue with our present national priorities (or objectives), I don't believe anyone would disagree that "national defense" presently has a higher priority than education, money spent being the measure of priorities in this case. The issue is more accurately stated, "Who will do the needed classified research?" If professors do not, then more private firms or more government engineers will, and they will be much less likely to walk the thin line of sharing the unclassified aspects of their research with the academic and professional community.

The loss to the academic community will be that of those professors who are enjoying their classified research more than teaching (a loss universities can ill afford), support for much advanced research presently being done by professors, and that fringe-area information.

The loss to the defense establishment will be some talent very hard to replace, but perhaps more important, considerable communication with that segment of America's point of view. In light of recent events, less communication between defense and academic interests could hardly be desirable.

In the final analysis, the decision will rest with the professors themselves. I can't foresee the defense establishment pleading with professors to assume classified research, nor can I foresee prolonged student interest in such a complex issue.

To a degree, I envy professors engaged in classified research. What could be more rewarding or enjoyable than a combination of an academic atmosphere and a relevant, nationally significant, adequately funded research task? It's too bad such a situation doesn't offer a liberal, 20-year retirement plan.

Ray E. Huebner, Major, U.S.M.C.
Fort Meade, Md.

A boost for bionics

For many years I have been fascinated by articles and papers describing the communication systems possessed by certain animals and insects. The piece on moths in the March issue is another in the series of amazing revelations.

Back around 1960, the *National Geographic* carried a beautifully illustrated article on bats by Dr. McCue of the Lincoln Laboratory at M.I.T. From this we learned that a bat emits beeps varying from about 100 Hz at 1/20-second intervals while cruising, down to 20 Hz at 200 per second as he homes-in on his target. For eons bats have been using echo location with FM, no less!

Then, in *American Scientist*, June 1961, a paper was presented by Roeder (of Tufts) and Treat (of C.C.N.Y.) on the subject of "The Detection and Evasion of Bats by Moths." By means of special hearing devices under each wing joint, the moths had themselves a DEW system. Studies were made of evasive tactics, the most popular being a power dive into the grass!

And now, the remarkable story by Hsiao and Süsskind (*Spectrum*, March 1970), which suggests the use of infrared and electromagnetic radiations by moths.

We are rightly proud of our microminiaturization programs and our ICs, but Mother Nature hasn't done such a bad job for a few million years! She seems to have known how to build transducers, servo systems, gating circuits, power supplies, etc., in tiny packages and literally by the millions!

We've got a way to go!

E. E. Pearson
Philadelphia, Pa.

of our current society. In addition, it will give this large group of dedicated scientists and engineers a feeling of being needed during a critical time of transition for them, for the aerospace industry, and for our nation.

S. M. Brainin, Ph.D.
Sherman Oaks, Calif.

Portable pensions

I agree with Dennis Beech on his "Portable Pensions." The electrical engineers of the United States have long needed some standard pension that they can count on when they move. Let's face it, we are portable. We take everything else with us except the pension we have earned.

The IEEE appears to be the best organization to handle our pension.

J. Lawrence Pfalzer, P.E.
Bothell, Wash.

Ground-fault interrupters

We note that the article by Dalziel on ground-fault interrupters (*Spectrum*, January 1970) makes no mention of an electronic high-sensitivity ground-fault interrupter manufactured for the past two years by Saparel, a joint subsidiary of Thomson-Houston and Compagnie Générale d'Electricité. As compared with the American device described by Dalziel, it has the advantage of not failing in the absence of the supply on one wire for monophase, or even two wires for three-phase supply. Over 50 000 of these devices are installed in Europe.

F. Mayer, President
Laboratoire D'Electronique
et D'Automatique Dauphinois
Grenoble, France

WINCON

I have just received the meeting notice for WINCON 70, and am surprised by the classified section included.

From the meeting notice, it is clear that the classified section covers a wide range of topics, and is aimed at developing technologies for the 70s. At the same time, the "classified sessions access request" form has a "need to know" clause. First, it is a rare person who has a "need to know" about all of the topics to be discussed, yet there is no place to say what the applicant "needs to know." Second, the "need to know" section is to be signed by a government representative certifying that the person "needs to know" because he already works on similar government contracts. This excludes people and companies who may wish to enter these fields during the decade in competition with current contractors. It is not in the national interest to handicap new talent in the lucrative military supply business.

Kirk Beach
University of California
Berkeley, Calif.

An IEEE mailing announced "WINCON 70," a meeting sponsored by the Group on Aerospace and Electronic Systems and the IEEE Los Angeles Council. It also contained "information on a separate classified symposium to be held concurrently" and finished with the following note:

> "Items indicate technical sessions of a separate concurrent classified symposium on 'Aerospace Electronic Systems' cosponsored by Air Force Systems Command and Lockheed Aircraft Corp. They are included herein as a service to IEEE members in planning their time allocation. The IEEE does not sponsor classified meetings or sessions and the inclusion of this information in no way indicates IEEE sponsorship. The comingling of events in the schedules in no way indicates IEEE sponsored activities."

Now, I for one just don't believe that disclaimer. It's a phony. Imagine that an engineer sent, at his expense, a mailing to his friends and associates the following notice:

> "On February 10, 11, and 12, I will be at the Biltmore Hotel in Los Angeles to swim, dance the cha cha cha, and eat prime rib, rare. During the same period, my secretary will be at the same hotel to sit by the side of the pool, dance the hully gully, and eat prime rib, medium well done. The comingling of events in no way indicates my sponsorship of her activities, nor should anyone assume that we are going there together: clearly, the activities we are each engaging in are different."

Would anybody believe that disclaimer? Would your wife?

If the IEEE has a policy against

Focal points

Our decaying environment: top-priority issue for the '70s

A special staff report

Eight years ago, Rachel Carson, the noted marine biologist, introduced her best-selling book, *Silent Spring*. It dealt primarily with the hazards of the indiscriminate uses of herbicides, pesticides, and insecticides, and the author gave explicit warning of the ecological disaster that could ensue from such practices. Actually, the work was a rather mild indictment of the chemical industry and our patterns and customs in agriculture. Nevertheless, the book quickly became a cause celebre as shock waves of reaction and consternation rippled through a segment of industry. Spokesmen for the chemical interests derided her premises, scoffed at her conclusions, and made every effort to challenge Miss Carson's credentials as an expert in environmental matters. Although she found champions in the U.S. Congress and among fellow scientists who defended her contentions, public alarm soon changed to public apathy and her predictions were quickly forgotten.

If public concern at that time, coupled with the initiation of positive pollution controls and safeguards in every area of possible environmental damage, had prevailed, we would have had an eight-year lead toward avoiding the total mess in which we find ourselves today.

Now, one does not have to be either an environmental expert or an ecologist to sense that our much-vaunted technologically based civilization is in big trouble: the brown pall of "airborne garbage" that hangs like a perpetual curtain over our large cities; the litter, trash, and canine excrement strewn across every urban street; the smouldering refuse dumps; automobile graveyards; and the stench from streams and rivers, polluted by raw sewage, oil spills, and industrial wastes, all contain the grim evidence of the accelerating erosion of our planet and the degradation of living conditions. As one crusading newspaper columnist put it: "New York City has at last achieved the hygienic quality and appearance of 17th century London—just before the cholera struck and the plague decimated the population."

During the past several months, there has been a rude reawakening of the public consciousness, and the total impact of our rapidly deteriorating environment and concomitant ecological imbalances has produced a near hysteria; there is no shortage of copy in the mass media's present coverage of the subject.

The staggering array of component problems—from the 50 billion nondegradable (and nonreturnable) aluminum beer and soft-drink cans that are tossed out annually and the five million junk cars per year that are a portion of the solid trash clutter of the U.S., to air, water, and chemical pollutants—are steadily being compounded as the human population increases exponentially.

A major conference is convened

Perhaps reacting to the public clamor and the strident demands for immediate pollution abatement, the U.S. National Committee for the International Biological Program (IBP) and the Public Affairs Council cosponsored a three-day conference in Washington last February under the impressive title of "Environment: The Quest for Quality." The aims of the intensive seminar sessions, which attracted more than 400 conferees, were succinctly stated in the two paragraphs of the program's introduction:

"Man's rapidly growing ability to alter the face of the earth through technology can often produce far-reaching and destructive changes in the web of life that stretches so thinly . . . over our planet. In pursuing the quest for environmental quality, we must learn to predict the effects of technological change and help conserve and utilize the abundance of the living world.

"Hopefully, this conference will initiate a continuing dialogue between representatives of science, industry, and government that will produce a concerned partnership to preserve and protect the environment. Our goal must not be to conquer the natural world, but to live in harmony with it."

The 'triumvirate': science, government, industry. The strategy of the Washington conference was to stress and emphasize the essential cooperation of science, government, and industry as the key ingredient in defining the problems, and planning and implementing the solutions to the incredibly complex job of pollution abatement and control.

Noted names, reasoned rhetoric. The roster of principal speakers read like a *Who's Who* in science, politics, industry—and entertainment. Among the participants were the Hon. Robert H. Finch, Secretary of HEW; Stewart Udall, former Secretary of the Interior; the Hon. Russell E. Train, chairman of the Council on Environmental Quality; Dr. Lee A. DuBridge, science advisor to the President; Dr. Merril Eisenbud, head of the Environmental Protection Administration of New York City; Louis H. Roddis, president of the Consolidated Edison Co. of New York; and Arthur Godfrey.

In his keynote address, Secretary Finch stressed population control as one of the most controversial—but necessary—steps that must be applied without delay. In his view, we are all polluters, and the better we live, the more we degrade our environment. He urged a comprehensive approach to the problem of air quality, and emphasized that simultaneous solutions must be found to curb air pollution from automobile exhausts, incinerators, and industrial smoke; we cannot tackle the problem piecemeal and hope for overall success.

Three very significant passages

from Mr. Finch's text were—

"Unless industry begins to calculate the social costs of pollution, the by-products of its techniques of production, and reflects them in the market mechanism, there will be no . . . effective incentive system for reducing environmental degradation in the first place.

"Unless government becomes more self-conscious about the environmental impacts of its tax, land use, subsidy, and R&D programs, it will continue to play 'catch up'—with a higher and higher price tag.

"Unless the American people are really prepared to pay pollution 'taxes' and meet the costs of environmental restoration—costs that may range from less powerful autos to less frequently occupied bassinets—no political authority can control the excesses of affluence or rampant technology."

Finally, Mr. Finch observed that we must begin *now* to translate our concern into permanent machinery. "Ecologically speaking," Finch emphasized, "1980 is the day after tomorrow . . . the year 2000 is next week."

A train of thought. Russell Train classified the three general types of pollution, cited by President Nixon, as *municipal*, *industrial*, and *agricultural*. He cited the necessity of the recycling and reuse of solid wastes (garbage, newsprint, paper, disposable cans and bottles, etc.), and the conversion of waste industrial materials into useful by-products. All of these desirable ends must be achieved through the development of new technologies that will make such processes economically feasible.

To the rhetorical question, why not establish a NASA-like policy program and an analogous agency to focus on the objective of eliminating pollutants, Train replied that the general problem of attaining environmental quality is far more complex than putting men on the moon. Among several recommendations, he urged the development of nonpolluting "unconventional vehicles" (electric cars?) and the adoption of uniform codes of pollution controls—and penalties for abuse—by government agencies.

Scientists and educators speak out. Government spokesmen, however, did not dominate the forums. In line with the stated three-pronged approach to the conference, scientists and educators had their turn at bat. Dr. Frederick Sargent, II, dean of the College of Environmental Sciences, The University of Wisconsin, spoke on the scholarly theme of "An Environmental Ethic," in which mankind must view itself as totally dependent upon the natural environmental processes and conditions of the biosphere. Among the principles of this ethic "people must perceive the environment as a commons; it belongs as much to men as any other living organism, and it belongs as much to one man as to another." Sargent is convinced that the decade of the '70s is the "time limit for remedies, beyond which irreversible processes will ensue."

But Amitai Etzioni, chairman of Columbia University's Department of Sociology, voiced the question that may have been on the collective mind of a silent majority of his audience: Is this sudden concern for the environment just this year's fad—good for one solid go-around of lofty rhetoric—or do we really mean business this time? He chided his listeners with the observation that since "relatively simple problems (running commuter trains on time, providing adequate housing, etc.) apparently cannot be solved, how can we solve anything as complex as the environmental pollution problem?" But if we are serious in this effort, he advised us to "stop the rhetoric and start declaring our intentions."

In a semiserious slap at politicians, Etzioni remarked that "if any authority is less capable of carrying out major policies than the federal government, then it is the 50 states!" He considered revenue sharing between the federal and state governments for pollution-control purposes to be impracticable: the pyramidal layers of multiple-agency bureaucracies, red tape—and corruption—would effectively cancel out all theoretical benefits. And he warned that the taxpayer is in no mood to pick up the entire tab for costly control and abatement projects in order to help industry sustain its cherished products and profit margins.

Etzioni deprecated our habitual preoccupation with special study commissions as a prerequisite for legislation because "there is a wide divergence between research findings and policy-making conclusions in reports." In conclusion, he urged that NASA at least be used as a system-model approach for science–government–industry interaction.

The views of industry: a new note between some old lines. Among the conferees were top executives of the pulp and paper industry, investor-owned utilities, aluminum refineries, the oil producers, electric equipment suppliers, and the automobile industry. For the most part, the views expressed by this segment of the triad reflected an enlightened recognition of the tremendous scope of the common problem, and an acceptance of a share of the responsibility for pollution. A number of examples were cited of positive remedial action being applied to point sources of industrial pollution.

William H. Chisholm, president of the Oxford Paper Co., had statistics to prove that his industry was making some headway in the treatment of the effluent from paper mills before its discharge into streams, and he claimed that similar progress is being made in eliminating the airborne stench emanating from sulfite-process kraft-paper plants. Chisholm also asserted that the industry is replacing more timber, through reforestration programs, than it is cutting. And he claimed that "almost 30 percent of the virgin fibers used in the U.S. are recovered from waste paper to be re-used as paperboard, newsprint cardboard, and white printing papers." But he observed that collecting waste paper by present methods is expensive and can be done effectively only in large cities. Further, the treatment of secondary fibers, depending upon end use, can be very costly; and waste newsprint must undergo de-inking treatment, which can create an additional pollution factor. Chisholm expressed the hope that advanced research and technology would provide more economic solutions for these recycling processes.

Richard N. Bolling, general manager of the Metal Recycling Division, Reynolds Metals Co., drew an interesting analogy in comparing the earth to an interplanetary spaceship when he said:

"The earth is a larger version of a space vehicle, with a much larger population and sink of natural resources —but still a sink that is as limited as the resources aboard a spaceship. Thus almost all of our natural resources must be recycled and reused by processes analogous to those employed in the Apollo vehicles."

Bolling rated solid-waste disposal techniques—despite our present highly sophisticated technology—as still being in "a very primitive state of the art." Prior to the passage of the Solid Waste Disposal Act of 1965, the federal government's budget for the handling of this refuse was about $250 000 annually; today, the annual tab for improving disposal methods—most of which still are less than satisfactory—is of the order of $20 million. The enormous dimensions of this problem can be appreciated when one realizes that New York City alone generates about 20 000 tonnes of solid waste per day!

Bolling conceded that the present custom of discarding up to 50 billion nonreusable aluminum beer and soft-drink cans annually in the U.S. is no longer tolerable. In line with this revised viewpoint, the Reynolds Metals Co. has initiated an incentive plan whereby thousands of people in Los Angeles and Miami, for the past year, have been salvaging the aluminum cans from roadsides, beaches, parks, and neighborhood trash collections. The company pays a bounty at the rate of 10¢ per pound. The cans are shredded and returned to one of the Reynolds reclamation plants where the scrap aluminum is reprocessed.

A disturbing element apparent in one of the statements by an industry spokesman was the revival of the time-worn theme: Yes, we are concerned about pollution and the degradation of the environment, but you must understand that you, the consumer, will have to bear the cost burden of improving the quality of the environment; our primary responsibilities are to our stockholders and to maintain our profit margins.

The concurrent panel sessions

In exploring the question of "What Ought to Be Done to Solve the Environmental Crisis," three simultaneous panel sessions were held for the discussion of the respective roles of industry, government, and science. The writer attended the industrial forum, which featured Dr. Merril Eisenbud; Dr. Roger Revelle, director of the Center for Population Studies, Harvard University; and Dr. Fred Bowditch, director of the General Motors Emission-Control Engineering Staff.

Dr. Revelle urged industry to undertake R&D in new "life-support technologies" to counteract the ravaging effects of all types of industrial pollution. He agreed with Professor Etzioni that uniform federal standards of pollution control, coupled with severe penalties for violations, must be established. He cited the impracticality of situations in which one state has strict antipollution laws and an adjacent state, in order to attract industry, will have very lenient control ordnances.

Revelle is a strong advocate of population decentralization and better distribution, primarily into a minimum of 50 scientifically planned "new cities,"* with ultimate populations of 500 000 each.

He considered the recent increase in oil spill incidents, resulting from "supertanker" mishaps, as a very serious new element in the water pollution picture, and he suggested the establishment of a worldwide monitoring system for these vessels to ensure a reduction of accidents and the rapid handling of emergency situations if oil is discharged either in open sea or in coastal waters.

Dr. Eisenbud chided industry for its poor communications with city sanitation and pollution-control departments regarding potential difficulties in disposing of new packaging or container products. He cited, in particular, the problems associated with the incineration of the polyvinyl chloride wrapping films that are in widespread commercial and household use. When these materials are subjected to incinerator temperatures, they release hydrochloric acid (HCl), which will eat away the grates in a large city plant in about six months' time. Also, a popular brand of leftover food wrap will release cyanogen gas under high temperatures.

Eisenbud mentioned the disposal headaches in handling newspapers—especially the fat Sunday editions. For example, it costs New York City about 15 cents to get rid of each copy of *The New York Times*' Sunday edition (which, on occasion, can weigh 3.4 kg). Thus he urged industry, as a constructive step in pollution abatement, to cooperate with city agencies in advising them of troublesome situations that can arise with the introduction of new disposable products.

Finally, he accused the vehicular traffic in major cities of contributing such a high percentage of the total air pollution that private vehicles must soon be banned from downtown districts. And along parallel lines, he urged the automobile industry to build smaller cars, speed the development of compact internal combustion engines with greatly diminished noxious exhaust emissions, and explore alternative car propulsion systems.

Let's clean it up, by Godfrey

Arthur Godfrey, the radio and television celebrity, was the featured speaker at the conference banquet. Mr. Godfrey's credentials as an environmental and ecological authority seem to include the facts that he was very impressed by one or two books he read on the subject, and his belated discovery that an enzyme presoak he has been plugging on television commercials is creating ecological problems in sewage systems after it goes down the washtub drain. Nevertheless, Mr. Godfrey gave his views on the urgent need for population control as a top-priority goal in the remainder of this century. In addition, he is an electric car buff and has received the latest models from the manufacturers in the field for his use and evaluation.

Perhaps one should not be critical of Godfrey; because of his celebrity status, the average citizen may heed Arthur's advice on the solution of environmental problems that lie within individual control to a greater extent than similar admonitions from a lesser known, but more expert, authority in the subject area.

Concluding words from Udall

Former Interior Secretary Stewart Udall held a press conference following the final luncheon on February 20. Udall felt that the overall situation is so critical that a Department of the Environment should be created within the federal government and headed by a cabinet-level secretary. At the present time (and this was obvious to the writer after listening to presentations by various government spokesmen), agencies of too many departments of the government—Interior, HEW, Agriculture, etc.—have a "piece of the action." Interagency liaison and communications leave much to be desired. A consolidation of activities "under one roof" may prove effective. Udall was inclined favorably toward a suggestion that our offshore oil re-

* IEEE Spectrum is not a Johnny-come-lately on the environmental and pollution scene; articles appeared on these subjects—as well as the new cities concept—long before most of the news media climbed aboard the environmental and ecological bandwagon. See the articles "Science and the Salty Sea" (pp. 53–64, Aug. 1965); "Airborne Asphyxia—An International Problem" (pp. 56–69, Oct. 1965); and "Birth of the 'New City'—An Exciting Creation" (pp. 70–82, Apr. 1967).

serves be held in escrow until more sophisticated techniques are evolved to prevent oil blowouts such as those in the Santa Barbara channel and in the Gulf of Mexico. And he felt that our funding, from all sources, may have to be of the order of $50 billion or more annually to reverse the processes of environmental deterioration.

Summary of commissions, omissions, and impressions

One leaves such a conference overwhelmed by the staggering complexity of the total problem, and more than somewhat pessimistic about our chances of coping successfully with it before irreversible processes of environmental degradation set in. And it is rather discouraging to discover—after congratulating one's self for comprehending what one thinks is the total scope of the environmental pollution picture—that yet another dimension, in the form of another unthought-of pollution factor (such as the incineration of the polyvinyl chlorides), is added to one's sense of mental malaise.

Certainly, we have enough commissions actively searching for practical answers and solutions. But we are still uneasy. We are told that Nero fiddled while Rome burned. Are our present political leaders fiddling around while the world goes up in smoke—smoke pollution, that is? Much lip service has been paid to the problem, but, at some point, science, government, and industry must put the money where its collective mouth is. Thus far, that is not happening. And as long as our order of commitments is in disarray, one can foresee little in the future as reason for optimism.

Sacrifices will be required by everyone to pay the huge toll of environmental neglect: taxes will increase, profit margins will be squeezed, and the stockholder will have to share the economic pinch on the consumer.

Wake up, everybody; it's *much* later than we think.

Gordon D. Friedlander

Meteorological satellites mark a decade in space

The first terrestrial infrared observation system satellite, Tiros, was launched on April 1, 1960. Since then, a total of ten Tiros, nine ESSA, and one ITOS satellites have been successfully orbited to provide nearly continuous space observations of this planet's weather phenomenons.

Originally an experimental system, in February 1966, the Tiros Operational System (TOS), was implemented with the successful orbiting of the ESSA 1 and 2, providing the world's first operational satellite system capable of observing the earth's cloud cover on a daily routine basis. Now, second-generation improved Tiros operational system (ITOS) satellites are under development.

The Tiros Operational System is sponsored by the U.S. Department of Commerce, and is managed and operated by the Environmental Science Services Administration's National Environmental Satellite Center, under the technical direction of the National Aeronautics and Space Administration's Goddard Space Flight Center (NASA/GSFC).

To meet the full operational objectives of the system, two TOS meteorological satellites must be in orbit at all times; one carrying an automatic picture-taking APT subsystem for direct local readout to APT stations throughout the world, and a second carrying an advanced (AVCS) vidicon camera system capable of storing global video data for readout to associated ground stations that immediately relay the data to the National Environmental Satellite Center (NESC) for processing and analysis.

More than 1 275 000 television pictures have been returned by the Tiros and ESSA satellites. Tiros I's primary objective was observing the earth's cloud cover by means of slow-scan television cameras in an earth-orbiting, spin-stabilized satellite using both a wide-angle and a narrow-angle television camera.

Tiros II, orbited on November 23, 1960, additionally demonstrated an experimental, five-channel, scanning IR radiometer and a two-channel nonscanning IR device. These devices, developed by the NASA Goddard Space Flight Center, measured the thermal energy of both the earth's surface and atmosphere in order to provide data on the planet's heat balance.

A magnetic torquing coil for satellite stabilization was added to Tiros II (and all Tiros satellites thereafter) so that a controlled magnetic field about the satellite would interact with the earth's field of space.

Tiros III, IV, V, VI, and VII were launched between July 1961 and June 1963 to provide continuous observation of the earth's cloud cover. The spacecraft each contained two, slow-scan, vidicon television camera systems as the primary sensors.

Tiros VIII, launched in December 1963, included an APT camera. (The APT camera utilizes a very-slow-scan vidicon, as compared with the television camera. The latter requires 2 seconds to scan its 500-line image; the APT camera requires 200 seconds for readout of its 800-line image.) By virtue of the 2-kHz bandwidth of the APT system, Tiros VIII was able to transmit direct, real-time, television pictures to a series of 45, relatively inexpensive, APT ground stations located around the world.

Tiros IX, the first "wheel-mode" satellite, was launched in January 1965 to expand the capability of the Tiros satellites to provide complete global-weather observation on a daily basis. This represented an increase of four times the daily observation provided by the predecessor Tiros satellites.

Although Tiros IX differed from its predecessors in many aspects, a primary difference was its spin orientation, and hence picture-taking capability. In Tiros IX, the television cameras were mounted diametrically opposite one another and looked out through the sides rather than through the baseplate of the satellite as it spin-tumbled in orbit.

Tiros X, the last of the research and development series of standard Tiros satellites, was launched in July 1965 to provide hurricane and tropical storm observations.

ESSA 1 was launched on February 3, 1966, into a 740-km near-polar, sun-synchronous orbit to become the first operational satellite providing global observation on a daily basis. This satellite (like its predecessor, Tiros IX) utilized two vidicon camera systems, wherein a pair of pictures (one from each camera) produced a picture swath 3500 km wide and 1300 km long along the orbit track.

With ESSA 1 on station and providing operational global observation for readout in the United States, ESSA 2 was successfully placed in orbit on February 28, 1966. ESSA 2 was actually the first of the TOS-design spacecraft. It was launched into a 1400-km sun-synchronous orbit to complement ESSA 1 in the Tiros Operational System by providing direct, real-time readout of APT pictures to the APT ground stations located throughout

Spectral lines

The electrical engineer and public policy. Are our engineering schools laying an appropriate background for participation in the formation of public policy? Does the profession want to be in the public eye for policy formation?

It can be claimed that electrical engineers are not active in the formulation of public policy. In a sense this is true. With a few notable exceptions, such as David Packard and Hubert Heffner, there are very few electrical engineers in the public eye who are making national policy. Nor are electrical engineers often vocal in the debating of public issues that are of concern to intellectuals, businessmen, politicians, and the press. This is unfortunate, because our real influence on the structure of society and national policy is very great. That influence is generally constructive, but without an appropriate public image we are likely to lose not only public support for our activities, but also recruitment of the highly talented people we need from the high schools if we are to continue to develop.

To participate in public policy formation to a greater extent and more visibly, there are a number of changes we must make. First, we need to recognize the significance of our accomplishments. Second, we need to improve our communication of these accomplishments to the rest of the population. Third, we need to recognize those aspects of the current problems to which we can contribute, either personally or collectively.

As a beginning, some examples may be worth reviewing. Electrical engineers have radically modified the methods of communication between various segments of the population. Radio and television have completely changed the structure of family entertainment, and distribution of news, advertising, and political campaigns. The development of radar, fire control systems, and aerial surveillance has changed the nature of war. The telephone, the computer, and the jet aircraft have increased the size of the organization that can be managed and the way in which its parts can be distributed around the world. Electric light at low cost has lengthened our active hours, changing social patterns in many ways.

From these examples it should be clear that electrical engineers have had a major part to play in shaping every aspect of our political, social, economic, and personal activities. Thus we have more to do with public policy than do many more vocal segments of the population. However, if we are to have the nature of these contributions understood we must communicate more effectively with the rest of the population—particularly with the intellectual community. How often do electrical engineers take the time and effort to write articles for *Harper's*, *The Atlantic Monthly*, *Saturday Review*, *The New York Times*, *Scientific American*, or *Science* to show how our accomplishments relate to the rest of the world? Unfortunately, the answer is "rarely." Additionally, the question could be asked as to who would be interested in what we have to say, and why. It is my belief that there are many areas in which our profession can productively bring special skills and backgrounds to bear on problems of the day. People with a background in network theory, control systems, and probability are in a position to comment on such things as changes in economic policy, the layout of transportation systems, or stream pollution in such a way that, with just a little effort, they can become among their communities' most informed analysts or critics.

Furthermore, it would appear that we should be attempting to forecast the social and political changes our technology is bringing about. Is it not now an appropriate time to attempt to predict the effect of the picture telephone on business and on our highways and air transportation systems? For example, is it not possible that the picturephone and the computer will make it probable that more people may work at home rather than drive to an office? If so, what will this do to the divorce rates? If low-cost computing were accessible from every telephone it would be feasible to institute Athenian democracy on a nationwide scale. Is this a desirable goal? Our speculations in these and related areas ought to be recorded and debated if they are to help shape national policy.

As background for this broader scale of activity our engineering schools should be challenged to expand the scope of their activities to include the training of many people outside the discipline. A background vocabulary in concepts such as feedback, network theory, probability, information theory, and switching logic should be made available to the majority of college graduates in all fields. This means service courses by electrical engineering departments for students majoring in liberal arts, medicine, business, education, etc., on a scale well beyond anything yet attempted. The Engineering Concepts Curriculum Project course is a good start, and the popularity of the computer as the world's most sophisticated educational toy may make it possible to reach students so that this is not as ridiculous a suggestion as it may at first seem.

Business, sociology, medicine, and psychology are already borrowing some of our vocabulary and concepts. If our electrical engineering departments are to facilitate the information transfer, the profession stands to gain in recognition as well as in the kinds of service it can render.

In summary, the horizon of what we call electrical engineering and the areas where we expect our members to participate, individually and in groups, are going to have to expand if we are to continue to flourish as a profession.

Frank S. Barnes
Vice Chairman, Publications Board

The President's address at the 1970 Convention Banquet

J. V. N. Granger ***President IEEE***

For this year's International Convention, the IEEE chose as a theme: "Launching the Spectacular 70s." In the brief space allotted me, I should like to express my apprehensions about the kind of spectacle the seventies are likely to present, and my concern that engineers, by and large, are ill-equipped for their responsibilities in the decade ahead.

In the sixties, the U.S.—along with every other industrialized nation—was forced to a new recognition of the broader consequences of technological progress and to a reluctant—and often painful—reappraisal of the social and cultural price of progress. This reawakening has emphasized three basic truths: first, that the ultimate impact of those "technological breakthroughs" for which we strove mightily a decade ago was seldom foreseen, if, in fact, it was foreseeable; second, that a mortgage on society takes a long time, and a great deal of money, to pay off; and finally, that it is very hard indeed to fix the responsibility for the undesirable results of technological progress, no matter how many groups are ready to claim credit for the benefits. It is hard to believe that this new awareness of these deficiencies of our civilization will disappear with the opening of a new decade, and even harder to imagine that the solutions to these problems simply await the "launching" of that decade.

Many engineers seem to have great difficulty in accepting the idea that they have a particular responsibility for the undesired social effects of technology. "We are applied scientists," they say, "and science is simply the organized search for knowledge. It is unfair, or illogical, to judge the results of science as good or bad." True, but if we are applied scientists, the operational word is "applied." Engineering is the application of science to practical problems—that is to say, to problems that affect people. The goal of engineering is to create social consequences—particular social consequences, certainly; but affecting our society and our culture is what engineering is about. If some of the effects are unforeseen or undesirable, can we shift the responsibility to the "pure" scientists from whom we borrow our methods and beg our facts?

Some of us resort to another rationale. "Engineers don't make these decisions," we say. "The bosses do," or the marketing department, or the sponsors in Washington; "they have the authority." Of course they have authority: the authority to allocate resources. But that kind of authority is insufficient, as every boss, every marketing man, every project sponsor knows. Engineers have another kind of authority. Their authority is that of expertise; the authority that comes from knowing how. Unless this type of authority is also available, and committed to the project, the first kind has no meaning. Industrial organizations, and government agencies, do with technology what their engineers are able to do. They can't do more than that, and our society demands of them that they not do less.

Let me cite as examples three major social problems whose current status—if not their origins—is largely in the hands of engineers. The first is the problem of war. In our lifetime, the technology of warfare, and the danger warfare poses to society, have changed completely. As one result, the nations of the world have expended, since 1900, some $4000 billion dollars on military affairs. Currently, the U.S. and U.S.S.R. spend on military and related matters as much money as the entire world spends on public health and public education. The whole world is caught up in an arms race, and in this race engineers are the runners. While we pound along—wondering, perhaps, if there is a finish line—we might reflect on the fact that the arsenals of the nuclear powers already contain the explosive equivalent of 15 tonnes of TNT for every man, woman, and child on earth.

Consider next the less morbid, but equally threatening,

problem of starvation. At least one third of the world's population receives less food daily than medical authorities regard as essential to health. From the engineering viewpoint, the problem can be described as an unfavorable ratio between the energy value of food produced and the energy expended in producing it. With even the most modern agricultural techniques, to plant, cultivate, harvest, process, and deliver to the consumer one calorie of food uses one calorie of fossil fuel, and three or more calories of fuel are consumed in cooking that food. We are, quite literally, eating up our fuel reserves and, in the process, fouling our atmosphere, our water supply, and the very land on which we live. Here again, we are running a race with time. The engineering challenge is to find ways to speed up the rate of conversion of the energy of sunlight into other forms—to shift from geological time to real time. The solar energy that falls on the state of New York each year is twice as great as the total, annual, world production of fossil-fuel energy.

A third example of the social consequences of technology is the problem of waste disposal. To focus on just one great achievement of modern technology, consider the no-deposit, no-return bottle. Every day in the United States we throw away enough no-deposit no-return bottles to reach (if laid end to end, as engineers naturally would place them) from New York to Rome, Italy. Here, we might recall that the Babylonians invented glass bottles 3500 years ago, and the glass in their trash heaps hardly has deteriorated at all.

These all-too-familiar examples of the social consequences of engineering are offered to illustrate my apprehensions about the "spectacular seventies," and to demonstrate, as I believe they do, that engineers are not properly equipped to assume responsibility for—or even to foresee—the full impact of their work. We need help. We can hope to find that help, I believe, from other professionals who, like engineers, apply the methods and discoveries of science to the problems of people living together, unavoidably, in a real world. We must open the dialogue, and undertake to communicate in a language we can all understand, with the economists, the ecologists, the sociologists, and the psychologists: the whole gamut of people who are professionally concerned with our world and our fellow human beings, and with the quality of the life we lead and the life our children will inherit. With their help, we may come to understand what we know, or failing that, know what we understand.

In the words of the book of Common Prayer: "We have left undone those things which we ought to have done; And we have done those things which we ought not to have done; And there is no health in us." May God grant us the wisdom, the courage, and the strength to face, together, the consequences of what we do together.

Early schemes for television

Various proposals for "seeing by electricity" were put forward around 1880. Though only paper plans, they established principles that led to the reality of mechanical television in the 1920s

George Shiers Santa Barbara, Calif.

More than a dozen schemes for sending visual images by electricity appeared from 1877 to 1884. Some used multiwire lines and mosaic arrays; others used single lines and a scanning method—autographic, spiral, linear. Selenium cells and incandescent filaments were common elements. Basic ideas on scanning speed, repetition frequency, synchronism, picture elements, and beam modulation evolved during these years. Some schemes employed magnetooptic effects, others used polarized light, and an optical equivalent of the cathode-ray tube was proposed for one receiver. Mechanical problems were finally solved by the scanning disk, which, 40 years later, with the aid of electronic techniques, became the foundation for practical mechanical television. Both facsimile and television proposals were covered, partly because they were inseparable during this era and partly to show the continuity of developments.

The possibility of "seeing by electricity" first became of real interest during the late 1870s. Two events of that decade gave impetus to the search for ways of transmitting pictures and views: the discovery of the light sensitivity of selenium in 1873, and the invention of Bell's telephone in 1876. Rising interest in electric lighting elements also promoted interest in "electrical vision." From 1877 a variety of proposals established basic principles that, over seven years, were developed and finally incorporated in the near-practicable invention of Paul Nipkow in 1884. A chronology of this period is given in Table I.

Selenium and light

Willoughby Smith, chief electrician of the Telegraph Construction Company, used selenium rods as high resistances for continuity checks of the Atlantic cable (1866). Selenium proved to be unsuitable, however, because of wide variations in resistance. Later tests to find the cause revealed the fact that the resistance was diminished when a rod was exposed to light. This discovery of the effect of light on selenium was announced by Smith early in 1873.[1,2] Despite the obvious value of this phenomenon, only a few workers studied the physical properties of selenium during the next decade, and few attempts were made to develop the selenium cell as an electric device.[3] Nevertheless, selenium, though inefficient and capricious, was a key component in all the early schemes and retained its eminent place until efficient phototubes became available after World War I.

Early television,* or "telectroscopy" as it was called, evolved from facsimile telegraphy. This sister art was over 30 years old when the telephone was born. Actually, most of the proposals employing selenium for sending pictures by electricity were directly related to facsimile, with means for instant visual reception thrown in, as it were, as alternatives.

Facsimile, or the copying telegraph

Without going into the history of facsimile,[6,7] a brief reference to the "copying telegraph" is necessary to show what techniques were available during the mid-1870s. The first plan for an "automatic telegraph" was patented[8] in 1843 by Alexander Bain, a Scottish watchmaker, telegraph inventor, and pioneer of electric clocks. To avoid coding and decoding, Bain devised a way to reproduce letters and words of the original message as a series of stains in chemically prepared paper.[9]

Variations of Bain's scheme (based on sequential scanning and synchronized movements) were developed by others, particularly Frederick Bakewell (1847) and Giovanni Casseli (1861). The Casseli system was in service in France during the 1860s. During the next ten years a variety of proposals for other "writing telegraphs" appeared. These schemes, sometimes known as the "telautograph," employed coordinate control whereby the movement of a pen or style is resolved into, and reconstituted by, two separate rectilinear motions. Therefore, the principles of scanning and synchronism—basic to facsimile and television employing sequential signals—were well established when proposals for sending pictures and views by electricity with the aid of selenium

* The word "television" was coined in 1900 by a Frenchman named Perskyi.[4] Hugo Gernsback introduced it in 1909 in an article in his magazine.[5]

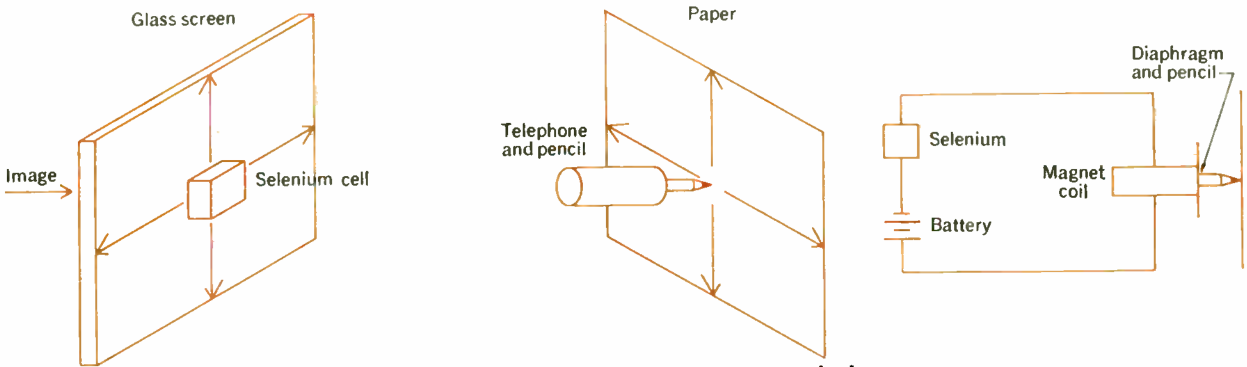


FIGURE 1. Constantin Senlecq's telectroscope, 1877. Facsimile system employing a single selenium cell and a pencil attached to a telephone diaphragm.

entered the literature. (The principle of synchronous control was used by Charles Wheatstone in the early telegraph days; see Refs. 10–13.)

The telectroscope

The idea of using selenium as a pickup element (the counterpart of the microphone) for transmitting graphic materials occurred to several workers around 1877. A French lawyer, Constantin Senlecq, was the first to publish his ideas that year.[14] (In a later account,[15] the claim is made that it "was invented in the early part of 1877.") His plan for a telectroscope (see Fig. 1) included an early adaptation of Bell's telephone.

Senlecq supposed that his apparatus would reproduce the tonal shades of an image obtained in a camera obscura. He avoided any mention of the mechanical linkages by merely specifying "any system of autographic telegraphic transmission." His plan, although rudimentary, was advanced for the times; and had the merit of combining two new elements in an attempt to extend existing techniques for picture transmission.

A proposal for directly converting electric signals into

I. Chronology of facsimile and television proposals, 1877–1884

Year	Inventor	System	Circuit	Reproducer	Remarks
1877	Senlecq[1]	Fac.	Single	Telephone and pencil	Autographic
1878	De Paiva	—	—	Single incandescent element	Selenium-coated plate
1879	Redmond[1]	TV	Multiwire	Incandescent mosaic	Selenium mosaic
	Redmond[2]	—	Single	Single incandescent element	Single selenium cell
1879	Perosino	Fac.	—	Electrochemical, single-point	Paper record on cylinder
1880	Middleton	Multipurpose	Multiwire	Thermoelectric mosaic	
1880	Ayrton, Perry[1]	TV	—	Apertured mosaic	Electromagnetic shutters
	Ayrton, Perry[2]	—	—	Silvered magnetic mosaic	Plane-polarized light, Kerr effect, analyzing screen
1880	Carey[1]	Fac.	—	Electrochemical, multipoint	Selenium mosaic, wire mosaic
	Carey[2]	TV	—	Incandescent mosaic	Selenium mosaic
	Carey[3]	Fac.	Single	Electrochemical, single-point	Spiral scan, clockwork drive
1880	Sawyer	TV	—	Spark gap	Spiral scan, selenium helix, light pipe
1881	Senlecq[2]	Fac.	—	Electrochemical, multipoint	Selenium mosaic, wire mosaic
	Senlecq[3]	TV	—	Incandescent mosaic	Mechanical selector, rotary switch, synchronizing pulses
1881	Bidwell[1]	Fac.	—	Electrochemical, single-point	Pinhole cylinder
	Bidwell[2]	—	—		Pinhole box, linear scan, flyback
1882	Lucas	TV	—	Optical. Polarized light beam on screen	Beam modulation, beam scanning, continuous scan, receiver only
1884	Nipkow	—	—	Electrooptical. Polarized light and direct viewing	Apertured disks, Faraday effect, automatic flyback, continuous scan

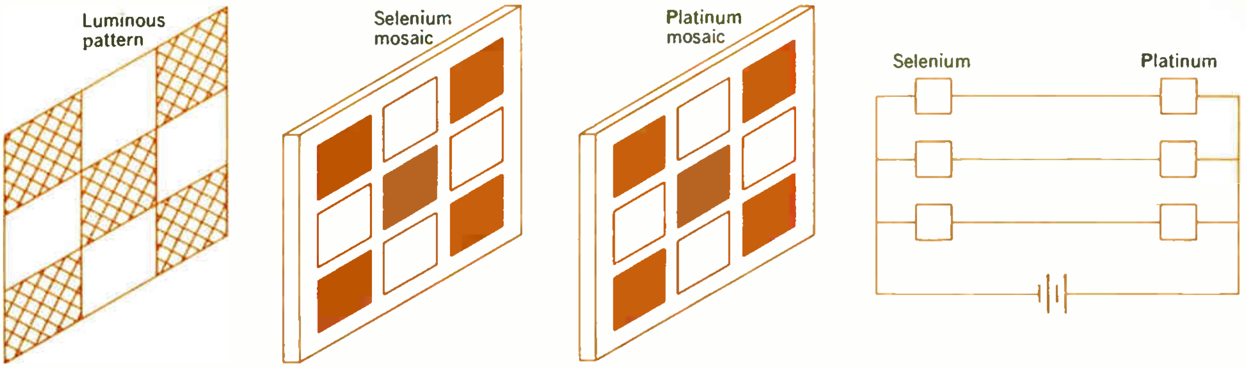
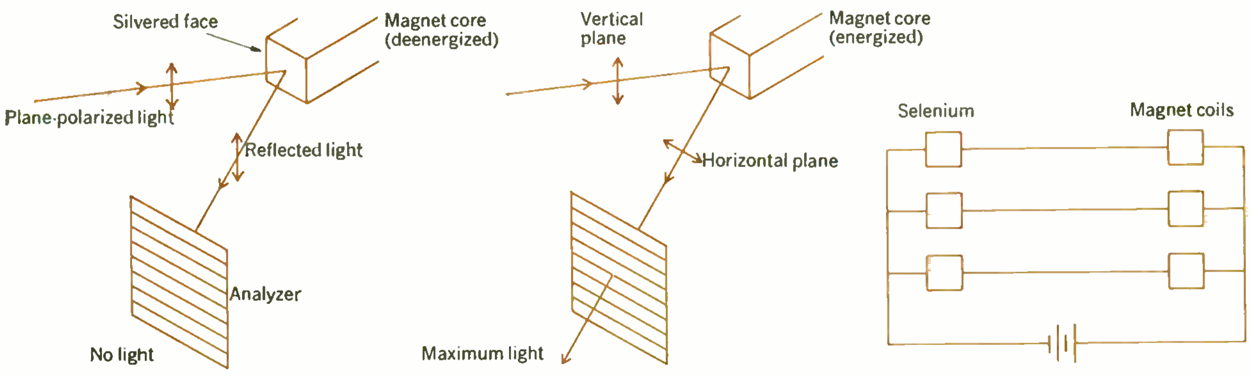


FIGURE 2. Denis Redmond's electric telescope, 1879. Multiwire system with a mosaic of incandescent elements for visual reception.

FIGURE 3. Ayrton and Perry's second proposal for seeing by electricity, 1880. A receiver mosaic of electromagnets with silvered surfaces on the ends of the cores is flooded with plane-polarized light and viewed through an analyzing prism. The plane of polarization of the reflected light is rotated in proportion to the current in the respective circuit.



light for reproduction purposes soon appeared. Realizing that an incandescent element could serve as the converse of selenium, a Portuguese physics professor of Oporto, A. de Paiva, outlined his plan for an "electric telescope" early in 1878.* De Paiva suggested projecting an image onto a selenium-coated plate that was scanned by a metal point. Signals from this transmitter were to operate a relay and an incandescent element at the receiver. The motions of the point and the lamp were to be effected by the usual autographic means.

Selenium and platinum mosaics

The relationship between the structure of the ear and its telephonic model and the comparable imitation of the eye in possible apparatus for "electric vision" now began to emerge. An obscure inventor, Denis Redmond† of Dublin, revealed his plans for "transmitting a luminous image by electricity" early in 1879.[17] In his "electric telescope," Redmond employed mosaics patterned after the eye; they consisted of "a number of circuits, each containing selenium and platinum arranged at each end, just as the rods and cones are in the retina."

Redmond's multicircuit plan, shown in Fig. 2, eliminated problems of scanning and synchronism. A luminous pattern was projected onto the selenium mosaic. The bright parts of the image were reproduced by incandescence of the respective platinum elements in the receiver mosaic. There were no moving parts and the optical system was nothing more than a simple camera lens. Although the plan contains only the barest essentials, it is a true television system and appears to be the first of its kind employing selenium.

Unlike other inventors of the period who produced no more than paper plans, Redmond claimed to have done actual experiments. It seems that his efforts were rewarded, because he declared: "I have succeeded in transmitting built-up images of very simple luminous objects." However, he did not describe how the mosaics were made, nor how to prepare selenium or construct the platinum elements.

Redmond, recognizing the practical barrier of a multiwire circuit, also considered a single-wire system. But this introduced the greater problem of synchronizing the motions of the cell and the incandescent element. He therefore proposed to adopt the principle of the copying telegraph, but he did not give any details of this experi-

* De Paiva's proposal was not widely known, apparently, since there are no contemporary accounts in English literature. Another little-known proposal employing selenium for "telephotography" was put forward in 1879 by C. M. Perosino. His plan, employing sequential scanning, single-line transmission, and chemical recording on a revolving drum, is probably the first of its kind.[16]

† Little is known about Redmond. Recent inquiries in Dublin and London have not brought to light any information to supplement his published accounts.

ment. Like de Paiva, Redmond recognized the importance of persistence of vision and the need for a minimum scanning frequency. He proposed to arrange his system "so that every portion of the image of the lens should act on the circuit ten times in a second, in which case the image would be formed just as a rapidly-whirled stick [brand] forms a circle of fire."

Redmond was also aware of the basic defect of selenium as a light-sensitive element: the sluggishness of response that quickly darkened the inventive horizon. This inertia plagued inventors for many years. Consequently, Redmond's attempt to employ a single circuit "failed through the selenium requiring some time to recover its resistance." (He also stated: "I am at present on the track of a more suitable substance than selenium." His proposal elicited several letters two weeks later[18] and another one in May 1880 asking for further results.[19])

The photophone and its consequences

The potentialities of selenium as a link between electricity and light, as well as its physical properties, were now of great interest. A quite different line of development—the use of a light beam to convey audible tones—was taken up by several workers, including Graham Bell, during the late 1870s. Bell became interested in discussions on the possibility of hearing the sound of light via selenium and the telephone during a visit to England in 1878. Upon returning to the United States in the autumn, he started work on a new telephonic system that employed a beam of voice-modulated light instead of wires between transmitter and receiver.

An extensive series of experiments by Bell and his co-worker Sumner Tainter with selenium cells and "undulatory light" led to the "photophone."[20] Then, before it was practically applied, Bell deposited the related documents with the Smithsonian Institution. This unusual act aroused great curiosity among scientists and stimulated others who suspected that he had developed a system for "seeing by telegraph." The increase in correspondence on this subject and in reports of experiments during 1880—the boom year for incipient television—appears to be a direct result of news and speculations about Bell's new "visual telegraph."

An elegant scheme

Two British professors, William Edward Ayrton and John Perry, referred to Bell's papers when they announced their plan for "seeing by electricity" in *Nature*, in April 1880.[21] They recognized the practical difficulties, however, and merely advanced suggestions, stating: "It has not been carried out because of its expensive character, nor should we recommend its being carried out in this form." They also declared that "it is well to show that the discovery of the light effect on selenium carries with it the principle of a plan for seeing by electricity." But this pronouncement was rather tardy because they had privately discussed their ideas "some three years" before; besides, Redmond had already published his plan. [Ayrton and Perry wrote, "suggested to us some three years ago more immediately by a picture in *Punch*." However, their memories were at fault, since the only cartoon published during the period from July 1875 that clearly applies is one in *Punch's Almanack for 1879*, dated December 9, 1878. This prophetic illustration, showing a wide-view screen, has the imaginary and somewhat derisive caption, "Edison's Telephonoscope (Transmits Light as Well as Sound)." Their announcement evidently prompted Redmond to call public attention to his plan in a letter to the *Times*,[22] in which he mentioned "a relay of peculiar construction" and pointed out that he had not patented his apparatus.]

Ayrton and Perry had two multicircuit schemes, both employing transmitter mosaics "made up of very small separate squares of selenium." Their first receiver was an apertured mosaic with light arranged to pass through the openings. A needle, magnetically operated, obscured each opening. An increase of light on a given cell would increase the line current to the respective coil. Thus, the needle would be pulled aside and admit more light through in proportion to the original light intensity.

Their second scheme was boldly based upon a recent advance in physics. In 1845, Michael Faraday passed a beam of plane-polarized light through a block of heavy glass mounted in the pole gap of an electromagnet.[23] He found that the plane of polarization was rotated when the magnet was energized (Faraday effect). In 1877 John Kerr, a Scottish physicist, discovered a related effect when plane-polarized light is reflected from the poleface of a magnet.[24]

The co-inventors felt that Kerr's experiment suggested "a more promising arrangement." Their second receiver plan, shown in Fig. 3, consisted of electromagnets arranged in a mosaic pattern. Silvered soft-iron squares were attached to the ends of the cores. This mosaic was to be flooded with plane-polarized light and viewed through an analyzer. With the transmitting mosaic dark, the magnets would not be energized and the reflected light would be cut off from view. With sufficient light on a given cell, the reflected beam from the respective magnet would pierce the analyzing prism and present that portion of the image with a corresponding intensity.

Although Ayrton and Perry were fully occupied in the new field of electric power, the possibility of seeing by electricity stayed on their minds. A rudimentary model of a somewhat different plan was later used by Perry for lecture demonstrations. This instrument, capable only of reproducing alternate stripes of light and shade, was called a "telephote," or "pherope."[25]

Perry was an early prophet of radio and television. He foresaw communications without wires before the pioneer work (1886–88) of Heinrich Hertz on electromagnetic waves was widely known. Concerning "the people of one hundred years hence," he wrote: "They will probably speak to one another at a distance without any artificial connection between." He also declared: "They will probably be able to see one another's actions at great distances, just as if they were close together."[26]

A thermoelectric plan

In March 1880, a different scheme was announced by Henry Middleton of St. John's College, Cambridge.[27] He spurned selenium, however, and suggested a multipurpose plan employing thermoelectric elements arranged as mosaics and connected by a multiwire circuit.

Middleton, like Redmond, pointed out "a striking analogy between the camera of the instrument and that of the human eye." He also equated "the conducting system" with the "optic nerve." He believed that his plan would be adaptable for all kinds of reproductions. Through the agency of heat, he supposed that "these

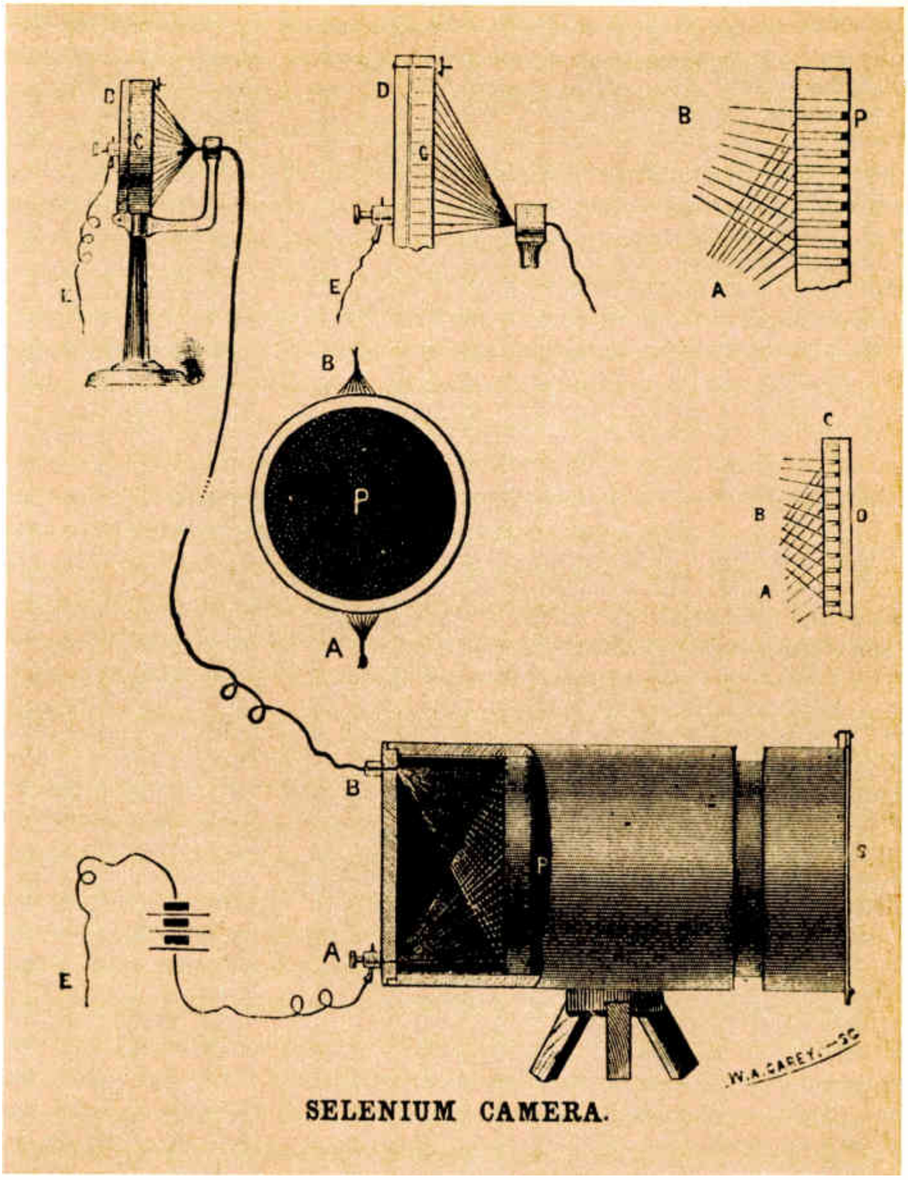


FIGURE 4. Carey's multiwire scheme for seeing by electricity, 1880. (Reproduced from Scientific American.)

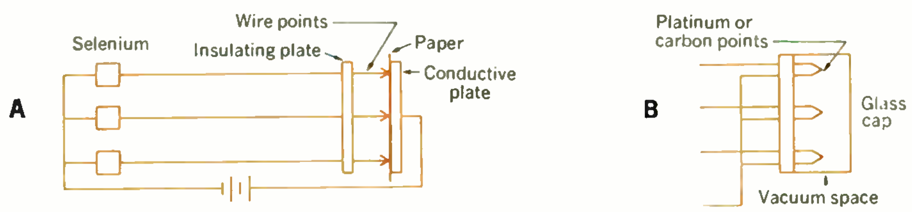


FIGURE 5. Carey's first plan (A) with a receiver mosaic of wire points for electrochemical recording. Alternative proposal (B) with a mosaic of incandescent elements for visual reception.

images can be either received directly or by reflected light...and projection on a screen...or by suitable apparatus they can be retained as a photograph, a thermograph, or chemicograph."

Two American plans

Meanwhile, U.S. inventors had not been idle in exploring the new field, nor immune from the enticements of selenium. Comprehensive plans for two schemes appeared in the *Scientific American* early in June 1880.[28] The inventor, who had originally submitted his ideas in the spring of 1879,[29] was George R. Carey, of Boston. The article contained engravings that portrayed a selenium camera, probably the first illustration of its kind; see Fig. 4. Indeed, Carey was the first to publish "constructional" details. The careful delineation of the parts gives the impression that the apparatus was built, although there is no evidence to support this.

In his first scheme, Carey employed a circular mosaic of selenium elements connected by separate wires to a similar mosaic of wire points at the receiver. A sheet of chemically prepared paper was inserted between these points and a metal plate. See Fig. 5.

To furnish a visual image, Carey proposed an incandescent mosaic as a substitute for the wire array at the receiver. Platinum or carbon "points" were mounted

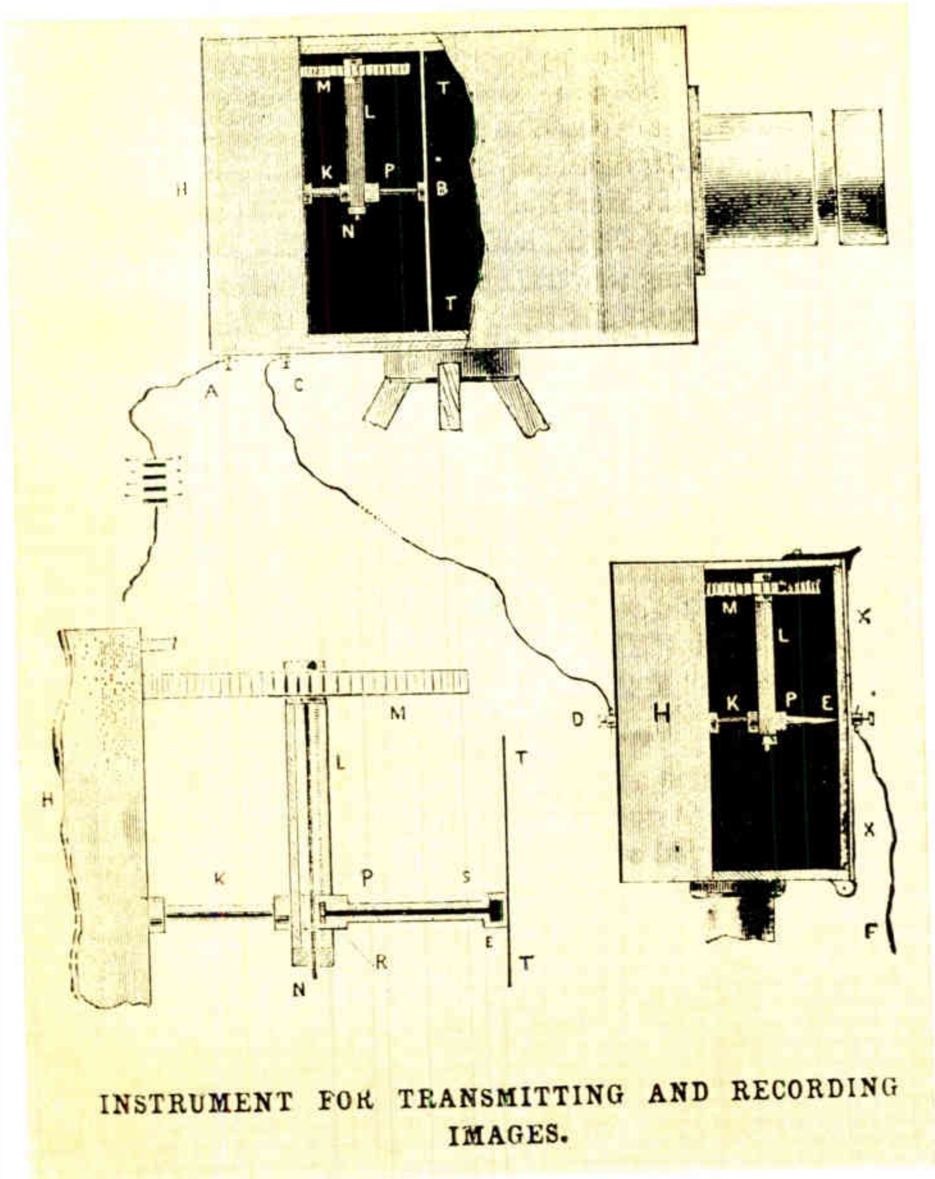


FIGURE 6. Carey's instruments using spiral scanning for transmitting and recording images along a single-wire circuit. (Reproduced from Scientific American.)

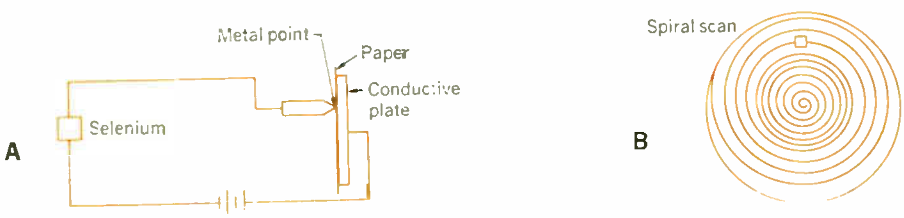


FIGURE 7. Carey's single-circuit plan for electrochemical recording (A). The selenium cell and the metal point, both operated by clockwork, were arranged to travel a spiral path (B).

in an evacuated space "covered with a glass cap." The inventor confidently stated: "These points are rendered incandescent by the passage of the electric current, thereby giving a luminous image instead of printing the same."

Carey, realizing the practical objection to a cable between the camera and the distant station, proposed another method employing a single line. In this second scheme (see Fig. 6), he introduced the novel idea of spiral scanning. As shown in Fig. 7, a single selenium cell in the camera was caused to "describe a spiral line upon the glass, thus passing over every part of the picture" projected on it. The receiver contained a metal plate carrying a sheet of chemically prepared paper over which a metal point traced a similar spiral path. A clockwork-driven mechanism in each instrument produced the motions of the cell and the point. Since this single-circuit plan was intended only "for transmitting and recording," the inventor did not advance an alternative suggestion for luminous reception. Both proposals refer to a "one-shot" scan.

Except for the alternative suggestion of incandescent elements, both of Carey's schemes relate to facsimile. However, he is often given credit for the first suggestion of a "television" system in 1875. These later accounts[30] describe the mosaic plan with multiwire connections

FIGURE 8. William Sawyer's proposal for transmitting visual images, 1880. The light pipe traverses the image and a flat helix of selenium wire in a spiral path. A spark gap carried by an index describes a similar path in a darkened case at the receiver.

and incandescent elements. They also variously refer to selenium cells or a light-sensitive mosaic of photographic materials, with or without line relays at the receiver. But this disclosure of June 1880 appears to be the first published by Carey related to an electrical system employing selenium.

The rather tenuous link between published reports, private plans, and the growth of technical ideas was strengthened by a quick response to Carey's article published in the *Scientific American* the following week. The issue for June 12, 1880, carried the account[31] of another scheme by William Edward Sawyer, an electrical engineer of New York. This contributor, also a telegraph inventor and pioneer of electric lamps, revealed that his plan dated back to the fall of 1877. At that time he had described to business acquaintances "the principles and even the apparatus for rendering visible objects at a distance through a single telegraphic wire." Interestingly, Sawyer was concerned only with a visual system, although his earlier work was on facsimile. He also proposed spiral scanning, novel optomechanical arrangements in both instruments, and a spark-gap receiver; see Fig. 8.

The transmitter contained a flat helix of fine selenium wire mounted in a darkened case. Light from the image was piped into this case through a fine tube. In an unspecified manner, the tube was arranged to traverse the image and the selenium coil, starting at the outside and finishing at the center. The receiver was vaguely described as a similar darkened case in which an "index" traced a spiral path identical to that of the light pipe, or scanning tube, at the transmitter. The index carried fine platinum points connected to the secondary of a "peculiar induction coil." Tiny sparks between these points were supposed to reproduce the instantaneous level of light of the original image.

Sawyer gave no other details of his plan but he did describe its operation. Like Carey's, this was a one-shot scan, with no mention of repetitive action. Recognizing the need for rapid motion consistent with the persistence of vision, he wrote: "The speed being sufficiently great it is obvious that...an exact image of the object... would be reproduced before the eye of the observer placed at the darkened chamber of the receiver."

Sawyer was aware of the deficiencies of selenium: its sluggishness and inadequate sensitivity. He understood the absolute need for isochronous motion and declared that "isochronism is unattainable." He also recognized that an acceptable reproduction would require a vast number of individual points (picture elements) accurately registered to provide reasonable detail (definition).

The first to state this problem, Sawyer declared (with reference to about 6.5 cm^2 of surface): "To convey with any accuracy an image...this surface should be composed of at least 10 000 insulated selenium points." (This figure represents a good-quality halftone screen.) Also, discounting single-line scanning, and with alignment of the picture elements in mind, he added that these points were to be "connected with as many insulated wires leading to the receiving instrument; for the variation of the one-hundredth of an inch either way will 'throw a line out of joint.' "

Sawyer was a severe critic of any scheme, including his own. Pessimistically he stated: "There is no likelihood of any plan of this kind ever being reduced to practice, for some of the difficulties in the way of all of the plans are insuperable." Thus, the problems facing any would-be inventor of a practicable system for transmitting visual images were now emerging from the mists of thought. A fast and sensitive pickup device and an equally reponsive visual reproducer were essential. Practical mosaic arrays would have to contain large numbers of these elements.

The superiority of sequential signals along a single line also was becoming recognized. This approach eliminated cumbersome and costly cables, but introduced the greater problems of constant speeds and synchronous scanning. The related need for repetitive scanning—still a vague idea—at a frequency compatible with persistence of vision had to be satisfied in some way. In recognition of these fundamentals, any proponent had to incorporate adequate optical and mechanical means to put these principles into effect. The invention of such means that would bring any scheme closer to the borderline between fantasy and feasibility was the real difficulty—and the greatest one of all.

Sawyer's views were offset a few months later by a more cheerful opinion from Oliver Joseph Lodge, an English physicist. In December 1880, he lectured on "The Relation Between Electricity and Light" at the London Institution.[32] In concluding his lecture, Lodge said: "I must just allude to what may very likely be the next striking popular discovery...the transmission of light by electricity; I mean the transmission of...views and pictures by means of the electric wire."

Scheme for a fugitive picture

Early in 1881 Senlecq made his second contribution to the inventive pool with a plan[15] that incorporated some notable features already proposed by the American inventors. His new "telectroscope" was a conglomeration of ideas based upon the dial, or step-by-step, telegraph introduced in 1840.[10-13,33] These codeless systems, also known as the "printer" or "ABC" tele-

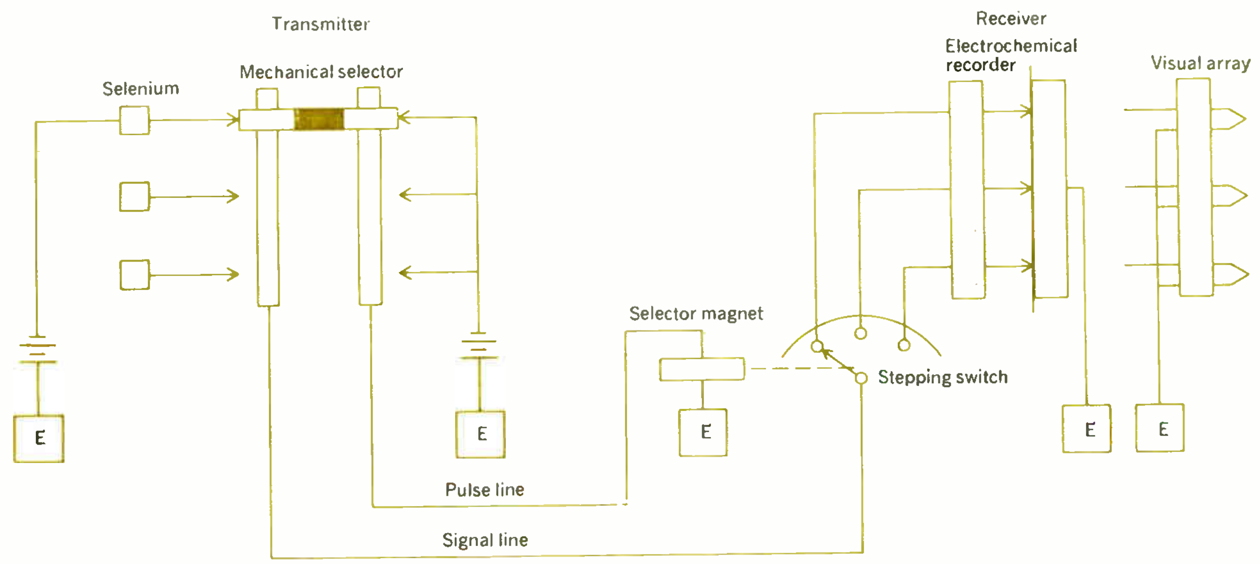


FIGURE 9. Senlecq's double-line facsimile system employing mosaics and contact selectors. An incandescent array was suggested for obtaining a transient visual image.

graph, employed lettered dials. Pulses were sent along the line as the dial was set to a given character.

Senlecq's plan included the first clear proposal for effecting positive synchronism in a picture transmission system. The heart of his apparatus, shown in Fig. 9, was a mechanical selector, or "rectangular transmitter," as he called it; a cumbersome device that permitted only a one-shot scan. The corresponding portion at the receiver connected the signal line to a mosaic array.

The receiver mosaic consisted of wire points and a metal plate with a sheet of paper between them for chemically recording the impression. The receiver elements were individually connected to contacts on a circular disk, or rotary switch. This switch was stepped by pulses along a second line, the pulses being controlled by the duplicate half of the transmitter selector. This selector, mounted vertically, was furnished with a two-circuit slider. Thus, during its motion under gravity, picture elements were connected sequentially to the signal line "intended to conduct the various light and shade vibrations."

Senlecq believed the contacts ought to "insure the perfect isochronism of the transmitter and receiver." However, it seems he ignored the limit to the rate of travel that would be imposed by the inertia of the receiver mechanism. Nevertheless, he firmly stated: "The picture is, therefore, reproduced almost instantaneously."

This plan is primarily a facsimile system. But, to keep up with the modern trend, Senlecq suggested an alternative visual receiver. He adopted Carey's idea of platinum elements and, to allow for contingencies, included Sawyer's induction coil. He described the operation in fanciful terms: "By the incandescence of these wires according to the different degrees of electricity we can obtain a picture, of a fugitive kind, it is true, but yet so vivid that the impression on the retina does not fade during the relatively very brief space of time the slide occupies in travelling over all the contacts." Senlecq was the most persistent of these pioneers. He kept faith with his dream for sending visual images over wires, and returned with another scheme in 1907.[34]

Interest in the properties of selenium increased during 1880–81, with emphasis on research on obtaining crystalline selenium in the most photosensitive form and on constructing practical cells. A well-known investigator, Shelford Bidwell, lectured on "Selenium and Its Applications to the Photophone and Telephotography" at the Royal Institution in March 1881.[35] Bidwell described various forms of selenium and their qualities, commented on the results of work done by others, emphasized selenium's capricious behavior, and gave details of his own experiments.

Bidwell was intent on phototelegraphy and made no reference to visual reception. His instrument, simply designed for demonstrations, was essentially the same as Bakewell's of 1847, except that selenium was used in the transmitter instead of an on–off contact. The cell was mounted inside a rotating cylinder with a pinhole midway between the ends. A fixed image about 5 cm square was projected onto the side of this cylinder. The receiver cylinder carried a sheet of chemically prepared paper with a platinum style in contact. The cylinders were coupled mechanically and arranged to move along their axes. As they slowly revolved, the pinhole and point scanned the image and paper, respectively.

This demonstration appears to be the first in public to show successfully the potentialities of selenium for picture transmission. Bidwell had faith in his work, for he made several improvements and devised another version during the next few months. He replaced the transmitter cylinder with a cam-operated box so arranged that the pinhole scanned the image vertically with a flyback between adjacent "lines."[36]

Bidwell was most active during 1881 and retained a keen interest in phototelegraphy for many years. Interestingly, his critical attitude in 1908 toward early forms of television[37] prompted the first bare suggestion for the "employment of two beams of kathode rays" that foreshadowed all-electronic television.[38–41]

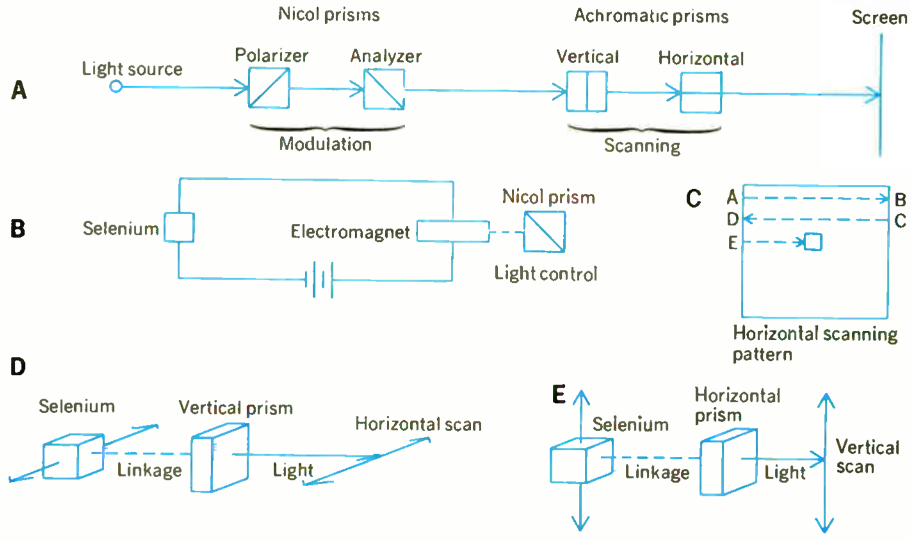


FIGURE 10. A telectroscope receiver (A) proposed by William Lucas, 1882. The light beam is modulated by rotating one of the Nicol prisms (B) proportional to the instantaneous level of light on the selenium cell. A horizontal scanning pattern (C) is produced by the combined motions of the vertical prism (D) and the horizontal prism (E).

An optical receiver

The report of Bidwell's lecture in the *English Mechanic* evidently stimulated one reader, William Lucas,* to pursue his ideas on apparatus for seeing by electricity. In a letter on "The Telectroscope,"[42] published in the same magazine in April 1882, he said he had "lately been giving a good deal of thought to this subject." He clearly saw his objective and asserted that "provided. .the practical difficulties can be overcome. . .an image in light and shade will be formed upon a screen. . ." However, he was concerned only with a receiver, which he believed could be used with a sequential transmitter, such as Bidwell's cylinder model. Although it was impracticable and only a partial solution to one half of a system, this proposal is the first to incorporate all the features essential for the reception of *continuously moving images*.

Lucas depended wholly upon optical methods. His scheme, shown in Fig. 10, has two important new features: beam modulation and beam deflection by oscillating scanning prisms.[43] Direct lighting from a local source and a moving light spot on a screen are also novel. A strong beam of light from a lantern was projected through a pair of Nicol prisms and then through a pair of ordinary achromatic prisms to illuminate a small spot on a screen.

The Nicol prisms (one the polarizer, the other the analyzer), with one of them rotatable through 90 degrees, comprised the optical modulating system. At extreme settings, light would either pass or be cut off; in between, the intensity of the beam would be proportional to the relative positions. One achromatic prism was placed vertically, the other horizontally, with both arranged to be partially rotatable about their axes. Together they comprised an optical scanning system. When the vertical prism was turned the spot of light would move across the screen; similarly, movement of the horizontal prism would swing the light beam up and down. In considering these parts together, Lucas declared: "Hence, by this arrangement, we can vary the position of the spot of light upon the screen, and augment or diminish its brightness at will."

Lucas suggested an electromagnet for turning one of the Nicol prisms. He gave no mechanical details nor did he suggest ways to operate the scanning prisms. However, he clearly envisioned the total functions and accurately described the operation: "The spot not only moves synchronously with the selenium cell, but its brightness also varies as the brightness of the portion of the image which the cell receives upon it." He described and illustrated the required motions with reference to a back-and-forth linear scan with horizontal traces. He also pointed out that the cell and the spot of light, on completing the last trace at the bottom, would return to the start at the top left-hand corner. This type of scan is the predecessor of today's "raster and flyback."†

A remarkable similarity exists between this optical receiver and the high-vacuum cathode-ray tube. With the electrostatic type, for example (ignoring focusing methods), the essentials are: light source—hot cathode; light beam—electron beam; Nicol prisms—biased grid; rotatable prisms—deflection plates; light screen—fluorescent screen. But the basic cathode-ray oscilloscope was yet to be invented; by Ferdinand Braun in 1897.

There is an interesting sequel to the Lucas proposal. He wondered whether the resistive changes would be sufficiently rapid and of sufficient magnitude to effect control of the Nicol prism. A reply by Llewelyn B. Atkinson appeared in the same magazine two weeks later.[44] Commenting on the scheme, he thought it was "certainly most ingenious, and. . .in theory is all right." But he also clearly pointed out the main problem: "In practice I am afraid the inertia of the moving parts connected with the Nicol's prism would render it impracticable." These words evidently dismayed Lucas, because he apparently dropped his plans.

Atkinson is said to have devised a rotating drum

*Little is known about Lucas. Recent inquiries in London have not brought to light any information to supplement his published accounts.

†Bidwell's pinhole box was the first transmitter employing a linear scan with flyback. Lucas referred to Bidwell's "parallel lines close together." However, since the Lucas scan required a flyback only between frames, his receiver was not compatible with the Bidwell transmitters.

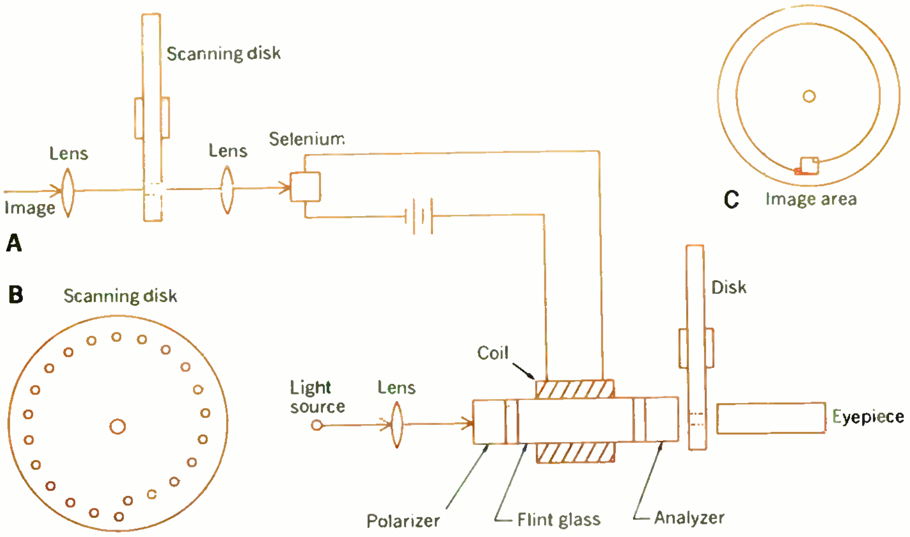


FIGURE 11. Paul Nipkow's plan (A) for an electric telescope, 1884. Two identical apertured disks (B) rotate in synchronism ten times per second. An image is dissected by the transmitter disk to produce sequential signals. The light valve at the receiver is based on Faraday's magnetooptic effect. Light from a local source is modulated in proportion to the line current. The image area (C) is viewed through an eyepiece.

with a series of peripheral mirrors to serve for sequential and repetitive scanning. This was the same year (1882), but he did not publish an account at that time. A similar proposal was made in 1889 by Lazare Weiller, who is generally given credit for this.[45] Late that year a note by Atkinson appeared in a London electrical journal.[46] With reference to "an integrating apparatus for producing the whole image," he observed that the idea "was first, I believe, published in the *English Mechanic* about 1881 or 1882, and was then, as far as publication goes, new."

A faint echo of these distant days returned in June 1936. In a brief note in *Nature*, on the scanning principle, Lucas quoted Atkinson's remarks and pointed out that "The communication thus referred to..." was his own.[47]

The master television patent

The process of exploring an image to obtain a sequence of electrical values proportional to the respective light values (and the reverse for reception) was now becoming a basic idea. However, regardless of the scanning means, coordinated motions of a complex order appeared to be essential. A suitable mechanism had to be delicate, precise, constant, and effective at speeds that would provide visual continuity. Although such a mechanism was a vital objective, it was often the least considered; perhaps because it presented the greatest difficulty in the way of a practical solution. Thus, for mechanical reasons, the dream of "seeing by electricity" was still unrealized.

These difficulties were overcome by Paul Nipkow, a student of natural science in Berlin. His solution was exceedingly simple and fundamentally sound—a spinning perforated disk. During Christmas 1883, Nipkow experimented with a disk perforated with a spiral of small holes near the edge. With the disk rotating, each hole revealed the field of view in consecutive strips; or line by line, as in reading. Of course, the process was reversible and identical disks could serve for the transmitter and receiver: one to dissect and the other to reconstitute the image. In a remarkably short time he selected the other elements required and prepared the details for a complete system. He filed his plans for an "electric telescope" early in January 1884.[48]

Nipkow's scheme is shown in Fig. 11. The transmitter consists of fixed lenses, a scanning disk, and a selenium cell. The composite light values of an image are displayed on the disk. As it rotates, each hole acts like a sliding shutter. Individual beams of light from each aperture are presented to the selenium cell in a continuous series. The "flyback" between each line and between each complete scan (or frame) is automatic. The disks contained 24 holes or lenses and were to rotate synchronously and in phase ten times per second.

While Nipkow thus reduced mechanical scanning in both instruments to its simplest form he also avoided any other moving parts at the receiver. He adopted Faraday's magnetooptic effect as the basis for a "light valve" to modulate the light beam at the receiver. This consisted of a block of flint glass placed inside a magnet coil with a polarizing prism at each end.

Light from a local source, polarized in one plane by the first prism, is blocked by the second prism. Current through the coil is proportional to the conductivity of the selenium. A high level of light at the transmitter therefore increases the strength of the magnetic field and rotates the plane of polarization accordingly. The light passing through the analyzer then has an intensity proportional to the original picture element. The spinning disk distributes these contiguous light values over the image area in the eyepiece with sufficient rapidity to create the illusion of a complete picture.

Nipkow's scheme, simple yet technically elegant, ended a seven-year quest for sending visual images over wires. Mechanical problems related to rapid scanning and synchronism, hitherto "insuperable," were neatly solved by a spinning, apertured disk. The master patent in the television field was issued to Nipkow on January 15, 1885. By all accounts, no apparatus was constructed nor did Nipkow attempt to exploit his invention; the patent lapsed a few years later.

A wide variety of television proposals appeared during the next 40 years for both wire and radio transmission. All of the early methods, and some new ones, were tried—spinning disks, drums, and wheels; rotating mirrors, prisms, and lenses; vibrating mirrors, apertured belts, light banks, and commutators—in attempts to realize "distant electric vision." Nipkow's disk finally prevailed in 1926 when reception of moving images in halftones was first demonstrated by John Logie Baird in London.[49]

During the following seven years, mechanical transmission apparatus was highly developed to its practical limits, particularly in England, Germany, and the United States.[50,51] From 1930, the picture tube replaced all moving parts in receivers. Then, with the introduction of practical camera tubes during the early 1930s, and associated radio techniques, mechanical parts were totally replaced and high-definition television became a reality.

REFERENCES

1. Smith, W., "The action of light on selenium," *J. Soc. Telegraph Engineers*, vol. 2, pp. 31–33, 1873; vol. 5, p. 183, 1876; *Am. J. Sci.*, vol. 5, p. 301, 1873.

2. Garratt, G. R. M., and Mumford, A. H., "The history of television," *Proc. IEE*, vol. 99, pt. IIIA, pp. 25–42, 1952. Most accounts of this discovery are incorrect. The original correspondence given on pages 25–26 describes the circumstances.

3. Barnard, G. P., *The Selenium Cell*. London and New York: Constable, and Richard R. Smith, 1930, pp. 10–17.

4. Wilson, J. C., *Television Engineering*. London: Pitman, 1937, pp. I, II.

5. Gernsback, H., "Television and the telephot," *Modern Electrics*, Dec. 1909.

6. Jones, C. R., *Facsimile*. New York: Rinehart, 1949, pp. 1–23.

7. Korn, A., and Glatzel, B., *Handbuck der Phototelegraphie und Telautographie*. Leipzig: Otto Nemnich, 1911.

8. British patent 9745, 1843.

9. Bain, A., "Automatic telegraphy," *Eng. Mech.*, vol. 2, pp. 273–274, 1866. In this account, from a paper read to the Society of Arts on January 17, 1866, the inventor describes his system and subsequent improvements.

10. Prescott, C. B., *History, Theory, and Practice of the Electric Telegraph*. Boston: Ticknor and Fields, 1866, pp. 160–168.

11. King, W. J. "The development of electrical technology in the 19th century: 2. The telegraph and the telephone," Smithsonian Institution, Washington, D.C., 1962, pp. 291–296.

12. Marland, E. A., *Early Electrical Communication*. London: Abelard-Schuman, 1964, pp. 94–98.

13. Walmsley, R. M., *Electricity in the Service of Man*. London: Cassell, 1890, pp. 793–794.

14. "The telectroscope," *Eng. Mech.*, vol. 28, p. 509, 1879: *Sci. Am.*, vol. 41, p. 143, 1879.

15. "The telectroscope," *Eng. Mech.*, vol. 32, pp. 534–535, 1881; *Sci. Am. Supp.*, vol. 11, p. 4382, 1881.

16. Barnard, G. P., *op. cit.*, pp. 264, 288.

17. Redmond, D. D., "An electric telescope," *Eng. Mech.*, vol. 28, p. 340, 1879.

18. *Eng. Mech.*, vol. 28, pp. 585–586, 1879.

19. *Eng. Mech.*, vol. 31, p. 235, 1880.

20. Bell, A. G., "On the production and reproduction of sound by light: the photophone," *Proc. Am. Assoc. Adv. Sci.*, vol. 29, pp. 115–136, 1880: *Engineering*, vol. 30, pp. 253–254, 407–409, 1880, vol. 32, pp. 29–33, 1881: *Nature*, vol. 23, pp. 15–19, 1880; *Proc. IRE*, vol. 50, pp. 1995–1996, 1962; see Ref. 3, pp. 257–258, for numerous other references.

21. Ayrton, W. E., and Perry, J. J., "Seeing by electricity," *Nature*, vol. 21, p. 589, 1880; *Times (London)*, p. 13, Apr. 22, 1880; *Eng. Mech.*, vol. 31, pp. 177–178, 1880.

22. *Times (London)*, p. 10, May 13, 1880.

23. *Phil. Trans.*, 1846; also *Experimental Researches*. London: R. Taylor and W. Francis, 1855, vol. 3, pp. 1–4.

24. *Phil. Mag.*, ser. 5, vol. 3, p. 321, 1877; vol. 5, p. 161, 1878.

25. Walmsley, R. M., *op. cit.*, pp. 782–784.

26. *Ibid.*, p. XXV.

27. *Eng. Mech.*, vol. 31, p. 178, 1880: described at a meeting of the Cambridge Philosophical Society on March 8, 1880.

28. Carey, G. R., "Seeing by electricity," *Sci. Am.*, vol. 42, p. 355, 1880; reported also in *Eng. Mech.*, June 18, 1880, and in *Design and Work*, June 26, 1880.

29. "The telectroscope," *Sci. Am.*, vol. 40, p. 309, May 17, 1879. According to this short editorial notice, Carey's plans were already fairly complete. "We hope to present to our readers before long the details of these interesting instruments." The reason for the delay (unusually long for those days) is not known.

30. See, for instance, Swinton, A. A. C., "Television, past and future," *Discovery*, vol. 9, p. 337, 1928; Hogan, J. V. L., "The early days of television," *J. SMPTE*, vol. 63, pp. 169–173, 1954; Abramson, A., *Electronic Motion Pictures*. Berkeley and Los Angeles: Univ. Calif. Press, 1955, pp. 17–18; Zworykin, V. K., Ramberg, E. G., and Flory, L. E., *Television in Science and Industry*. New York: Wiley, 1958, p. 4.

31. Sawyer, W. E., "Seeing by electricity," *Sci. Am.*, vol. 42, p. 373, 1880.

32. Lodge, O. J., *Modern Views of Electricity*. London: Macmillan, 1907, p. 358.

33. Wheatstone and Cook, British patent 8345, 1840.

34. "The Senlecq telectroscope," *Sci. Am. Supp*, vol. 64, pp. 372–373, 1907.

35. *Proc. Roy. Inst.*, vol. 9, pp. 524–535, 1881; also "Selenium and its applications to the photophone and telephotography," *Eng. Mech.* vol. 33, pp. 158–159, 180–181, 1881.

36. Report of the British Assoc. for 1881, p. 777; Lister, W. C., "The development of photo-telegraphy," *Electron. Eng.*, vol. 19, pp. 38–39, 1947; Ref. 2, pp. 27–28. This apparatus is in the Science Museum, London.

37. Bidwell, S., in a letter commenting on optimistic reports that "distant electric vision" would be possible within a year, *Nature*, vol. 78, pp. 105–106, 1908.

38. Swinton, A. A. C., "Distant electric vision," *Nature*, vol. 78, p. 151, 1908.

39. Garratt, G. R. M., and Mumford, A. H., *op. cit.*, p. 31.

40. McGee, J. D., "Electronic generation of television signals," in *Electronics and Their Application in Industry and Research*, B. Lovell, ed. London: Pilot Press, 1947, pp. 138–139.

41. Jensen, A. G., "The evolution of modern television," *J. SMPTE*, vol. 63, pp. 175–176, 1954.

42. Lucas, W., "The telectroscope, or seeing by electricity," *Eng. Mech.*, vol. 35, pp. 151–152, 1882.

43. Maurice Leblanc, French electrical engineer and inventor, is credited with a proposal for mirror scanning. *La Lumière Electrique*, vol. 2, p. 477, 1880; Ref. 2, p. 28.

44. Atkinson, L. B., *Eng. Mech.*, vol. 35, p. 194, 1882.

45. Weiller, L., *La Lumière Electrique*, vol. 34, p. 334, 1889.

46. Atkinson, L. B., *Telegraphic J. Electrical Rev.*, p. 683, Dec. 13, 1889.

47. Lucas, W., "The scanning principle in television," *Nature*, vol. 137, p. 981, 1936.

48. German patent 30 105, Jan. 6, 1884; Ref. 7, pp. 440–444.

49. Demonstrated to members of the Royal Institution on January 27 at 22 Frith Street, Soho. *Times*, p. 19, Jan. 28, 1926; Percy, J. D., *John L. Baird*. London: Television Soc., 1952, p. 5; Moseley, S., *John Baird*. London: Odhams, 1952, pp. 76–77. Original apparatus (1925) is in the Science Museum, London.

50. Wilson, J. C., *op. cit.*, pp. 389–419.

51. Abramson, A., *Electronic Motion Pictures*. Berkeley and Los Angeles: Univ. Calif. Press, 1955, pp. 51–64.

George Shiers (SM) is a free-lance technical writer, consultant, and author of several electronics texts. He also teaches courses in scientific and technical writing and in technical editing at the University of California Extension, Santa Barbara. Mr. Shiers has been employed in the electrical and electronics industries since 1923. From 1939 to 1946 he was an inspector, tester, and supervisor of radar, radio transmitters, and aircraft landing equipment for A. C. Cossor and Standard Telephones and Cables. He was associated with the American Instrument Company from 1948 to 1953, and in 1953–58 with D&R, Ltd., and Curtiss-Wright Corporation. Mr. Shiers was an instructor at the Adult Education Center of Santa Barbara City College from 1955 to 1968 and has been on the U.C. Extension staff since 1967. He has been doing free-lance work since 1958 and is a senior member of the Society of Technical Writers and Publishers.

Outlook for binary power plants using liquid-metal MHD

The evidence compiled to date suggests that the liquid-metal MHD topping-cycle power plant is a technically feasible proposition that makes good economic sense

L. L. Prem, W. E. Parkins
Atomics International Division, North American Rockwell Corporation

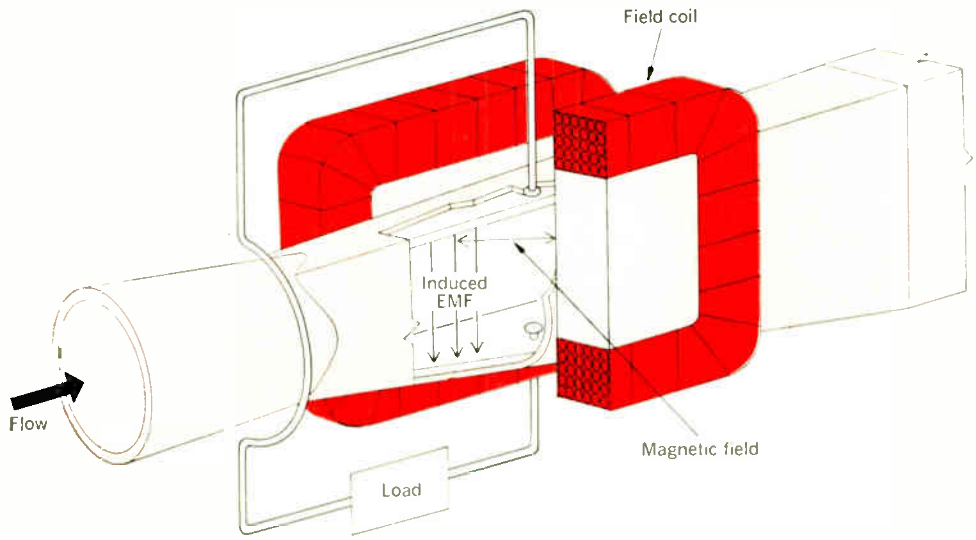


FIGURE 1. Principle of magnetohydrodynamic power generation.

Preliminary testing and extrapolations thereof indicate that liquid-metal MHD can be used as a topping cycle to increase the efficiency of large central-station power plants. Because maximum temperatures as low as 870°C are effective, such binary plants are possible with existing material technology. The best present choices appear to be a potassium working fluid and either a (helium- or sodium-cooled) nuclear reactor or a fossil-fueled furnace. Cost estimates for a possible plant with 1-GW output—based on the use of a coal-fired furnace operating at 870°C with a condensing type of MHD cycle—suggest that, for a capital-cost outlay approximately equal to that for a conventional coal-fired plant, 13 percent more efficiency is achieved by the plant with the topping cycle.

In recent years a large number of different methods for producing electric power from heat have been undergoing experimental development. Among those methods that do not employ rotating or reciprocating machinery (direct conversion) magnetohydrodynamic generation is considered to offer greatest promise as a means of improving the performance of central-station plants. Elimination of the Rankine steam cycle in the temperature range in which it is effectively utilized in modern generating stations has never been seriously proposed. Rather, MHD has been considered as a topping cycle in a higher-temperature regime.

The principle of magnetohydrodynamic power generation is based on utilizing the primary heat input to produce a high-velocity stream of electrically conducting fluid, and then interacting that stream with a magnetic field (for example, as illustrated in Fig. 1) to convert the kinetic energy of the stream into electric energy.

Approaches to MHD power conversion are of two basic types, depending upon whether the electrically conducting fluid is gaseous or liquid. In the former case the gas must be ionized, and the principal problem is to achieve sufficient ionization efficiently at temperatures that are not too extreme. In MHD power conversion utilizing a liquid working fluid in the generator, the principal problem is to achieve sufficient liquid density efficiently in a high-velocity stream. In both cases the major obstacle basically is to obtain adequate electrical conductivity in the stream under practical operating conditions.

The special panel on magnetohydrodynamics appointed by the President's Office of Science and Technology has reviewed the status of the technology and prospects for improved central-station power generation related to the use of MHD, and has recommended a program of development.[1]

Choice of working fluid

For MHD power conversion based on the use of a liquid working fluid, metals have been the only substances seriously considered, because they alone meet the requirement of high electrical conductivity.

A second constraint in the choice of working fluid is imposed by the need to convert thermal energy into kinetic energy. This conversion can be accomplished in a practical way only through vaporization; hence the boiling point must not be at an excessively high temperature.

As a third constraint, the chosen material must have a sufficiently low melting point to permit circulation under reasonable engineering conditions.

Substances that might conceivably fulfill all of these requirements are Hg, Cd, and the alkali metals.

Examining these candidates for possible use in large MHD–steam binary power plants results in further eliminations:

The vapor pressure of mercury is too high for use in the topping-cycle temperature range. A melting point of 320°C, though by no means insurmountable, has discouraged serious consideration of cadmium.

Among the alkali metals, cesium is not sufficiently available for large-scale use.

The boiling point of lithium (1330°C at 1 atmosphere pressure) is regarded as too high for present application.

The remaining working-fluid candidates are, therefore, sodium, potassium, and rubidium—the last being questionable because of its relative unavailability.

Development work directed toward the possible application of liquid-metal MHD in central-station plants has been based principally on the use of potassium as the working fluid. Its melting point of 65°C, normal boiling point of 760°C, high electrical conductivity, and other physical properties—in addition to its availability—make it a good engineering choice. (In the future, sodium may be preferred because of its lower cost. But because the boiling point of sodium is 130°C higher than that of potassium, there is more difficulty developing an adequate heat source for use with it.)

Choice of MHD cycle

The characteristics of the thermodynamic cycle are strongly influenced by the method used to solve the key problem in liquid-metal MHD—that of producing a high-speed stream with sufficient liquid density to exhibit good electrical conductivity. (Obviously, all candidate cycles are based on a closed recirculating system.) For central-station plants, the heat source could be a fossil-fueled furnace or nuclear reactor, providing reliable operation is obtainable at temperatures appreciably above the upper limit (~540°C) of the steam cycle.

In the heat source, liquid metal is boiled and produces a two-phase vapor–liquid mixture of low vapor quality—i.e., a low weight ratio of the vapor component compared with the entire two-phase mixture. (Since the liquid density is approximately 600 times greater than that of the vapor, a typical low-quality stream of 15 percent represents approximately 99 percent vapor by volume.) Such a mixture is not electrically conducting. Conversion of the thermal energy to kinetic energy is accomplished by expanding the mixture through a nozzle.

The various liquid-metal MHD cycles being investigated differ in the way the effect of the vapor fraction in the resultant two-phase stream is minimized in order to achieve the necessary bulk electrical conductivity. All proposed cycles then direct the final stream of fluid into an MHD generator for conversion of kinetic into electric energy. Any remaining kinetic energy is converted to pressure in an adjoining diffuser section.

One approach to the problem of vapor reduction is based on condensation by injection of a low-temperature side stream of the liquid metal into the vapor–liquid mixture leaving the nozzle. The introduction of the side stream does reduce thermodynamic efficiency, but this loss can be minimized by refinements in the cycle—involving multiple expansions of the vapor–liquid mixture and heat economization in the stream returning to the heat source. This type of MHD condensing cycle has been investigated principally by Atomics International,[2-4] Allgemeine Elektrizitäts-Gesellschaft,[5-7] and both the High Temperature Institute of the U.S.S.R. Academy of Sciences[8] and the I. V. Kurchatov Institute of Atomic Energy[9] in Russia.

A second proposed approach to vapor reduction utilizes mechanical separation of the liquid and vapor. Since this invariably involves impingement on a surface, losses occur in the kinetic energy of the liquid stream; these losses adversely affect the overall efficiency. A variety of flow patterns and separation geometries is possible to optimize performance. This type of mechanical-separation cycle has been studied by the NASA Jet Propulsion Laboratory,[10,11] and by the Argonne National Laboratory.[12]

A third general approach to the vapor problem in liquid-metal MHD cycles is to establish conditions in the stream entering the generator that give acceptable output with the as-expanded mixture of vapor and liquid. The Argonne National Laboratory[13] and the TRW Corporation[14] have investigated this type of "non-separated" cycle. A related method that uses a free jet in the generator, with the liquid fraction concentrated in the center of the two-phase stream, has been proposed by a Russian team.[15]

In the past, several other types of liquid-metal MHD cycles have been studied, but none are of current interest. For the remainder of this article, the condensing type of MHD cycle will be used to illustrate the possible application to large-scale power generation. This particular approach has been the most thoroughly investigated for the central-station objective.

Nuclear reactor heat source

The source of heat for a liquid-metal MHD–steam binary power plant must be capable of boiling the MHD work fluid at a temperature a few hundred degrees higher than the approximate 565°C at which the MHD working fluid will reject heat to the steam cycle. Without such a temperature increment, the efficiency gain using the topping cycle will be too small to justify the added plant complexity. Since the problem of assuring long-operating-life construction materials becomes more difficult as the heat-source operating temperature is raised. As a compromise, a boiling temperature of 870°C is suggested as a reasonable initial target for the MHD cycle. This temperature is very suitable for a potassium working fluid since it results in a potassium vapor pressure of 262×10^3 N/m².

For a nuclear-reactor heat source to provide a coolant outlet temperature of 870°C or more, the choice of coolant is limited to an inert gas or an alkali metal. (At the surface temperatures that necessarily would exist in the reactor core, any gas other than a noble gas would react with the materials of construction. For example, even with special alloys, use of carbon dioxide is limited to surface temperatures of approximately 760°C.)

Gas cooling is, therefore, restricted to a choice of helium, neon, or argon—the first two being preferred. Considerable experience has been obtained using helium coolant based on the AVR (operated by the Arbeitsgemeinschaft Versuchsreaktor GmbH) plant in Germany, the Dragon reactor (operated by the European Nuclear Energy Association) in England, and the Peach Bottom plant (of the High Temperature Gas Cooled Reactor Associates) in the United States.

The AVR and the Dragon reactor were designed for an outlet temperature of 750°C and the Peach Bottom reactor for a temperature of 725°C. The Dragon reactor has actually logged long periods of operation at 850°C.

Since electric power production from reactors has been based on use of the steam Rankine cycle, there has been little motivation to increase coolant temperature. Several European groups are now considering the design of reactor plants that use direct gas-turbine Brayton cycles, for which higher temperatures are desirable. For example, a group at the United Kingdom Harwell Laboratory is proposing a 1000-MW helium-cooled fast-reactor plant with an outlet temperature of 980°C.[16] Such a reactor would be suitable for boiling potassium at 870°C in an external heat exchanger for a liquid-metal MHD topping cycle. As an extreme in high operating temperature, the Los Alamos Scientific Laboratory has operated the helium-cooled UHTREX experimental reactor at an outlet of 1315°C. All of these helium-cooled reactors have made use of coated uranium-carbide fuel.

Of the alkali-metal, high-temperature-reactor coolants, only sodium and lithium have sufficiently low vapor pressure to be considered for installations having average outlet temperatures of 870°C and above. Considerable experience has been obtained with both of these liquid metals in high-temperature circulation systems.

Sodium and its alloy with potassium (NaK) have been used in reactors up to approximately 700°C. Lithium has been circulated in experimental loops at temperatures above 1100°C.

As a reactor coolant, lithium has an excessively high neutron absorption unless it is enriched in the lithium-7 isotope. For a large system, an enriched lithium inventory would greatly increase capital costs and lithium, consequently, is not a practical choice.

I. Conditions in furnace tubes in high-temperature section

	Conventional	Fluid-Metal MHD
Fluid	Water	Potassium
Fluid temperature, °C	540	870
Fluid pressure, 10^6 N/m²	24.7	0.27
Vapor	Superheated	Low quality

Of all the alkali metals, sodium is probably the only liquid-metal reactor coolant suitable for use with a liquid-metal MHD power-conversion cycle. To this time, however, there has not been a need for developing sodium-cooled reactors with outlet temperatures in excess of 600°C for use in central-station power plants. (Experimentation above 600°C with any of the alkali metals has been of interest for military and space-power applications rather than for central-station power production.)

Although no design for a high-temperature, sodium-cooled thermal reactor requiring some neutron moderating material may be practical, a fast reactor could be designed for operation with an outlet temperature in excess of 870°C using sodium (or helium) coolants.

For reasons of strength, the fuel cladding and structural material for the fast reactor would necessarily be based on refractory-metal alloys. The fuel itself would be some refractory compound of uranium and plutonium, most probably the oxide.

Fossil-fueled furnace heat source

Compare a conventional fossil-fueled furnace of a central-station plant with a design suitable for incorporating a liquid-metal MHD topping cycle. The combustion temperatures for both applications will be in the range of 1300–1500°C. The feedwater and air preheating conditions can also be identical so that the flue gas exhausts at temperatures that are standard practice. There is a difference, however, in the conditions that pertain to the fluid in the tubes in the high-temperature section of the furnace, as is shown by Table I.

Whereas the tube temperatures necessarily will be higher in the plant with the MHD topping cycle, the pressures are very much lower. (A very similar experience, though one requiring less longevity, involving the conditions required for the MHD plant has been obtained by the Mine Safety Appliances Corporation in the production of potassium metal.)

It is to be expected that pulverized bituminous coal will be the fuel for the central-station potassium furnace since it is the most commonly used fuel for power generation. With the potassium temperature inside the tubes at 870°C, flame and combustion temperatures typical of a conventional steam furnace should be adequate. Application of special combustion technology such as fluidized bed and pressurized furnace could conceivably improve furnace efficiency and reduce furnace volume.

The heat transfer coefficient at the potassium side will be approximately 20×10^7 J/h·m²·°C for non-boiling and boiling in the zero to 15 percent (vapor) quality range. Although the boiling-heat-transfer coefficient for potassium typically is higher than that for water, a phenomenon termed boiling instability has been observed with potassium and other alkali metals. Under certain conditions boiling is periodic, causing flow instability and vapor-quality control problems. Recent experiments with boiling potassium at Atomics International have shown that stable conditions can be achieved by assuring that saturated liquid enters the boiling section of the furnace.

Heating of the potassium to saturation or near-saturation temperature could be performed in tube banks in the primary convection-heat-transfer section of the furnace. The vaporizing part of the boiler would then consist of multiple tubes in parallel attached to inlet and outlet headers, probably located in the secondary convection-heat-transfer section. Saturated or near-saturated liquid potassium would enter the inlet header and then enter the tubes in which it would be vaporized to the 10–15 percent quality. Each tube would have an orifice at the inlet end to maintain flow stability in the parallel-tube system and to assure boiling stability in each tube. A "once-through tube" type of design would be preferred.

The gas side of the exchanger is subject to corrosion and fouling by ash and slag, and to erosion by ash. These gas-side effects may be somewhat different than in a steam generator because of the higher tube temperature. Due to the presence of SO_2 and SO_3 in the stack gases, compounds are formed with other substances found in the flue gas that can cause corrosive effects. These compounds can condense in the liquid phase on the tube surface and have been found to produce corrosion in temperature ranges in the neighborhood of 300, 650, and 900°C. The severest corrosion is in the 625 to 700°C range, which is the tube surface temperature approached in superheaters and reheaters of modern steam stations. Once the temperature range of a specific compound is exceeded, the corrosion rate drops sharply. A number of methods[17,18] have been studied to reduce and control the fire-side corrosion of coal-fueled boilers.

In a furnace heating potassium for an MHD plant, corrosion should be less severe because the tube operating temperature during boiling would be approximately 925°C, which is above the range of highest corrosion. To reduce corrosion effects further, tube temperatures in the neighborhood of 650°C can be avoided by bleeding back the highest-temperature potassium and mixing it outside of the furnace with potassium at about 600°C to raise the mixture above 700°C.

Thermal to kinetic energy converter

The high-velocity liquid-metal stream is produced by converting the thermal energy of the fluid into kinetic energy. In order to investigate concepts for an efficient conversion system, various test programs have been carried out. The NASA Jet Propulsion Laboratory has investigated the mechanical separation of liquid–vapor mixtures using water and nitrogen gas, NaK (sodium–potassium alloy), and nitrogen, as well as liquid lithium and cesium vapor. The Russian research teams have worked with liquid–vapor mixtures of water as a simulation of two-phase liquid-metal streams and have conducted tests with a potassium loop facility. At Atomics International, a boiling-potassium facility, shown in Fig. 2, capable of operating up to 870°C, has been used for a number of experiments. These included (1) determination of the performance of two-phase expansion nozzles, (2) measurements of the rate of vapor condensation resulting from injection of a low-temperature stream, and (3) measurement of frictional pressure drop occurring during two-phase flow.

Such experiments with potassium covering thousands of hours of high-temperature operation have shown that, even with two-phase flow, erosion and corrosion rates can be extremely low. The results also have verified performance predictions and indicate that a thermal-to-kinetic energy converter of practical dimensions can be designed to produce a highly conductive, high-speed stream of liquid metal.

Generator

Considerable experimental and analytical work has been carried out on the problems associated with converting the kinetic energy of the metal stream into electric energy. The great attraction of the liquid-metal MHD is that either dc or ac power can be generated, in contrast to plasma MHD, which can generate only dc power efficiently. Most investigators have selected the induction-generator principle to produce ac electric power. It is not certain if the synchronous principle could also be utilized for an efficient type of liquid-metal MHD generator, but no serious effort has been devoted to it.

Figure 3 shows a schematic diagram of a conventional- and a linear-induction generator. In the conventional-induction generator, polyphase stator windings, fed by the excitation current, produce a rotating magnetic field that induces current loops in the short-circuited rotor windings. These current loops induce a three-phase load current in the stator windings if the speed of the rotor exceeds that of the traveling magnetic field.

In the linear-induction generator, the polyphase stator windings are distributed at the top and bottom of the channel to produce a linearly traveling magnetic field. The interaction between the stator magnetic field and the electric current induced in the fluid flowing in the channel causes the electromechanical energy conversion. If the fluid velocity exceeds the field velocity (negative slip), electric power is generated in the stator windings. If the magnetic field velocity exceeds the velocity of the fluid (positive slip), electric energy is converted to fluid pressure and the device functions as an EM pump.

The linear-induction-type MHD generator has several advantages. Since the metal stream and the stator are magnetically coupled, no contact is necessary between the working fluid and the electrical parts of the generator. The magnetic-field excitation is provided by current flowing through the stator and the load, thereby providing a quasi-self-regulating feature to control the load voltage and current phase relation.

Test programs conducted at various laboratories have demonstrated the generation of three-phase power at 60 Hz and higher frequencies. These tests[19-23] were conducted using either NaK alloy or mercury at ambient temperatures and have simulated the electrical conditions expected in a high-temperature MHD generator. Figure 4 shows Atomics International's constant-slip linear-induction generator on the test stand; it produced up to 7 kW at 60 and 280 Hz under self-excited conditions.

A typical generator will consist of two stators producing a traveling magnetic field and a channel carrying the high-velocity fluid. The channel is sandwiched between the two stators. The MHD generator probably will be a variable-velocity type, in which the velocity of both the working fluid and the magnetic field is varied along the

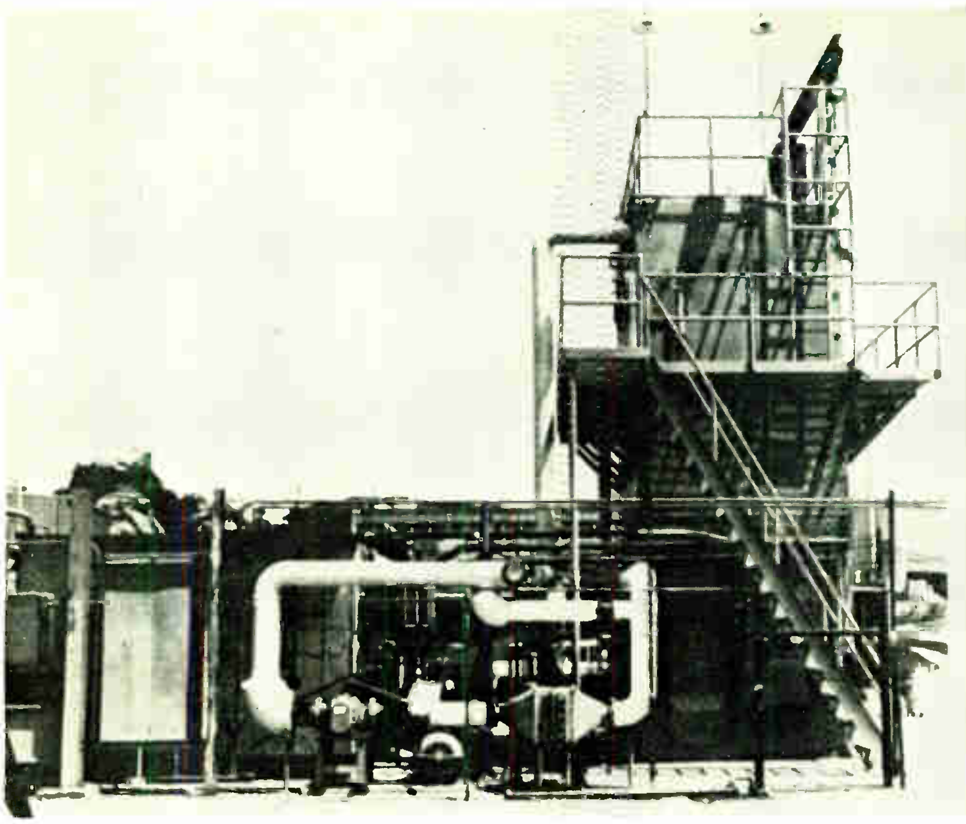
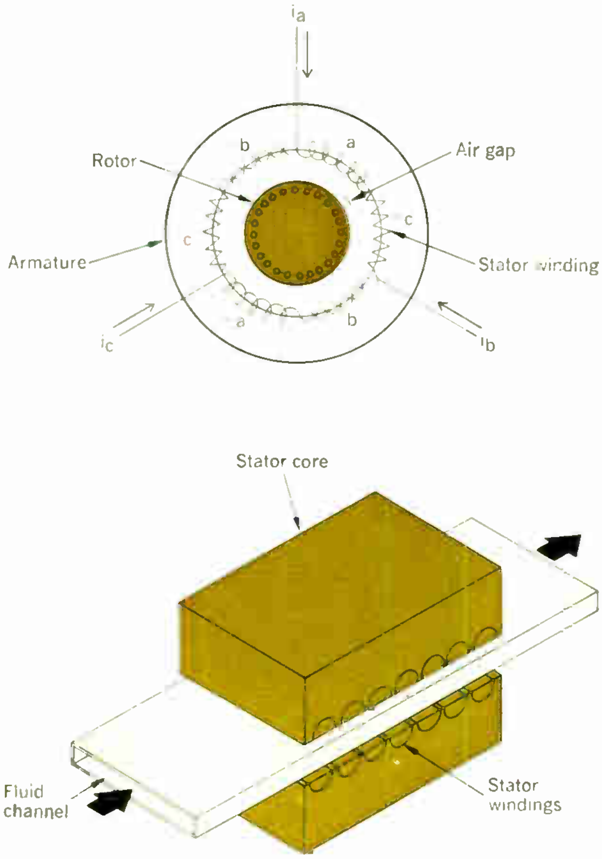


FIGURE 2. Boiling-potassium test-loop facility at Atomics International field laboratory.

FIGURE 3. Comparison of arrangement for conventional- and linear-MHD induction generators.



flow path. These gradients are created by increasing the channel cross section gradually from entrance to exit and decreasing the pole pitch of the electrical windings.

Based upon the results of the referenced test programs, an overall generator efficiency (converting kinetic to electric energy) of 70 to 80 percent can be expected.

Construction materials

Materials' selection for alkali-metal containment within the MHD power converter, the heat exchangers, and the furnace must be based on long-term tests to verify a sufficiently long-life capability, assuring an economic design.

The MHD cycle is a high-temperature, low-pressure, direct-energy conversion system using no rotating or reciprocating components. The low pressures and lack of dynamic stresses ease the problem of selecting materials with sufficient high-temperature strength. Liquid-vapor mixtures of the metal working fluid are accelerated and decelerated as the fluid passes through the various parts of the converter (nozzle, injector, generator channel, and diffuser). Good resistance to erosion is, therefore, another requirement. For the MHD cycle discussed—employing a maximum working-fluid temperature of 870°C—type 316 austenitic stainless steel should be adequate. If further testing should indicate a need for greater high-temperature strength, nickel- or cobalt-based alloys such as Inconel or Haynes 25 could be substituted.

A type 316 stainless-steel loop containing potassium was operated in the 870°C to 925°C range for a total of 8000 hours at Atomics International. During this time, the facility was thermally cycled daily from ambient to operating conditions and incurred no visible damage. It is noteworthy that the exterior of the stainless-steel piping

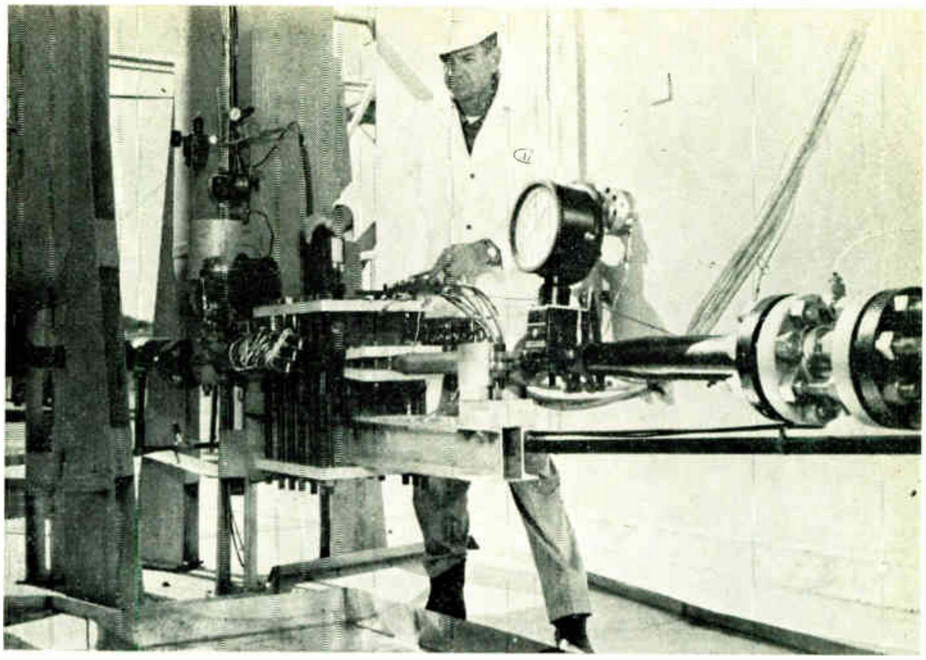


FIGURE 4. Constant-slip liquid-metal induction generator on the test stand at Atomics International field laboratory.

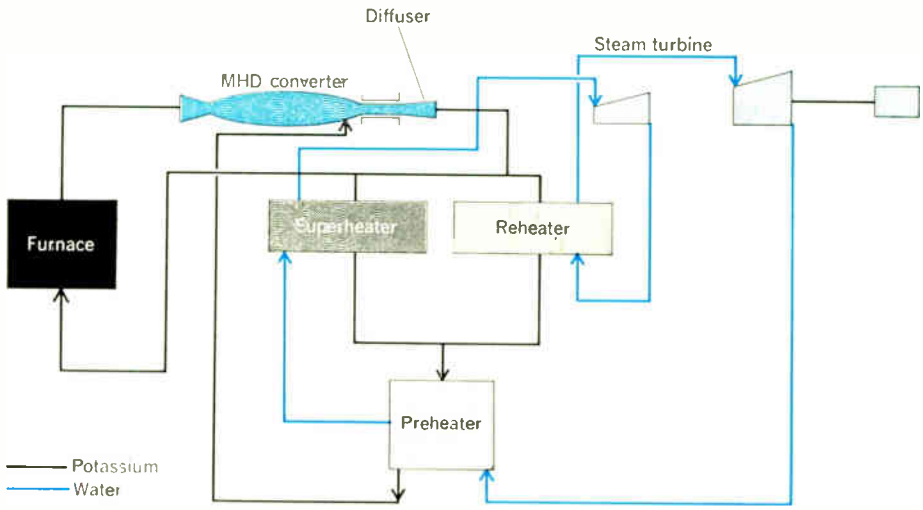


FIGURE 5. MHD-steam binary power-plant schematic representation.

was exposed to air during this period.

Tubing materials circulating the working fluid for the remainder of the plant also require special selection. For the heat exchangers, including the steam superheater and reheater, 300- or 400-series stainless steel should be satisfactory. The same material also could serve for the low-temperature tubing in the economizer and preheater sections of the furnace. The most severe conditions will have to be met in the high-temperature furnace section. Here it is anticipated that type 316 stainless steel, or nickel- or cobalt-base alloys for greater high-temperature strength, will be required.

If it should be possible to develop higher-temperature liquid-metal MHD plants in the future—perhaps up to a maximum temperature of 1100°C—it would be necessary to employ refractory metals such as tungsten, molybdenum, or niobium alloys. None of the alloys mentioned are subject to appreciable corrosion by alkali metals as long as the oxygen content of the fluid is maintained below certain limits.

MHD-steam binary power plant

The various liquid-metal MHD concepts previously described could be incorporated into a central-station power plant. The schematic diagram of a liquid-metal MHD-steam binary plant is shown in Figure 5. The principal parts of this plant are: (1) fossil-fueled furnace or nuclear reactor with external heat exchanger, where the working fluid is heated and partially vaporized; (2) MHD converter, where the thermal energy of the working fluid is converted into kinetic and then into electric energy; (3) diffuser, where the portion of working-fluid kinetic energy not utilized in the generator is converted into fluid pressure; (4) superheat and reheat exchangers, where the thermal energy of the working fluid leaving the diffuser produces steam for the conventional plant. The working fluid leaving the heat exchanger is returned to the heat source.

The overall efficiency of the binary plant can be expressed as $\eta_T = [\eta_M + (1 - \eta_S)]\eta_F$, where η_M is the MHD cycle efficiency, η_S is the steam-cycle efficiency, and η_F is

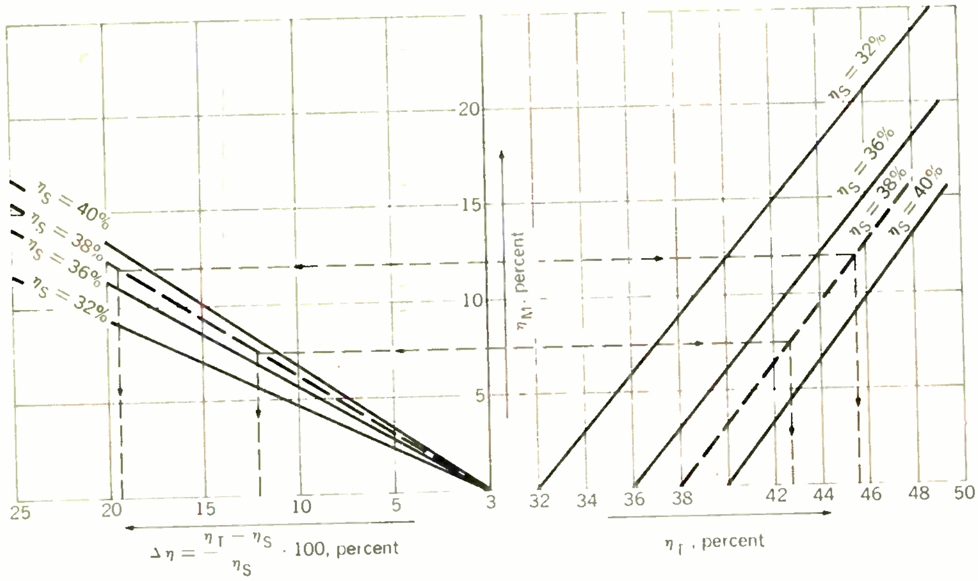


FIGURE 6. Binary-plant efficiency.

the furnace efficiency. Of course, the furnace efficiency need not be included as a factor if the heat is supplied by a nuclear reactor and there is no heat lost to flue-gas exhaust. For simplicity, the effect of the furnace efficiency will not be considered in the subsequent discussion. Figure 6 shows η_T as function of η_M for selected values of η_S. Also shown on this diagram is $\Delta\eta$, the percentage increase in overall efficiency, resulting from the use of the topping cycle, as a function of η_M.

Condensing-MHD topping cycle

Figure 7 shows the condensing type of MHD cycle as a topping unit for an MHD–steam binary plant. The flow diagram shows multistage expansion and regenerative injection. The thermal energy of the partially vaporized potassium at 870°C is expanded in five stages down to a back pressure corresponding to the vapor pressure of potassium at 565°C. The multistage expansion and multiple injection permit utilization of the available enthalpy and simultaneously limit the fluid velocity to approximately 100 m/s and thereby limit excessive losses from fluid friction as well.

The aim of regenerative injection is to match the temperature and flow velocity of the injected streams to that of the main stream in order to reduce irreversible thermodynamic losses. The injected stream to the last stage is cooled below the saturation temperature and condenses the principal vapor fraction prior to entering the generator channel. The potassium leaving the electric generator passes through the diffuser, where the major portion of its kinetic energy is converted to pressure.

A pump raises the pressure to circulate the fluid through the heat exchangers and to return it to the furnace. Potassium leaving the pump divides into three circuits.

The first circuit supplies fluid for the injection stream to each stage except the last.

The second circuit leads to the heat source; there the potassium undergoes feed heating from 565°C to about 780°C. This temperature change is achieved by bleeding potassium from the effluents of the individual stages and mixing into the main stream.

The third circuit supplies the potassium that preheats, vaporizes, and superheats the steam for the conventional portion of the plant. This potassium, cooled during the process, is injected upstream of the electric generator for purposes of vapor condensation. This third circuit could also be used to preheat the combustion air in a fossil-fueled installation. A 565°C temperature of the potassium leaving the MHD generator is chosen to provide sufficient "temperature drive" to produce 540°C steam-superheat and -reheat temperatures.

Liquid-metal MHD–steam binary plant economy

An economic evaluation of the binary plant described in the preceding section and using coal as fuel has been reported.[4] Since that publication, costs have risen. A present-day revised estimate of capital and power costs is, therefore, presented.

The cost of the generated power is comprised of capital, fuel, and operating costs. The succeeding analysis covers capital and fuel costs only, with the following assumed conditions:

Plant size, electrical MW	1000
Plant load factor, %	80
Amortization, %/yr	
Investor-owned	14.7
Consumer-owned	8.0
Fuel cost, ¢/10^9 joules	40–30–20–15
Steam cycle efficiency, %	32–36–38–40

Figure 8 shows the heat supply and heat rejection of an MHD–steam binary plant as the function of MHD-cycle efficiency for various steam-cycle efficiencies.

The detailed cost breakdown of a typical 1000-MW coal-fired, modern steam station is shown in Table II. Also shown are the estimated costs of a liquid-metal MHD–steam binary plant for a 7.5 percent efficient MHD cycle.

Using Fig. 8, the heat supplied and the heat rejected for a 7.5 percent efficient MHD cycle and an assumed 38

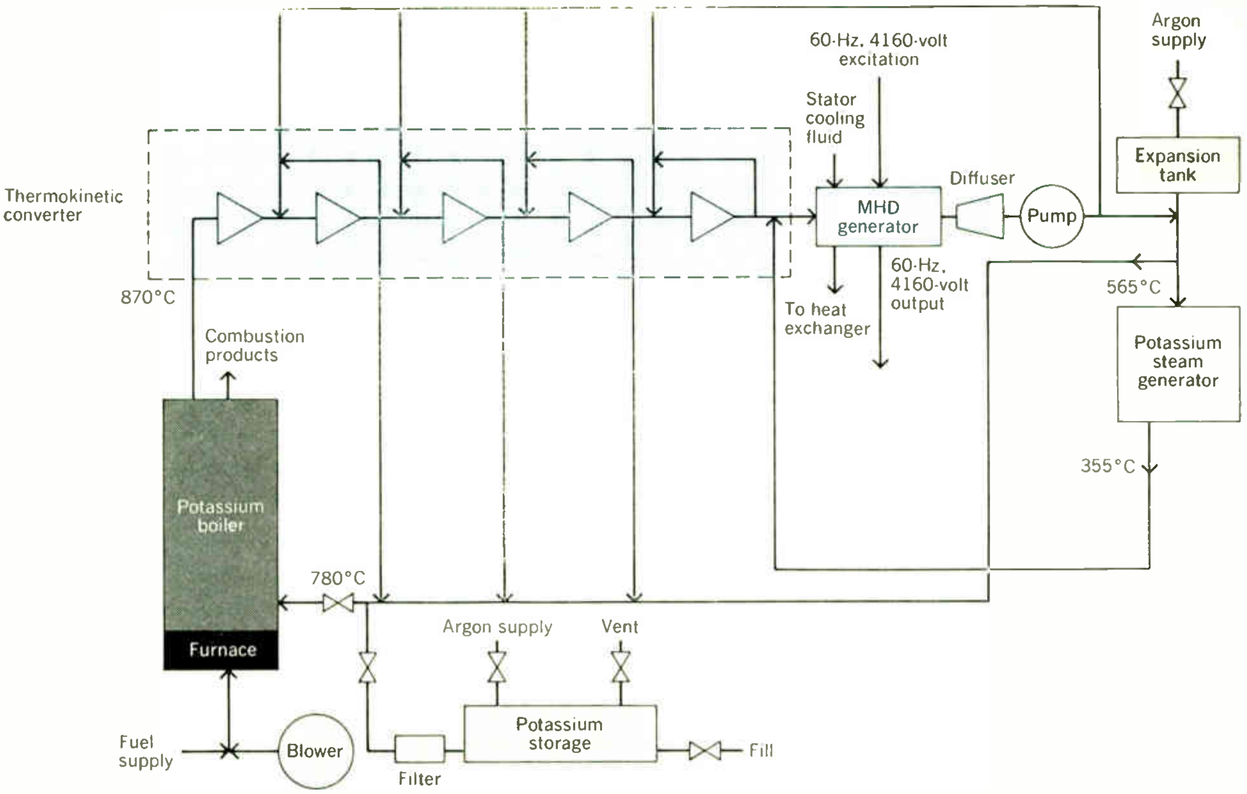


FIGURE 7. Flow diagram for condensing MHD topping cycle. Arrangement is only illustrative.

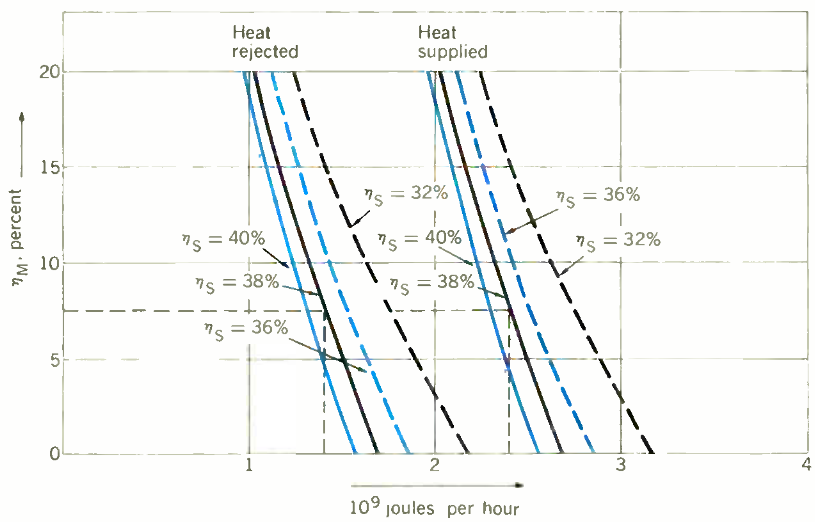


FIGURE 8. Heat supply and heat rejection for 1000-electrical-MW MHD–steam binary plant.

percent efficient steam plant are 2.45×10^9 J/h and 1.40×10^9 J/h compared with 2.78×10^9 and 1.73×10^6 J/h for a 38 percent efficient steam plant without a topping cycle. The topping cycle results in an 11.7 percent saving in heat supplied and a 19 percent decrease in the cooling requirement. For a binary plant with 1000-MW output, 175 MW is produced by MHD and 825 MW is produced by the steam plant.

Table II indicates that the cost of a conventional coal-fired steam boiler is \$32 per electrical kW. The 11.7 percent by which the heat supply is reduced results in a furnace-cost reduction of approximately 10 percent—equivalent to a cost reduction of \$3.20 per electrical kW generated.

The heat released in the furnace provides the heat input to preheat, partially evaporate the potassium, preheat the feedwater to saturation, and preheat the combustion air. The feedwater preheating is reduced by 17.5 percent, an amount proportional to the fraction of total power output generated by the MHD portion of the plant. It represents about 20 percent of the furnace-heat input. Therefore the reduction in feedwater-heating surface area results in a saving of approximately 4 percent in furnace cost, equivalent to \$1.30 per electrical kW.

The high-temperature section of the potassium furnace represents approximately 30 percent of the entire heat-transfer surface area. The cost of the tubing material of a typical boiler is about 20 percent of the entire boiler cost. The cost of the tubing material of the high-temperature section of the potassium furnace is assumed to be three

II. Cost breakdown for conventional plant and MHD–steam binary plant, in thousands of dollars

	Conventional Steam	MHD–Steam Binary
Land improvement	800	800
Power station building	10 700	10 700
Other structures	2 700	2 700
Boiler and accessories	32 000	29 000
Draft equipment	7 600	6 500
Feedwater equipment	4 300	3 700
Coal-handling system	5 000	4 500
Light-off oil equipment	80	80
Ash and dust handling	1 800	1 600
Water supply and purification	1 400	1 200
Instrumentation and control	1 500	1 350
Boiler and turbine piping	10 200	9 000
Turbine–generator and auxiliaries	25 000	21 200
Condenser and auxiliaries	3 300	2 700
Circulating-water system and cooling tower	7 700	6 400
Accessory electric equipment	10 700	10 000
Miscellaneous power plant equipment	800	800
Main transformer	1 600	1 600
MHD converter		4 000
Steam generators		10 000
	127 180	127 830
Engineering, construction, management, facilities, and interest during construction	24 320	24 400
	151 500	152 230

times that of the cost of the corresponding section of a steam boiler. Therefore, the increased tubing material cost for the potassium furnace is approximately 12 percent of the cost of a steam boiler, and is equivalent to \$3.80 per electrical kW. Potassium inventory and special safety and storage provisions may amount to an additional cost of \$1.80 per electrical kW.

The potassium furnace generates low-quality vapor, so the heat transfer between flue gas and the working fluid proceeds at a higher rate than in the conventional furnace. Although detailed studies are not presently available to determine the extent of the reduction, a conservative estimate is that a 20 percent reduction of heat-transfer surface area can be realized. This would result in an approximately 13 percent lower furnace cost, equivalent to \$4.10 per electrical kW. Summarizing these data, the cost of the coal-fired potassium furnace supplying 2.45 $\times 10^9$ J/h is \$29 per electrical kW.

Due to the reduction in the required heat input and to the fact that the steam-turbine power rating is reduced by the power output of the MHD plant, the size of the equipment for furnace draft, feedwater, coal handling, ash and dust handling, and water supply and purification is correspondingly reduced. These size reductions will decrease the cost of the equipment by an average of about 10 percent. The cost of the turbine–generator, including its condenser and auxiliary equipment and cooling water system, will be reduced by an amount more commensurate with the decrease in output rating—in this case approximately 15 percent.

The steam generators of the binary plant need only

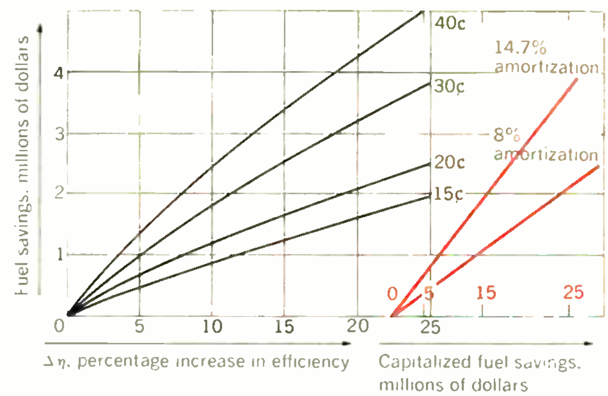


FIGURE 9. Fuel cost saving resulting from MHD topping.

vaporize and superheat the steam since feedwater preheating is provided by the furnace. Their cost has been estimated to be \$10 million. The cost of the MHD converter, including the electric generator and exciter, is estimated at \$20 per electrical kW.

The cost of the component equipment of a liquid-metal MHD–steam plant based on the above considerations is also summarized in Table II. The total capital cost of a 1000-MW, MHD–steam binary plant comprising a 7.5-percent-efficient MHD cycle and a 38-percent-efficient steam plant is \$152.2 million. The use of a more efficient MHD cycle would result in a lower capital cost. For example, for an assumed 12-percent-efficient advanced MHD cycle, a binary plant cost of \$146.0 million has been estimated.

Figure 9 shows the fuel saving as a function of the percentage increase in overall efficiency $\Delta\eta$. Also shown in Fig. 9 is the capitalized fuel saving for 14.7 percent and 8.0 percent amortization rates, indicating the difference between providing capital for an investor-owned or consumer-owned utility.

In order to compare the operating economics of power plants, the difference in fuel costs can be amortized and combined with capital expenditures. For a coal price at the plant site of about 30 cents per 10^9 joules and an MHD-cycle efficiency of 7.5 percent, the yearly fuel saving is \$2.1 $\times 10^6$ as shown in Fig. 9. If capitalized, the amount of this fuel savings—at 14.7 percent amortization rate—is \$14.7 million. Combining the capital expenditure of \$152.2 million, shown in Table II, and the capitalized fuel saving of \$14.7 million, the effective cost of the binary plant would be \$137.5 million. For a more advanced, 12-percent-efficient MHD unit, the yearly fuel savings of the binary plant would be \$3.2 million, corresponding to a capitalized fuel savings of \$21.0 million. Using this figure with an estimated plant cost of \$146.0 million yields an effective capitalized cost of \$125.0 million. As illustrated by these two examples, the estimated combined capitalized fuel saving and plant cost of a liquid-metal MHD–steam binary plant is attractive when compared with the capital cost of \$151.50 per electrical kW for a modern steam station without a topping cycle.

Summary

Although several liquid-metal MHD power-conversion cycles have undergone exploratory engineering and experimental investigation, no complete cycle has yet been operated that converts heat to electricity. High-temperature experiments have demonstrated the conversion of heat into a high-velocity stream of liquid metal, but all generator testing has been performed separately and at ambient temperature.

Obviously, more development work and experience with liquid-metal MHD in actual plant operation would have to be carried out before performance estimates could be assured. Liquid-metal MHD does offer, however, one of the few feasible approaches to increased efficiency and decreased thermal pollution of future central-station plants.

This is a revised version of an article that was presented at the IEEE Winter Power Meeting, New York, N.Y., January 25–30, 1970.

REFERENCES

1. *MHD for Central Station Power Generation: A Plan for Action*, Panel on Magnetohydrodynamics of the President's Office of Science and Technology, June 1969.

2. Prem, L. L., and Parkins, W. E., "A new method of MHD power conversion employing a fluid metal," *Proc. 1964 Internat'l Symp. Magnetohydrodynamic Elec. Power Generation (Paris)*, vol. 2, p. 971, European Nuclear Energy Agency (ENEA), paper 63.

3. Prem, L. L., "Analytical and experimental results of the fluid metal MHD power conversion program," *Proc. 1966 Symp. Magnetohydrodynamic Elec. Power Generation (Salzburg)*, vol. II, p. 1019, International Atomic Energy Agency (IAEA) and ENEA, paper SM-74/184.

4. Prem, L. L., "Fluid metal MHD–steam binary plant economy for central station plants, "*Proc. 1968 Symposium on Magnetohydrodynamic Elec. Power Generation (Warsaw)*, vol. III, p. 2005, IAEA, paper SM-107/24.

5. Radebold, R. D., *et al.*, "Energy conversion with liquid metal working fluids in MHD Staustrahlrohr," *Internat'l Symp. 1964 Magnetohydrodynamic Elec. Power Generation (Paris)*, vol. 2, p. 985, ENEA, paper 64.

6. Radebold, R. D., *et al.*, "Energy conversion with liquid metal working fluids in MHD Staustrahlrohr," *Proc. Symp. Magnetohydrodynamic Elec. Power Generation (Salzburg)*, vol. II, IAEA and ENEA, paper SM-74/30.

7. Radebold, R. D., "Energy conversion with liquid metal working fluids in MHD Staustrahlrohr," *Symp. 1968 Magnetohydrodynamic Elec. Power Generation (Warsaw)*, vol. III, p. 1439, IAEA, paper SM-107/5).

8. Boldyrev, V. M., *et al.*, "Thermodynamic analysis of new cycles for liquid metal MHD generators," *Symp. 1968 Magnetohydrodynamic Elec. Power Generation (Warsaw)*, vol. III, p. 1587, IAEA, paper SM-107/142.

9. Bogomolov, B. G., *et al.*, "Results of research on a single component system for a liquid metal MHD converter," *Symp. 1968 Magnetohydrodynamic Elec. Power (Warsaw)*, vol. III, p. 1563, IAEA, paper SM-107/135.

10. Elliott, G. D., "Two fluid magnetohydrodynamic cycle for nuclear electric power generation," *Am. Rocket Soc. J.*, vol. 32, p. 924, June 1962.

11. Elliott, G. D., *et al.*, "Theoretical and experimental investigation of liquid metal MHD power generation," *Proc. 1966 Symp. Magnetohydrodynamic Elec. Power Generation (Salzburg)*, vol. II, p. 995, IAEA, and ENEA, paper SM-74/177.

12. Petrick, M., and Lee, K. Y., "Liquid MHD power cycle studies," ANL-6954, June 1965.

13. Petrick, M., and Roberts, J. J., "Performance of space power liquid metal MHD cycles utilizing a two phase flow generator," *Space Craft and Rockets*, vol. 4, p. 967, Aug. 1967.

14. Sense, K. A., and Gelb, G. H., "Magnetohydrodynamic power generation using a bifluid liquid metal generator," *AIAA J.*, vol. 5, p. 862, May 1967.

15. Dmitriev, K. I., "Investigation of a liquid metal jet MHD generator," *Symp. 1968 Magnetohydrodynamic Elec. Power Generation (Warsaw)*, vol. III, p. 2035, IAEA, paper SM-107/134.

16. Gratton, C. P., *et al.*, "A gas cooled fast reactor with direct cycle potential," presented at the IAEA Symp. Advanced and High Temperature Gas Cooled Reactors, Julich, Germany, Oct. 21, 1968, paper SM-111/67.

17. Cain, C., Jr., and Nelson, W., "Corrosion of superheater, and reheater of pulverized coal fired boilers," *Trans. ASME J. Eng. for Power*, vol. 11, p. 468, Oct. 1961.

18. Borio, R. W., *et al.*, "The control of high temperature fire-side corrosion in utility coal fired boilers," West Virginia University, Morgantown, Apr. 1969, PB-183716.

19. Rowe, I., "Sixty-cycle test results of the cascade generator," *Ninth Symp. Eng. Aspects of Magnetohydrodynamics*, p. 171, Apr. 1968.

20. Prem, L. L., "High frequency variable fluid velocity MHD generator," *Proc. Symp. 1968 Magnetohydrodynamic Elec. Power Generation (Warsaw)*, vol. III, p. 1835, IAEA, paper SM-107/23.

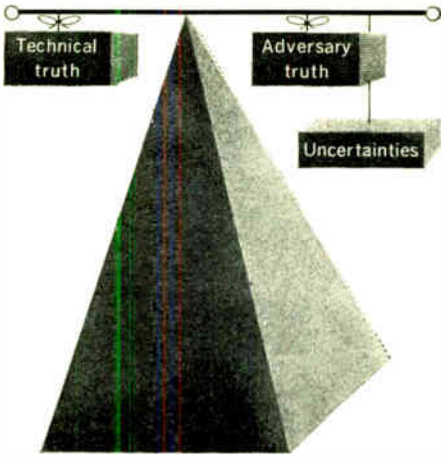
21. Elliott, G. D., "Performance capabilities of liquid metal MHD induction generators," *Proc. Symp. 1968 Magnetrohydrodynamic Elec. Power Generation (Warsaw)*, vol. III, p. 1859, IAEA, paper SM-107/41.

22. Ulber, M., and Schulz, T., "Experimental results with a liquid metal MHD induction converter, "*Proc. Symp. Magnetohydrodynamic Elec. Power Generation (Warsaw)*, vol. III, p. 1979, IAEA, paper SM-107/6.

23. Baranov, G. A., *et al.*, "Experimental investigations on liquid metal MHD generators," *Proc. Symp. 1968 Magnetrohydrodynamic Elec. Power Generation (Warsaw)*, vol. III, p. 2047, IAEA, paper SM-107/136.

Lawrence L. Prem is supervisor, energy conversion, of the Research and Technology Division at Atomics International, a division of North American Rockwell Corp. There he oversees all phases—design through testing—of advanced power-conversion cycles, including magnetohydrodynamic, thermoelectric, and thermionic systems. Prior to joining Atomics International in 1959, Mr. Prem had his own consulting-engineering firm for water supplies, industrial-water treatment, and small power-generating systems (1940–1944); designed and evaluated thermal power cycles and studied overall system performance of central power stations at Ebasco Services (1946–1956); and engaged in operation and performance analyses of gas-cooled, pressurized-water and boiling-water power reactors at the Nuclear Products Division of ACF Industries. Mr. Prem has written many articles on MHD-power generation for central stations and terrestrial and space-power applications. He is a member of the ASME, the American Nuclear Society, and the AIAA. He has recently been appointed consultant to the U.S.–German Natural Resources Panel on MHD.

William E. Parkins joined Atomics International in 1948 and is now director of its Research and Technology Division, having advanced from group leader, to chief of engineering, to director of the Organic Reactors Department, to associate technical director. His responsibilities now cover areas in energy conversion radiation effects, instrumentation, and metallurgy, among others. Previously, Dr. Parkins had been an assistant professor in the Physics Department of the University of Southern California and before that (from 1942 to 1946) he was a research associate at the University of California, where, as part of the Manhattan Project, he worked on the development of quantity isotope separation using electromagnetic techniques. Dr. Parkins received the B.S.E.E. degree from Montana State College and the Ph.D. degree in physics from Cornell University. He is author of some 40 scientific and engineering articles. He is a Fellow of the American Physical Society and the American Nuclear Society; and he has served as delegate to international meetings sponsored by the U.S. Atomic Energy Commission and the International Atomic Energy Agency.



Engineering truth in competitive environments

The success of decisions in both public affairs and industry depends today on the correct assessment of technical uncertainties. In an atmosphere of adversary confrontation, the efforts to hide them can prove the source of much harm

Raymond M. Wilmotte Management Consultant, Washington, D.C.

The lack of understanding, analyzing, and communicating technological "uncertainties" are presented by the author as seriously undermining the effectiveness of decision-making in both public affairs and industry. Uncertainties are as important to truth as certainties and should be part of all forms of technical communication. "Technical truth," it is pointed out, is not developed in the legal process of adversary confrontation. On the other hand, "adversary truth," as presented by the contestants, is only part of the truth, for it excludes uncertainties, which are left to the perspicacity of the audience. In the well-publicized ABM controversy, the technical atmosphere had degenerated into that of an adversary confrontation, and technical truth with its uncertainties could not emerge. This basic and typical deficiency of the ABM controversy is not limited to public affairs: it exists strongly in industry and takes its toll in reducing the quality of decision-making in inefficient operations and in unnecessary crises, all carrying a burden of cost. It appears that the damaging effects of inattention to technical uncertainties could be radically reduced under a carefully worked out and nurtured environment.

In a recent article in IEEE SPECTRUM (August 1969), the late Seymour Tilson gave an outstandingly competent reporting of a controversy of national importance involving technology. The reporting had a message that took the form of a question. It was stimulated by a statement that the Director of Research and Engineering of the Department of Defense, Dr. John Foster, made in the midst of the controversy. "I want to point out," he said, "that one does not obtain a meaningful technical judgment by taking a vote of the scientific community, or even of Nobel Laureates." "How then," asked Seymour Tilson, "does one obtain a meaningful technical judgment?"

A lesson from the ABM debate

This statement and question were made in the context of the ABM controversy, a controversy that split the Senate almost exactly 50:50—a split undoubtedly largely political, but affected also by the fact that the technical discussion left the Senate and the public better informed about some of the mechanics and critical features of the ABM, but confused as to the conclusions that could be drawn.

Tilson's question opens up an area of importance, one that is particularly critical to the scientific community today, when society is beginning to question the pragmatic value of technology. But the more important aspect of this question, as will be shown, is its bearing on the management of technology—on the relationship between decision-makers of government and industry on the one hand and scientists and engineers on the other. The ABM controversy is an important incident that brings this larger problem to the fore.

What are the practical conditions that would enable scientists and engineers, individually or as a community, to give the public and the decision-makers technical information and advice that is reliable, fully truthful, and of practical use? What were the conditions in the ABM controversy, for example, that inhibited the scientific community from providing the advice that society could reasonably expect of it? The expertise was there, but the technical foundation that would have been helpful for decision-making was not provided. What conditions are favorable for allowing engineers—individually and as a community—to give the most effective service to society? How can these conditions be provided?

The present analysis leads to the conclusion that favorable conditions are rare, but in many cases—possibly in most—it may be practical to set up a routine that will develop more meaningful technical judgment than was possible in the ABM debate.

Scientists and engineers used to be thought of as rather special people, different from others. It was generally believed that what they said was likely to be free from personal bias, that they could be depended on to present a balanced picture, and that they would reach a conclusion through an objective analysis of the facts, not by selecting the facts that support a predetermined conclusion. Their candor in technical areas was viewed as very special. What made them appear special was the way their thinking was structured in the limited area of their technical expertise—an area in which they often could talk at length and objectively because here their human emotions and personal interests were assumed not to be operative.

Others, when asked to do so, certainly would be willing to raise their right hands and swear to the truth, the *whole* truth, and nothing but the truth ... and then to take advantage of a few socially accepted deviations, such as witholding aspects of the truth that might be damaging to one side of an argument, or introducing expressive adjectives that might create a more desirable impression than the bare facts might warrant, or avoiding explanations that might clarify a point that they hoped would remain misunderstood. Scientists and engineers, though, were expected to do more than merely use sentences that were true in themselves; they had the reputation for wanting also to communicate what they thought was the whole truth—without equivocation, subterfuge, or guile. The whole truth clearly is not limited to what one knows and to one's opinions; it includes also the *uncertainties* about one's knowledge and experience, so far as one is aware of them.

Two ways of seeking truth

Scientists have been accustomed in their work to question anything about which they were unsure. Whenever they could, they would seek to remove their uncertainties. When they could not, they were expected to state what the uncertainties were, thus giving full information to their audience and possibly leaving members of that audience to fathom questions left unanswered. This is the way in which science uncovers the secrets of nature. In broad terms, the constant questioning—the delving into uncertainties in a continuous and systematic way—may be said to be the scientific process. Some aspects of the process are routine to all scientists and engineers. In the measurement of a physical quantity, it would be unheard of for a professional to question the necessity of giving a number without qualifying it with the accuracy (the uncertainty) of the measurement.

The mental attitude of the individual who sees that there is a gap in the truth when uncertainties are not expressed is altogether different from the attitude attending the process of finding the truth by the legal process of adversary confrontation, for that method in effect eliminates the voluntary disclosure of uncertainties. Scientists are inherently unsympathetic with this legal process, at least on technical matters. They would question the integrity of an engineer who would swear that a power line produced a force on a hand-held steel reinforcing rod a few feet away, without explaining that the force was a small fraction of an ounce. But the client—possibly others too—would admire the lawyer who obtained a large settlement from a power company by arguing the existence of this force and withholding mention of its size.* In fact, the lawyer might have been considered delinquent in his responsibilities if he had brought out that the size of the force was negligible! To do so was the responsibility of the opposing lawyer.

As scientists and engineers have encountered more and more the value system that controls political life, their natural bent on technical matters has given way with increasing frequency as their emotions and personal interests have become more closely involved.

The success of scientists and engineers in the development of technology—the complexity of the systems they can put together, their ability to analyze complex operations into elementary parts from which one can begin to understand the whole—moves them into social prominence. Their advice is sought by Presidents. They have begun to express opinions on all kinds of subjects, asserting the same degree of authority that they rightfully use in areas where they are truly expert.

It is not surprising, therefore, that on some matters of great national import involving technology, one now finds scientists and engineers espousing opposite contentions. One finds them presenting well-organized arrays of technical facts and analyses mixed with overtones of political opinions, and opposing groups reaching contrary conclusions. The public, which has begun to believe it possible that technology is doing more harm than good, has watched these encounters and is coming to the conclusion that scientists and engineers are not special people after all. They are much like everyone else.

"Technical truth" should be seen to be different from the "adversary truth" presented in adversary confrontation. The former includes both the findings and the uncertainties, the latter only a set of findings. Just as a technical measurement is not complete without an analysis and statement on the probability of error, so a technical conclusion is not complete without an analysis and statement of its uncertainties. The fact that uncertainties of measurement can be expressed quantitatively does not relieve the scientist from the responsibility of listing and explaining his nonquantifiable uncertainties. The importance of recognizing the difference between technical and adversary truth, as we shall see, is not limited to the political arena but carries over into industrial life.

The scientific process in the ABM controversy had all the earmarks of endeavoring to establish the truth on technical matters by adversary confrontation, which, though possibly best for legal proceedings, does not work out in the technical arena. It did not work with the ABM. In this case, well-known scientists, men who could be relied upon to know and understand the technical intricacies of the problem, presented for all to hear very different conclusions, not only on what action should be taken but also on the technical analyses undergirding their recommendations. How could the audience that they were addressing decide which set of analyses and conclusions was the correct one? Scientists as a community failed to give the country what it could reasonably expect—a reliable foundation of technical conclusions on which politicians could build their decisions.

In the technical arena, the truth requires an overwhelming consensus of the scientific community. Unless the consensus is overwhelming—that is, unless there are extremely few reasonable scientists likely to disagree

* The legal case outlined actually took place.

when presented with the facts, analyses, and uncertainties—the "technical truth" in the area under consideration has not been reached. Where technical conclusions differ, the development of technical truth requires an effort to examine the uncertainties that are the basis of the differences, to try to reduce the gap or devise ways for so doing.

It is to be noted that there is little depth to an agreement unless it includes agreement on the nature of uncertainties. This concept brings out a basic difference between the processes for developing technical truth and adversary truth. In a technical controversy, technical truth is reached when the two sides have convinced each other what the truth is. In adversary controversy, there is no effort to have the two sides agree as to what is the truth. The truth is established by the *audience* whom the participants are addressing—Congress, a judge, a jury, or the public. The decision of the audience becomes the truth.

The importance of uncertainties

The quality of the truth obtained with adversary confrontation depends heavily on the ability of the audience to fill in the information or uncertainties known to or obtainable by the participants, but not provided by them.

The controversy over the ABM involved some technical and some political factors. There was a wide gap of disagreement in both. One can well understand the difficulty of bridging the gap on questions in which the scientific community has no particular competence—such as the probable Soviet reaction to the building of the ABM—and recognize the impossibility of carrying out tests or reliable analyses that would be helpful to bridge them. But it is more difficult to understand why there was a wide gap on technical matters. It could have been helpful, for instance, for the two sides not only to give their opinion on the estimated performance of a Soviet attack and of the ABM defense against it, but for them to have also included their uncertainties, the reliability of the assumptions, and the facts and analyses they used, in terms that would be broadly understood. These should have been an essential part of the engineering process. With them, a better understanding of the reasons for the differences in conclusions could have been developed. But in the environment that existed this simple approach seemed impossible.

What could have been done? Probably nothing, in the environment that was allowed to develop. Probably a lot, in a different environment requiring only a slight change in discipline. The change may require consistent effort but should become so routine as to take place almost unconsciously.

No scientific or engineering study should be considered complete without an "uncertainty analysis." No system or component is really understood by its designer until he has carried out such an analysis.

Uncertainty analysis is an important part of the design process and needs to be applied not once in a while, but routinely. In the case of the ABM, it should have been possible to reduce drastically a number of critically important technical differences—the difference between 25 percent and 5 percent in the estimates of the number of our Minuteman missiles surviving the first Soviet attack; the difference between the estimates of 4:1 and 1:1 in the cost ratio of defense to attack; the difference between "hardly effective" and "seriously confusing" in the evaluation of penetration aids. It may be difficult to reduce the range of reasonable uncertainty on the reliability of ABM, particularly its computer, and the human problem of operating the system for the first time on a few minutes' notice after years of being on the alert, but even there one could hope that the wide range of disagreement could be reduced, or analyzed into its component reasons.

Why was it not possible for the scientists on either side of the controversy to develop their uncertainties and establish the reasons for the differences in their conclusions? The answer is that the environment was that of adversary confrontation and the scientists in the controversy followed its well-established pattern. The controversy could not lead to the "technical truth" because the parties were not trying to reach a conclusion, but to prove one. They were addressing the public and its representatives, the nontechnical decision-makers. In such an environment, one side cannot admit uncertainties unless the other side reciprocates. The result is that description of uncertainites is avoided wherever possible. The whole truth could not, therefore, be developed. There is little doubt, however, that if it were routinely considered that good engineering requires an uncertainty analysis covering assumptions, facts, analyses, and opinions, reasons for differences would be clarified and the differences greatly reduced.

What the ABM controversy can teach industry

In industry, the truth developed is sometimes the technical truth, but more often—and at considerable expense—it is the adversary truth that prevails, with the customer or a superior as the "audience."

One can generalize from the example of the ABM that whenever the purpose of a technical presentation is to "sell" rather than communicate something, and competition exists, the foundation for a process of adversary confrontation is established.

In industry, the selling environment comes from what might be termed the "think-positive syndrome." Corporate management is constantly "selling" the corporate image to customers; divisional vice presidents sell their capability to corporate management; middle-management people sell their ideas to divisional vice presidents; engineering managers sell their competence to the program manager—and so on, each seeking recognition and avoiding being the bearer of bad news.

At each level, the conditions are ripe for adversary confrontation. "Think positive" is the advice stated or implied that travels from each level to the next lower one. That advice is often interpreted to mean "concentrate on positive things" even though the most positive thing to do may be to concentrate on negative things.

The syndrome inevitably tends to obscure uncertainties until they become visible as deficiencies, to let negative things develop until they reach crisis proportions, to make difficult the introduction and operation of managerial feedback loops, to undermine attempts at measuring performance; in sum, to postpone the discovery of trouble. In large programs, it tends to hide from the program manager the true condition of his program. Near its end, he is often faced with urgent and competing demands from his managers for additional funds and more time, and has quite an inadequate background of information on which to judge the relative merits of the demands—and usually has no time to acquire more. He becomes the "audience" of an adversary confrontation.

Effects of the think-positive syndrome

The generalized effect of the syndrome is to distort all managerial feedback loops in which it is manifested. It thus degrades decision-making processes, for they all depend in one way or another on feedback of information. The effectiveness of feedback depends on assessing accurately and communicating speedily changes in a situation, in order to check whether the operation conforms with the plan and what uncertainities arise in their development. The syndrome tends to degrade both the accuracy and the speed. It always delays information, often injects errors, and may even prevent entirely the establishment of a communication channel.

It would clearly be desirable for uncertainties to be brought into the open, not to overemphasize them but to bring them into proper balance with other information. They would help guide the progress of a program, show where timely support might prevent the development of serious problems, and provide major support to decision-making generally.* Schedule and cost controls are essential, but they cannot be fully effective without better information of the true state of a program, the hurdles that it faces and may face, and a better estimate of its probable outcome than is currently possible.

The effect of the "think-positive" syndrome on a program or an operation may be answered by asking a few questions such as the following.

It is generally admitted that many problems originate at managerial interfaces. Why then are much effort and many charts devoted to detailing line-managerial responsibilities and practices and hardly any to interface responsibilities and practices? Why do routine audits of operations concentrate on the adequacy of line operation and gloss over interface operations? Why does communication of defective interface operation have to go up the line, across, and down on the other side, leading to delays and distortions rather than in the first instance by a *routine* straight-across path? Is it that the circuitous path helps "control" the natural flow of negative information, of uncertainties, in the operation?†

Operations across managerial interfaces are a good example of some of the effects of the think-positive syndrome. A short discussion with a lower-level manager in charge of an operating unit typically develops the following information: He knows what his unit is expected to produce, and who receives his product. He knows the expected costs and schedules. He knows the areas that interface with his unit, but when there are many he may forget some as he lists them. He will also know what flows across the interfaces but he will miss some items as he talks about them. It may be difficult to know whether he has left out anything important. He has made no list, nor does he keep a record of what flows or what fails to flow across the boundaries of his unit, unless it is connected with some hardware inventory for which he is accountable. He keeps close track of his output, personnel, costs; quality nearly always takes secondary place. When asked about his principal problem areas—what gets in his way in seeking to meet his cost and schedule assignments—he gives clear answers with examples of recent experiences. His analysis of the causes of his problems nearly always leads to the operation of an adjacent unit that does not provide what he needs at the time that he needs it, or provides something that is deficient. He has always been able, he explains, to wangle something to overcome these problems. He is proud of his success in some particularly difficult situations and the compliments he received. He is clearly better at fighting fires than at preventing them. When conditions grow bad beyond his endurance, he brings the matter up at the weekly staff meeting, following which something sometimes happens, sometimes not. By investigating the other side of an interface that appears to give trouble, it is usually easy to find the true nature of a problem. Not infrequently, other problems are uncovered at the same time. In many cases, it is relatively simple for the managers on either side of an interface to agree to some simple routine reporting giving each side information on the flow across the interface and the deficiencies encountered. For instance, the manager of a manufacturing shop could advise production control on the number of times each week his production has been hampered by failure to provide the planned accumulation of parts and materials. This simple information developed on a *routine* basis will speak more clearly than many orders from above.

Curing the think-positive syndrome

Another common example is that of a unit whose responsibility is to issue reports—statistics, perhaps. The unit generally endeavors to demonstrate its importance by expounding on the number of reports distributed and the managerial ranks on the distribution list. Seldom does the unit make an analysis of the "uncertainties" of its activity—how well are the users' needs or wants served, and to what extent does the report provide for them information that is useful in a form that is convenient and takes up a minimum of time to use? What the reports were planned to do is often known; what they actually do and what they could do are seldom known, certainly hardly ever reported. It is usually simple and requires no great effort to have from time to time *personal* interviews with a sample of key users, to discuss the uncertainties of those who prepare the report and thus be able to reduce them (the uncertainties, that is!) to a minimum.

An interesting case involved an area that was under review in a wide search for the reasons for problems that were besetting a large program. The area made a

* An important application of this principle is in the communication of the results of mathematical modeling or simulation modeling to a decision-maker. For him to make effective use of the model and its outputs he must understand its assumptions, approximations, and sensitivities; in other words, its uncertainties. Without this information, the model can lead him seriously astray.

† Sometimes acting in accordance with the rules of the think-positive syndrome may appear to benefit an individual or even to be necessary to maintain his status within an organization. In most cases, however—possibly in every case—this is an illusion. The benefit, when it exists, is usually temporary. In the long run, the syndrome inevitably causes damage, and he who can consistently overcome it will be recognized and will benefit from this recognition. It is important when acting contrary to the rules of the syndrome that uncertainties be brought out in a forthright manner, free from a sense of explaining a deficiency, but rather from the point of view of presenting a fact and, where appropriate, the corrective action that appears desirable. Understanding, recognizing, and acting to counteract the syndrome's damaging effects will help channel personal goals and emotional reactions along steady and constructive lines rather than along temporary and damaging ones.

self-audit. It uncovered some 50 places of defective operations, 48 of which originated outside the boundaries of the area. The audit was thorough and quite accurate. The interesting feature of the episode was not the audit itself or the effort that followed to correct the specific symptoms uncovered, but the lack of interest in answering the basic questions: Why had these defects originating across the interfaces remained uncovered and why had not those who knew of their existence taken steps to help correct them and, if they had, why had they been unsuccessful? Was it the syndrome's inhibiting power?

The preceding are examples of simple cases generally applicable to junior managers. There are many such throughout a major operation. Relatively little effort is needed to introduce routine corrective feedback that can counteract many of the syndrome's effects at these levels. Similar conditions in more complex form exist at higher levels. The common basis for operational problems appears to be the unwritten but generally accepted law that the mention of uncertainties should be avoided as much and as long as possible. The reason for this law lies in the fact that much of our activities take place in an atmosphere of adversary confrontation.

There is little doubt that the think-positive syndrome is damaging and costly. As a start at developing a corrective trend, scientists and engineers should make it a routine on technical matters to include an uncertainty analysis, to expect one from their peers, and, if necessary, to demand it.

A concluding note

It seems appropriate to apply a modicum of uncertainty analysis to the previous discussion. What are the uncertainties associated with the stated and implied recommendations for industry? Most of the analysis in this article is subjective reasoning and therefore open to criticism by those with different subjective thinking. There is, to date, little experimental verification of the effectiveness of such recommendations. What there is, follows.

Concentration on interface operations in managerial audits has been found to be an effective technique for locating problems—the degree to which managers did or did not understand their true responsibilities, their place in the scheme of things, and the irrationalities of some of their behavioral patterns. It is also consistently true in corporations that uncertainties in engineering design, though known, are not systematically passed up the line or communicated across the interface to inspection or test. These uncertainties are manifested in a lack of knowledge of areas that could not be inspected and of parts that are not fully exercised in final test. There is plenty of knowledge and documentation of what tests and controls can do, but little of what they cannot do and what remains undone. Usually, for example, little information is available on why a test procedure has failed to give warning of a defect in design. The lack of information on this negative side makes it difficult to assess the relative values of different test procedures.

More complex situations occur in design engineering. It is not uncommon for a subsystem manager, for instance, to supervise and review the design of the components of his subsystem and yet not know the weak spots that are known or suspected by the component designers. The subsystem manager usually knows that certain desirable analyses and tests had to be discarded because of limitations of budget or schedule, but generally he has only a vague idea of the uncertainties introduced by their omission. It is even less common for plans, procedures, and implementation of final testing—qualification and acceptance tests—to reflect the existence of these uncertainties. The systematic transmission of uncertainty information could be very helpful, first to the subsystem manager, then to the system manager and to the manager of testing, and thence to the program manager, not only to direct the program as it progresses but also to develop a deeper understanding of exactly what has been designed and produced under their direction. This flow of uncertainty information takes the managers beyond the performance of the elements of the system and of the system itself as the work progresses, giving them greater ability to make rational projections of what is likely to occur. It will generally permit corrective action before it is too late or excessively costly, and at the end it will give a more accurate sense of the degree of confidence that can be placed in the system—that its performance will be maintained, that it can be safely duplicated, and how it can be improved.

As yet, there has been no opportunity to apply broadly the concepts and principles outlined here. Will behavioral patterns prevent an effective application? The answer to this question is not known and represents an important uncertainty. A subjective judgment is that they will often be a serious impediment, but that effective application can be developed in a suitable environment.

The author wishes to express his appreciation for interesting and valuable suggestions made by the late Seymour Tilson during the preparation of this paper.

Raymond M. Wilmotte (F, L) received B.A., M.A., and Sc.D. degrees in engineering from Cambridge University (Corpus Christi College), England. On graduating, he joined the National Physical Laboratory, the British equivalent of the National Bureau of Standards, engaged in research on antennas. Arriving in the United States in 1929, he worked on blind landing techniques for the Aircraft Radio Corp., Boonton, N.J. In 1932, as consultant to the broadcasting industry, he designed, built, and proved out the first directional antenna in the regular broadcast band to protect the service area of a station from the interference of another cochannel station. He has continued consulting throughout his career, first in broadcasting and subsequently with the government through the Wilmotte Laboratory, with contracts on radar, proximity fuze, antenna, and communications R&D. He was one of the first to correlate wide-band signals optically using ultrasonics.

In 1958, Dr. Wilmotte joined the advanced military systems group of RCA and became program manager responsible for the development and production of the "Relay" spacecraft, the first NASA communications satellite. During recent years, he has been a consultant on special aspects of management to major electronics corporations, nonprofit organizations, and government agencies. Dr. Wilmotte has recently coauthored a study that was published by the ASCE on technology and decisions in transportation, using the problem of airport access as an example. He has received the Bureau of Ordnance Development Award from the Navy Department for his efforts in W.W.II, published over 50 professional papers, and been awarded more than 40 patents.

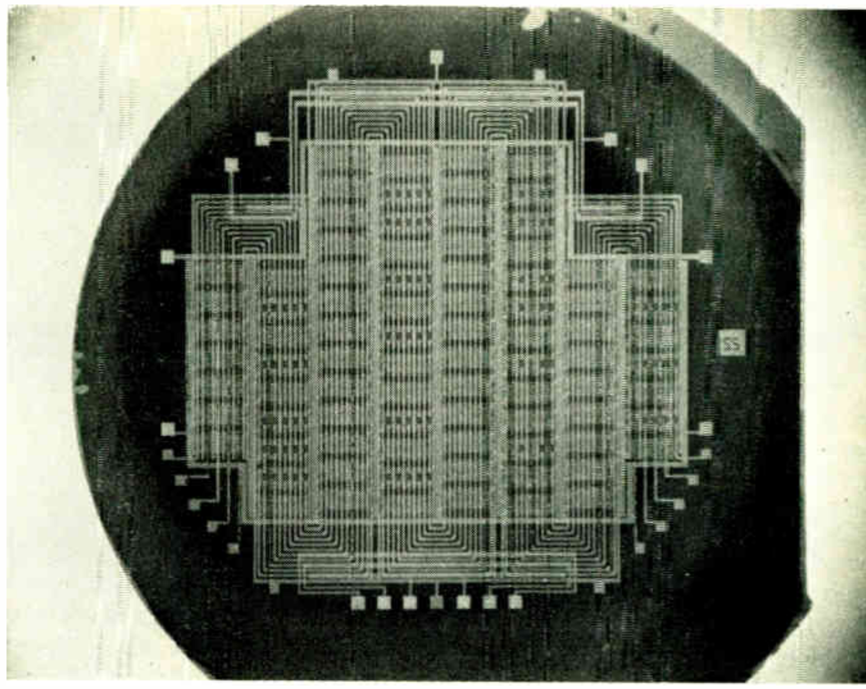


FIGURE 1. **Digital correlator, with two-layer discretionary interconnection.**

Technological advances in large-scale integration

Large-scale integration is now coming of age, and within a short time its impact on the semiconductor industry is expected to be dramatic and far-reaching

Herschel T. Hochman, Dennis L. Hogan Honeywell Inc.

Not very long ago the concept of large-scale integration was just that—a concept. But since that time most of the more difficult technological problems have been resolved and many others are well on their way to solution. The important potential advantages of LSI—reduced cost, improved reliability, size and weight reductions, and computerized fabrication—served to provide the impetus for their rapid development. Focusing on the digital correlator as an example, this article describes the techniques and problems involved both in the basic design and in the fabrication processes.

Today the semiconductor industry is on the threshold of a new revolution in solid-state technology. This revolution encompasses computer-aided large-scale integrated-circuit design, computer-aided generation of artwork and/or masks, and advanced fabrication techniques combining multiple dielectric layers with specific methods of metal deposition. It is the culmination of several years of intensive investigation and investment in what was originally believed to be a product of the scientist's overactive imagination. The initial successful results are beginning to blossom forth from laboratories around the United States, as exemplified by Texas Instruments' 1000-bit shift register[1] and Honeywell's large-scale IC correlator. This article will trace the history of such a program, using as its principal subject the digital correlator.

Design

This revolution lends itself to large-scale integration. An earlier article[2] emphasized the means of achieving high-yield large-scale integrated (LSI) circuits, a prerequisite to approaching this new integrated "system" concept. Actually, a 3.2-cm to 6.25-cm wafer, with thousands of components connected through two or more layers, can represent a total system.

Figure 1 shows a monolithic system called a digital correlator. This circuit is composed of a cellular array of

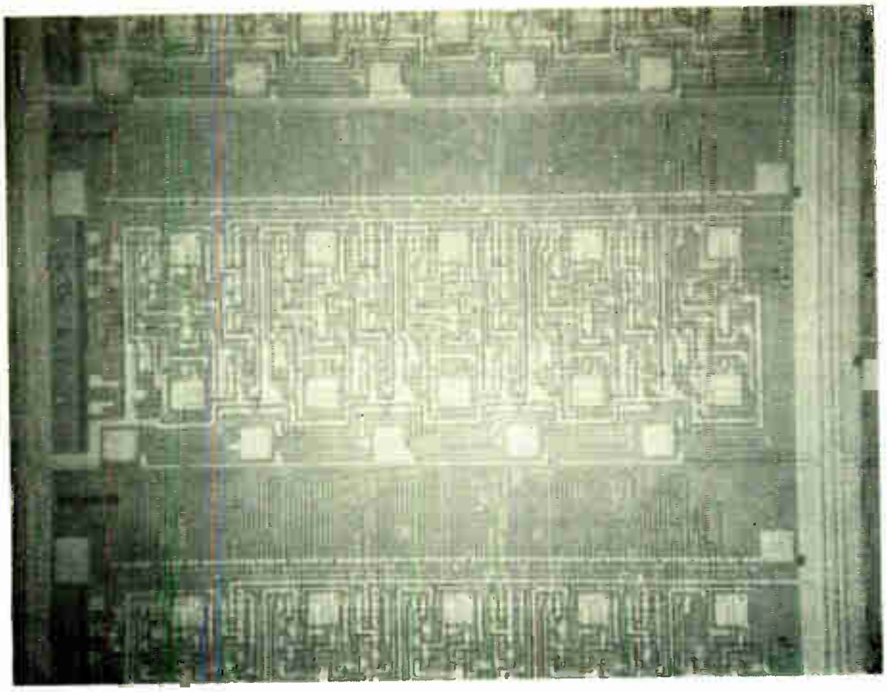
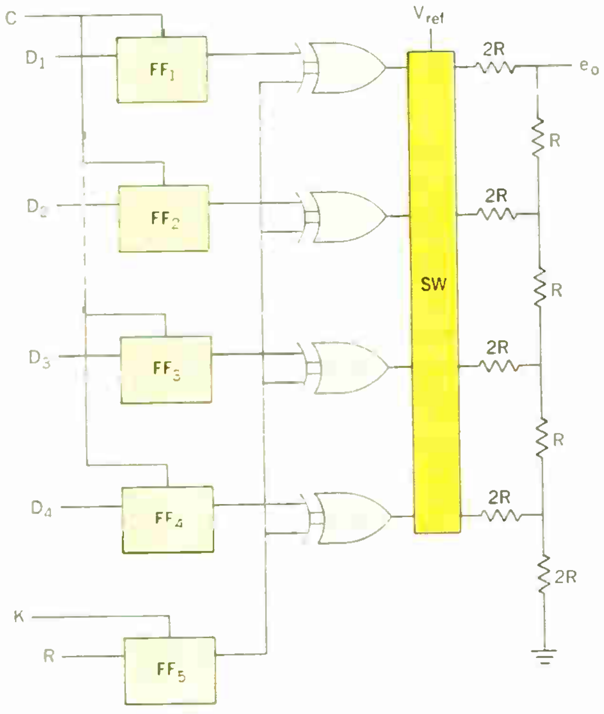


FIGURE 2. Basic monolithic cell. Note the presence of common ground and power lines and the large input-output pads.

FIGURE 3. Block diagram of basic cell.



medium-scale integrated circuits, arranged in a cruciform pattern. Typically, the average number of operating cells on the array was 60 to 65 out of the possible 84, or a 70 to 77 percent yield. Figure 2 shows the geometrical layout of the basic cell. Physical dimensions of each cell are 3175 by 1400 μm. This system contains 84 cells, but this is by no means the limit that can be placed on this 3.2-cm wafer. As the wafer size and packing density increase, obviously the cell count will also increase. Packing density can be increased by using smaller geometries and shallower diffusions, both well within the present state of the art.

Single-cell operation. The basic cell of this particular digital correlator configuration is depicted in block diagram form in Fig. 3(A). The cell is tested in wafer form before the dielectric is applied, and from this test procedure discretionary masks are generated.

The cell consists of five master-slave flip-flops (*FF*), four EXCLUSIVE OR gates, a four-bit binary ladder, and the necessary ladder switches. FF_1 through FF_4 use a common clock. The true outputs of each of these four flip-flops are connected in an EXCLUSIVE OR arrangement to the output of FF_5, which is the reference signal *R*. The outputs of the EXCLUSIVE OR gates drive ladder switches, which in turn drive the binary ladder. The resultant analog output of the ladder, e_o, is the collective cross-correlation function of the four flip-flop outputs to the reference for that particular set of data. Clearly, in this case, the data in FF_1 through FF_4 are weighted according to their respective input to the binary ladder.

Figure 4(A) shows the signals that are applied for testing. The resultant output, e_o, is the recurring stepped ramp function shown in Fig. 4(B). Each step has a duration of $1/c$ seconds (where c = clock frequency), and an amplitude of $V_{ref}/16$ volts.

At the probe level, each individual cell is checked for

1. Function at both the minimum and maximum values of V_{cc} and V_{ref}.
2. Power dissipation.
3. Any obvious ladder error (dc).
4. Any obvious unaccountable speed limitation.

After probe, all electrically acceptable cells are visually examined for potential defects. A cell that successfully meets all of these requirements is marked "good."

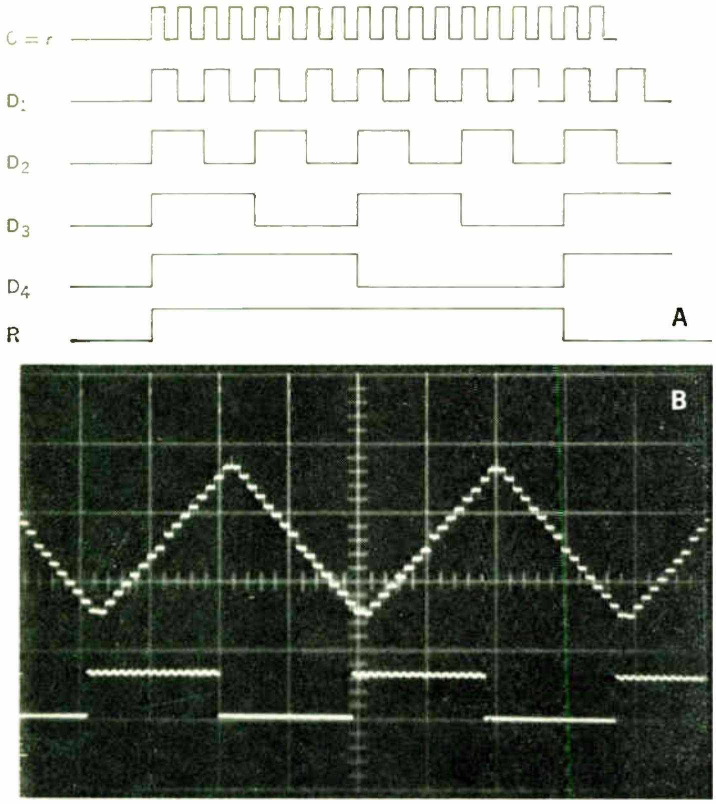
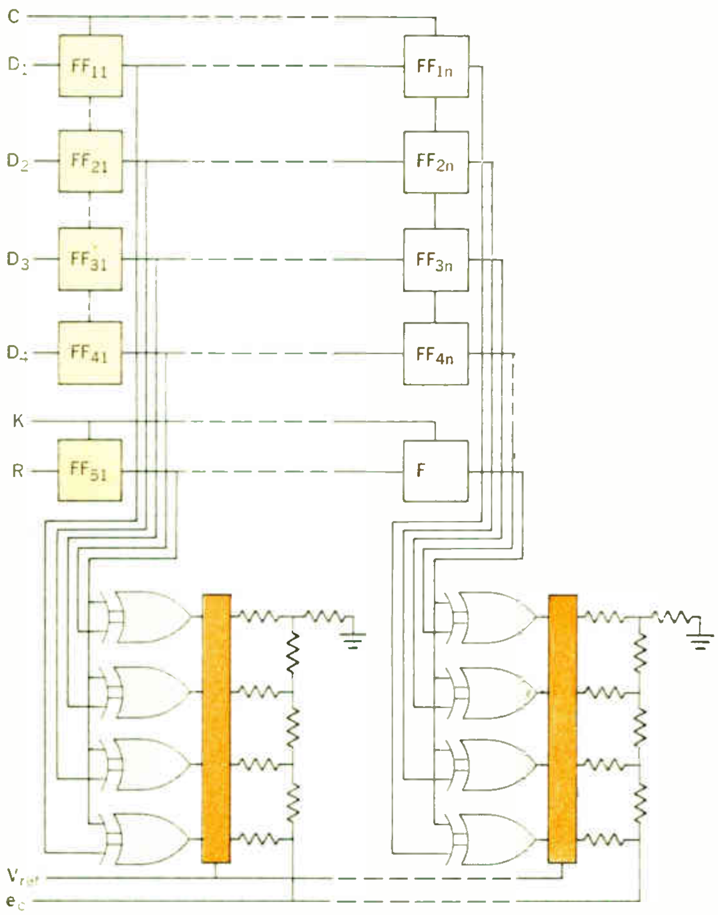


FIGURE 4. A—Applied testing signals. B—(Top) Analog output of cell e_o; (bottom) reference signal R.

FIGURE 5. Series connection of good cells to form an ultimate "system."



System operation. Through multilayer discretionary interconnect techniques, all of the cells found to be good at the probe level are connected in series, as depicted in Fig. 5. For any set of four digital data streams impressed on the data inputs, an aggregate cross correlation with the reference function is achieved at e_o. The number of stages in the correlator determines the time volume of the data streams that are being correlated at any particular time.

As a test for a typical correlator of n stages, the same signals that are applied to the single cell for testing are applied to the correlator inputs, with one exception; that is, the reference signal is a square wave of duration $2n/c$. The output signal at e_o will be a recurring stepped-ramp function with each step having a duration of $1/c$ seconds and an amplitude of V/n volts.

Correlators constructed in the manner described offer a new dimension in microcircuit application to a technology that heretofore has been limited to tapped-delay-line techniques. Prior to the described technique, a digital equivalent to the delay line made of ICs and discrete components was an awesome undertaking in terms of the volume of hardware, requiring approximately 100 000 components for a 1000-stage correlator.

In the case of direct delay-line replacement, the quantization rates and levels must be sufficient to describe the analog data stream accurately. Thus, for high-resolution systems it is desirable to operate at the highest clock rates attainable. The 1000-stage correlator has operated as a system under probe at about 2 MHz, with individual cells operating to 3.5 MHz. An operating capability at 10 to 20 MHz is envisioned for two to three years hence.

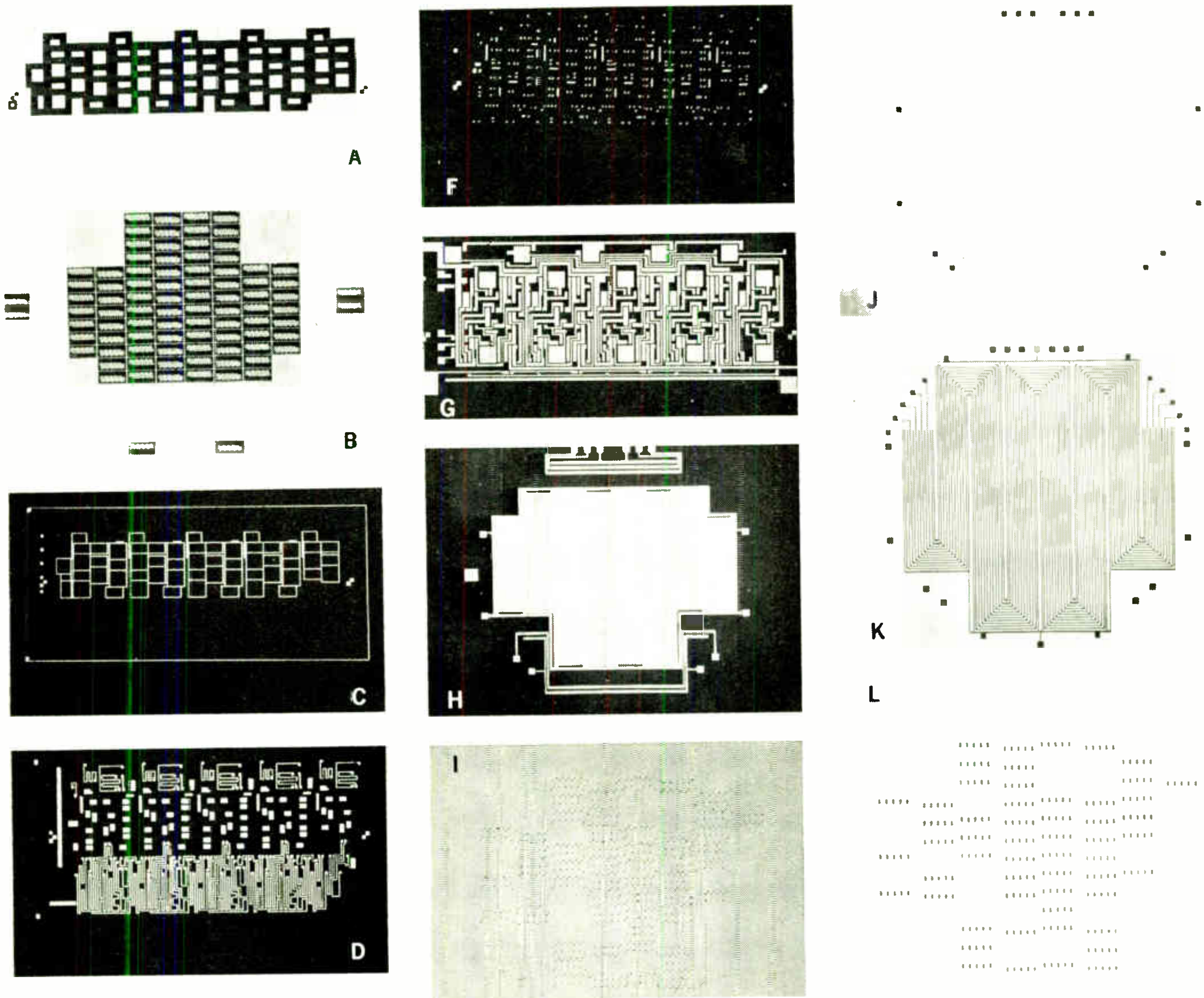
The cell-to-cell communication scheme was accomplished through discretionary masking of a deposited dielectric sandwiched between two layers of metal. A more detailed description of the fabrication process follows.

Layout and mask considerations

Although computer aids for design and layout are certainly applicable to this system, the organization and partitioning were accomplished without them. For the convenience of the V_{cc} and ground-line layout, each column of cells was oriented 180 degrees with respect to its neighbor column. To minimize the number of layers of dielectric and metal used, an isolated bus-bar arrangement was patterned in the first-layer metal with the intraconnection of each individual cell. Two separate masking operations accomplished this procedure. The smallest element used in the circuit was 6.3 μm wide by 9.0 μm long. The resistor line width was 6.3 μm throughout the circuit. Figures 6(A) through 6(L) show the complex series of masks needed to fabricate this system.

Because of the small geometries used, it is difficult to photograph the actual masks and obtain good resolution. Therefore, for the convenience of the reader, photographs were made directly from the artwork. For the sake of clarity, it should be noted that the images seen in all masks except Figs. 6(H), 6(J), and 6(K) are stepped and repeated in a cruciform array. This is seen in the first two mask photographs. Figure 6(A) is the buried collector mask, which, after stepping and repeating, on the working plate will appear as in Fig. 6(B). Figs. 6(H) through 6(L) were taken directly from the working plate, resulting in the patterned array in Figs. 6(I) and 6(L).

Figures 6(A) through 6(G) are standard layout masks,



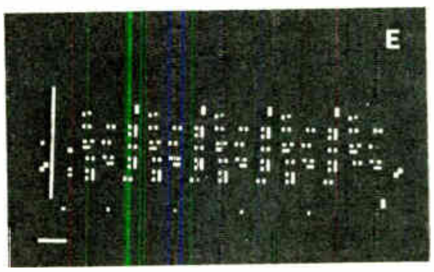


FIGURE 6. Mask sequence. A—Buried-collector image. B—Buried-collector working mask. Image has been stepped and repeated in patterned array Note 180° orientation of alternate columns. C—Isolation image. D—Base image. E—Emitter image. F—Contact image. G—Metal image, first-layer metal. H—First-metal-layer bus-bar mask; 20-to-1 reduction. Note identifying number. I—Discretionary contact mask; opens contact windows in borosilicate glass; 55 good cells. J—Contact mask; opens contact windows in borosilicate glass over bus bars of Fig. 6(H). K—Second-metal-layer interconnection; connects cells to bus bars. L—Discretionary mask for segmenting short-circuiting bars.

which would be used if this wafer were later to be scribed and packaged for an individual die. The only deviations in this series of masks were the 180-degree rotation of cells, which required two reticles for the step-and-repeat operation, and the requirement that oxide be left in areas separating the cells to avoid short-circuiting the various power, ground, and signal lines interconnecting the cells. Figures 6(H) through 6(L) are the masks needed to complete this specialized wafer fabrication. All masks except three are reduced 400 times through standard first-reduction and step-and-repeat operations. The three masks shown in Figs. 6(H), (J), and (K) are reduced only 20 to 1 and working plates are made directly from this first reduction.

Let us consider the mask sequence. The masks in Figs. 6(A) through 6(G) are used following standard IC manufacturing techniques. The result is a wafer containing 84 separate cells having only common ground and power lines. Large 127- by 127-μm aluminum input–output pads are located at specific locations within each cell for future contact to the second-layer metal. These pads are also used for cell probing. This can be seen referring again to Fig. 2 The mask in Fig. 6(G) is used for metal removal and leaves aluminum surrounding the perimeter of the 84-cell array. The mask in Fig. 6(H), then applied, patterns on the wafer a set of isolated bus bars as well as an identification number. This number is useful for tracing each wafer to its unique discretionary mask. These

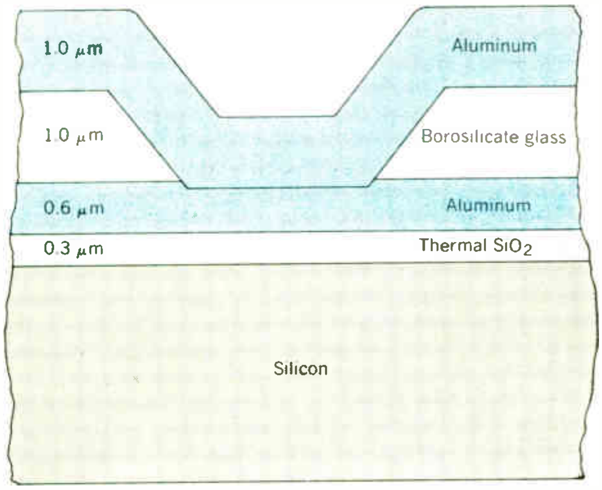


FIGURE 7. Cross section of multilayer structure.

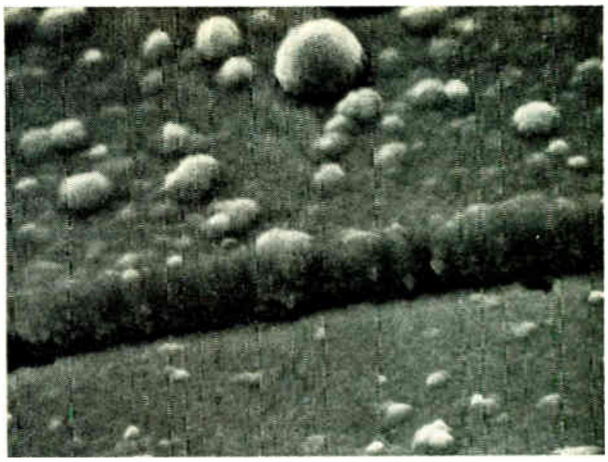


FIGURE 8. SEM photo showing discontinuity of metal as it crosses oxide step (5500X).

bus bars will eventually make parallel connections to conductors in the second metal layer. The wafer is now sintered and sent for cell probing. A map that duplicates the wafer layout and precisely locates good and bad cells, is then prepared.

The map is used to generate a discretionary mask, as seen in Fig. 6(I). This mask is used to open 76- by 76-μm contact holes in the deposited dielectric, which lies directly over the 127- by 127-μm input–output aluminum pads. The mask shown in Fig. 6(J) is then applied to open contact holes in the dielectric only at the outer bus-bar locations. This two-step operation is necessary since it is not feasible to generate a mask that can open all wafer contact holes in one operation. This would constitute a step-and-repeat pattern of a 400-to-1 reduction on the same plate that contains the 20-to-1 reduction. Metal is then deposited over the entire wafer, after which the Fig. 6(K) mask is applied. The metal is etched to form a pattern that allows contact of all good cells to the bus bars. However, at this point the good cells are short-circuited, since the metal lines are connecting inputs to outputs. Application of the mask in Fig. 6(L) will segment these lines, separating the input and output lines. The discretionary pattern for this mask is identical to that of the 6(I) mask. The wafer now represents a complete "system" and is electrically tested.

Obviously, certain steps must be taken to insure that (1) the wafer will remain in one piece throughout the many processes and (2) the dielectric will remain free of pinholes through the many masking operations. In the first place, the wafer has a minimum thickness of 254 μm to insure minimum warpage and maximum resistance to breakage. Second, to obtain insurance against pinholes, any operation that requires masking over the dielectric [Figs. 6(I) and (J)] will use two identical masks applied in sequence. A defect in the first mask will not be coincident in the second mask, and polymerization of all resist was thereby allowed where necessary.

Diffusion consideration

Processing of the wafer follows standard techniques up to completion of the individual cells. The sheet resistivity used is 200 ohms per square, and base and resistor diffusion depth is approximately 3 μm, as verified by groove and stain techniques. Because of the need for multiple layers (as seen in the construction shown in Fig. 7) and the nature of the dielectric and metal system used, the ratio of thermal and dielectric glass to metal is important. It was determined that the most reliable process was one that would minimize the step height at the thermal oxide boundaries—both at the oxide differential where impurities were deposited as well as at regions of contact opening. To reduce the steps in question, final thermal oxide thickness on the wafer ranged from 0.25 to 0.35 μm, as compared with standard integrated circuits, which have an oxide range on the same die of 0.25 to 1.0 μm. A large step in the oxide can create a high-resistance region or, for that matter, a completely open circuit where the metal crosses the step. For example, assume that the step in the oxide has been sharply cut and the differential is 0.7 μm. If a metal layer of 0.7 μm is deposited, the difference between the top and bottom layer will not allow enough aluminum to deposit at the boundary to assure a continuous layer. To illustrate the last point, Fig. 8 is a scanning electron microscope (SEM) photograph of a second-metal-layer aluminum discontinuity as it crosses a deposited oxide step. This type of discontinuity is extremely difficult to detect visually and is not always discovered until electrical evaluation has commenced.

Metalization

The metal system used for this multilayered structure is aluminum, and its thickness and methods of application are important considerations. In the previous discussion it was pointed out that oxide step heights must be related to the metalization procedures. In the first layer the ratio of thermal oxide to metal was optimized at 0.5 (that is, 0.3 μm/0.6 μm). However, the ratio of deposited dielectric to second-layer metal was 1.0 (that is, 1.0 μm/1.0 μm).

To avoid the possibility of thin metal over the step, point sources were avoided in the evaporation procedure. To accomplish this, a multiple source was mounted to simulate evaporation from four directions. Although a 1.0 ratio is not optimum for use with thermal oxide, it will be seen that the nature of the particular deposited glass produced a step that allowed this ratio to be acceptable.

Figure 9 is an SEM photograph showing the aluminum as it crosses a thermally grown oxide step. The aluminum is of sufficient thickness and proper flow to minimize the possibility of a break in this region. Figure 10 shows the excellent quality of the aluminum film with a minimum amount of regrowth.

Obtaining ohmic contact between top and bottom metal layers rates as one of the major concerns in the fabrication cycle. Consider the removal of the dielectric from the contact region. It is difficult to ascertain when the deposited dielectric has been completely etched out of the contact hole. There is no visible change in coloration when the acid has finally removed the glass and begins to attack the aluminum. It is, therefore, possible to leave a very thin glass layer in the contact hole, which will later cause a high resistance between metal layers. If it is assumed that all the glass has been removed, it is now necessary to clean the resist from the wafer without degrading the oxide or metal. Since the types of cleaning solutions used are of limited strength, it is possible to leave contamination in the contact windows. Another common problem is the formation of aluminum oxide, which occurs even at room temperature. Since aluminum oxide is a very stable compound, standard cleaning solutions will not remove this barrier layer. All of the foregoing possibilities contribute to the existence of high resistance between the two layers. One answer to this problem would be to use other compound-layered metal systems, but this approach tends to complicate the fabrication process. Another solution that has proved successful is the process of sputter etching. In fact, the ideal condition is sputter etching to clean out the contact windows and remove the aluminum oxide layer, followed by sputter deposition of aluminum. This can be done without breaking vacuum.

A control sample was processed with the device wafers. This sample was invaluable for the evaluation of film thickness and the measurement of contact resistance and dielectric strength. A control sample was also used to compare the contact resistance between aluminum layers that were filament-evaporated as opposed to those subjected to sputter cleaning followed by sputter deposition. The latter technique resulted in a contact resistance several orders of magnitude less than the former, and this result was achieved *without sintering*. This consideration becomes extremely important for certain deposited oxides that could degrade at sintering temperatures.

Dielectric considerations

Of all the processes used in the manufacture of this circuit, the one that stands out as the most significant source of potential failure is the process involving dielectric deposition. There are several methods that could be used to deposit the glass. These include reactor deposition at temperatures in the range of 200°C to 400°C, as well as sputtering. To complicate matters, there are various dielectrics that could be used. Among these are silicon dioxide, silicon nitride, phosphorus-doped oxide, boron-doped oxide, and aluminum oxide. To make the proper choice of material and technique, it is necessary to interrelate the desired properties of the dielectric with the difficulties inherent in the fabrication processes.

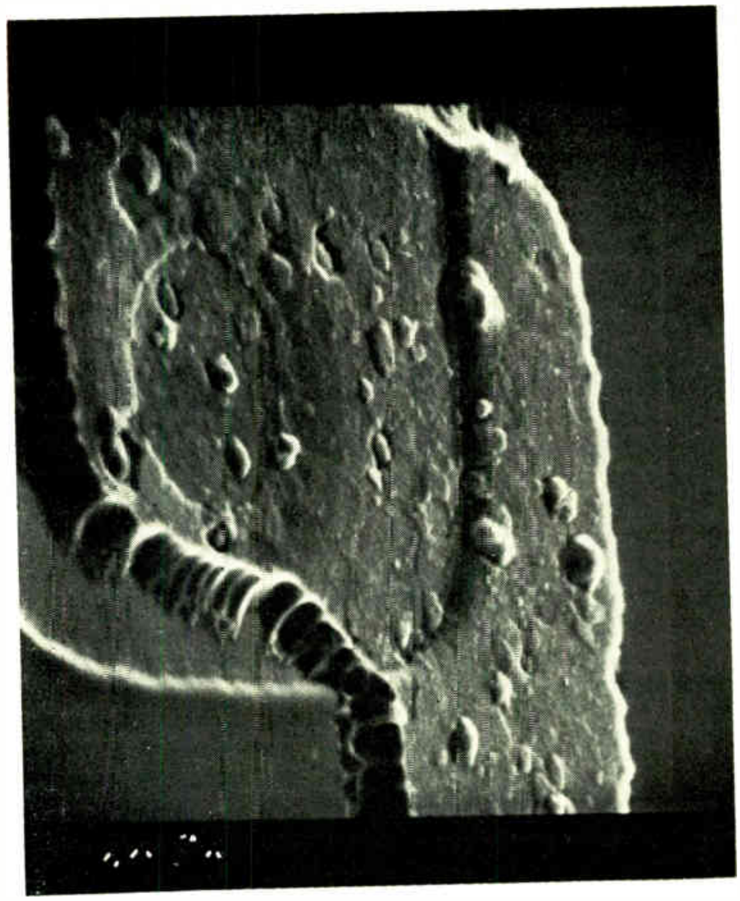


FIGURE 9. SEM photo of first-layer metal as it crosses oxide step (9500X).

FIGURE 10. SEM photo of aluminum over oxide (17 500X).

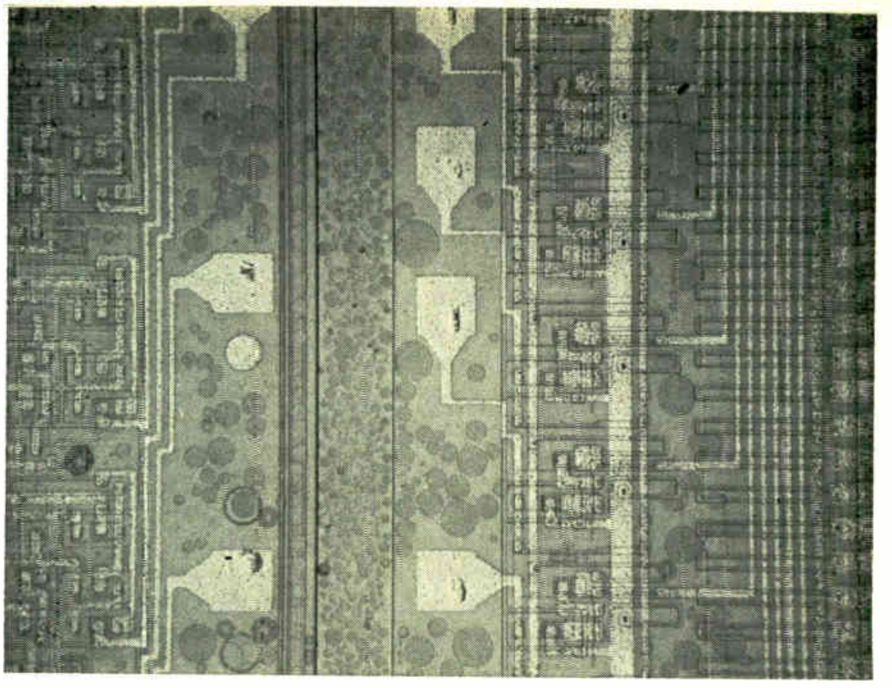


FIGURE 11. Surface of test wafer covered with dielectric. Holes are caused by stress in film resulting in eruption of oxide.

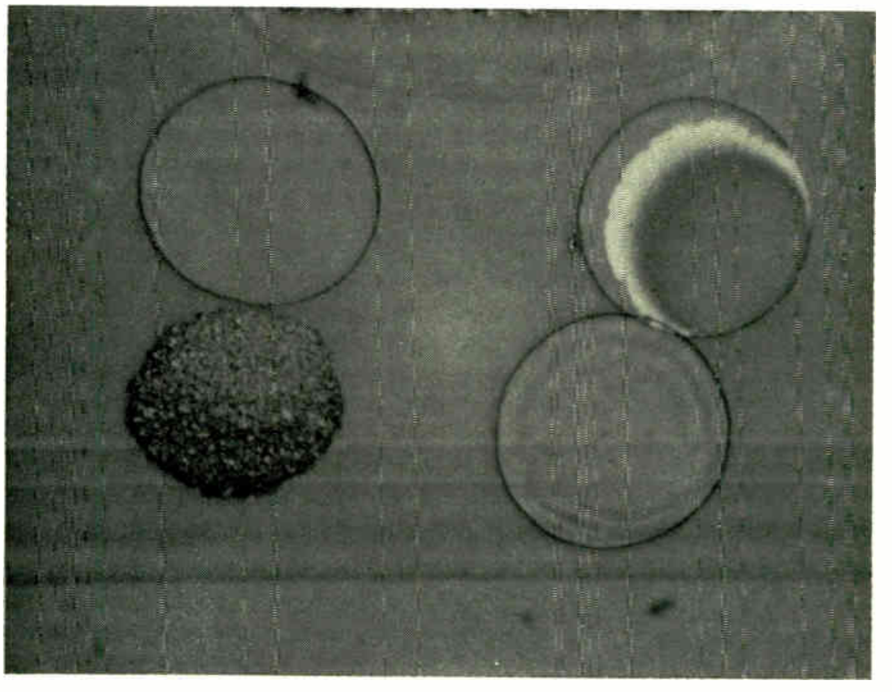


FIGURE 12. Close-up photo of erupted area. Fringed disk is dielectric lying next to area from which it was removed. Other disk is sputtered aluminum originally covered by oxide disk.

Some of the properties that the dielectric should possess are as follows:

1. The dielectric should be able to withstand sintering temperatures (about 525°C), together with the temperature shock of furnace entry and withdrawal, without damage. A furnace operation may be necessary to achieve an ohmic contact between the two layers of metal.

2. To minimize film stress, the thermal expansion coefficient of the dielectric should match, as closely as possible, that of the material upon which the dielectric is deposited.

3. The film should be etchable in chemical solutions that are used with standard photoresist, since it is necessary to use the various photoresist emulsions (such as KTFR) to obtain maximum resolution and minimum image size.

4. The dielectric strength of the film is an important factor and will determine the minimum thickness that can be used. Obviously, the film breakdown should occur at a high voltage.

5. Leakage is a prime consideration. The film should appear as a true insulator when viewed from either metal-film plane.

6. The film should have no effect on device performance because of ionic charge nor should it adversely affect the metal conductor lines that lie beneath it.

7. The dielectric should be chemically inert.

Although several compounds might rate as possible

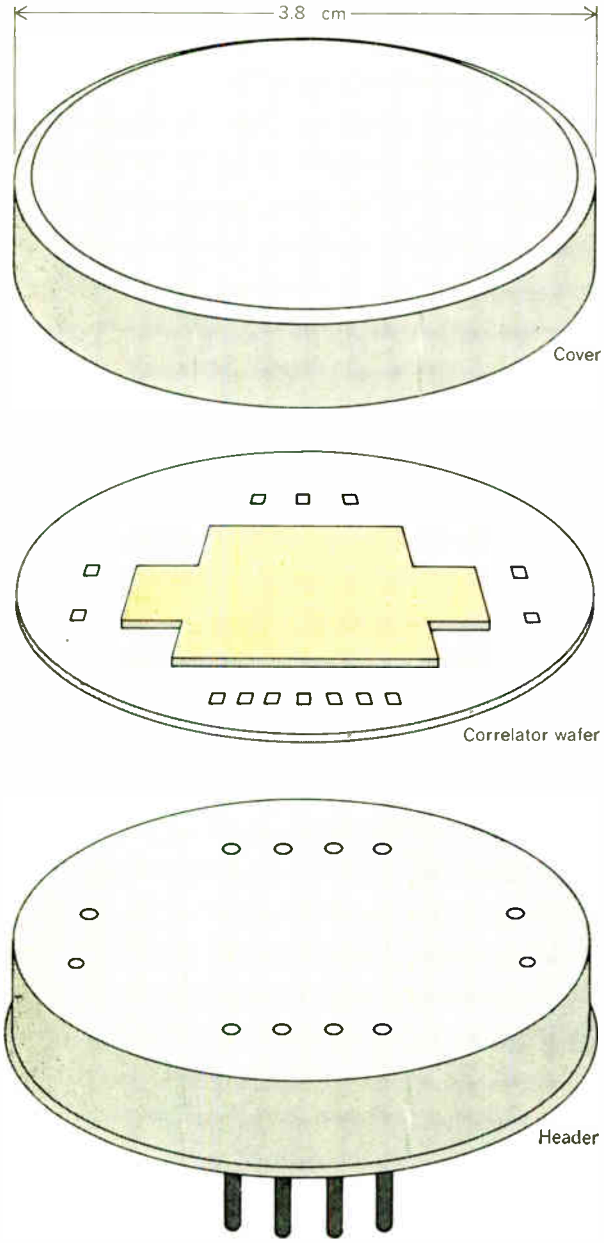


FIGURE 13. LSI mounting in large package.

candidates and fulfill these qualifications, for this program a boron-doped oxide in the form of a borosilicate glass was chosen. The oxidation of silane (SiH_4) and diborane (B_2H_6) yields silicon dioxide (SiO_2) and boron trioxide (B_2O_3) through the following reactions:

$$SiH_4 + 2O_2 \rightarrow SiO_2 + 2H_2O$$
$$B_2H_6 + 3O_2 \rightarrow B_2O_3 + 3H_2O$$

When these two oxides are mixed homogeneously, a borosilicate glass (B_2O_3:SiO_2) is formed.

The reactor used for this deposition is similar to the standard bell-jar/hot-plate system used throughout the industry. The gases are metered through F&P Tri-flat flowrators, which give good control over deposition parameters. The growth rate is approximately 2×10^{-9} meters per second and the thickness reproducibility has proved to be within ±5 percent from run to run. In accordance with the foregoing list, the borosilicate glass properties have been evaluated using a special wafer specifically prepared to test the desired parameter:

1. *Temperature stability.* The oxide integrity remained intact after repeated quenching from 525°C to room temperature. At the completion of the test, the water was subjected to a metal etchant. Any crack or pinhole that developed would allow an attack to occur on the metal under the oxide film. This condition did not occur.

2. *Expansion coefficient.* The coefficient of expansion of B_2O_3:SiO_2 is approximately 3×10^{-6}, as compared with 0.5×10^{-6} for SiO_2 and 3×10^{-6} for silicon.

3. *Etching properties.* The borosilicate film used standard photoresist and chemical etchants. The etch rate is approximately 0.5×10^{-9} m/s. In an earlier section, it was noted that a ratio of 1.0 was allowable for the deposited glass to top metal layer thickness without fear of a metal discontinuity across the oxide step. The reason for this lies in the etching characteristics of the film. This borosilicate film has a graded concentration resulting in more rapid etching at the top than at the bottom. Therefore, a sharp step is not formed. Instead, a slope results with a rather shallow gradient (Fig. 7), allowing the metal to maintain an adequate thickness and flow throughout its length.

4. *Dielectric strength.* The dielectric strength was approximately 10^{-6} to 10^{-7} V/cm.

5. *Conductivity.* A Tektronix 576 curve tracer was used to check leakage current. This instrument can easily measure to less than 200 pA. Using this value as the criterion, no leakage was detected between layers when the voltage was extended to breakdown.

6. *Film interaction.* To test for the effects of the dielectric on junction properties and to simulate the correlator wafer, completed integrated-circuit wafers were probed and measured. Only the metal was removed and borosilicate glass was deposited. Contacts were then opened in the glass and new metal was deposited and etched in accordance with the original circuit pattern. The wafer was then sintered. Wafer probing results showed that the yield had not decreased. Device parameter measurements and tests performed on packaged circuits indicated that the borosilicate glass has no degrading effect on device performance. These results tend to confirm the conductivity measurement and show that there is no ionic-charge buildup within the oxide.

7. *Chemical properties.* The film has never shown chemical interaction with materials with which it is in intimate contact.

Throughout the program, control samples were tested for pinholes both chemically and electrically (that is, using capacitors). The results of these tests gave a high confidence level for the use of borosilicate glass as a dielectric well-suited for IC multilayer work.

The dielectric program was not without its share of problems. In some instances during the early phase of the program, stress within the film resulted in oxide destruction. Figure 11 shows the manner in which the film literally erupted, causing large holes to appear. Figure 12 is a close-up photograph showing two such areas. One area shows a disk of oxide identified by the characteristic fringes in proximity to its original location; the other area shows a patch of sputtered aluminum that also had a glass disk covering it during the metal removal operation. This is the reason the metal had not been etched away. The oxide disk was then purposely removed, leaving the rough-appearing metal intact.

Deliberate observation of this layer following each operation narrowed the triggering mechanism to the combination of sputter etching followed by sputter deposition of aluminum. In all cases in which sputter etching was followed by filament evaporation the condition did not exist.

Sufficient data were examined to verify that this catastrophic failure mode was caused by the relieving of stress within the film during sputter deposition of aluminum. Stress is not unusual in oxide films. In thermally grown oxides, there is a net thermal expansion between the oxide and silicon, causing a compressive stress in oxide of the order of 3.5 n/m^2 (50 000 lbf/in^2).

There are several options available for solving this problem. Among these are modifications of the oxide, which change the inherent properties of the material. It is known that the stress of the film is magnified as thickness increases, as deposition rate increases, and as the ratio of oxygen to silane mixture increases. This has been proved experimentally.[3] A change in any parameter introduces a new set of problems. For instance, a variation in oxygen to silane would result in a change in the etch rate. Another immediate solution, which ultimately resulted in success, involved a compromise between sputter etching and evaporation. The wafer was sputter-etched to remove oxide and contamination from the contact windows. Then it was immediately removed to the filament evaporator, where aluminum was deposited. Taking advantage of the high-temperature property of the dielectric, the second metal layer was then sintered to the bottom layer, thereby reducing the contact resistance to a negligible quantity. As stated previously, since maximum adhesion of metal to oxide and minimum contact resistance are achieved by the process of sputter etching followed by sputter deposition, these will eventually become an integral part of the process. The ultimate goal of any investigation carried out for the purpose of controlling stress will be geared toward maintaining the inherent desirable characteristics of the film.

Basically, the film has proved to be worthy of further investigation. As with all new materials, additional effort will certainly bring forth the full potential of this dielectric. It has many of the basic characteristics desired of an insulating film and is compatible with integrated-circuit manufacturing processes.

Packaging

Packaging and sealing have always been weak links in the long chain of IC processes. This article will not dwell on the many packaging techniques that are possible for this type of device. However, one method, which can accommodate several wafers, is shown in Fig. 13.

Summary

There are many obvious reasons for integrating large numbers of circuits into one "system" on a single die. Elimination of large numbers of packages not only reduces size and weight but results in substantially increased reliability. Internally, die-to-die interconnections are eliminated; moreover, external multipackage lead connections are reduced. The performance of the circuit is improved as speed of operation is increased.

In the final analysis, the most important reason that underlies this approach is the dollar-savings potential. Savings are realized in the areas of highest costs—those involving assembly, packaging, and testing. Two basic methods of wiring can be used to produce the product discussed here: fixed or discretionary interconnection. The latter has been chosen in light of the high cell yield and amenability to computer techniques for determining the interconnection routing and generation of the masks. Automation can easily be programmed as early in the process as the wafer-probing operation. In the decade of the '70s, the "systems" concept will reach fruition and open many new areas of application heretofore untouched.

Obviously, a program of this magnitude is not a one-man effort. The authors gratefully acknowledge the contributions of R. Oblinger, R. Moyer, S. Smith, and A. Archer.

The authors also acknowledge the aid of Mr. John DeVaney, Jet Propulsion Laboratories, Pasadena, Calif., for the SEM photos.

REFERENCES

1. *Electronics*, Dec. 8, 1969.

2. Hochman, H. T., "The art of building LSIs," *IEEE Spectrum*, vol. 6, pp. 29–36, Sept. 1969; see also correction, p. 17, Nov. 1969.

3. Lathlaen, R., and Diehl, D. A., *J. Electrochem. Soc.*, pp. 620–622, May 1969.

Herschel T. Hochman (M) received the B.S.E.E. degree from The Johns Hopkins University in 1962 and has done graduate work at the University of Dayton. For the past ten years he has been involved in all phases of semiconductor technology, including dielectric isolation, thin films, and radiation hardening of digital and linear bipolar and MOS circuitry. Mr. Hochman was a charter member of the Westinghouse R&D Microcircuit Group in Baltimore, Md. He set up the National Cash Register Microcircuit Group Laboratory in Dayton, Ohio, where he was manager from 1962 to 1966. He then joined the Norden Division of United Aircraft Corporation as chief of the R&D Microelectronics Group. In 1967 the production activities of the Minuteman program were made a part of this activity. He joined Honeywell Inc., St. Petersburg, Fla., in 1968, as a staff engineer and supervisor of LSI circuit processing.

Dennis L. Hogan received the B.S.E.E. degree from the University of Illinois in 1960. He then joined Honeywell in St. Petersburg. He has gained experience in electronic circuit design concerned with inertial guidance systems and computer I/O equipment. Among his designs are the proportional TCAs, the precision voltage reference, and the pulsed-current supplies associated with accelerator rebalancing in the Centaur and Gemini space vehicles. In 1965 and 1966 he led a study and hardware development program in municipal traffic control. As a result of this effort he obtained a patent on a phase-modular solid-state digital traffic controller. In 1966 Mr. Hogan joined the Monolithic Subsystems Group, and since has been involved in various phases of LSI technology, including design, masking, packaging, and testing. His primary concern has been the design and development of medium- to large-scale custom bipolar arrays. He is supervisor of LSI design and test at the Honeywell facility.

Toward high stability in active filters

Through continued research, active filters have recently exhibited a phenomenal drop in sensitivity, and consequently a sharp rise in stability. These subsystems are now competing with, or forging ahead of, passive filters in a number of applications

Philip R. Geffe Westinghouse Electric Corporation

About four years ago, the consensus among network theorists was that active synthesis was headed nowhere because of high sensitivities. At that time, active filters had a well-deserved reputation among design engineers for poor stability. Practical active filters were plagued with self-oscillations, nonadjustability, nonreproducibility, and high thermal coefficients. Active network theory could accomplish nothing except explain the poor results. Since then, however, the picture has changed from total gloom to overjoyed optimism. The sensitivity problem now has several solutions, and active filters are more stable than passive filters, at least in some cases.

The purpose of this article is to show how systematic research has led us from unusable high-sensitivity networks to the present designs, which are both stable and practical. However, before we begin, the concept of sensitivity should be clearly defined.

The meaning of sensitivity

In calculating sensitivities, what we should like to do is to find the fractional, or percentage, change in performance from a given fractional change in the independent variables of the network—that is, the values of the active and passive elements. Suppose, for example, that Q is a function of a passive element whose value is Z. Then we define the *macroscopic sensitivity* of Q to Z as

$$\bar{S}_Z{}^Q = \frac{\Delta Q/Q}{\Delta Z/Z} \qquad (1)$$

By "macroscopic," we mean simply that we wish to use realistic magnitudes for $\Delta Z/Z$. Realistic magnitudes usually fall in the range from 0.1 to 5 percent. If we can obtain the function in Eq. (1) then our problem is solved by means of the following relationship:

$$\frac{\Delta Q}{Q} = \bar{S}_Z{}^Q\left(\frac{\Delta Z}{Z}\right) \qquad (2)$$

Unfortunately, we have found that the function $\bar{S}$ is mathematically intractable in most practical cases. But if we are willing to relax our requirement that $\Delta Z/Z$ should be realistic, then we can proceed with ease. Specifically, we shall let ΔZ be a differential quantity, and we define the *differential sensitivity* of Q to Z as

$$S_Z{}^Q = \frac{\partial Q/Q}{\partial Z/Z} = \frac{\partial Q}{\partial Z}\left(\frac{Z}{Q}\right) \qquad (3)$$

Clearly, then, the two sensitivity functions approach identity as ΔZ goes to zero. Remember, however, that what we want is $\bar{S}$, but what we must settle for is S.

This means that we must take our sensitivity calculations with a grain of salt, keeping in mind that we are not dealing with truly differential quantities.

Our principal concern is to determine the stability of ω_0 and Q of a network. The calculations for this determination, based on Eq. (3), are therefore very easy to carry out, because both ω_0 and Q are simple algebraic functions of the passive and active element values.

We wish to emphasize that these calculations are important. We must choose specific circuits out of a list that contains several dozen networks, some of which are inherently bad. The sorting tool to use for separating the bad from the good is Eq. (3). Another advantage here is that Eq. (3) permits us to determine the precise effects of thermal coefficients on network performance.

Emphasis on passive Q sensitivities

Our discussion is limited to active resonators, which are defined as circuits that have a single peak, at ω_0, in the frequency response, and therefore have only one value of Q. Composite filters of any complexity can be formed by cascading simple sections of this type. Experience shows that all RC-amplifier resonators give

$$\omega_0 \propto \frac{1}{\sqrt{R_1C_1R_2C_2}} \tag{4}$$

Here we use the proportionality symbol because ω_0 is sometimes dependent on the active elements as well. From Eq. (4), therefore, we always obtain

$$S_Z^{\omega_0} = -\tfrac{1}{2} \tag{5}$$

where Z is any one of the passive RC elements. We also find that dependence of ω_0 on the gain A nearly always gives

$$|S_A^{\omega_0}| < \tfrac{1}{2} \tag{6}$$

Since gain can be stabilized with feedback at low frequencies, this is not a problem. Similarly, the use of stabilized gain means that we do not usually have to worry about the *active* sensitivities of Q. These are sometimes numerically large, but high sensitivity to something that does not change is, after all, not a defect.

It is when we come to examine the sensitivities of Q to the passive elements that we find cause for alarm. With some circuits, for example, the Q can jump to infinity (self-oscillation). In less unpleasant cases, thermal stability can easily be ruined. Adjustability requires both trimpots and a long-suffering temperament.

By combining theroetical results with practical experience, we insist that every circuit designer understand the following basic fact of life:

The practicality of an active filter design method rests absolutely on demonstrating low sensitivities of Q to the passive elements.

Of course, this condition is necessary but not sufficient. We must look for other practical features as well.

Negative-impedance converters

A negative-impedance converter (NIC) may be thought of as a gadget that changes $+Z$ into $-Z$. If the NIC is absolutely perfect, then we may assume that any passive network elements can be labeled with minus signs wherever we like. Such an idealized NIC network is shown in Fig. 1. The network is a resonator having $\omega_0 = 1$ and any value of Q greater than ½. The element values shown represent the Horowitz optimum, which give the lowest possible sensitivity. Nevertheless, the circuit gives

$$S_Z^Q = \pm(Q - \tfrac{1}{2}) \tag{7}$$

for all the network elements Z. This is very high—a Q of 200 gives a sensitivity of 199.5. Thus a thermal coefficient of 100 parts per million per degree C for an element contributes a thermal coefficient of nearly 2 percent per degree C for the Q.

At one time (four to ten years ago) this was a very glamorous subject among network theorists, and many papers were published on NIC networks and their applications. Now we realize that this was all a mistake, and we never should have done it. Today we have no reason to suppose that NIC networks will ever be useful in filter design.

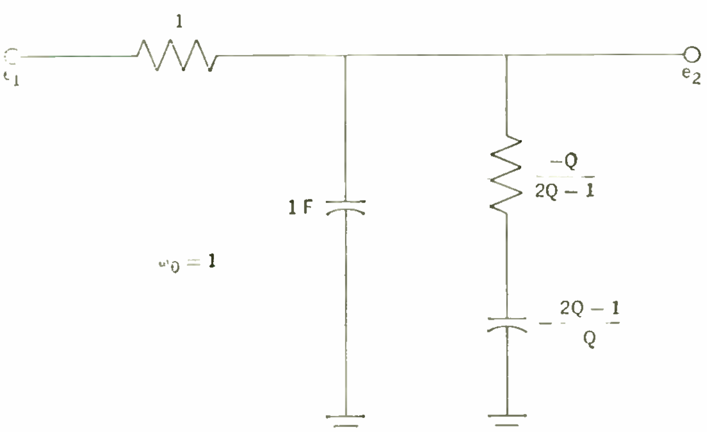
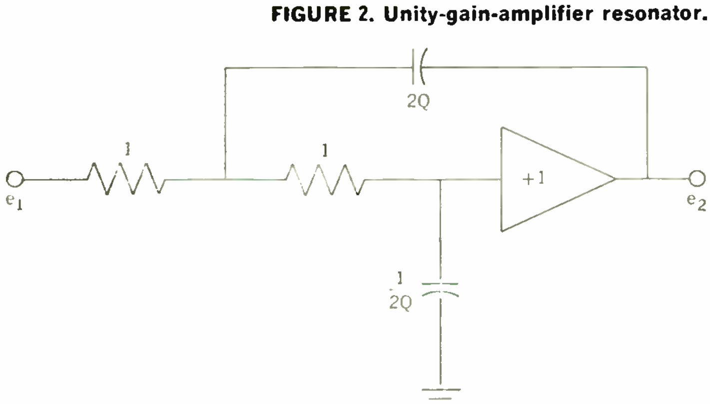


FIGURE 1. RC-NIC resonator.

FIGURE 2. Unity-gain-amplifier resonator.



Unity-gain amplifiers

In 1955 Sallen and Key published a catalog[1] of 18 RC-amplifier resonators. At that time the merits of sensitivity analysis were not yet appreciated by engineers, and the term was not then used. Since then a few of these networks have been found to be useful. Figure 2 shows a resonator that uses a voltage-follower amplifier. Once again, the circuit is normalized for $\omega_0 = 1$, and any Q may be specified. The network gives

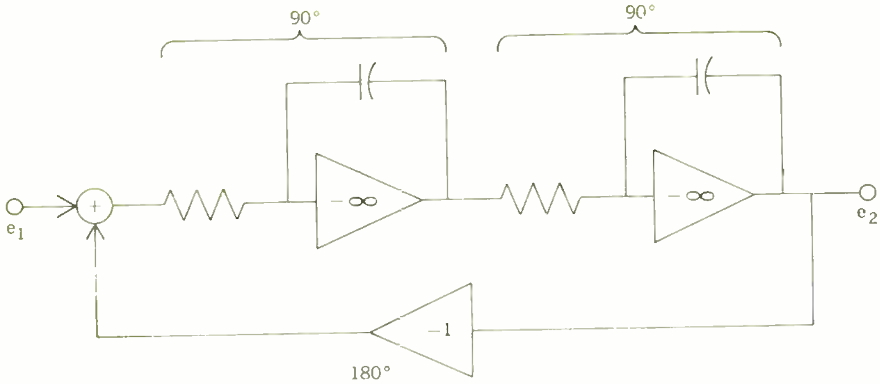
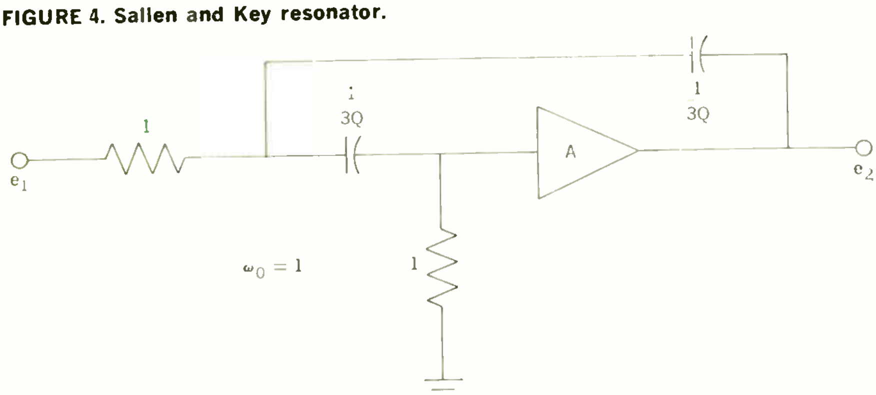


FIGURE 3. Dual-integrator resonator.

FIGURE 4. Sallen and Key resonator.



$$S_R^Q = 0 \qquad S_C^Q = \pm\tfrac{1}{2} \qquad S_A^Q = 2Q^2 \tag{8}$$

These equations show that the network exhibits very good performance for simple low-Q filters. But the high active sensitivity makes a high Q unobtainable even with operational amplifiers.

The dual integrator resonator

The network shown in Fig. 3—sometimes called the "analog computer method"—has been studied in several forms.[2-4] Inspection of the figure shows unity gain around the loop and a phase shift of 360 degrees. Accordingly, the circuit is an oscillator having a pair of gain poles on the $j\omega$ axis in the s plane. According to a well-known network theorem, if we damp both capacitors with parallel resistors to the same value of Q, then the poles move to the left in the s plane; thus, the oscillator becomes a resonator. Since the Q of the resonator depends only on the effective Q of the passive RC combinations, we find that

$$S_Z^Q = \pm 1 \tag{9}$$

A more detailed analysis shows that the Q is insensitive to everything in sight, including amplifier parasitics. This network is now widely used for Q values of several hundred having thermal coefficients of a few parts per million per degree C. It is more stable than passive LC resonators.

Temperature-test results on a resonator of this type are shown in Table I. Metal-film resistors, NPO capacitors (which have a zero temperature coefficient), and type μA 702 amplifiers were used. Compensation was achieved by the use of tuning capacitors consisting of 73 percent NPO and 27 percent mica. The thermal drifts in Q were apparently random and exceeded the measurement error by such a small amount that no significant conclusions could be reached. Frequency drift with temperature was less than would be expected from a quartz-crystal resonator at 7.5 kHz.

Another Sallen and Key circuit

The Sallen and Key catalog contains another network having astonishingly good properties. In Fig. 4 the amplifier gain must be set to $-A = 9Q^2 - 1$. It follows, therefore, that the Q is severely gain-limited. The quality

I. Results of temperature tests

Temperature, degrees C	Δf_0, parts per million Uncompensated	Compensated
105	630	−54
85	609	0
65	503	72
45	291	54
25	0	0
5	−411	−126
−15	−623	18
−35	−1060	−108
−55	−1656	−377

of the performance:

$$S_A^Q = -S_A^{\omega_0} < \tfrac{1}{2} \qquad (10)$$

$$S_Z^Q = \pm\tfrac{1}{6} \qquad \text{for all } Z \qquad (11)$$

is very good, however. This circuit is from three to six times *less* sensitive than a passive resonator.

Optimizing the network

The design formulas shown in Fig. 4, which are derived by setting all RC products equal, are not unique. In Fig. 5 we have moved one RC product toward the condition of zero loading of the other. At the same time, we see that the gain requirement is $4.165Q^2 - 1$, and is approaching $4Q^2 - 1$. But the really remarkable result here is that

$$S_Z^Q = \pm\, 0.01 \qquad \text{for all } Z \qquad (12)$$

A Q-invariant resonator

By considering the limiting processes taking place in the circuit of Fig. 5, one may easily be led to suspect that something interesting might happen if the two RC networks were isolated by an amplifier; this is indeed the case.[5] In Fig. 6 we have

$$-A_1A_2 = 4Q^2 - 1 \qquad (13)$$

$$S_Z^Q = 0 \qquad \text{for all } Z \qquad (14)$$

This remarkable result is implausible, but it is certainly true. Furthermore, it happens that we can readily obtain a formula for the actual (or macroscopic) sensitivity, as follows:

$$\frac{\Delta Q}{Q} = \frac{-\epsilon^2}{8 + 4\epsilon} \qquad (15)$$

where

$$\epsilon = \frac{\Delta Z}{Z} \qquad (16)$$

Thus a 1 percent passive-element change causes a Q change of about 12 parts per million.

Conclusions

In the foregoing pages we have laid all the emphasis upon the dramatic fall of sensitivities that has occurred in the past four years. Not all of the low-sensitivity circuits, however, are equally useful. Thus the Q of the networks in Figs. 4 through 6 are severely gain-limited. Moreover, from a purely practical point of view, it is more significant to calculate the active sensitivities with respect to the open-loop gain than to the nominal gain. Nevertheless, these circuits have a definite field of usefulness unrecognized until recently.

We have come a long way in four years. No doubt, many improvements will be made in the future, but at least we can now say that active filters are in head-on competition with passive filters. In many practical cases, they are actually winning the competition.

The author would like to thank Anatol Zverev for unflagging encouragement and for many lively and helpful discussions on network theory.

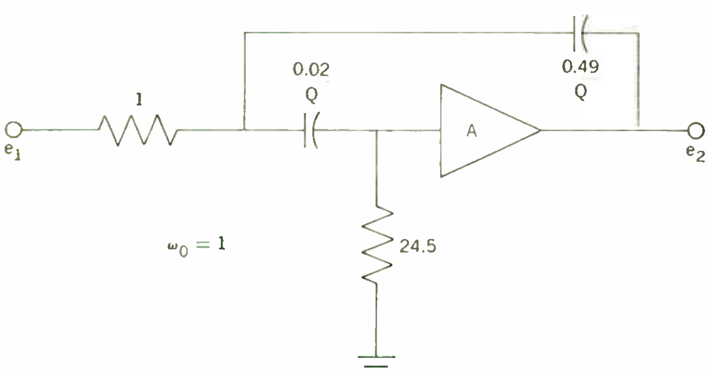
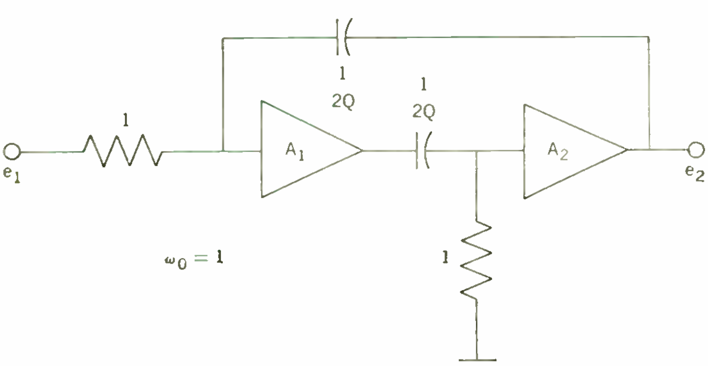


FIGURE 5. Optimized resonator.

FIGURE 6. Q-invariant resonator.



REFERENCES

1. Sallen, R. P., and Key, E. L., "A practical method of designing RC active filters," *IRE Trans. Circuit Theory*, vol. CT-2, pp. 74–85, Mar. 1955.

2. Kerwin, W. J., Huelsman, L. P., and Newcomb, R. W., "State-variable synthesis for insensitive integrated circuit transfer functions," *IEEE J. Solid-State Circuits*, vol. SC-2, pp. 87–92, Sept. 1967.

3. Geffe, P. R., "RC-amplifier resonators for active filters," *IEEE Trans. Circuit Theory*, vol. CT-15, pp. 415–419, Dec. 1968.

4. Tow, J., "Design formulas for active RC filters using operational-amplifier biquad," *Electron. Letters*, pp. 339–341, July 24, 1969.

5. Geffe, P. R., "A Q-invariant active resonator," *Proc. IEEE (Letters)*, vol. 57, p. 1442, Aug. 1969.

Philip R. Geffe (SM) was born in California. In 1952 he studied network synthesis under Ernst Guillemin. Though a mathematics major, he has been working in network theory and design for nearly 20 years and has published more than 30 papers in this field. He is the author of a well-known engineering book, "Simplified Modern Filter Design," published by Rider in 1963. Other subjects of his published work include cryptology, computer-aided design, literary criticism, and science fiction.

Mr. Geffe at present is a fellow engineer at the Westinghouse Defense and Space Center, Baltimore, Md., and was formerly chief filter engineer at the Triad Transformer Corporation and director of engineering at the Hycor Division of IRC. He is a member of the Acoustical Society of America and the American Association for the Advancement of Science.

International flows of energy sources

Petroleum is the main commodity exported by many nations that are developing to those that are developed. This is a comparatively recent turn of events—and one with important ramifications

Joel Darmstadter Resources for the Future, Inc.

Although solid fuels still remain a dominant energy source for generating electricity throughout the world (taken as a whole), the overall fuel-energy supply picture has changed dramatically in the last 45 years. In 1925, coal was the overwhelming source of caloric content; today it ranks second to oil. Four decades ago —and until World War II—the United States was a significant net exporter of energy supplies. Today the role of major supplier falls on the Middle East and Africa—and together they provide more than half of the world's fuel energy. Reported are details of the various energy supply sources by type and origin.

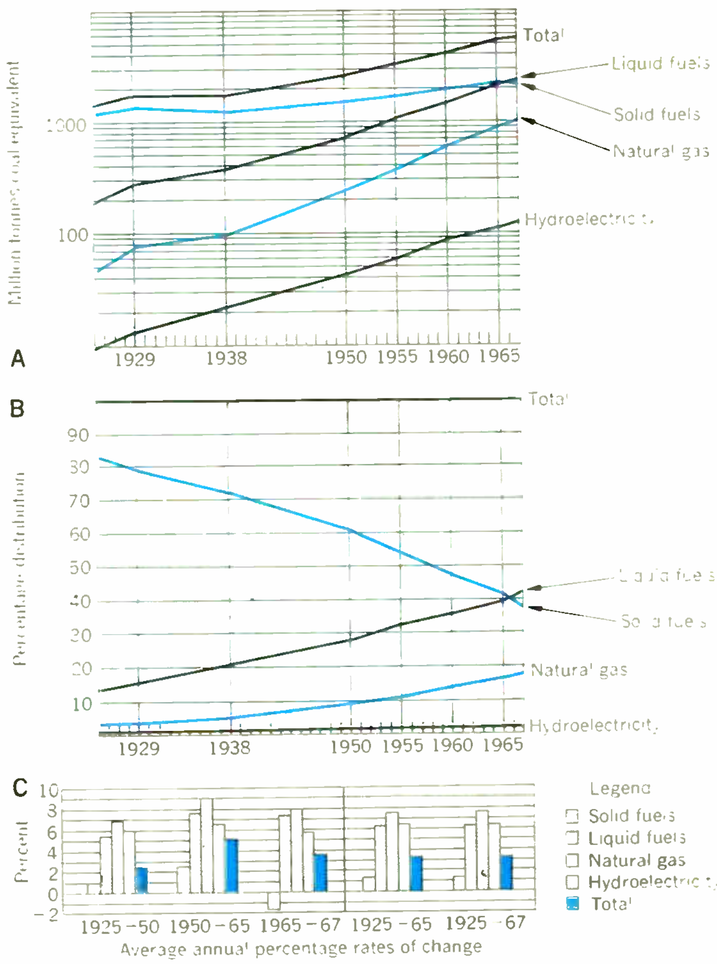
The period since the 1920s—with which this article is concerned—was one in which a fundamental shift occurred in many parts of the world away from coal and toward petroleum as a primary energy source. Along with this shift, a new degree of reliance on worldwide energy flows emerged, as numerous consuming areas that were formerly self-sufficient in energy supplies (such as Western Europe) began turning to new and distant supply sources (such as the Middle East) to satisfy their fuel requirements. The fact that within a matter of decades the preeminence in world energy ouput, once enjoyed by a country like Great Britain, could be matched or exceeded by countries like Venezuela or Kuwait is pointed evidence of this significant transformation. A review of these developments provides a historical backdrop against which contemporary issues of interdependence in world energy supplies can be readily perceived.

The rising importance of oil and natural gas has been striking and in marked contrast to the long-term decline of solid fuels (essentially coal). Hydroelectricity, although also assuming a greater relative role in total energy, nonetheless remains of minor importance on a worldwide basis. Nuclear energy is, of course, insignificant for the period under review. [See Fig. 1(A).]

Although coal had already slipped from its high-point supremacy at the turn of the century (when its share of energy consumption amounted to about 95 percent*), in 1925 coal's 83 percent share still made it preeminent among the four primary commercial energy sources—coal, oil, gas, and hydro. During the ensuing four decades, the solid-fuel proportion has dropped steadily,

* The 1900 estimate comes from P. C. Putnam.[1] It should be noted that in 1900, fuel wood—deducted for purposes of this calculation—is estimated by Putnam to have been far more important than consumption of oil, gas, and hydro taken together.

FIGURE 1. A—During the years between 1925 and 1967 the consumption of fuels in absolute tonnage has changed dramatically for some types and very little for others. B—The use of fuels on a relative basis (percent of total consumption) is a significant criterion. C—The average annual percentage increased consumption for five different "conglomerate" intervals.[2]



registering successively lower percentage shares in each of the benchmark years shown in Fig. 1(B). By 1967, coal's 38 percent share of world energy consumption represented less than half its relative importance in the mid-1920s—the relative slippage having been particularly pronounced since World War II.

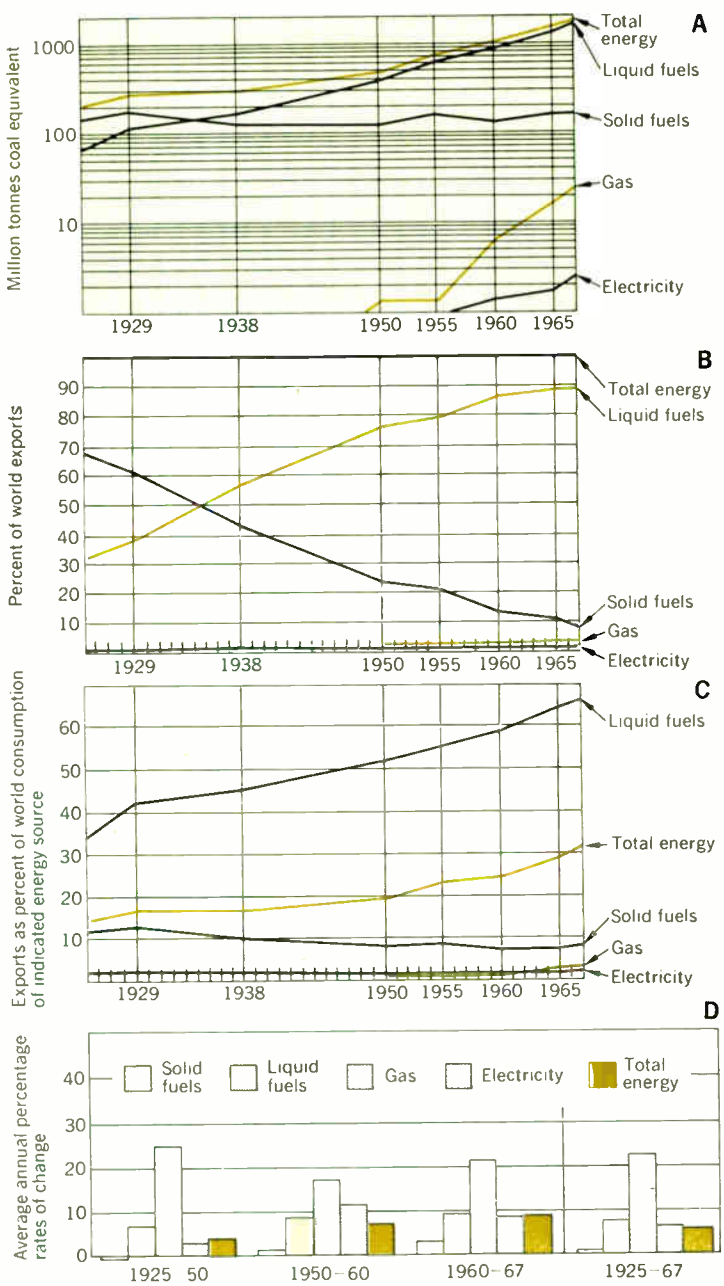
In absolute terms, worldwide solid-fuel use did increase—by about one billion tonnes between 1925 and 1967.* Even so, neither for the period as a whole, nor for the years since 1950, was this increase markedly higher than worldwide population growth. As a result, the worldwide per capita level of coal consumption has changed little over the years, and in such key energy-consuming areas as North America and Western Europe it has actually gone down.

Collaterally, with the declining relative importance of solid fuels, liquid fuels by 1967 had come to occupy the lead among energy sources, with a share of 42 percent of world energy consumption, compared with 13 percent in 1925. Liquid fuels accounted for over half the expansion in worldwide energy consumption over this period.

Consumption of natural gas rose even more rapidly than oil—its long-term annual growth rate of somewhat over 7½ percent per year contrasting with a rate a bit over 6 percent for liquid fuels. Natural gas accounted for a mere 3 percent of world energy consumption in 1925; by 1950, it was 10 percent, and by 1967, 18 percent.

Hydro consumption, on the basis of percentage increase, rose as fast as oil between 1925 and 1967; but its starting base was very small and hydro's 2 percent share of world energy use in 1967 still makes it a minor factor in a global context. Moreover, the hydro share has shown signs of leveling off in recent years as the number of sites available for ready exploitation shrink, especially in parts of the world that have traditionally been in the forefront of waterpower development.

FIGURE 2. The amounts of energy exported across borders has altered measurably in the years between 1925 and 1967. A—The change in absolute units compared on a million-tonne coal equivalent basis. B—Change on a percent basis of total world exports. C—Change as a percent of the world consumption of the indicated sources. D—The average rates of change per annum during the periods indicated. Data for 1925-1965 are from Ref. 2; data for 1967 estimated from information in World Energy Supplies, Statistical papers, series J, no. 12, United Nations, New York, 1969.



Growth in energy trade

The disparate developments in the consumption of the different energy forms have been accompanied by vast changes in world energy trade, which has risen rapidly since the 1920s. (See Fig. 2.) As indicated in a comparison of Fig. 2(D) with Fig. 1(C), growth of world energy trade (close to 5½ percent yearly) has exceeded that for total energy consumption. In 1925, about 14 percent of the primary energy consumed had crossed borders; by 1967 the proportion was up to 31 percent.

Since energy trade in the earlier part of this period was characterized to a substantial extent by *intra*regional trade—particularly exchanges of coal among proximate European countries—the long-term, petroleum-dominated expansion of *inter*regional trade was even more rapid than the graph would indicate. During the interval for which comparable data exist (1929–1965), world energy consumption increased at the average annual rate of 3.3 percent, and total world energy trade rose by 4.8 percent a year, whereas interregional trade among the ten principal areas of the world is estimated to have gone up over 6 percent yearly.† Related to these statistics is the fact that around half the total international energy trade in 1929 involved trade within major world regions; by 1965, only about one quarter consisted of intraregional trade.

World energy trade (based on value rather than tonnage) has also grown faster than the aggregate dollar value of all world trade. Energy's share in the value of

* The absolute decline between 1965 and 1967 was largely due to reduced energy consumption in Mainland China attributable to the internal unrest spurred by the cultural revolution.

† That is, considering trade among the following areas: United States, Canada, Western Europe, Oceania, Africa, and the (present) communist Caribbean, other Latin American, Middle East, Far East, and other Asian countries (see Table I).

world trade was somewhat over 6 percent in 1929. (It had been under 5 percent prior to the outbreak of World War I.) By 1967 it had risen to approximately 10 percent, being valued at about $21 billion.[3] As in the case of the volumetric data just cited, it seems probable that the increasing percentage share of energy in world trade would be still more marked if the figures could be adjusted to exclude trade within major regions.

The dominant force in the expansion of world energy trade has clearly been liquid fuels. Comprising less than one third of world energy exports in 1925, they rose steadily and captured 90 percent of the energy exports in 1967. Liquid fuels are seen, from Fig. 2(B), to have accounted for virtually the entire increase in energy trade over the four decades.

As liquid fuels rose to dominance in world energy trade, solid fuels, conversely, fell sharply; from two thirds of the world total in 1925, they declined to under 9 percent in 1967. As Fig. 2 shows, coal (in absolute terms) exhibited little long-term change in tonnage traded.

Gas and electricity—largely limited to natural gas and electricity exchanges between Canada and the United States, and electricity sales within Western Europe—historically have accounted for only trivial shares of international energy trade. Movements of pipeline gas within Europe and slowly rising ocean transport of liquefied natural gas (LNG) may alter this situation.

Geographic direction of world energy flows

The long-term shift from coal to petroleum, described in the preceding section, has been accompanied by a growing geographical imbalance between the location of energy supply sources, on the one hand, and the central areas of energy demand, on the other. In a concise fashion, Fig. 3 summarizes this aspect by showing changes either in net export capacity or net import dependence in energy between 1925 and 1967 for different parts of the world. The former measure refers to surplus exports over imports in relation to total energy production, expressed in percent; net import dependence refers to excess imports over exports in relation to total energy consumption, also expressed in percent. (The underlying absolute figures are expressed in coal equivalents.*)

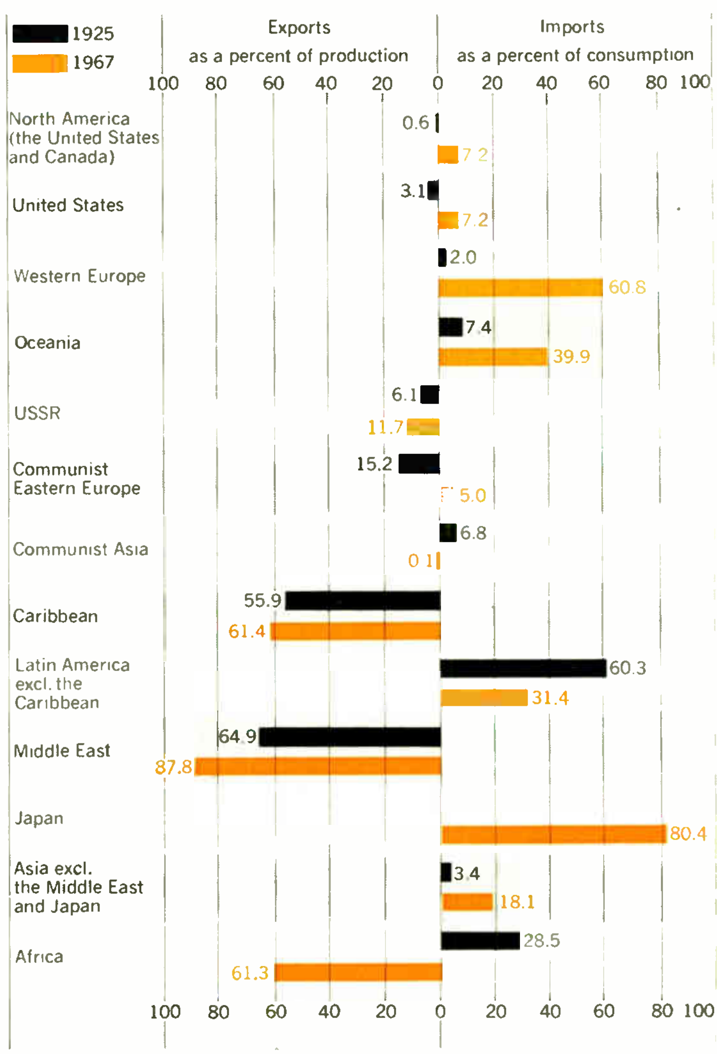
Increased import dependence was experienced by such relatively developed parts of the noncommunist world as North America, Western Europe, Japan, Oceania, and South Africa. The increase in import dependence was fairly modest in the case of North America: In 1925, a very small share of total production (around one half of 1 percent) was exported; in 1967, a bit over 7 percent of consumption was attributable to net imports.† (The recently prevailing North American share has actually been somewhat higher—in the neighborhood of 8½ percent; the 1967 figure was down due to reduced net imports associated with the Middle East conflict of that year.) Among the major energy-consuming regions of the world, North America and the communist area as a whole came closest in recent years to energy self-sufficiency.

The increase in the net import/consumption share for Western Europe between 1925 and 1967 was enormously greater than that for North America: only 2 percent in 1925, by 1967 it had risen to 60 percent.

Of the areas listed in Fig. 3, Japan exhibited the most dramatic change of all: A zero trade balance in 1925 gave way four decades later to an import/consumption share of 80 percent. (Among the major industrialized countries, only Italy in recent years has been faced with a higher degree of net import dependence.) Other areas with greater net import dependence in 1967, compared with 1925, include communist Eastern Europe and the less-developed Asian countries outside the Middle East.

Conversely, the increased export capability of the oil-producing nations of the Middle East, whose net export share of output was 65 percent in 1925, recently has risen to nearly 90 percent of an enormously expanded output. North Africa and tropical Africa both made huge jumps from deficits to surpluses—although the latter's role (involving primarily Nigerian oil) has so far remained relatively small in terms of recent levels of net exports.

FIGURE 3. Increasing dependence of many of the world's industrialized countries on the import of oil from, in particular, the Middle East is reflected in this "before" and "after" bar graph representation of world energy trade.



* Both measures relate, of course, to statistics reflecting the prevailing economic and policy circumstances for the area and year in question. Policy changes in such matters as import controls, fuel taxes, shut-in productive capacity, or subsidies can bring about a different statistical picture of net foreign "dependence."

† However, this relatively mild degree of import dependence was supported by U.S. policy placing severe restrictions on oil imports.

Soviet Russia's net export/production share of 6 percent in 1925 had doubled by 1967. Non-Caribbean Latin America decreased the net import component of its consumption between these years, although, with over a 30 percent net import dependence in 1967, the improvement nevertheless left the area with a substantial deficit.

It is well to keep in mind the geopolitical issues bearing on this changing pattern of flow of the world's energy economy. It has produced a sense of anxiety about the reliability and adequacy—under various circumstances—of the sources of energy supplies for numerous fuel-deficient regions and countries. On the other hand, for major producing areas—such as the Middle East, North Africa, and the Caribbean—the assurances of stable and growing markets are a critical element in their aspirations for economic development. In view of recurrent political crises in the Middle East as well as an almost chronic uncertainty over contractual relationships between host-country governments and the concessionary international oil companies, such considerations have assumed heightened importance in recent years. Although limited, for lack of available data, to the two years 1929 and 1965,

I. Major interregional exchanges of solid and liquid fuels by origin and destination, 1929 and 1965*

(1) Exports from	(2) Imports to	(3) Fuel category	(4) Million† Tonnes Coal Equivalent		(5) Total World Interregional Exports		(6) Percent of Exporting Region's Total Interregional Energy Exports		(7) Percent of Importing Region's Total Interregional Energy Imports	
			1929	1965	1929	1965	1929	1965	1929	1965
Middle East	Western Europe	liquid	3.7	303.2	2.7	26.2	80.4	55.3	8.8	50.2
Africa	Western Europe	liquid		151.6		13.1		92.8		25.1
Western Europe	Africa	solid								
Middle East	Far East	liquid		132.8		11.5		24.2		83.2
Caribbean	United States	liquid	21.7	124.8	16.0	10.8	67.2	52.3	94.3	65.3
Caribbean	Western Europe	liquid	6.9	57.1	5.1	4.9	21.4	23.9	16.5	9.5
Total communist area	Western Europe	liquid		41.3		3.6		44.8		6.8
Middle East	Africa	liquid		36.2		3.1		6.6		71.3
Caribbean	Canada	liquid	1.8	30.4	1.3	2.6	5.6	12.7	6.6	53.5
Middle East	United States	liquid		29.6		2.6		5.4		15.5
Canada	United States	liquid		24.4		2.1		95.3		12.8
United States	Canada	liquid	6.2		4.6		12.3		22.6	
		solid	17.7	15.5	13.1	1.3	35.0	26.0	64.6	26.9
United States	Western Europe	solid		22.6		2.0		38.4		3.7
		liquid	12.3		9.0		24.4		29.4	
Middle East	Oceania	liquid		21.9		1.9		4.0		72.8
Total communist area	Western Europe	solid		21.8		1.9		23.7		3.6
Caribbean	Other Latin America	liquid	1.7	15.0	1.3	1.3	5.3	6.3	15.3	41.0
Total communist area	Caribbean	liquid		13.8		1.2		15.0		62.4
U.S.S.R. and communist Eastern Europe	Western Europe	solid	11.5		8.5		57.8		27.4	
U.S.S.R. and communist Eastern Europe	Western Europe	liquid	6.0		4.4		30.2		14.3	
Western Europe	Other Latin America	solid	5.9		4.3		36.4		53.2	
Communist Asia	Far East	solid	3.5		2.6		100.0		38.0	
United States	Caribbean	liquid	3.0		2.2		5.9		68.2	
Western Europe	U.S.S.R. and communist Eastern Europe	solid	3.0		2.2		18.5		96.8	
United States	Far East	liquid	2.9		2.1		5.7		31.5	
United States	Other Latin America	liquid	2.7		2.0		5.3		24.3	
Far East	Communist Asia	solid	2.2		1.6		40.7		53.7	
United States	Oceania	liquid	1.4		1.1		2.8		41.2	
Sum of above			119.5	1041.8	88.0	90.1				
All other solid fuels			6.4	22.5	4.7	1.9				
All other liquid fuels			9.8	92.2	7.2	8.0				
Total world interregional			135.6	1156.6	100.0	100.0				

* Derived from detailed matrix tables (showing the origin and destination of interarea energy flows) appearing in a forthcoming study.[2] The diverse sources consulted to construct these underlying matrix tables frequently included geographically unallocable energy imports or exports. When there was no corollary information on the basis of which estimates of the regional origin and destination of such shipments could be hazarded, they were excluded from the table. Their exclusion obviously results in a somewhat less than complete picture of world flows by region of origin and destination. The problem applies primarily to 1929; in that year, perhaps 10 percent of the world's interregional energy trade is geographically unaccounted for. For 1965, coverage can be assumed to be virtually complete.

† (a) 1965 listings ranked for the most part according to percentage of world interregional exports, and (b) natural gas and electricity flows excluded; most significant among such flows were Canadian natural gas shipments to the United States, amounting to about 15 million coal equivalent tonnes (or 35 percent of Canada's energy exports) in 1965.

the statistical picture presented in Table I provides the broad quantitative backdrop to such issues. This table shows, among other things, the extent to which the world's interarea movements of energy* have come to be dominated by Middle Eastern (and additionally, in recent years, African) petroleum.

Earlier, I pointed out that foreign trade played a far smaller role in the world energy economy four decades ago than it has in recent times. (See Fig. 2.) Moreover, of the international energy movements that did take place in the 1920s, a preponderant share was attributable to intra rather than interarea trade. Thus, over 70 percent of the 1929 energy imports of West European countries originated within Western Europe, compared with about 15 percent in 1965. The turnabout reflects, of course, the wholesale shift from coal, indigenous to the region, to foreign oil.

The interregional energy movements highlighted in Table I† refer to all flows of coal and oil amounting to 1 percent or more of worldwide interregional energy trade (both fuels combined), and tabulated (for the most part) in order of importance for 1965. In looking over the figures in the table, one quickly notes: (1) the concentrated importance of a handful of particular regional flows within world interarea energy trade (see columns 4 and 5); (2) the important role of such flows within the energy exports or imports of certain areas (columns 6 and 7).

At the head of the 1929 list (in terms of world energy movements) were Caribbean oil exports to the United States; these represented 16 percent of world energy flows in that year, two thirds of the Caribbean-area exports, and virtually the entirety of U.S. energy imports. The U.S. coal shipments to Canada ranked next in importance on the world scene in 1929 and constituted significant shares of both U.S. energy exports and Canadian imports. The next three most important movements in 1929 comprised, respectively, Western Europe's imports of U.S. petroleum, present-day communist-area coal, and Caribbean petroleum. These last three energy flows represented about 30 percent of world interarea energy trade and 70 percent of Western Europe's imports.

However, as already noted, net energy imports from foreign regions did not figure importantly in Western Europe's energy consumption in the 1920s. That situation changed decisively during the ensuing four decades; and, in the mid-1960s, Western Europe's imports of Middle Eastern and African oil (Table I) contributed to 40 percent of the world energy flows, three fourths of Western Europe's energy imports, and dominant shares of the exporting area's oil shipments. Since, in recent years, net imports have risen to paramount importance in relation to West European energy use, oil imports from just these two areas have contributed 40 percent to Western Europe's total energy use from all fuels.

Although the Middle East has figured significantly in West European energy imports for the greater part of the post-World War II period, the rapidly expanding role of Africa—particularly North Africa, and within North Africa, Libya—dates primarily from the past decade. Libyan petroleum contributed practically nothing to Western Europe's energy imports and consumption in 1961; by 1968, that North African country alone provided around one fourth of Western Europe's energy imports—with the African share as a whole increasing to 30 percent.[4] (The closing of the Suez Canal in 1967 strengthened Libya's attractiveness as an oil supplier.)

Table I reveals the Middle East's emergence as the preeminent energy export area throughout the world: In 1965, the region's liquid-fuel exports to five other areas—Western Europe, the Far East, the United States, Oceania, and Africa—accounted for 45 percent of the world's interregional energy trade (i.e., the trade in liquid and solid fuels). (If African oil exports to Western Europe are included, the figure rises to nearly 60 percent.[3]) Moreover, Middle Eastern oil accounted for 50 percent—75 percent if African oil shipments are included—of Western Europe's total energy imports. Note especially, relative to total energy imports, the Far East's (chiefly Japan's) paramount reliance on the Middle East; the 1965 figure is well over 80 percent.

A few other principal changes between 1929 and 1965 in world energy movements might be noted. The relative importance of the present-day communist area's coal shipments to Western Europe declined sharply—whether measured by proportion of world energy trade, by a share of the communist area's energy exports, or by a share of Western Europe's energy imports. United States coal exports to Canada ceased to be of much importance in world energy movements. The Caribbean area's oil movements held up better. Its exports to the United States in 1929 were 16 percent of world energy flows, and 11 percent in 1965. Moreover, Caribbean oil exports to the U.S. in 1965 still comprised the biggest shares of Caribbean energy exports and U.S. energy imports.

Among regional energy exchanges that have disappeared as a factor of any importance in the world's interregional energy trade are West European coal shipments. For example, that region's coal exports to non-Caribbean Latin America, Africa, and today's communist Europe (including the U.S.S.R.) represented nearly 15 percent of world energy movements in 1929. Similarly, the United States had been a notable oil exporter in 1929, shipping significant quantities to Canada, Western Europe, and numerous other regions. These U.S. oil exports accounted for over one fifth of aggregate worldwide energy flows in 1929. By 1965, U.S. oil exports had essentially disappeared from the world scene.

"Value" direction of world energy flows

A brief word may be added on the dollar magnitude of world energy flows corresponding (in an approximate way) to the volumetric regional movements that have been reviewed.‡ As mentioned earlier, the overall value

* Unless otherwise indicated, the discussion of energy movements in this section throughout refers to solid and liquid fuels—that is, it excludes the generally negligible interarea exchanges of gas and electricity.

† The table's concept makes a good deal of analytical sense, for if we were to tabulate the direction of total trade (i.e., interregional plus intraregional energy shipments), we would invite misinterpretation of data for areas where, in a sense, a kind of double-counting takes place. For example, if we were to tabulate the direction of the Caribbean area's total (rather than merely its interregional) exports, we would find a large proportion destined right within the area. But all this represents is Venezuelan crude oil shipped to Dutch West Indies refineries prior to its export (in the form of refined products) to the United States and elsewhere. By excluding intraregional movements, we are freed from this kind of distortion.

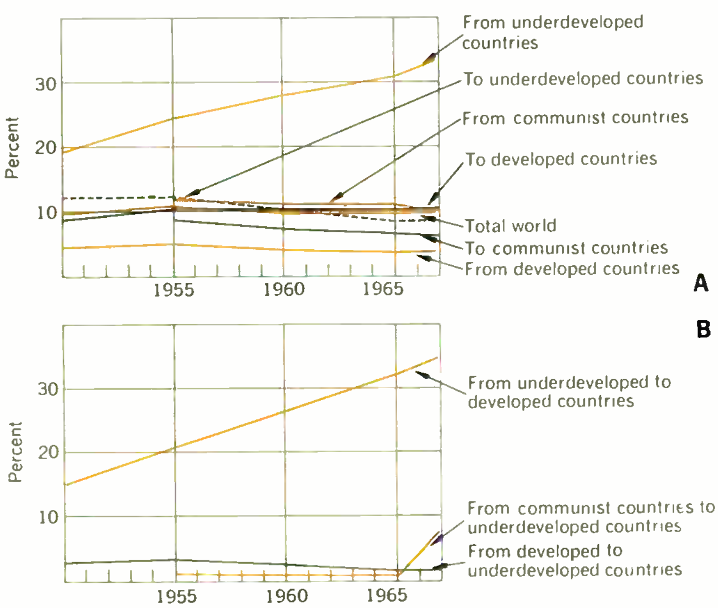
‡ Unlike the discussion in the preceding paragraphs of the previous section, where tonnage figures on "energy" referred to coal and oil, references to the "value" of energy shipments cover all mineral fuels included in *Standard International Trade Classification, no. 3.*

of world energy trade in 1967 amounted to about $21 billion, of which—if 1965 relationships prevailed[3]—interregional trade, involving tonnage flows discussed previously, accounted for perhaps $15 billion. As with the tonnage figures, the most important regional flow involved Middle Eastern exports to Western Europe—amounting to approximately $3½ billion—and African exports to Western Europe—of nearly $2 billion. Other major flows included Middle Eastern exports to Japan of nearly $1½ billion and Latin American exports to the United States of $1 billion. Japan's energy imports from all areas approximated $2 billion, the largest such figure for an individual country anywhere. The $2 billion represented over 20 percent of Japan's merchandise imports.

A somewhat different perspective on the value of world energy trade appears in Fig. 4, which shows world energy flows relative to the value of all merchandise trade for the world and different country groupings.

A particularly striking statistic is the continuously rising share that energy represents with respect to the total exports from underdeveloped countries to developed regions of the world. From 15 percent in 1950, this figure has risen steadily, reaching over one third in 1967. The absolute value of energy flows from underdeveloped to developed areas in 1967, virtually all due to petroleum, is estimated at $10 billion. One half of this sum originated in the Middle East. Only a portion of this amount, of course, is retained by the host country in the form of taxes, royalties, and other earnings. The data nonetheless testify to the extent to which oil dominates an important sector of world trade. Particularly, the figures suggest caution in dealing aggregatively with the export potential of the underdeveloped countries of the world, for so large a portion of that potential appears to reflect only a single commodity originating in only limited parts of the world. Indeed, a recent analysis of trends in world trade[5] finds that

FIGURE 4. Energy trade as a share of the total trade of, and between, selected regions for the years 1950 67. Reference 4 is source of information.



Note: In 1967 energy constituted 0.4% of trade between underdeveloped and communist countries.

". . . the developing countries' share in world exports of primary commodities has fallen continuously since 1953. If fuel exports are excluded, this trend is still more striking. World exports of fuels have grown at almost twice the rate of other primary commodities and the developing countries have managed to capture an increasing share of these exports. The developing countries' exports of nonfuel primary commodities have grown less than half as fast as world exports of these commodities. Therefore, except for the fuel component, the decline in the developing countries' share of world primary exports would have been quite precipitous."

One final percentage in the tabulation deserves mention. Only a handful of underdeveloped countries are net exporters of energy. Much of the underdeveloped world is energy-deficient and the nearly 9 percent, or close to $4 billion, of underdeveloped nations' total merchandise imports accounted for by energy imports places a not inconsequential foreign exchange burden on such countries. Subject to the development of refining capacity (which can save to some extent on foreign exchange) and/or new discoveries in these countries, such foreign-currency requirements for fuel-import requirements seem destined to grow rapidly in the years ahead, and will constitute an important factor in programs for economic development.

This article has been adapted from Part I of a forthcoming study conducted at Resources for the Future, Inc. In this study,[2] the author's collaborators include other staff members of the organization. In addition, Sam A. Schurr's role as constructive critic and Sally Nishiyama's research assistance are gratefully acknowledged.

REFERENCES

1. Putman, P. C., *Energy in the Future*. Princeton, N.J.: Van Nostrand, 1953, pp. 439–440.

2. Darmstadter, J., *et al.*, *Energy in the World Economy: A Statistical Review of Trends in Output, Trade and Consumption since 1925*. Baltimore, Md.: Johns Hopkins Press (To be published.)

3. *Monthly Bulletin of Statistics*, United Nations, Mar. 1969. (Value estimates for earlier dates taken from the study referred to in Ref. 2.)

4. *Statistical Review of the World Oil Industry*, British Petroleum Co., London, 1969.

5. "International trade policies—the export performance of developing countries," *Monthly Rev.*, Federal Reserve Bank of Kansas City, pp. 11–12, July–Aug. 1969.

Joel Darmstadter has garnered his credentials in the field of economics. First, he received the B.A. degree from George Washington University, Washington, D.C., in 1950. Two years later, he earned the M.A. degree from the New School for Social Research, New York. Since then—with time out for active duty in the U.S. Army (1955–1957)—he has served as economist and researcher for various organizations. Prior to joining Resources for the Future in 1966, where he is now a senior research associate, he was an associate director of the National Planning Association's Center for Economic Projections. Mr. Darmstadter has contributed to another book in addition to the one upon which this article is based; he has also produced other articles. He is a member of a number of professional organizations, including the American Economic Association.

The Stanford instructional television network

To meet the needs of the 300 to 400 off-campus employed graduate students enrolled at Stanford each year, the university has set up a closed-circuit television system linking campus classrooms with participating employer organizations

Joseph M. Pettit Stanford University
Donald J. Grace Kentron Hawaii, Ltd.

This article describes a novel, large-scale instructional television system now in operation at Stanford University, under the auspices of the School of Engineering. The network brings the campus classroom and instructor to graduate students employed by participating organizations at inconvenient distances from the school, and talk-back capability is included to provide a live classroom situation. No detailed analysis of the system's benefits has yet been made but, after approximately a year of operation, all informal reaction has been favorable.

Why should a university such as Stanford be interested in embarking on an instructional television project? Historically, of course, for more than 75 years Stanford has been a conventional undergraduate residential university, with a few professional schools such as law and medicine. Engineering, also, has been a regular undergraduate curricular offering since the day the university opened; and graduate work commenced almost immediately, although on a rather modest scale as compared with the size of the undergraduate enrollment. During the past decade, however, the graduate enrollment has forged ahead, and there are now three times as many graduates as undergraduates in engineering.

The HCP program

Of the roughly 1450 graduate students in the School of Engineering, two thirds are on campus full-time, although most are employed part-time as teaching or research assistants. The other third, numbering between 300 and 400 students during the year, are employed off campus in one of the numerous San Francisco Bay area industrial, governmental, or research organizations that have increased so dramatically in number during the past 20 years. These students attend Stanford in a daytime release program—the Honors Cooperative Program (HCP)—since no evening courses are offered by the university. Under this plan they can earn the master's degree in two calendar years by taking two courses per quarter. Students can also work toward the degree of engineer and the Ph.D. degree on a part-time basis, although Ph.D. candidates must spend at least a year in full-time residence while completing their dissertations. During its 15 years in operation, more than 1000 graduate degrees in engineering have been granted under HCP.

The program has had both advantages and disadvantages. Attending daytime classes in company with the regular graduate students on campus assures the off-campus student that he is getting the best instruction that Stanford has to offer. The HCP students seldom comprise more than 30 percent of the total class, so there can be no question of their performance establishing the standards for any course. Among the disadvantages to the student, and his employer, is the fact that his workday is interrupted, not only by the time spent in class but by the time lost in driving and parking (which may actually exceed the instruction time by as much as a 2-to-1 ratio for a single class). A calculation for one of the large companies showed that in one year their HCP students lost time in driving and parking equal to 2½ man-years of engineering time. The geographical problem thus makes it difficult to attend even one course per term, let alone two—unless they are given consecutively. This means that a student may choose two consecutive courses just for convenience even though they might not be best suited to his program. Some potential students are prevented entirely from studying at Stanford because of its distance from their place of employment. Students do commute from as far as San Jose, but seldom from San Francisco, and never from Oakland or Berkeley. An additional disadvantage is that HCP students may be forced to miss classes because of business trips, field tests, client conferences, etc.

Instructional TV in operation

After observing the experience with closed-circuit television at several other universities, notably the University of Florida, which connects its main campus with several sets of remote classrooms as far distant as Cape Kennedy and Orlando, and the consortium of schools in the Dallas–Fort Worth area known as TAGER, we initiated a feasibility study in the spring of 1967 to consider linking Stanford classrooms with remote classrooms on the premises of 20 to 30 of the organizations participating in our part-time graduate program. We ascertained that the employers could readily assist us with the cost of the capital facility, and that the cost of operating the system would represent only about a 25 percent increment on the fees presently being paid. Total capital cost of the Stanford portion of the four-channel network is of the order of \$625 000; each participant's share of this amount depends on the organization's size, and either can be paid in a lump sum or prorated over five or ten years. For even the largest company, the annual cost is less than the salary of a technician. Participants are responsible for installing their own receiving facilities, subject to technical specifications and guidelines provided by Stanford.

But what about the quality of the instruction? Would it meet our standards? Would it be as good for the student as if he were sitting in the classroom on the campus? Here we were able to review to our satisfaction the experience of other universities. We feel it is essential that one-way video transmission be combined with two-way audio to provide a highly effective live classroom situation wherein all students can see and hear the presentation of the professor, and all students can ask questions or be called upon. The fact that the professor is not able to see all of his students is not a vital one; most of the students in our courses are in the classroom on the campus, thus affording a live setting with adequate visual feedback. Another minor deficiency is that the picture tube does not have the storage capacity for visual material that a large blackboard has. Suitable classroom technique on the part of both professor and students can minimize this deficiency. Our experience to date seems to bear out this initial confidence in the teaching aspects.

We are concentrating on graduate courses at the master's degree level. Since no thesis is required for the master's degree at Stanford, it theoretically might be possible for a student to complete an entire degree program via television. However, we do not feel this would be desirable, and practical circumstances will undoubtedly prevent it in any event. The variety of courses that students take is far too great for the capacity of our system, even with four classes being transmitted simultaneously throughout the daytime teaching hours. Also, some graduate classes, such as laboratory courses, small seminars, etc., are not suited for television. Moreover, we want the student to become well acquainted with one or more of the faculty. He is obliged to come to the campus for regular advising, and we try to assure that he take at least one seminar on campus.

By utilizing only the regular teaching hours of 8 A.M. to noon and 1–4 P.M., it is possible to televise 180 three-unit courses during a calendar year. This represents more than 5000 hours of academic lectures per year. Since the typical master's degree program in engineering requires only about 15 courses, the four-channel system capacity should allow a diverse course representation from all ten graduate engineering departments at Stanford as well as from related fields (statistics, computer science, mathematics, chemistry, etc.). However, a survey of courses taken by HCP students during the 1966–67 academic year indicated that to televise all of these courses would require 14 channels! It is reasonable to project that on the average about 75 percent of the courses taken by a part-time master's degree student in engineering will be televised, with the remaining courses taken on the campus. Correspondingly smaller percentages of televised courses are anticipated for the engineer's degree and Ph.D. students.

Network member organizations are permitted to make "off the air" video tapes of Stanford lectures at the request of their students who wish to make up missed classes or use them for course review. Such tapes cannot be employed in any other way and must be erased within two weeks of the end of each quarter. Tapes are also occasionally made at Stanford for the same purposes or at the instructor's request for study and self-appraisal.

In developing the system, we realized that the television facility could provide additional educational benefits beyond the part-time degree-oriented program for matriculated students that was the initial focus for our studies.

One addition was the creation of a "nonregistered option," which permits industry graduate students to take televised courses in remote classrooms without being matriculated at the university. They are tested and graded to the same standards as regular students, but their performance does not affect the standards. Included in this category are students who already have degrees, students who do not want to complete all of the work for a degree, and students who want a degree but are not presently academically qualified. For this last category, Stanford will allow such students to become matriculated, and to "transfer" completed units by petition, if as nonregistered students they perform well enough in competition with matriculated students.

Auditors from participating organizations are permitted in the remote classrooms for televised courses at reduced fees. They receive no testing or grading, nor are records kept for them. Also, selected seminars in research fields of interest to the network members are televised and are available to all personnel from these organizations at no cost.

We hope to have a two-way link to the University of California at Berkeley, for sharing lectures, special seminars, and perhaps courses as well. Cooperative arrangements with San Jose State University already have been initiated, and similar arrangements are under discussion with the University of Santa Clara.

Finally, the system is free many hours a week during the early mornings and evenings when Stanford courses are not being held, and this affords a great opportunity for continuing education of all kinds. A separate nonprofit corporation, the Association for Continuing Education (ACE), has been established to provide such programming; its membership comprises the companies and organizations who participate in the Stanford graduate program. The organizational details of ACE were worked out by a formation committee composed of representatives of the 16 charter member companies and Stanford. Under the bylaws, nine members of the ACE board of directors are elected for staggered two-year terms by the participating organizations and a tenth board member is appointed by Stanford. The ACE has a full-time general manager who works with a curriculum committee from the companies in developing courses and hiring instructors. The courses include testing and grading, and a certificate is issued to each student, and to his employer, upon completion of a course. ACE

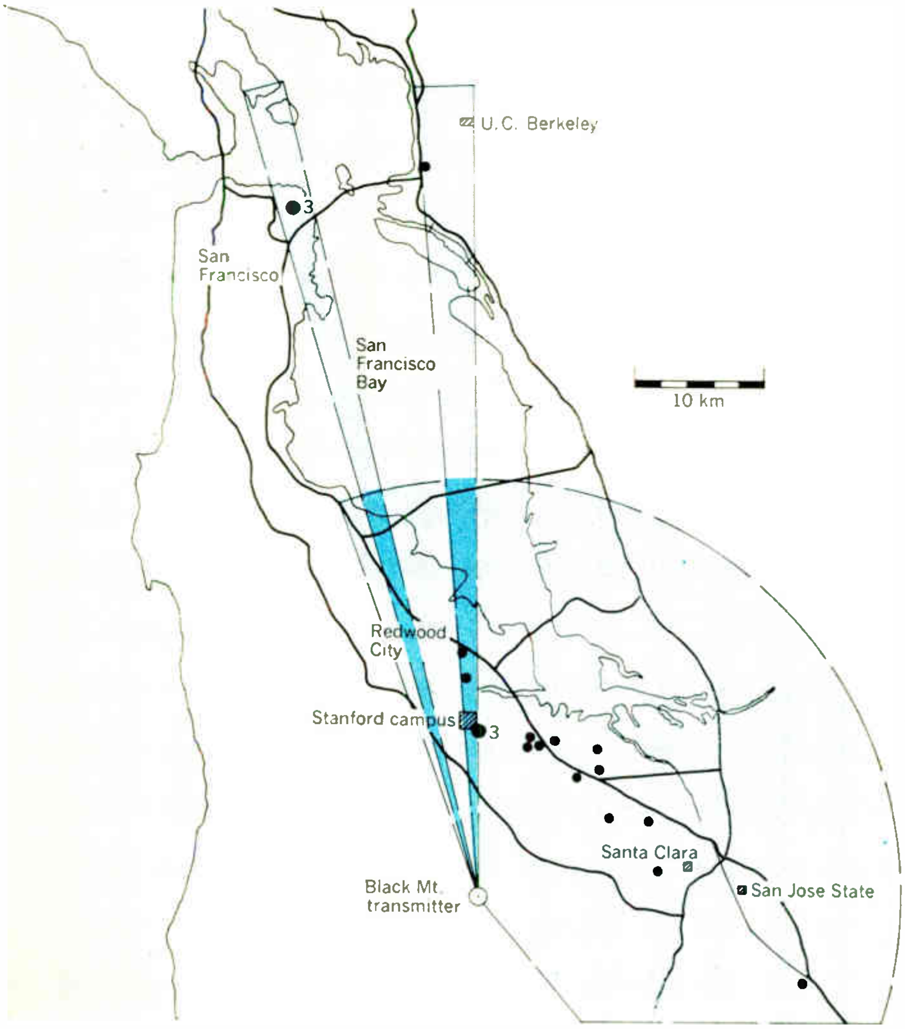


FIGURE 1. Geographic distribution of San Francisco Bay area participants in Stanford instructional television network. Areas in color show approximate coverage of transmitting antennas.

operates on a break-even basis, recovering its costs from nominal tuition charges. The courses are also televised live to remote students in the Bay area, who are given the same talk-back capability that is provided for Stanford students. The programming capacity available to ACE is enormous. By operating four hours per day on weekdays during the weeks that Stanford is in session, more than 3000 hours of lectures per year can be presented. If the demand develops, ACE can extend its programming into the late evening hours, Saturdays, and the daytime hours between Stanford quarters to achieve a total of 14 000 hours per year. Recently, ACE entered into negotiations with International Video Corporation and its affiliate, International Video Institute, to make video tapes of ACE courses for national and international distribution.

Considering all of these features, we believe that the Stanford instructional television network can greatly augment both formal degree-oriented and continuing educational opportunities in the San Francisco Bay area.

Technical aspects

Figure 1 shows the geographical distribution of the 25 organizations presently participating in the network, as well as the campuses of Stanford, the University of California at Berkeley, San Jose State, and the University of Santa Clara. The initial technical consideration involved alternative methods for conveying the television signal to the participants; suggested techniques included leased common-carrier facilities, point-to-point microwave links, CCTV or CATV distribution systems, and broadcast.

For reaching all of the initial locations involved, with the capability of adding other participants later, the broadcast approach appeared to have the most flexibility and growth potential. However, at very-high and ultra-high frequencies, broadcast allocations are scarce and station construction costs are high and so a multichannel network would be practically impossible to set up. Fortunately, in 1963 the FCC designated a band of 31 television channels at microwave frequencies for the use of educational institutions. Known as ITFS (Instructional Television Fixed Service), this type of service represented the optimum solution for Stanford's needs. The ITFS portion of the television system is discussed in further detail in succeeding paragraphs.

A typical studio classroom on the Stanford campus is shown in Figs. 2 and 3, with views from the front and back of the room. Considerable effort was devoted to making these facilities look more like classrooms than television studios. A solid-state monitor is provided

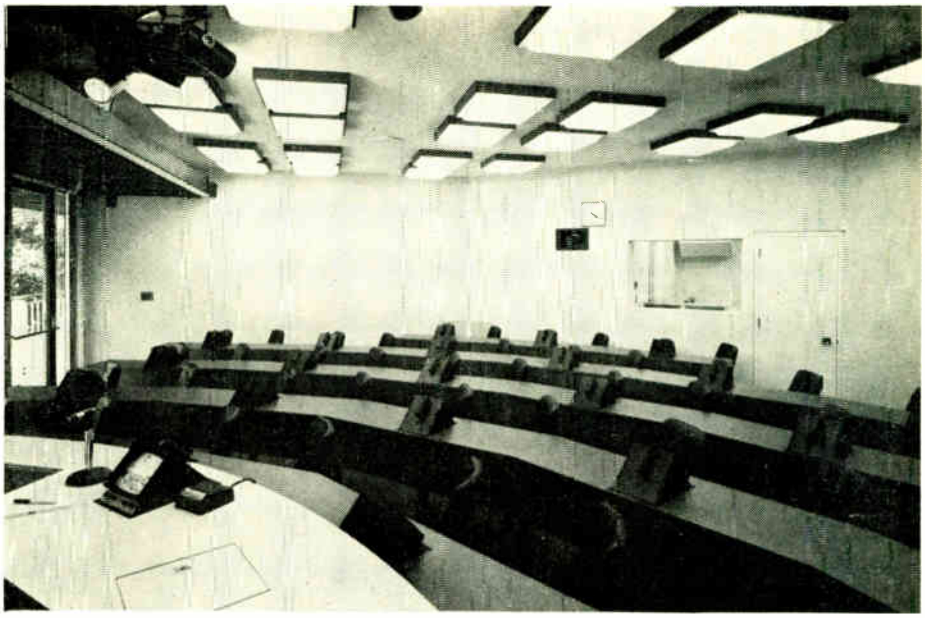


FIGURE 2. Front view of studio classroom. The rear camera is mounted on the back wall; the control room is behind the glass window.

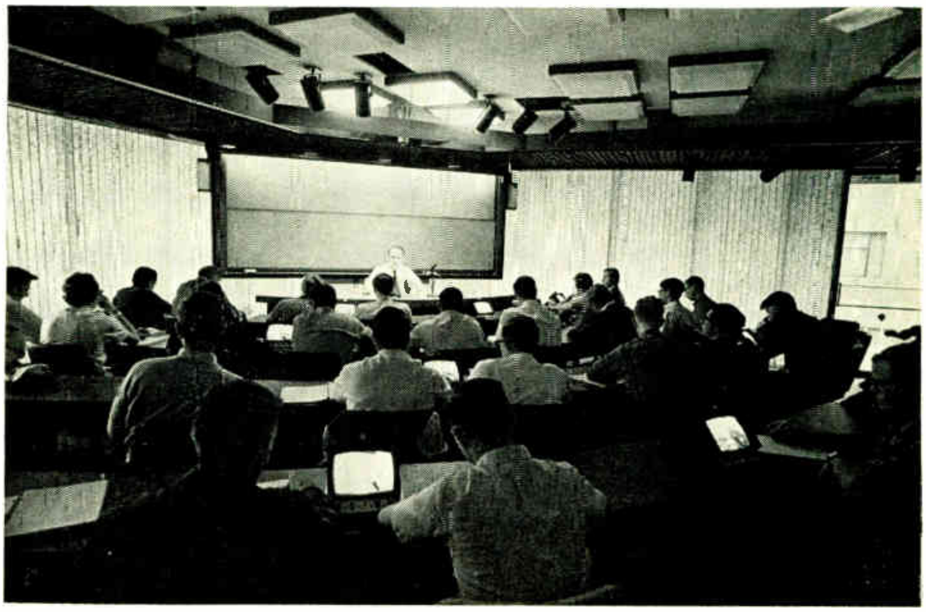


FIGURE 3. Rear view of studio classroom. The overhead camera is mounted in the ceiling directly above the instructor.

for each two students. Each monitor has a microphone mounted on top of it, which is actuated by a "push-to-talk" switch on the front of the monitor.

There are two cameras in each room, one over the instructor's desk and the other at the rear of the room. Both cameras have remote-controlled tilt–pan–zoom capability. The overhead camera is used for viewing information generated by the instructor at his desk (as shown on the monitors of Fig. 3), viewgraphs, slides, and other materials that the instructor may bring into the class. The rear camera can view the entire classroom, show close-ups of the instructor, or follow the instructor's work at the blackboard.

Associated with each studio classroom is a satellite monitor room that can be used for overflow from large classes, for seminars and small classes, or for closed-circuit television lectures. In addition, an auditorium has been outfitted for televising or receiving large seminars, guest speakers, colloquiums, and special events.

The studio production staff for each televised class consists of a single student operator who is responsible for the camera controls, switching of cameras, audio control, and the talk-back system. Student operators are observed and instructed by a licensed engineer in the master control room.

A simplified video block diagram of the studio classroom is shown in Fig. 4. Signals from both cameras pass through the camera controls, a switcher, and video amplifier to the master control room. The appropriate signal is relayed back to the classroom from master control for distribution to the studio classroom monitors.

Television signals from all four Stanford classrooms are carried by coaxial cable to the centrally located master control room on campus where they pass through

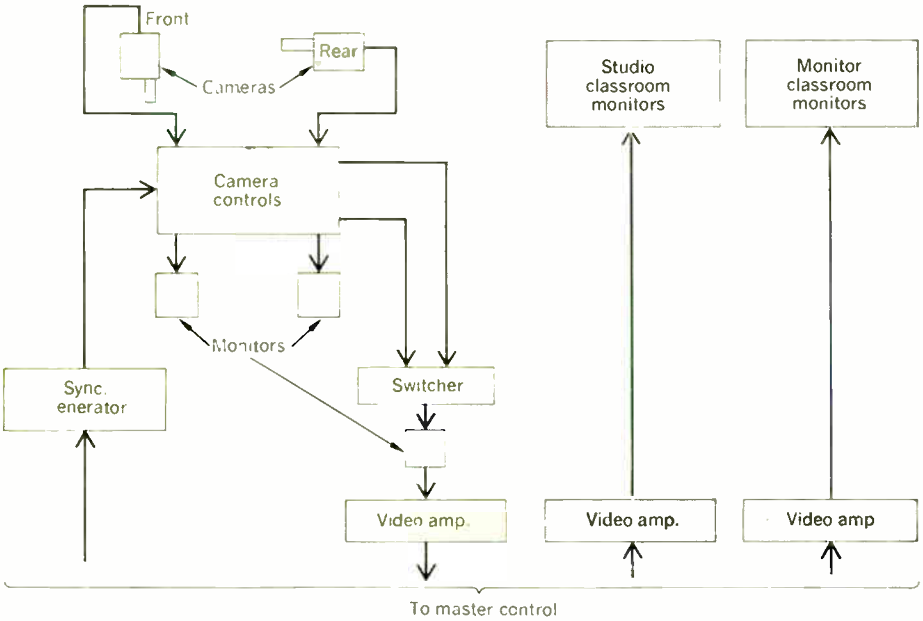


FIGURE 4. Simplified video block diagram of studio classroom.

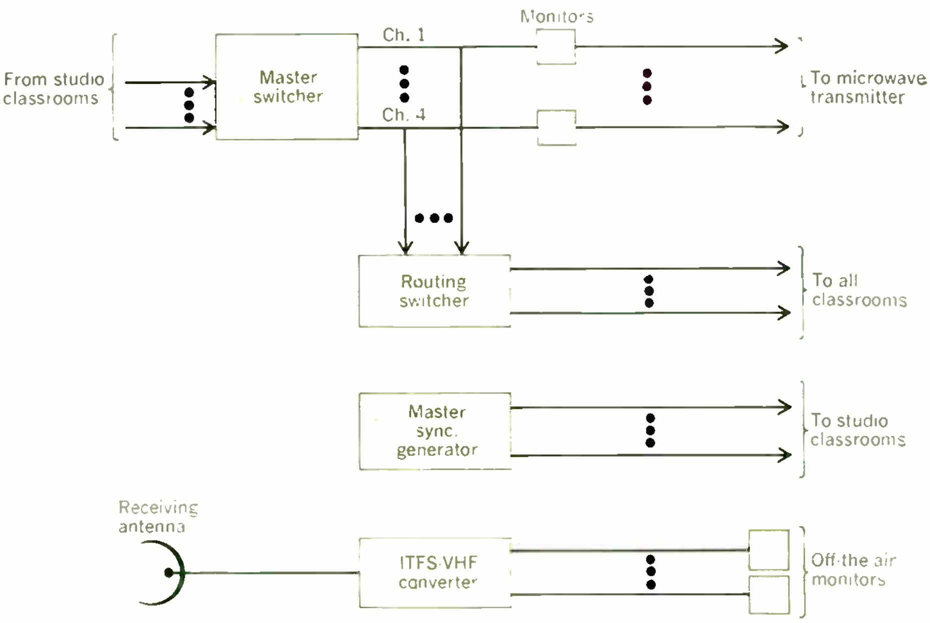


FIGURE 5. Simplified video block diagram of master control room.

a master switcher and monitors before being relayed on a 12-GHz microwave link, with 4-foot (1.2-meter) dishes, to our transmitter atop Black Mountain, some 12 km from the campus. A simplified video block diagram of the master control room is shown in Fig. 5. Both video and audio switchers have been designed to be completely flexible so that any room can be connected to any other room and to any channel. In addition, a receiving antenna and ITFS VHF converter are located at master control so that the television broadcast can be monitored directly off the air.

The transmitter facility atop Black Mountain is shown in Fig. 6. At this location the 12-GHz signals are converted down to baseband and back up to the ITFS band for transmission over the Bay area. The maximum transmitter power output permitted in the ITFS band is 10 watts per channel, which certainly limits coverage, but reduces system cost considerably over that required for conventional VHF and UHF television broadcast stations. Seven of the available 10 watts are radiated from an omnidirectional antenna that was modified to cover only the desired azimuthal arc of 160 degrees (see Fig. 1). This antenna is the pillbox mounted near the top of the 15.8-meter tower. The vertical pattern of the antenna drops rapidly above the horizon and more gradually below the horizon. The resultant gain of the antenna is about 17 dB, giving a significant increase in effective radiated power of the transmitter and an effective coverage range of 35–40 km, with receiving dishes from 0.6 to 1.8 meters in diameter. In order to reach San Francisco (55 km away), 1 watt of the transmitter power is fed from a 10-foot (3-meter) parabola, and 8-foot (2.4-meter) parabolas are used at the receiving sites. Finally, to reach the Emeryville–Berkeley area (63 km), 2 watts are fed from a 2-meter dish, with 3-meter parabolas at the receiving terminals.

Figure 7 shows the broadcast-related services between 100 kHz and 10 GHz. The ITFS band extends from 2500 to 2686 MHz. As this band of frequencies is at approximately 25 times the middle of the VHF band and five times the middle of the UHF bands, its transmissions require special antennas and frequency converters before they can be viewed on a conventional television receiver.

Figure 8(A) shows the distribution of the 31 ITFS channels allocated by the FCC. Each channel occupies 6 MHz to provide for the standard modulation format (AM video, FM audio). Channels are typically allocated in groups of four, with adjacent channels in each group separated by the 6-MHz bandwidth of interlaced channels from another group, as illustrated in Fig. 8(B). The total frequency spread is thus 42 MHz.

Conversion of the ITFS signals to the VHF television band is illustrated in Fig. 9. The four channels are converted directly to VHF with as many channels as possible being fitted into unused channels in the television coverage area. In our case, channels 8, 10, and 12 were available. An extra VHF-VHF conversion was necessary to accommodate the fourth ITFS channel so that it now appears on channel 3 in the San Francisco area. Once the conversion process has been accomplished, conventional television receivers and video distribution systems can be used for routing the signals to as many monitors as desired at the remote facilities.

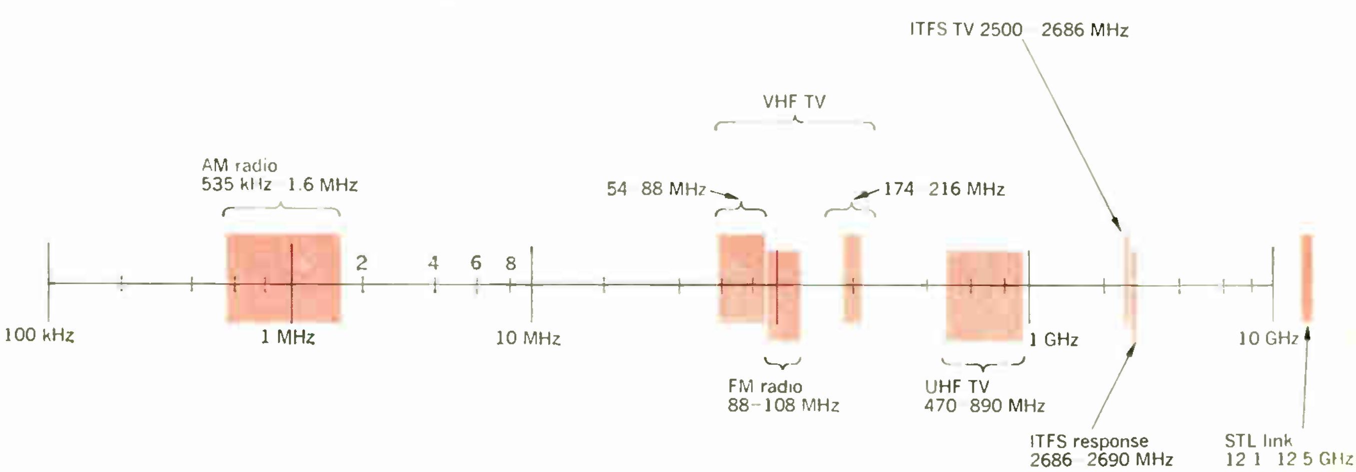
The typical television signal flow is summarized in the block diagram of Fig. 10, which shows the four basic locations involved in the total system.

To provide talk-back capability for the live classes being televised, a careful study of various alternatives was made. The result was a proposal submitted by Stanford to the FCC for a "Rule-Making" that would permit FM radio talk-back in the 4-MHz range at the upper end of the ITFS band (2686–2690 MHz) for each of the 31 available television channels in any given region. A favorable Rule-Making decision was made by the FCC in June 1969, enabling us to proceed with the licensing of a pilot system. Spectral distribution of the response station channels is shown in Fig. 8(B). The first "type acceptance" models of the talk-back system are being designed by Genesys Systems, Inc., for the Stanford network.

The talk-back transmitters provide a maximum of 250 mW of FM speech signal, as shown in the block diagram of Fig. 11. Each transmitter can be switched remotely to any of four crystal-controlled frequencies assigned to the licensee, although a single transmitter can operate on only one frequency at a time. The units are all

FIGURE 6. Black Mountain transmitter facility. Semi-omnidirectional antennas are mounted on the tower; directional antennas are mounted on pipes attached to the transmitter building foundation.

FIGURE 7. Spectral distribution of broadcast services. The ITFS television transmission and response station bands are contiguous. The Stanford studio–transmitter link is in the 12-GHz point-to-point service band.



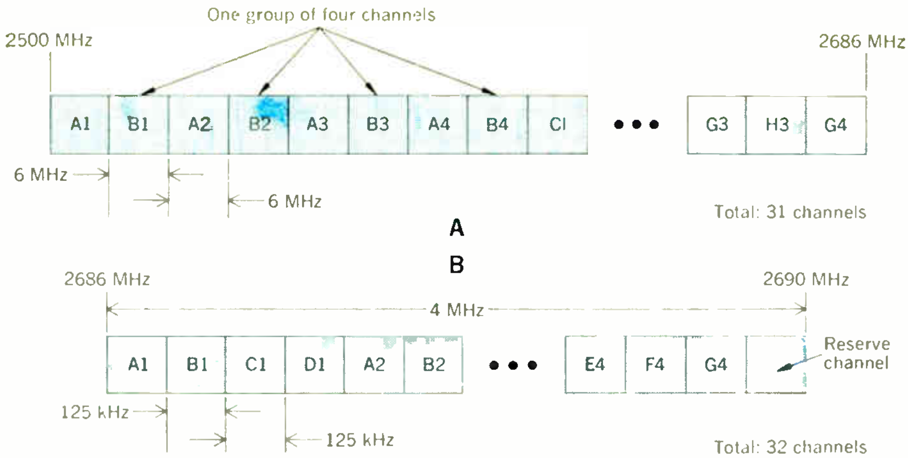


FIGURE 8. A—Distribution of ITFS television transmission channels. The Stanford network operates in the E group. B—Distribution of ITFS response station channels. The Stanford allocation is in the E group, corresponding to its transmitter frequency assignment.

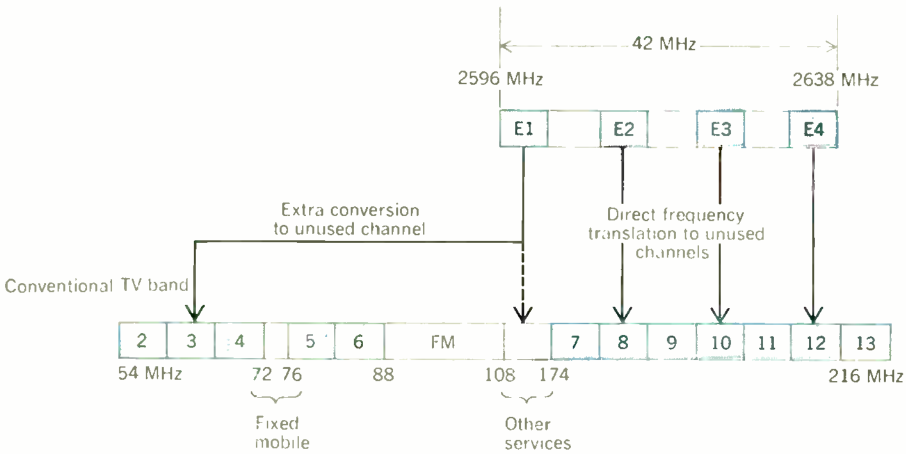


FIGURE 9. Conversion of ITFS transmissions to the very-high-frequency television band.

solid state and start with four crystal oscillators stable to ±0.0005 percent over −30°C to +60°C. These are followed by a phase modulator and frequency multipliers and amplifiers. The transmitters are keyed remotely with a switch on the microphone, which applies direct current to all of the RF transistors.

The units are designed for a peak deviation of ±25 kHz and a modulation passband from 300 Hz to 10 kHz. Frequencies below and above these values could be transmitted by the equipment if required.

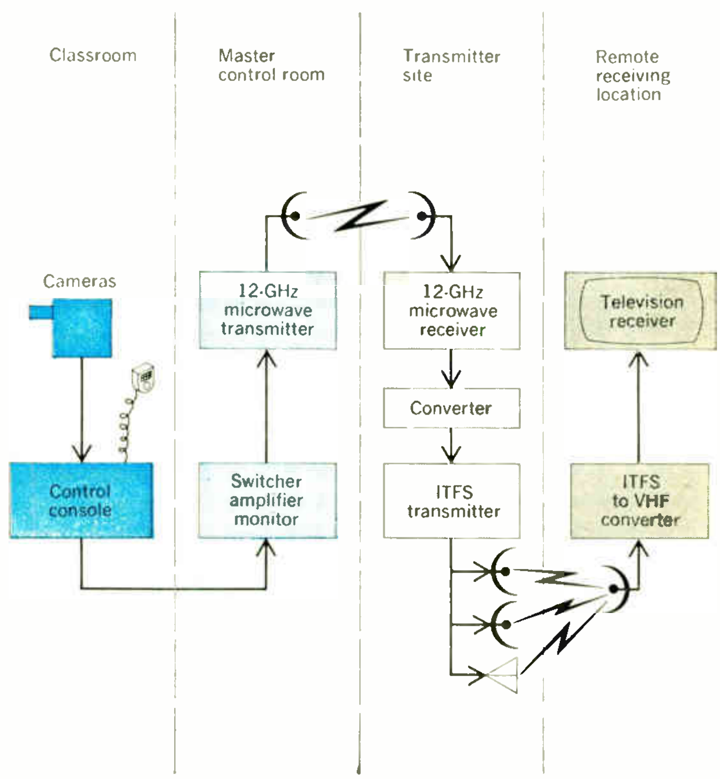
All of the equipment is located indoors except the last "times 6" multiplier, which is usually mounted on the antenna mast.

Talk-back transmitting antennas will be mounted in a common plane with receiving antennas at the remote classrooms, cross-polarized to reduce crosstalk. On Black Mountain, also, the talk-back receiving antennas are mounted collinearly with the transmitter antennas, as illustrated in Fig. 6.

In the interim before the talk-back transmitter system is installed, we are using conventional dial-up telephone lines for student questions. These lines are connected into the audio portion of the television system so that all students can hear questions and answers.

Two channels of the television system were initiated in April 1969, with 15 graduate engineering courses and two seminars being telecast on a regular basis. Ten courses and one seminar were offered during the summer

FIGURE 10. Typical television signal flow for the Stanford ITFS system.



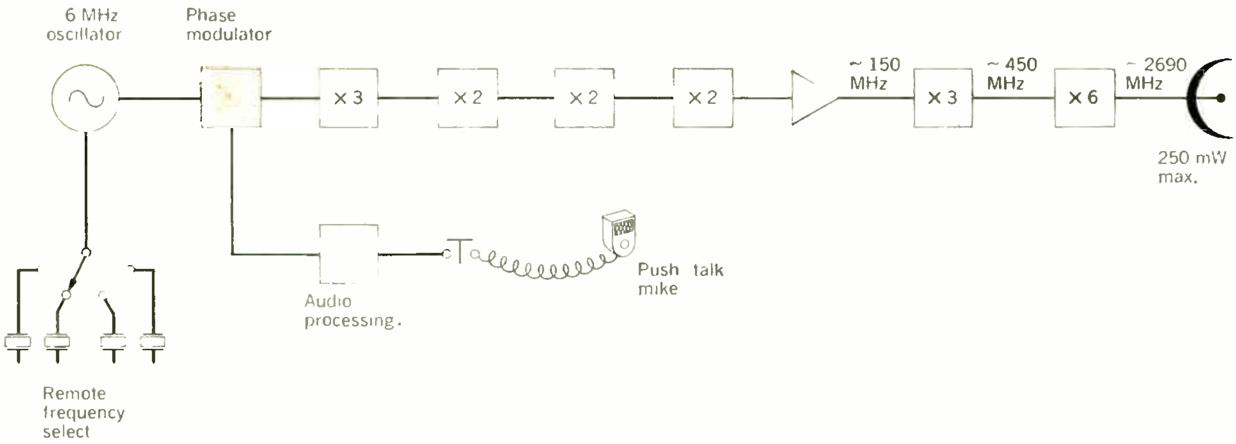


FIGURE 11. Simplified block diagram of a four-channel talk-back transmitter. The basic 6-MHz crystal frequencies are multiplied a total of 432 times up to the ITFS response station band.

quarter. In October 1969 the remaining two channels were implemented, with a total of 31 Stanford courses, representing all ten departments in the School of Engineering, being televised. Plans call for 38 courses to be televised during the spring of 1970.

A year later

ACE began televising continuing education programming on the network in May 1969, with four courses. In October the number of courses offered increased to ten, including such diverse titles as: Fortran IV, Systems Engineering, Secretarial Skills, and Seminar in Human Behavior. In addition, San Jose State College offered a course in digital logic for credit at that institution under the auspices of ACE. ACE projections called for the offering of 11 courses during the spring of 1970, depending on the demonstrated need established by member organizations.

When the courses are in session, a driver makes daily rounds to all network participants to deliver class notes and other material distributed by the instructors and to collect homework and examinations from the students. Both Stanford and ACE operate under an honor code, making it possible for remote students to take their examinations at their company plants instead of having to travel to a campus.

Although there has not yet been an opportunity to do detailed studies of the reactions of faculty and students to the television system, all of the informal reaction has been favorable. There have, of course, been many excellent suggestions for improvement and expansion of the facilities, which we hope to implement as soon as time and finances permit. Meanwhile, the Stanford instructional network got off to a most productive start just two years after the feasibility study was begun, and during its first nine months of operation has demonstrated the viability of televising live instruction to remote students.

Essentially full text of a paper presented at WESCON, San Francisco, Calif., August 19–22, 1969.

Joseph M. Pettit (F) received the B.S. degree from the University of California in Berkeley in 1938 and the engineer and Ph.D. degrees from Stanford University in 1940 and 1942 respectively. From 1938 to 1940, he was a teaching and research assistant at Stanford, and from 1940 to 1942 an instructor at Berkeley. During World War II, Dr. Pettit was engaged in radar countermeasures work on the staff of the Radio Research Laboratory at Harvard University, in 1944 in India and Chin as technical observer with the 20th Air Force, and in 1945 England as associate technical director for a laborat associated with the Harvard project. For this wartime w he was awarded the Presidential Certificate of Merit 1945, he joined Airborne Instruments Laboratory, and since January 1947 has been on the faculty of Star University, where he is professor of electrical engine and dean of the School of Engineering. Dr. Pettit's r society memberships include the National Academ Engineering and the American Society for Engine Education. He is a registered professional engineer i e state of California, and is associated with several co panies as a director or consultant. He has written num rous technical articles as well as several textbooks.

Donald J. Grace (SM) received the B.E.E. and M.S. degrees in electrical engineering from Ohio State University in 1948 and 1949, respectively, and the Ph.D. degree in electrical engineering from Stanford University in 1962. He also attended the University of Oklahoma and the Polytechnic Institute of Brooklyn. He was an instructor in electrical engineering at Ohio State University from 1948 to 1949, and from 1949 to 1951 was employed as a research engineer at Airborne Instruments Laboratory. He joined the staff of the Stanford University Electronics Laboratories in 1951 as a research engineer, becoming senior research engineer in 1962. The following year he was named associate director of the Systems Techniques Laboratory and in 1966 was appointed director of this facility. During this time he also served as acting associate professor of electrical engineering. In 1967 he became an associate dean of the School of Engineering and director of the Stanford instructional television network. Dr. Grace is currently director of research at Kentron Hawaii, Ltd., a subsidiary of LTV Aerospace Corporation. He joined the firm late in 1969. He is a member of Tau Beta Pi, Sigma Xi, and Eta Kappa Nu.