VOLUME 2 ☐ NUMBER 6 JUNE 1965

IEEE spectrum

features

35 Spectral lines

36 Plasma thrustors for space propulsion
David B. Miller
The propulsion requirements of certain upcoming space missions can be met by an electric thrustor using a plasma system

46 Esthetics and electric energy
Gordon D. Friedlander
Public reaction to ugliness in engineering and architectural design has produced some interesting and esthetic results in the design of new power facilities

56 Acoustics of the concert hall
T. J. Schultz
Careful observations and sound-field laboratory simulation experiments reveal that the energy relationship between early and late sound is critical for concert hall acoustical quality

68 Performance of interconnected systems following disturbances
C. Concordia
The critical period immediately following loss of generation is examined in terms of the most important system parameters

81 Magnetoelastic waves—new mechanisms for energy transport
George P. Rodrigue
Relatively long delay times are now achievable in microwave structures through use of electromagnetic wave propagation

86 IEEE Reports for 1964
- Introduction B. M. Oliver, President
- Report of the Secretary Haraden Pratt
- Price Waterhouse & Co. audit report

95 Authors

Departments: *please turn to the next page*

the cover

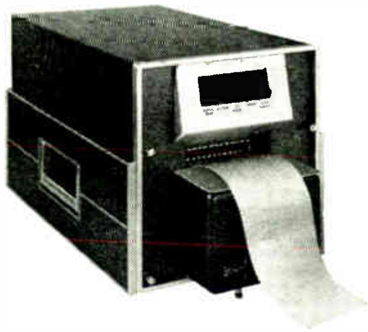
Suspended panels or acoustical "clouds" in New York City's Philharmonic Hall are shown on this month's cover. By closing the gaps and spaces between the panels, low-frequency reflection was improved. For an interesting paper on modern acoustical design of large concert halls, see page 56.

THE INSTITUTE OF ELECTRICAL AND ELECTRONICS ENGINEERS, INC.

departments


INTEGRATED CIRCUITS
Design Principles and Fabrication
INTEGRATED CIRCUITS


CRUSADING ENGINEER'S CMC CHECK THE SPECS
Order Yours




00000000

Correspondence

Machine recognition of language

With reference to the article, "Machine recognition of language—Part I" (March, pages 114–136), I wish to correct one point of fact regarding the organizational structure at the Air Force Cambridge Research Laboratories.

The Data Sciences Laboratory, one of nine such laboratories, is headed not by me but by Robert M. Alexander. Within it are two branches concerned with aspects of speech: the Digital Speech Compression Branch, headed by Caldwell P. Smith; and the Speech Research Branch, for which I have responsibility.

Weiant Wathen-Dunn
Air Force Cambridge
Research Laboratories
Office of Aerospace Research
Bedford, Mass.

With regard to machine recognition of human language, we would like to point out a fairly extensive effort that was undertaken at the IBM Research Center at Yorktown, N. Y., from 1955 through 1960. We believe that this effort was the first to utilize a computer in the analysis of speech sounds. Further, we believe that the use of multivariate statistical analyses were first applied to speech by our group.

Our work has been described in two articles. The first, "The Use of the IBM 704 in the Simulation of Speech Recognition Systems," was presented to the 1957 Eastern Joint Computer Conference. This report describes specially designed speech selection and analog-to-digital conversion equipment. Also, initial spectrum analysis and statistical programs are enumerated.

The second is a research report, "Spoken Digit Recognition Using Vowel–Consonant Segmentation," published in the *Journal of the Acoustics Society of America* in January 1962. This spoken digit recognition was a system of analysis set up on ten speakers and tested on these ten plus 40 more. These 50 speakers, 25 male and 25 female, each uttered the ten spoken digits once. The recognition system outlined in this report correctly identifies 97 per cent of these utterances correctly; 1½ per cent were rejected as unknown. The final 1½ per cent were substitutional errors. We believe this was the first indication of such success for multiple speakers uttering the ten spoken digits without prior training.

Gerald L. Shultz
International Business
Machines Corporation
Rochester, Minn.

Upon reading the article on machine recognition of human speech, it occurred to us that our research in this area might be of interest.

The ultimate objective of our continuing program, which we have been carrying on for the past five years, is the statistically valid description of the variations in and relationships among key parameters of speech. To achieve this, we first developed instrumentation capable of processing speech in real time with unexcelled precision and spectral resolution. With the aid of this equipment, we have been analyzing a great number of utterances of various words by different speakers under different speaking conditions.

The present objective of this effort is the determination of a statistically valid body of reference information that would settle once and for all the ultimate performance limitations of all spectral speech - pattern - recognition systems operating on the acoustic level without the use of linguistic or semantic information.

We have also devised a unique, and still unpublished, real-time high-precision pitch-extraction method, and are currently constructing a real-time precision pitch extractor for AFCRL in connection with a novel vocoder being developed there.

A. H. Sonnenschein
Federal Scientific Corporation
New York, N. Y.

Golden anniversary in radiotelephony. The first all-electronic radiotelephone transmission took place just a half century ago—on Easter Sunday 1915—from Montauk Point, L.I., to Wilmington, Del., a distance of about 200 miles. It proved to be a historic event, an integral part of the birth of electronics, although it was not reported in the press at the time. The event also had

57 million component-hours is a lot of reliability…*

and that's just what you get with Amperex 100 Kc circuit blocks

Designers of industrial, automatic-control-devices, and instrumentation, who are looking for ultra-reliability, ultra-simplicity and ultra-economy for their circuits need look no further than the Amperex line of 100 Kc Circuit Blocks and accessories for their solutions.

By combining different blocks, available off-the-shelf, designers can quickly build-up logic assemblies for control systems of unparalleled reliability without expending large amounts of time and money on research and development.

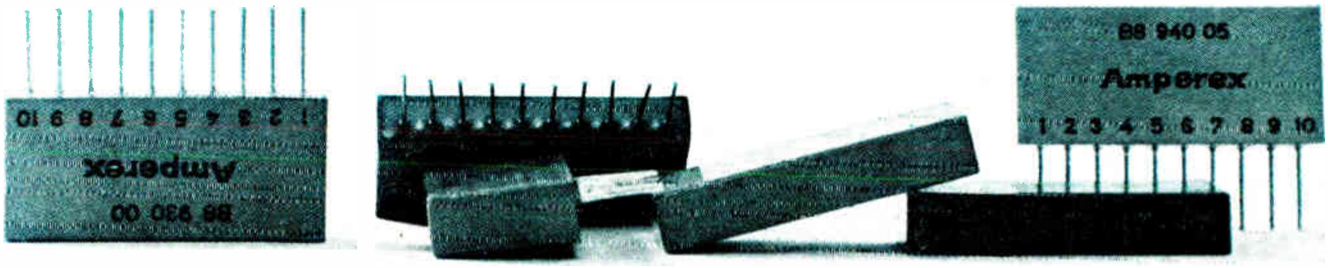
Reliability is insured by a 7-stage quality control process that begins at assembly, prior to potting, and is applied to every stage of production. This extreme care pays off in the field, where in application after application, equipment downtime is held to a minimum.

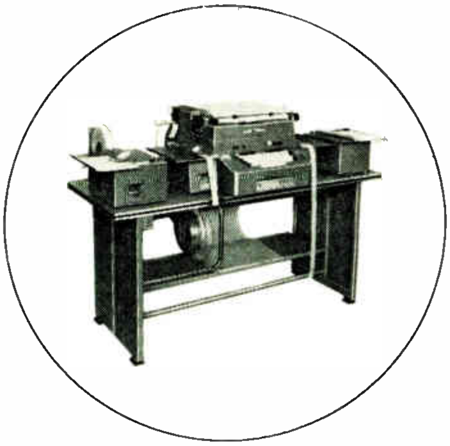
Amperex circuit blocks feature a heavy degree of loading and excellent fan-in, fan-out over the entire temperature range from −20°C to +60°C.

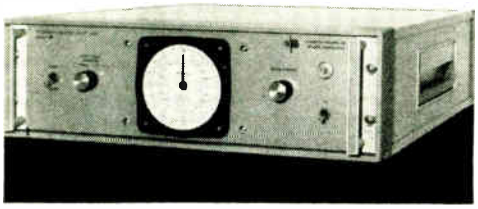
And, if you are worried about cost… Amperex circuit blocks are more economical to use than any other circuit you can buy or build yourself. There are more than 20 different basic blocks in the line, starting with a twin 2-input "AND" gate for only $1.75. The line includes pulse shapers, flip-flops, one-shot multivibrators, twin emitter followers, emitter follower/inverter amplifiers, twin inverter amplifiers, pulse logic units and others. Accessories for convenient mounting, including chassis, printed wiring-boards, locking-tags and power amplifier racks are also available off-the-shelf.

For our condensed catalog, price list, applications recommendations and *proof of the 57 million component-hours of reliability, write: Amperex Electronic Corporation, Digital Products Department, Hicksville, Long Island, New York 11802.

Amperex®







its amusing aspects. It is recalled here by one of the few surviving participants.

The electronic radiotelephone system that was put to the test that Sunday solved a long-standing problem—how to control by weak voice currents the much more powerful waves required for radio transmission. The secret proved to be to do the modulating at low energy, and then to amplify to the needed power level by means of a high-frequency amplifier. This had become possible with the perfection of Lee de Forest's grid triode into the high-vacuum tube by Dr. H. D. Arnold, of what was then the Western Electric Company branch of the Bell System. The conception of the scheme of weak modulation plus power amplification evolved naturally in the laboratory, participated in by Arnold, E. H. Colpitts, and Dr. H. J. van der Bijl. It had first appeared as a means of multiplexing wire lines in an electronic carrier system that had been tried out in the laboratory in 1914 by R. A. Heising. It was natural, then, that Heising should be given the task of putting together a radiotelephone transmitter using the newly developed tubes.

It was on the Wednesday before Easter, March 31, that Heising stepped off the train at Montauk to see his breadboard-mounted apparatus set up in the new station we had just completed for that purpose. The station had been erected in two months under the direction of John Mills and his assistant (myself), both of the American Telephone and Telegraph Company. The location was on the beach between the ocean and Fort Pond, chosen because it was low lying, near water, which would facilitate a good ground-wave getaway. The transmission path was to be over water, which meant that the receiving station would be down the coast somewhere. In reconnoitering, I had spotted the unused towers atop the Du Pont Building at Wilmington, and that place was chosen. R.V.L. Hartley was in charge of the receiving end, with the help of Austin Curtis and R. H. Wilson.

Heising at Montauk and Hartley at Wilmington were given only a few days in which to get set for the test. Heising took care to send only carrier and tone-modulated telegraph signals, because honored officials were to open the link for speech on Easter Sunday. H. D. Arnold had come down from New York, and on the evening of April 2 my immediate supervisor, John Mills, arrived with our superior, F. B. Jewett. Saturday, the third, turned out to be a snowy day, and I well remember how we watched from our vantage point atop the hill, in the old Montauk Inn, for the afternoon train that was to deliver a notable guest—Prof. Robert A. Milliken. And I remember how I ran down the hill in deep snow to intercept the vehicle that was taking him off to another hotel, thus meeting the famous man for the first time. The snow kept falling, and by evening we still anxiously awaited the main party of those who were to participate in the test. Not until 11 p.m. did the train chug to a halt at Montauk. At the Inn we welcomed, and provided with dry clothes as best we could, the weary visitors: J. J. Carty, chief engineer, American Telephone and Telegraph Company; Bancroft Gherardi, assistant chief engineer; O. B. Blackwell, American Telephone and Telegraph Company; Thurber and Scribner of the Western Electric Company; Col. S. Reber of the Signal Corps.

Sunday morning, the day of the tests, broke fair, but the Montauk hills seemed bleaker than ever in their mantle of snow and ice. When we examined the site we saw that our fear for the antenna had been realized. There it lay, on the ground—and with all that "top brass" back in the warm inn waiting for the demonstration! We were nonplused, but young enough to take it. There was nothing to do but to restore the antenna. I climbed one tower; friend Christopher of the New York Telephone Company climbed the other. The going was treacherous, for the tower angle irons were coated with ice. At the tops we found the sheaves blocked with ice, which prevented the halyards from giving with the ice load on the antenna wires. That was soon remedied and the antenna restored. Meanwhile Heising had entertained the visitors by explaining the operation of his apparatus.

The critical moment arrived, not too much delayed, with Carty saying, "Hello, Wilmington!" The answer came back promptly by wire, "O.K." Wilmington was hearing the speech well, as it had the tone telegraph earlier. The transmission went on, with each visitor taking his turn. At Wilmington, Hartley, Wilson, and Curtis repeated back the messages that were sent. The return line was then connected at Wilmington to the output of the receiver so that Montauk could receive back what was said. Then at Wilmington the line was disconnected from the radio receiver and at Montauk it was connected to the transmitter. This enabled the Wilmington engineers to talk to themselves via Montauk and the radio

THE BUSINESS PRINCIPLES OF AN AEROSPACE INDUSTRY

These statements of policy were presented at an Engineering Forum by Vice President of Engineering at McDonnell, Mr. Kendall Perkins. If you, as an engineer are encouraged to follow these principles in your work, you will gain. If you are successful in the pursuit of these goals, the Nation will gain.

". . . Organizations, like people, have personality and character. The things which make an organization distinctive are the ways in which it differs from other organizations. These generally stem from subtle differences in the principles which guide it and the practices it has learned to follow. What then are the guiding principles at McDonnell?

"*We believe it is a good business principle, for example, to give high priority to anticipating and doing our best to meet the needs of the customer*—those needs which are really sound and will not change tomorrow. This often means passing up the easy-to-get contract, or the quick and easy solution to a problem, or even the approbation of a customer representative who may have become oversold on a particular project or a particular solution to a problem. Anticipating real and lasting customer needs often means creating something the customer hasn't yet asked for and doesn't yet want to buy—and then developing it and presenting it in such a way that the need becomes sufficiently apparent and pressing to open the door to a contract.

"We're not always right in what we believe the customer should have but we've found that timely and energetic effort to find what he needs, and to find an optimum solution, pays off handsomely in the long run. It was this principle which led us to start work on a manned orbiting spacecraft more than a year before the NASA asked for bids on Mercury. The same principle led us to undertake the design of an unusually versatile, high performance fighter for the Navy more than a year before our first Navy contract for Phantom II's. Thus it might be said that our largest current contracts have stemmed from the practice of anticipating customer needs. We still look forward to sizable production contracts for products conceived several years ago and actively developed since.

"*We believe it is a good business principle to give high priority to meeting the needs of the individuals who make up our organization.* This means many things in addition to a fair salary. It means treating people as they should want to be treated—with fairness and understanding. It means defining responsibilities and necessary constraints, but not blocking initiative. It means opportunities for personal development by training, and freedom to transfer to other kinds of work. It means opportunities to contribute to attainment of worthy objectives. It means opportunities to advance to positions of responsibility and recognition, depending primarily on such contributions. It means the fairest and most thoughtful attention to adjustments in position and salary.

"We're not always right in our treatment of people but it's not for lack of trying at all levels. Our record has been outstanding in that we have close to the highest morale and close to the lowest percentage of terminations in the aerospace industry.

"*We believe it is a good business principle to effectively foster cooperation between people.* It may sound corny to talk about team action as much as we do. But nowhere in industry is there so great a need for cooperation—internal and external—as in the aerospace industry. Few other industrial products are as complex or as dependent upon such advanced engineering as a manned spacecraft or high performance aircraft. Few require so many kinds of engineering talent interacting toward the solution of so many kinds of problems. Few products require reconciling so many requirements expressed by so many people in so many documents. In short, there is a demand for effective coordination in the thinking of great numbers of people unmatched in any other industry.

"There is no such thing as an expert in all phases of an airplane, a missile, or a spacecraft. Successful systems of this complexity are developed only by employing the combined efforts of a team of people engaged in a wide variety of engineering and other activities. Technical areas are as far apart as chemistry and UHF radiation, hypersonic aerodynamics and gyroscope design, exotic high temperature materials and computer technology. No single brain can firmly grasp all these areas. Hence there is no substitute for an effective team—one whose members have learned to work together in harmony and mutual respect. The man who would lead such teams must be capable of grasping what is told by others and appreciating the implication, but he must be modest enough to depend on the abilities and judgment of others and delegate responsibility whenever he safely can. Advanced systems development cannot be successfully run in a high-handed manner.

"I feel we have been successful at McDonnell in creating a harmonious atmosphere and minimizing non-constructive controversy. I believe we have built a team where there is a real sense of pride in group accomplishment and, at the same time, recognition of individual accomplishment. There is acceptance of necessary constraints without undue loss of individual spontaneity. We in management do our level best to provide a climate where these things can happen.

"The process of fully considering inputs from, and working in close harmony with so many other people calls for a type of organization and a set of skills and habits not ordinarily taught in school. It calls for keeping our viewpoints as broad as we can. It calls for changing our minds when the logic of the situation demands. It calls for keeping the best interest of the customer and the company ahead of our own immediate desire. It calls for recognizing that the other fellow's opinion can validly differ from our own without signifying either poor judgment or questionable motives on his part. It calls for keeping our heads when those about us are losing theirs and blaming it on us. It calls for these and many other practices in good human relations.

"*We believe it is a good principle to make important decisions with the most meticulous care.* In comparing our company with others it strikes me that we are more careful than most about reaching our decisions. We have learned the importance of examining all alternatives, digging up all the pertinent facts, fully analyzing results, and being objective and thorough in our judgments. This has tended to become a habit, exasperating at times, but well worth it on balance. It began when the company was formed and, in my opinion, has had more to do with our success than any other single practice."

Engineers, Scientists, Physicists and Mathematicians with energy, enthusiasm, and great creativity are needed for projects in the national interest underway at McDonnell. If you would like to work where the business principles outlined above are corporate policy and where the pursuit of excellence is a permanent corporate goal, we urge you to complete and mail the brief resume form below.

MCDONNELL An Equal Opportunity Employer.

Mail This Form To: W. R. Wardle, McDonnell Employment, Dept. CC-6, Box 516, St. Louis, Mo., 63166

Name__________ Home Address__________

City & State__________ Phone__________ Age______

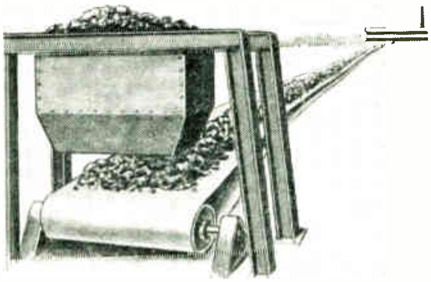
Education: BS______ MS______ Ph D______ Major Field:__________

Date Date Date

Primary Experience Area:__________ Present Position:__________

__________ Number of Years______ __________ I would like to receive application form ☐

FIRST FREE MAN IN SPACE



link. Thus was demonstrated an important feature of the new radio system, that of enabling integral wire-radio connections to be made.

The snow and ice had quite disappeared by noon and most of the visitors were able to take the early afternoon train back to New York and to go on to Wilmington where they witnessed the receiving operation. From Montauk, Jewett held two-way conversations with them by the radio–wire combination. The wavelength employed in these tests was 1700 meters.

Why the rush to carry out these tests—and why the precaution of having them so amply witnessed? The answer is this: For years, Carty had been watching the progress in radiotelephony, and since 1910 I had scanned the technical news and reported the activity, injecting some stimulating thoughts of my own. Radiotelegraph technology was yielding several forms of continuous-wave working, as distinct from the discontinuous spark method, a *sine qua non* for radiotelephony. By 1913 the Germans were outdistancing the Marconi Company in transatlantic wireless telegraphy by means of high-frequency alternators and the like. There was naturally talk about realizing transatlantic telephony. At that prospect, Carty came to life. He asked his assistants for an estimate of what it would mean to undertake that project. This was just before the vacuum tube arrived on the scene as a possible transmitter, by the grace of God! The main problem had been how to modulate the power required for transmitting, by means of the weak voice energy. When, in 1914, there gradually appeared the possibility of solving this problem by utilizing the power-handling ability of the high-vacuum tube, Carty obtained authorization to develop radio vigorously, with the result here seen.

Actually, the Montauk–Wilmington test was just the beginning. From Montauk a longer-distance test was undertaken—to Saint Simon's Island, Ga., a distance of about 700 miles. It took place in May, at the height of the atmospheric noise season. This, in turn, led to further worlds to conquer, nothing less than overseas transmission. That test, too, was successfully carried out the same year. The result was so startling for the times that it was heralded by front-page headlines. The details of that event have not yet been told, and must be left for another story.

Lloyd Espenschied
Kew Gardens, N.Y.

Spectral lines

Publication Objectives—II. In a previous "Spectral lines" article (April), the objectives of the IEEE publications were discussed with particular emphasis on their role in advancing the profession. In this article the effectiveness of the Institute's publications will be considered from the standpoint of advancing the capabilities of its members. It is in this latter role that there is need for new and imaginative thinking.

The rate at which science and technology have advanced in the post-World War II era is remarkably greater than the rate in the decades before the war. This fact has been widely recognized. Many industrial, educational, and governmental organizations concerned with technological developments are making strong efforts to adapt themselves to this rapidly changing environment. A major problem faced by these organizations is how to keep the scientific and technical abilities of their engineers and scientists abreast of new developments.

Many industrial and governmental laboratories are developing increasingly comprehensive in-house instruction programs to help maintain the capabilities of their technical staffs. Others permit their employees to devote a significant number of hours per week to technical education. In other cases technical staff members are given extended leaves of absence for improving and updating their knowledge and skills by returning to residence at universities. In turn, universities are developing special "continuing" education programs to take care of the specialized needs of the engineers and scientists who wish to update and expand their technical capabilities and understanding.

How are the professional societies in general and the IEEE in particular adapting themselves to this rapidly changing environment? Some significant steps have been taken. For example, some Sections have developed lecture series as a means of developing the necessary background knowledge needed to understand new fields. Tutorial and state-of-the-art sessions have been sponsored by Groups at their conferences to introduce their members to specific fields and to update them in rapidly developing areas.

But what about the publications which are the communication channel by which every member of the Institute can be reached? Special Issues of the PROCEEDINGS, that is, issues devoted to a single technical field including survey articles written by well-known specialists, are an example of a significant education effort. The 28 Special Issues that have published since their inauguration in 1951 have frequently performed a significant service to members as an introduction to a new field.

However, these issues are frequently written at a too advanced technical level for many of the Institute's members. It is here that there is much room for improved service and it appears that SPECTRUM has a significant role to play. Appropriately written articles could help to orient an individual in fields for which he has adequate background in the relevant mathematics, physics, biology, or chemistry. They might also help him to recognize what additional background he needs to understand new developments. However, it is not feasible to expect SPECTRUM to teach quantum mechanics to those electrical engineers who have never been exposed to modern physics. The potentialities of SPECTRUM as an instrument for advancing the individual member's capabilities need to be more completely exploited.

But perhaps there are other ways for the Institute to assist in the continuing technical education of its members. Here is where imaginative thinking is most needed. The Institute, with its Groups organized around technical specialties, its Sections organized on a geographical basis, and its publications devoted to specialized and general coverage, is a rather unique instrument for providing a variety of services. These services, in conjunction with those offered by universities in their formal degree programs, special short courses, and continuing education programs, and the variety of programs sponsored by governmental and industrial organizations, should be molded into such a form that engineers in all stages of their careers will be enabled to maintain and improve their technical and scientific capabilities.

The job that needs to be done is both large and complex. It will take bold thinking and action. We can start by learning how to utilize our present assets more effectively.

F. Karl Willenbrock

Plasma thrustors for space propulsion

Certain space missions will require relatively high propellant exhaust velocities. An electric thrustor using an electromagnetic (plasma) system can generate the needed velocities. However, much is still to be learned about plasma physics and engine technology

David B. Miller *General Electric Company*

When the molecules of a gas are ionized so that the gas becomes a conductor of electricity (plasma), the gas may then be accelerated by electromagnetic forces. Inasmuch as attainable velocities are higher than can be reached by accelerating a hot gas through a nozzle and because the magnitude of the magnetic force is appreciable, this method of producing high-velocity gas is being seriously studied for use in a reaction (rocket) engine. In this article, the need for this type of thrustor, based on the propulsion requirements for space exploration missions, will first be considered. Techniques of plasma propulsion will then be treated. It will be seen that plasma engines are in their infancy with much to be learned about the physics of a plasma and the technology of a plasma engine; also that the most likely application for these engines, fortunately, is in deep space missions, which are still some time away in the future.

Flight dynamics—need for electric propulsion

The analysis of any particular space mission is a rather complex task, involving many parameters, and is dependent on the optimization criterion selected.[1] One particularly simple and illuminating characteristic of any mission is the change in vehicle velocity (ΔV) needed to accomplish the mission. The approximate velocity changes required for various missions are listed in Table I.[2] These velocities are "ideal" since they have not been corrected for potential and dissipative effects. In addition, the Table I missions are "impulsive," with thrust being applied for negligibly short durations as compared with the total mission time (high thrust), and certain modifications must be made in the analysis for longer-thrust (low-thrust) and programmed thrust trajectories. The ΔV for a given mission accomplished by low thrust will be three to four times higher than the ΔV for the same mission performed by impulsive, high thrust.

A reaction-driven space vehicle receives its thrust, and therefore its change in velocity, by expelling propellant mass. The following independent parameters characterize the system:

M_p = propellant mass expended during the mission, kg
M_f = fixed mass—payload, vehicle structure, etc., kg
c = propellant velocity relative to the vehicle, m/s
$\dot{M}$ = rate at which propellant is exhausted from the vehicle, kg/s

(Therefore the thrust time, during which the velocity change ΔV is accomplished, is given by $\tau = M_p/\dot{M}$.) Integration of the equation of motion leads to the following expression[3]:

I. Velocity increments

Mission	"Ideal Velocity Change" ΔV m/s	"Ideal Velocity Change" ΔV ft/s	Mission Time, years
Earth surface to 300 nautical miles (nmi) circular earth orbit	7 600	24 900	
Earth surface to circular solar (heliocentric) orbit at earth–sun radius	11 000	36 100	
300-nmi earth orbit to elliptical Mars passage*	3 540	11 600	
300-nmi earth orbit to elliptical Jupiter passage*	6 400	21 000	
300-nmi earth orbit to elliptical Saturn passage*	7 300	24 000	
300-nmi earth orbit to "capture" as Martian satellite (6000 nmi)	5 400	17 700	
Earth to Mars circular heliocentric orbit transfer†	5 600	18 400	0.7
Earth to Jupiter circular heliocentric orbit transfer†	14 400	47 200	2.8
Earth to Saturn circular heliocentric orbit transfer†	15 700	51 500	6.1

* Single impulse, minimum energy, "hyperbolic passage" trajectory
† Double impulse, minimum energy (Hohmann) transfer

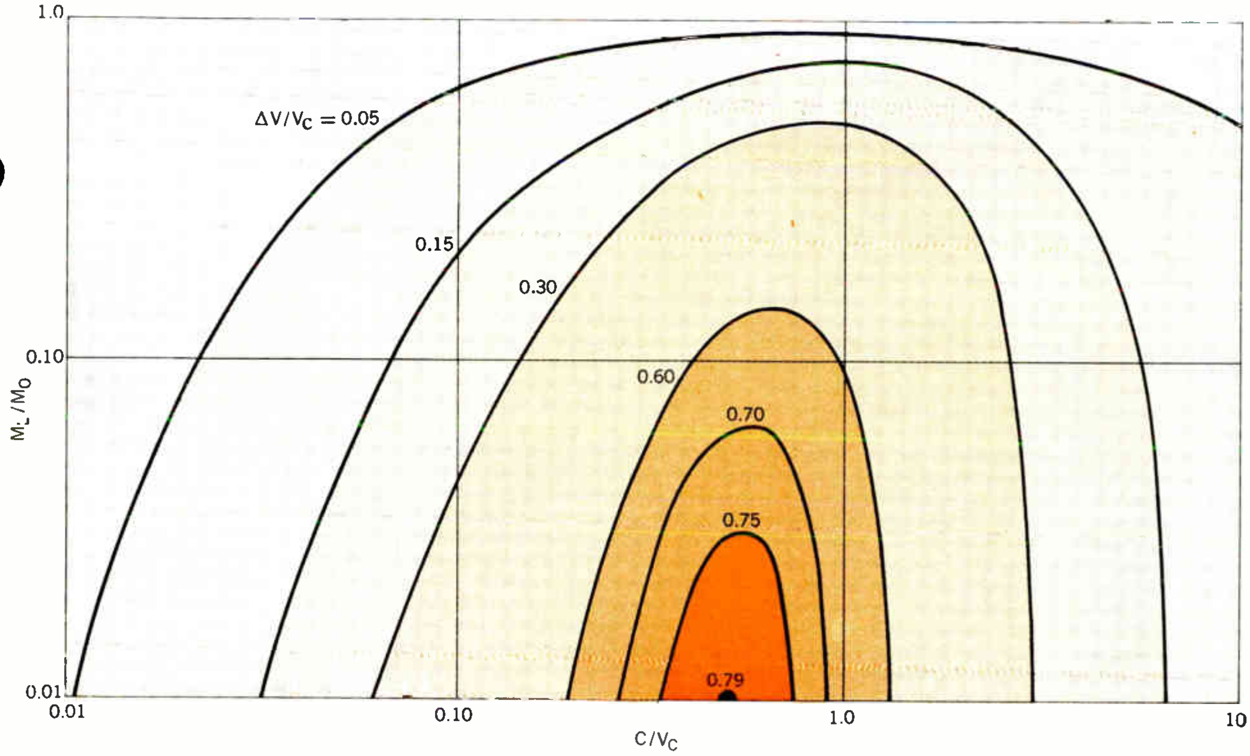


Fig. 1. Mass ratio (payload/total initial weight) as a function of exhaust velocity for various mission velocities ($V_c = \sqrt{2\tau/\alpha}$).

$$\Delta V = c \ln \left(1 + \frac{M_p}{M_f}\right) \qquad (1)$$

We can see from Eq. (1) that, for any given mission ΔV, c must be kept large enough so that the propellant mass M_p does not dominate the total initial mass $M_o(= M_p + M_f)$. As an example, we can take ΔV to be 20 000 m/s, which (as can be seen from the table, remembering the low thrust correction) is characteristic of an interplanetary mission. If a typical chemical propellant velocity—3000 m/s—is chosen, the ratio M_p/M_f from Eq. (1) is approximately 78.

Nuclear rockets, in which the propellant is energized by heat from a reactor, are projected to reach propellant velocities of perhaps 9000 m/s,[1] giving 8.2 for the M_p/M_f mass ratio. Thus, although the nuclear rocket provides a marked improvement, a large fraction of the initial mass is still invested in propellant. A higher propellant velocity appears desirable for the more difficult interplanetary missions, and so we must consider more precisely just what velocity is needed. To do this, however, gross characteristics of the propulsion system to meet this higher velocity requirement must be defined.

Chemical and nuclear rockets energize their propellant by a thermal heating process, and the exhaust velocity is therefore limited by the temperature capability of the chemical reaction or of the confining walls. Further increases in exhaust velocity can be realized by going to nonthermal (electric) acceleration procedures. Unlike the chemical and nuclear systems, this system requires a supply of electric power (mass M_W, power W) to be carried along, and an important parameter is therefore the power plant specific mass

$$\alpha = M_W/W \text{ kg/W} \qquad (2)$$

An additional convenient parameter related to α is a velocity V_c sometimes called the "characteristic velocity," defined as[3]

$$V_c = \sqrt{2\tau/\alpha} \text{ m/s} \qquad (3)$$

where τ is the mission time in seconds. Since the power W is given by ½ $\dot{M}c^2$, the characteristic velocity V_c is also reducible to $c\sqrt{M_p/M_W}$. The fixed mass M_f can now be broken down into M_W and M_L, the power plant mass plus the payload mass, including vehicle structure. Substitution of this into the rocket Eq. (1), with other proper substitutions, then gives[4,5]

$$\frac{M_L}{M_o} = e^{-\Delta V/c}\left[1 - \left(\frac{c}{V_c}\right)^2 (e^{\Delta V/c} - 1)\right] \qquad (4)$$

This equation is plotted in Fig. 1, which shows the mass ratio as a function of exhaust velocity for several mission velocities ΔV, both velocities being normalized with respect to the "characteristic velocity" V_c.

Several points should be noted from Fig. 1:

1. The "best" exhaust velocity—i.e., that exhaust velocity which maximizes the payload—is not necessarily the highest velocity attainable, but rather, for any given mission (ΔV, τ) and system (α), there is an optimum exhaust velocity. Above this value, too much mass is tied up in the electric power supply; below it, too much mass is needed for propellant.
2. Power-plant specific weight α should be minimum.
3. A trade-off between mission time and delivered mass must be made.

Further optimizations can be made by programming the thrust during the mission.[6] Using these most advanced analysis procedures, with required spacecraft weights and realistic power-plant specific weights being considered, the optimum exhaust velocities needed for the various desired deep-space (interplanetary) missions fall approximately in the range 10 000–100 000 m/s.[7-11] It is within this range of velocities that we would hope to operate our nonthermal electric engines.

Thrust considerations

Electric thrustors employ either of two basic electromagnetic forces, the Coulomb ($\mathbf{F}_e = e\mathbf{E}$) or the Lorentz ($\mathbf{F}_b = e\mathbf{v} \times \mathbf{B}$) reaction. (A third electric system, the electrothermal engine, which is a thermal device in which the propellant is heated by I^2R electric power, is not being included in this analysis. This type of thrustor shares with other electric devices the need to carry along an electric power supply but does not have the advantage of getting away from the thermal velocity limitation of chemical and nuclear rockets.) The Coulomb force is employed in the electrostatic (ion) class of thrustors. The electromagnetic (plasma) engines are based on the Lorentz interaction.

In both the electrostatic and electromagnetic engines, thrust is given by the rate of change of momentum, but thrust can also be evaluated in terms of the reaction force on the vehicle through the appropriate field. Let us consider an idealistic ion engine consisting of a pair of plane-parallel screen electrodes. Let a voltage be placed across this diode and let ions be created at one plane so that they accelerate across the diode and out through the other plane. If the ion current density is the maximum or space charge limited value, as governed by the Child–Langmuir relation, then it is easy to show that the thrust density can be expressed as

$$\frac{T_e}{A} = \epsilon_0 E^2/2 \tag{5}$$

where T_e/A is the thrust per unit cross-sectional area (newton/m²), ϵ_0 is the dielectric constant, and E is the electric field (V/m) at the exit electrode. Thus, the thrust density is identical to the change in field energy density across the exit electrode.

It is more difficult to define an "ideal" plasma accelerator equivalent to the parallel-plane electrostatic configuration just discussed. For purposes of comparison, however, it is sufficient to consider an infinitely extended plasma sheet whose thickness is z_1, carrying uniform current density J_x A/m², as shown in Fig. 2. The force per unit volume at a point in this plasma is

$$\frac{\mathbf{F}}{V} = \mathbf{J} \times \mathbf{B} \tag{6}$$

Let us assume that the magnetic field is B_0 behind the sheet and zero ahead of the sheet, as in the case of pulsed electrode accelerators to be described later. The field strength within the plasma can therefore be evaluated from the curl expression $\nabla \times \mathbf{H} = \mathbf{J}$, giving

$$H_y(0) = z_1 J_x \tag{7}$$

Now consider a sheet increment dz thick at position z within the sheet, as shown in Fig. 2. The force per unit area on this sheet is [substituting Eq. (7)]

$$d(F/A) = \frac{F}{V}\,dz = J_x B_y\,dz = \frac{B_y{}^2(0)}{\mu_0 z_1{}^2}\,z\,dz \tag{8}$$

Integration across the sheet then yields the final expression

$$\frac{F}{A} = \frac{B_y{}^2(0)}{2\mu_0} \tag{9}$$

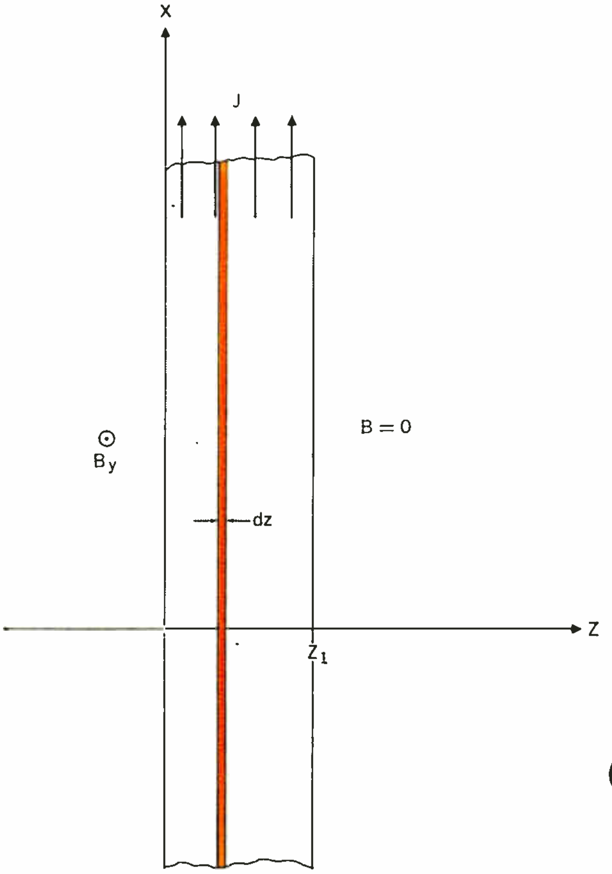
And we finally arrive at an expression for plasma thrust density, equivalent to the electrostatic expression (5), given by

$$\frac{T_b}{A} = \frac{B^2}{2\mu_0} \tag{10}$$

Thus, as in the electrostatic case, the thrust density is given by the change in field energy density.

A fundamental thrust comparison between the electro-

Fig. 2. Plasma sheet (infinitely extended in X and Y directions) carrying uniform current density J (amperes/m²).



magnetic and electrostatic engines can now be made, through the use of Eqs. (5) and (10). Dividing Eq. (10) by (5) gives

$$\frac{T_b/A}{T_e/A} = \frac{B^2/2\mu_0}{\epsilon_0 E^2/2} = \frac{1}{\mu_0\epsilon_0}\left(\frac{B}{E}\right)^2 = c^2\left(\frac{B}{E}\right)^2 \qquad (11)$$

where c is the speed of light, 3×10^8 m/s. Reasonable upper limits for the magnetic and electric fields are, respectively, 10^{-1} weber/m^2 and 10^6 V/m. This yields for the Eq. (7) ratio

$$\frac{T_b/A}{T_e/A} \cong 1000$$

Although the exact numbers to be inserted for the appropriate field strengths of actual devices may not be as given here, the general point to be observed is that the thrust density achievable by magnetic devices should be many times larger than that realized by electrostatic techniques. This result is of course not unfamiliar to electrical engineers.

Although a possible thrust density advantage of the plasma devices has been demonstrated, actual mission thrust requirements must be explored in order to determine whether this is an advantage of any consequence. Although a wide variety of spacecraft weights have resulted from planning studies,[6,7,9–11] 10 000 kg may be taken as at least indicating the proper order of magnitude for our purposes. If we use the ΔVs and mission times as given in Table I (i.e., not making the low thrust correction), then the average thrusts for such a vehicle are approximately 0.8 and 2.6 newtons, respectively, for the Saturn and Mars Hohmann transfers, neglecting the change in vehicle mass due to propellant ejection during the flight. For these cases, the saving in size by using a magnetic thrustor is of little advantage since in any case the engine cross-sectional area will be small.

If, however, we wish to use increased thrust to shorten the mission time, the situation changes. Consider, for instance, shortening the Saturn trip tenfold, from 6 years (~2000 days) to 200 days. This would require an average thrust of 8 newtons, in approximate agreement with mission planning studies.[7,12] Ideal engine areas from (5) and (10), using assumed field values of 10^6 V/m and 10^{-1} weber/m^2, are in this case 1.8 m^2 (ion) and 0.002 m^2 (plasma). These areas apply to the ideal exhaust stream cross section; an actual engine will require peripheral structure, which will reduce the effective thrust density. Currently, ion engines are yielding effective thrust densities of the order of one-tenth to one newton per square meter,[13,14] which is approximately a tenth of the "ideal"—and we can expect a similar reduction in effective plasma thrust density. As a consequence, actual engine areas now become 18 m^2 (ion) and 0.02 m^2 (plasma). The savings in structural and system weight and complexity to be effected with the plasma engine now become significant.

Efficiency

Several engine efficiencies can be defined[15] as follows:

$$\text{Power efficiency } \eta_p = P_e/P_{\text{in}} \qquad (12)$$

(where P_{in} is the electric power put into the engine circuit and P_e is the power in longitudinal motion of the propellant exhaust stream)

$$\text{Velocity efficiency } \eta_v = (\bar{V}^2/\overline{V^2}) \qquad (13)$$

(where $\bar{V}$ is the mean exhaust stream longitudinal velocity and $\overline{V^2}$ is the mean squared longitudinal velocity)

$$\text{Mass efficiency } \eta_m = \dot{m}_e/\dot{m}_o \qquad (14)$$

(where $\dot{m}_e$ is the exhaust stream mass flow rate and $\dot{m}_o$ is the inlet propellant mass flow rate)

$$\text{Total efficiency } \eta = \eta_p\eta_v\eta_m \qquad (15)$$

The power efficiency η_p takes into account the following factors:

1. Circuit losses.
2. "Frozen flow" power, accounting for energy invested in dissociation, excitation, and ionization.
3. Power losses from the propellant exhaust stream, such as radiation and particle collision with the confining structure.
4. Power invested in transverse particle velocities, resulting in stream spreading.

We may presume the mass efficiency to be unity or larger, on the assumption that all the injected propellant leaves the engine, although not necessarily as charged species, and that erosion of the engine structure might add mass to the propellant stream.

The total efficiency is reducible[15] to the following form

$$\eta = T^2/2\dot{m}\,p_{\text{in}} \qquad (16)$$

Of course, engine efficiency, and in particular power efficiency, is an important consideration, since any inefficiency of the engine is directly reflected in a necessary "oversizing" of the electric power supply. Equations (12)–(16) are useful in evaluating and comparing experimental engine performance.

Plasma (electromagnetic) propulsion techniques

We have investigated the propulsion requirements for space exploration and have in addition discovered that nonthermal electrical methods, and in particular the plasma methods based on a magnetic field reaction, have certain unique characteristics that qualify them for these exploratory missions. These electromagnetic (plasma) thrust devices will now be considered in more detail. Some important characteristics of a plasma will be mentioned first, and discussions of the several plasma thrustor types will follow.

Physics of a plasma

In general, the acceleration process in these electromagnetic devices depends on the field force being applied to the electron component of the propellant gas; this force is then transmitted by means of a charge-separation electrostatic field to the ion component. This means that the propellant must meet two requirements:

1. Most of the propellant particles must be ionized, so that field rather than aerodynamic (close encounter collisional) effects govern the action.
2. The distance through which the electrons separate from the ions, by virtue of the fact that the primary force is on the electrons only, must be small relative to the size of the device. (This is an extension of the basic definition of a "plasma," based on the Debye length,[16] which

describes the distance through which the electrons in a plasma can separate from the ions by virtue of the thermal energy content of the electrons.)

So long as the propellant meets these requirements, and may therefore be called a "plasma," the characteristic of major importance is the conductivity σ defined as the ratio of current to electric field. Expressions for conductivity of a plasma have been derived by many authors,[17–19] and here we will only touch on some results of these derivations. The important thing to note is that in the presence of a magnetic field the conductivity becomes a tensor, with current components flowing normal to the applied electric field. For a dc electric field, Delcroix[18] expresses the conductivity in tensor form as

$$\sigma = \frac{n_e q_e^2}{m_e \nu} \begin{bmatrix} \dfrac{\nu^2}{\nu^2 + \omega_c^2} & \dfrac{-\nu\omega_c}{\nu^2 + \omega_c^2} & 0 \\ \dfrac{\nu\omega_c}{\nu^2 + \omega_c^2} & \dfrac{\nu^2}{\nu^2 + \omega_c^2} & 0 \\ 0 & 0 & 1 \end{bmatrix} \qquad (17)$$

where n_e, q_e, and m_e are the electron density, charge, and mass, respectively; ν is the collision frequency; and ω_c is the electron cyclotron frequency (q_eB/m_e, B being assumed to be parallel with the z axis). If ion behavior is taken into account, as is done for instance by Chapman and Cowling,[19] then it will be found that the expression (17) results when ω_c/ν for the electrons is very large, while this same ratio evaluated for the ions is small. Under these conditions, the current, and in particular the transverse current or so-called "Hall current,"[17,19] will be primarily electron-carried, and, furthermore, this Hall current will be greater than the parallel current (the "direct current") in the ratio ω_c/ν.

In theory, one should be able to define a model, apply Eq. (17) to evaluate the current as a function of applied voltage, and from this evaluate the thrust from the ($J \times B$) expression. In practice, difficulties in evaluating boundary effects and in deriving valid expressions for the effective collision frequency preclude the use of this equation in a device design problem, except to indicate broad trends and basic mechanisms. We will therefore now turn to experimental configurations and results.

In discussing the various experimental devices, the following basic distinguishing characteristics should be noted:

1. *Electrode current vs. circulating current.* Plasma accelerators can be broadly classed according to whether the "driving" current (i.e., the current that participates in the $J \times B$ process) passes through electrodes into the plasma or is re-entrant and therefore closes on itself (circulates) within the plasma. This has an important bearing on the lifetime of the device since large currents passing through electrodes can cause severe erosion.
2. *Pulsed vs. continuous.* A plasma accelerator may work up to its theoretical thrust density limit $B^2/2\mu_0$ only if the power and mass flow are adequate, which, for reasonable magnetic fields, will be appreciable and will therefore lead to large thrust densities, as shown earlier. In addition, as a plasma accelerator generally operates with less stability and efficiency at low power, it may be desirable to operate the accelerator at high instantaneous thrust and power but to pulse the engine repetitively to achieve a desired (lower) average level. The characteristics of a pulsed device will also depend on the length of the pulse relative to the transit time of the plasma.
3. *"Hall" vs. "direct" current.* We have seen from Eq. (17) that these two types of currents may flow, and devices based on each are being studied. As has been shown, for $\omega_c/\nu \gg 1$, the Hall current will be much greater than the direct current, which might lead one to conclude that the $J \times B$ force will consequently be enhanced. Since, however, the power must be coupled in some manner from the circuit to the plasma, the real advantage of this Hall current is to raise the impedance level so that, for a given power level, currents will be lower and impedance matching more readily accomplished.

The rectangular duct accelerator

Early plasma acceleration experiments were carried out on the rectangular electrode geometry shown in Fig. 3.[20–25] Development of thrustors based on this geometry have ceased, however, because of the apparently insurmountable electrode heating and erosion problem, although some effort for hypervelocity test applications is still going on.[26] Note that, in addition to the direct-current electrode heating difficulty, this geometry also suffers from deleterious Hall current effects.

The coaxial self-field accelerator

When the plasma current in an accelerator is made large enough, the magnetic field of the current itself is sufficient and no external field need be supplied to achieve the Lorentz interaction. Rectangular self-field accelerators

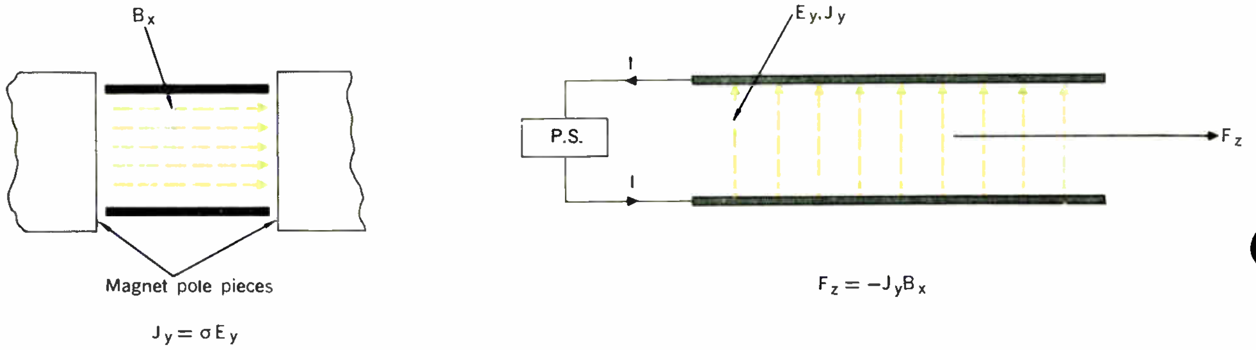


Fig. 3. Rectangular duct accelerator, with external field.

are being studied,[27] although coaxial configurations are currently receiving the most attention. The basic coaxial geometries, circuits, and fields are shown in Fig. 4. In this type of accelerator, the plasma current, which is essentially radially directed (J_r), generates an azimuthal magnetic field (B_θ) "behind" and within the plasma region, this magnetic field falling off to zero at the leading edge of the current sheet. The geometry is therefore closely analogous to the "ideal" situation presented in Fig. 2; the $J \times B$ thrust (F_z) is a result of the vector product of J_r and B_θ.

Both pulsed[28–37] and dc[38–40] versions of these cylindrical electrode geometries are under study. Each type is illustrated in Fig. 4, and will be considered separately in the ensuing paragraphs.

In the pulsed coaxial accelerator, Fig. 4(A), charged capacitors are electrically connected across the electrodes. When a pulse of gas from a fast-acting valve is introduced into the interelectrode region, an electric arc forms through the gas, ionizing the gas "puff" and magnetically driving the gas out the end of the electrode structure. Various propellant gases have been used. Typically, a potential of 1000 or more volts is employed, with capacitors in the range of 10–100 μF and very low circuit inductance, so that a transient current pulse of tens of thousands of amperes lasting several microseconds passes through the gas.[35] Damping of the L-R-C current pulse is approximately critical,[32] and a high percentage (>80 per cent) of the energy originally stored in the capacitors is transferred into the plasma.[36] The acceleration process can also be efficient, so that over 60 per cent of the stored capacitor energy appears as directed motion of the accelerated plasma jet while total efficiency η has been measured to be greater than 50 per cent.[35] The background pressure in the tank into which the accelerator was firing during these measurements was under 1×10^{-5} mm Hg. For continuing thrust, these accelerators are repetitively pulsed, with a dc power supply recharging the capacitors between each pulse.[32] Repetition rates up to 20 pps[32] and average power levels up to 30-kW input power have been achieved.[34] The major problem area currently is improvement of the gas valve so that the gas and current pulses are more closely matched, allowing less unaccelerated gas to escape through the accelerator. Lightweight, highly efficient, long-life capacitors would also be essential for the space propulsion application.

An important mechanism in the pulsed accelerator is the moving current sheet as the gas pulse is accelerated along the electrodes.[30, 34, 37] This motion contributes an $I(dL/dt)$ term to the circuit equation, thus raising the accelerator impedance. The mechanisms in the current sheet are apparently complicated and difficult to unravel completely, but the current sheet seems to act more like a wave passing through the gas and less like a snowplow accumulating the gas ahead of it. As a result, gas and current sheet velocities, while related, are not identical.

In the dc version of the Fig. 4 coaxial accelerator, the plasma current is time and space invariant. Since no motion of the current is involved as in the pulsed device, dc accelerator electrodes are in general much shorter than in the pulsed configurations. Lacking the dL/dt effect, dc accelerators generally also exhibit lower impedances than their pulsed counterparts; 2000–3000 amperes at 75 volts is typical.[39, 40]

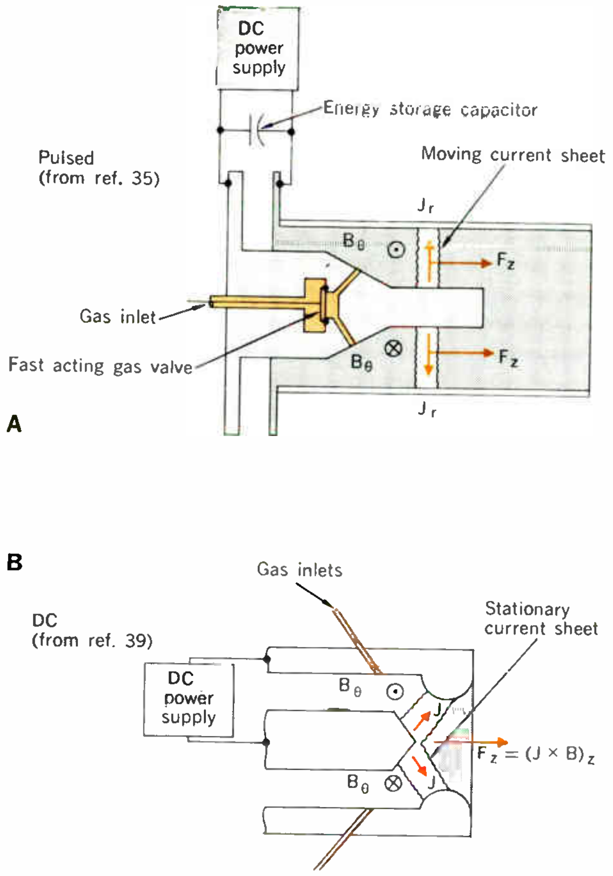


Fig. 4. Coaxial accelerators, self-field.

Power efficiencies of the dc accelerators have been quite good at high velocity (46 per cent at 100 000 m/s), but fall off to 13 per cent at lower (30 000 m/s) velocity.[40] Heavier propellants, in which proportionately less energy must be invested in ionization, might increase the efficiency at lower velocities. It should be noted that these results were obtained upon firing the accelerator into a relatively high background pressure environment (e.g., 0.2 mm); tests at pressures more nearly simulating space conditions should be made.

A problem in the dc coaxial accelerator is the erosion at the arc anode spot. A convenient method of reducing this heating is to introduce an axial magnetic field which causes the arc to rotate, thereby preventing any one anode spot from overheating.[40] An additional benefit of this is to introduce a Hall (azimuthal) current, the net effect of which is to raise the arc impedance. Hall current acceleration will be treated in a later section.

Induction accelerators

So far we have treated only electrode devices in which the circuit and plasma are coupled by means of conduction current passing through circuit electrodes into the plasma. A close analogy with dc motors can be drawn.[41, 42] Continuation of the analogy brings us to a third class of plasma accelerators, the induction devices, bearing direct analogy to induction motors. In the basic induction accelerator, shown in Fig. 5, a time-changing current in the coil surrounding the plasma induces an azimuthal electric field within the plasma, thereby driving an azimuthal current within the plasma. The axially directed force (F_z) is developed between this induced azimuthai current (J_θ) and the radial component (B_r) of the coil magnetic field.

The current, being reentrant, circulates wholly within the plasma. The accelerator is therefore electrodeless, and hence without the electrode erosion problem inherent in dc accelerators. Wall erosion problems are not eliminated, however, as will be shown.

Induction accelerators take two basic forms: single-coil,[42–52] in which the coil current, and therefore the magnetic field, are functions of time but are stationary in space; and multicoil,[41, 53–62] in which the time relationship of currents in the various coils is adjusted so that the magnetic field propagates as a traveling wave down the structure. This later multicoil mode bears a close analogy to the squirrel-cage rotor induction motor. Both single coil and multicoil accelerators may be run pulsed or CW.

In the single-coil stationary-field device, an important parameter is the ratio of the current period to the plasma transit time; if the period is approximately the same as the plasma motion time (and if the fields are strong enough) the plasma will be accelerated in bunches each half cycle,[49] while, if the frequency is high, an essentially continuous plasma stream will be formed.[51] A primary difficulty in the pulsed (lower frequency) accelerators is achieving appreciable coupling between the circuit and the plasma,[49, 50] although by properly "filling" the coil and by increasing the coil inductance an appreciable coupling efficiency (> 25 per cent) can readily be obtained.[52] Experiments with a CW higher-frequency (1.7-Mc/s) single-coil accelerator have also shown good efficiency,[51] with 30 per cent of the RF input power appearing in the accelerated plasma stream. In these 1.7-Mc/s tests, the ionization process was also noted to be relatively efficient.[51] Development of a single-coil accelerator as a propulsion device has not reacted the point where thrustor characteristics can be quoted.

Since original studies of the single-coil device indicated a problem with coupling, the multicoil, or traveling-wave, concept was advanced in order to allow the magnetic field more time to work on the plasma. Lengthening the acceleration path has the adverse effect of increasing the risk of significant energy loss from the plasma out to the confining walls. The longitudinal magnetic field should have the effect of insulating the plasma from the walls,[63] although there is little efficiency information yet avail-

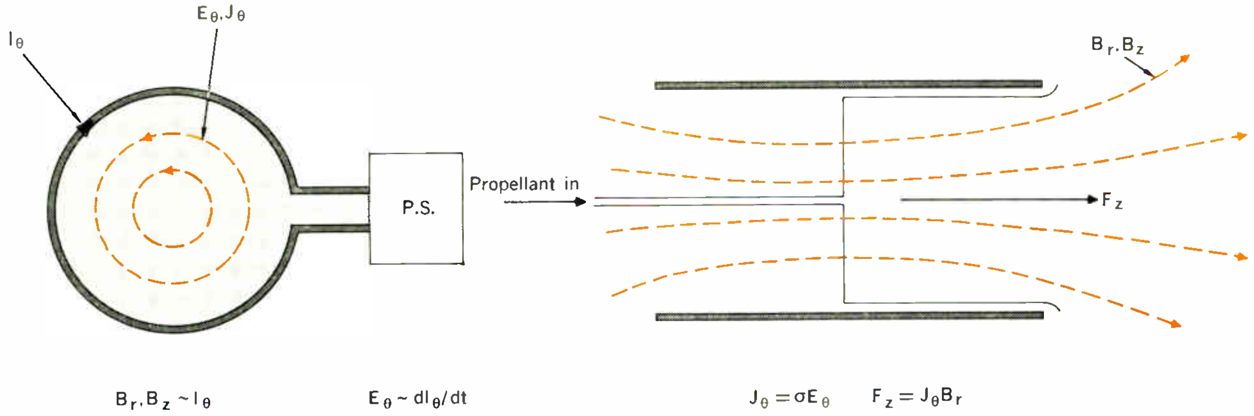
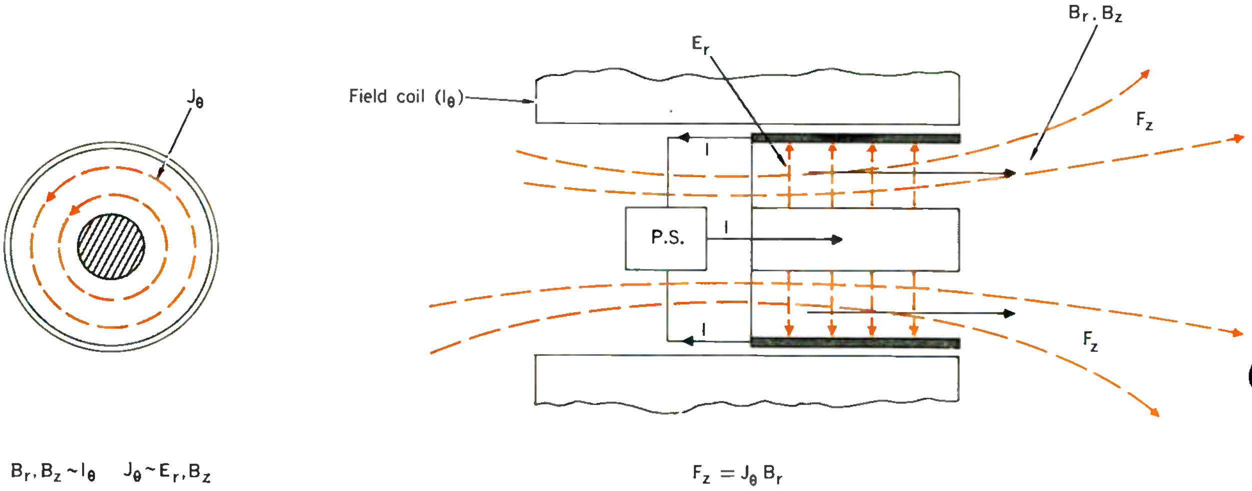


Fig. 5. Stationary-field induction accelerator.

Fig. 6. Hall-current accelerator.



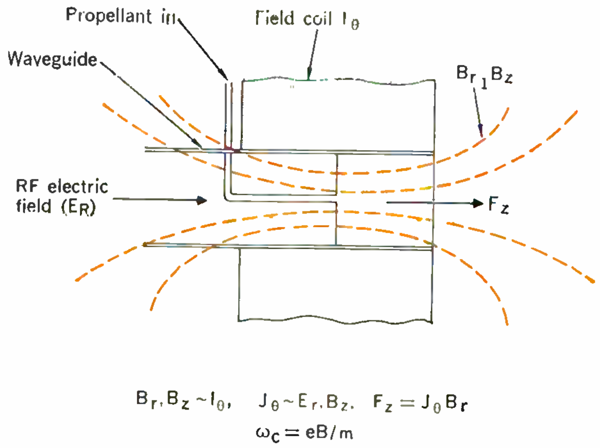


Fig. 7. RF (cyclotron-resonance) accelerator.

able in the literature. An interesting variation of the traveling-wave accelerator employs a transverse moving magnetic field.[62] Although this device features very strong field-plasma coupling and therefore transfers the power from the circuit to the plasma very efficiently, it does not have the magnetic wall insulation characteristic of the longitudinal field device, and consequently a large amount of the absorbed power is lost from the plasma to the walls within the accelerator.

Hall-current accelerators

The Hall current, represented by the off-diagonal terms in the tensor conductivity expression of Eq. (17), can be used to advantage in plasma thrustors (Fig. 6). Consider for instance immersing a coaxial accelerator in a dc, longitudinal magnetic field (B_z), as from a solenoid wound around the outer electrode. The radial electric field between the electrodes will now drive both radial and azimuthal currents through the interelectrode plasma; as has been mentioned, the azimuthal Hall current can be considerably greater than the radial current if the ratio ω_c/ν is high. If these currents are flowing in the fringing region of the solenoidal magnetic field, then an axial thrust will be exerted on the plasma due to the interaction of the Hall current (J_θ) with the radial component of the magnetic field (B_r).

In comparison with the equivalent coaxial accelerator without the superimposed magnetic field, the thrust of the Hall device at a given power level will not be increased because of the high azimuthal current. Benefits result from more indirect effects. First, the magnetic field raises the plasma impedance[64] so that, at a given power level, the Hall device electrode current, and therefore electrode erosion, will be reduced. Second, since the thrust-producing Hall current is re-entrant, it need not be as closely associated with the electrodes as the "nonmagnetic" counterpart, and the engine can therefore be a more "open" structure with acceleration taking place in the region downstream from the electrodes.[64] Loss of power due to plasma particles striking the confining walls is consequently reduced.

Coaxial[65,66] and annular [64,67] dc Hall accelerators are currently being studied. The following results are reported[64] for a high-power hydrogen accelerator:

Total thrust efficiency = 10–44 per cent
Exhaust velocity = 21 000–105 000 m/s
Arc power = 43–77 kW
Exhaust tank pressure = 0.3 torr

The electrode erosion rate of this accelerator is reported to be very low. In order to simulate space conditions more nearly, this type of engine should be tested at low background pressures. The power consumed by the dc magnetic field coil should also be minimized.

These Hall-current devices, as well as the induction accelerators previously described, fall into a general class of "magnetic expander" accelerators,[68] in which thrust is developed by the interaction of the circulating current with the radial component of the "expanding" magnetic field. The force can also be considered to be due to the diamagnetic plasma in a gradient of magnetic field. This force accelerates the electrons longitudinally down the field gradient, and, as has been previously suggested, the force is transmitted to the ions by a charge separation electric field.

Hall-current accelerators need not be dc. If an ac field is employed at sufficiently high frequency, the displacement current (dD/dt) will dominate; the device is "electrodeless," since no conduction current need pass through electrodes. In general, the circulating Hall current will oscillate at the driving frequency. If, however, the electric field frequency is adjusted to equal the electron cyclotron frequency ω_c, as defined with Eq. (17), then a very large dc component of the Hall current can be generated (Fig. 7).

The ac field in these electron cyclotron resonance devices is generally in the form of a microwave electromagnetic field propagating within a guiding structure such as a waveguide.[69–73] In order for such a wave to be able to propagate into the plasma, its propagation constant k, as defined by the expression for a propagating wave,

$$E = E_o \exp j(\omega t - kz)$$

must have a real component. The following expression for the propagation constant of a wave traveling parallel to the magnetic field can be derived from the well-known Appletron–Hartree expression,[74, 75] or from the electron equation of motion and Maxwell's equations:

$$k^2 = \left(\frac{\omega}{c}\right)^2 \left[1 - \left(\frac{\omega_p}{\omega}\right)^2 \left(\frac{1}{1 - (\omega_c/\omega) + j(\nu/\omega)}\right)\right] \tag{18}$$

where ω_p is the electron density frequency ("plasma frequency"), $\omega_p = \sqrt{n_e e^2/m\epsilon_o}$, and a right-hand, circularly polarized wave has been assumed. In general, these RF accelerators are run at sufficiently low densities so that the collision frequency is low.[72] In this case, (18) not only indicates the $\omega = \omega_c$ resonance, but also exhibits the familiar "plasma cutoff" phenomenon, with k becoming real (and propagation vanishing) for $\omega < \omega_p$.

Thus it is desirable in these devices to operate at as high a frequency as possible since this maximizes thrust capability by maximizing magnetic field and plasma density. Recent experiments have been performed at 8350 Mc/s, with more than 3 kW of RF power incident on the plasma.[72] The plasma in this case is inherently a good load, and in addition tuning procedures are very easily performed at these frequencies so that excellent coupling of the RF power to the plasma can be made; that is, greater than 95 per cent. Over 50 per cent of the 2600-W incident RF power has been observed in the accelerated plasma stream.[73]

Several difficulties exist with the cyclotron resonance accelerators. High particle flux densities on the "window" through which the RF power enters the plasma region make the design of that window extremely critical; ceramic techniques have been applied to solve this problem.[73] Perhaps more fundamental are the problems of obtaining efficient, long-life, lightweight magnetic field coils and RF generators. Such RF generators at high power (400 kW) and good efficiency (> 70 per cent) are now coming into being.[76] Cryogenically cooled magnets, with relatively low-power absorption, or permanent magnets, must be developed for feasible magnetic field generation.

Summary and conclusions

Space missions requiring relatively high propellant exhaust velocity have been identified. Thrust levels have also been shown to be high enough so that, on a theoretical basis at least, electromagnetic rather than electrostatic systems would apparently be more suitable. These applications are several years in the future.

Various engine configurations, all at the present time in an early development stage, are being explored. Operating characteristics, efficiency, power, weight, and life are now becoming attractive or show indications of promise, with perhaps the pulsed and dc coaxial accelerators and possibly the Hall-current thrustors coming along best. Several years will be required, however, to develop and test these engines adequately.

This article is an expansion of a paper presented at the W. G. Dow (Dow Chemical Co.) Seminar: New Research Frontiers in Physical Electronics, University of Michigan, Ann Arbor, Mich., Dec. 3–4, 1964.

REFERENCES

1. Seifert, H. S., ed., *Space Technology*. New York: John Wiley & Sons, Inc., 1959.
2. Ehricke, K. A., "Interplanetary Operations," *Ibid.*, chap. 8.
3. Langmuir, D. B., "Low-Thrust Flight: Constant Exhaust Velocity in Field-Free Space," *Ibid.*, chap. 9.
4. Johnson, P. G., "On Optimization of Powerplant Parameters," *NASA TN D-675*, National Aeronautics and Space Administration, Washington, D. C., Feb. 1961; also, "Beyond Apollo with Nuclear Propulsion," *Astronautics and Aeron.*, vol. 2, Dec. 1964, pp. 22–28.
5. Stuhlinger, E., and Seitz, R. N., "Electrostatic Propulsion Systems for Space Vehicles," in *Advances in Space Science*, F. I. Ordway III, ed. New York: Academic Press, Inc., 1960.
6. Irving, J. H., "Low-Thrust Flight: Variable Exhaust Velocity in Gravitational Fields," in *Space Technology*. New York: John Wiley & Sons, Inc., 1959.
7. Widmer, T. F., and Brown, H., "Applications of Nuclear Electric Propulsion to Advanced Scientific Missions," *Paper no. 64-714*, 3rd AIAA Biennial Aerospace Power Systems Conf., Philadelphia, Pa., Sept. 1–4, 1964.
8. Schwartz, I. R., and Stuhlinger, E., "The Role of Electric Propulsion in Future Space Missions," *Paper no. 62-2654*, 7th ARS Ann. Meeting and Space Flight Exposition, Los Angeles, Calif., Nov. 13–18, 1962.
9. Fimple, W. R., and Edelbaum, T. N., "Applications of SNAP-50 Class Powerplants to Selected Unmanned Electric Propulsion Missions," *Paper no. 64-494*, 1st AIAA Ann. Meeting, Washington, D.C., June 29–July 2, 1964.
10. Stearns, T. W., "Applications for Electric Propulsion Systems," *Paper no. 61-1751*, ARS Space Nuclear Conf., Oak Ridge Nat. Lab., Gatlenburg, Tenn., May 3–5, 1961.
11. Pinkel, B., "Electrical Propulsion for Space Missions: Planning Considerations," *Paper no. 64-715*, 3rd AIAA Biennial Aerospace Power Systems Conf., 1964.
12. Beale, R. J., "The Conceptual Design of a Nuclear-Electric Power Spacecraft for the Exploration of Jupiter," Tech. Rept. no. 32-115, Jet Propulsion Laboratory, Pasadena, Calif., May 1961.
13. Brewer, G. R., Zimmerman, R. L., Berman, D., and King, H. J., "Design Criteria and Performance of a Long Life Contact Ion Engine," *Paper no. 64-710*, 4th AIAA Elec. Propulsion Conf., Philadelphia, Pa., Aug. 31–Sept. 2, 1964.
14. Reader, P. D., "Experimental Performance of a 50-Centimeter Diameter Electron-Bombardment Ion Rocket," *Paper no. 64-689*, 4th AIAA Elec. Propulsion Conf., 1964.
15. Miller, D. B., and Gibbons, E. F., "Experiments with an Electron Cyclotron Resonance Plasma Accelerator," *AIAA J.*, vol. 2, Jan. 1964, pp. 35–41.
16. Spitzer, L., Jr., *Physics of Fully Ionized Gases*. New York: Interscience Publishers, 1956, pp. 16–17.
17. Linhart, J. G., *Plasma Physics*. Amsterdam: North-Holland Publishing Company, 1960, section 6.2.1.
18. Delcroix, J. L., *Introduction to the Theory of Ionized Gases*. New York: Interscience Publishers, 1960, sections 5.4 and 7.2.
19. Chapman, S., and Cowling, T. G., *The Mathematical Theory of Non-Uniform Gases*. Cambridge, England: Cambridge University Press, 1960, section 18.31.
20. Harned, B. W., Bowman, G. L., and Sherman, A., "Electromagnetic Plasma Propulsion Studies," presented at the 3rd AFOSR Contractors' Meeting on Ion and Plasma Propulsion, New York, N. Y., March 1960.
21. Cunningham, D. E., Weirick, R. G., and Block, R. B., "MHD Channel Flow," presented at the AIEE Symp. Engineering Aspects of MHD, Philadelphia, Pa., Feb. 1960.
22. Demetrades, S. T., and Ziemer, R. W., "Direct Thrust and Efficiency Measurements of a Continuous Plasma Accelerator," *ARS J.*, vol. 31, Sept. 1961, pp. 1278–1280.
23. Blackman, V. H., and Sunderland, R. J., "Experimental Performance of a Crossed-Field Plasma Accelerator," *Paper no. 62-2633*, 7th ARS Ann. Meeting and Space Flight Exposition, 1962.
24. Russell, G. R., Byron, S., and Bortz, P. I., "Performance and Analysis of a Crossed Field Accelerator," *Paper no. 63-005*, AIAA Elec. Propulsion Conf., Colorado Springs, Colo., Mar. 11–13, 1963.
25. Sunderland, R. D., and Asam, A. R., "Magnetogasdynamic Rocket for Space Propulsion," Final Rept., NASA Contract no. NAS3-2514, NASA, Washington, D.C., May 20, 1964.
26. Carter, A. F., Wood, G. P., McFarland, D. R., and Weaver, W. R., "Research on a One-Inch-Square Linear D-C Plasma Accelerator," *Paper no. 64-699*, 4th AIAA Electric Propulsion Conf., 1964.
27. Rosebrock, T. L., "Study of Plasma Mass-Velocity Distribution in a Pulsed Electro-magnetic Accelerator," Rept. 2736, Allison Division, Engg. Dept., General Motors Corp., Detroit, Mich., Aug. 1962.
28. Marshall, J., "Performance of a Hydromagnetic Plasma Gun," *Phys. Fluids*, vol. 3, Jan.–Feb. 1960, p. 134.
29. Gloersen, P., and Gorowitz, B., "Optical Observations of Plasmas Accelerated into a Vacuum," *Bull. Am. Phys. Soc.*, vol. 5, series 2, June 15, 1960, p. 351.
30. Burkhardt, L. C., and Lovberg, R. H., "The Current Sheet in a Coaxial Plasma Gun," *Phys. Fluids*, vol. 5, Mar. 1962, p. 341.
31. Hart, P. J., "Plasma Acceleration with Coaxial Electrodes," *Ibid.*, Jan., p. 38.
32. Gloersen, P., Gorowitz, B., Hovis, Jr., W. A., and Thomas, Jr., R. B., "An Investigation of the Properties of a Repetitively Fired Two-Stage Coaxial Plasma Engine," Tech. Information Series Rept. no. R62SD28, General Electric Co., Philadelphia, Pa., April 1962.
33. Gooding, T. J., Hayworth, B. R., and Lovberg, R. H., "Physical Processes in a Coaxial Plasma Gun," *Paper no. 63-004*, AIAA Elec. Propulsion Conf., 1963.
34. Gorowitz, B., Gloersen, P., and Rowe, J. H., "Performance Study of a Repetitively Pulsed Two-Stage Plasma Engine," Final Rept., NASA Contract NAS3-2502, Nov. 1963.
35. Gorowitz, B., Gloersen, P., Ruess, A., and Kenney, J., "Overall Efficiency Trends in a Coaxial Gun Plasma Engine System," *Paper no. 64-706*, 4th AIAA Electric Propulsion Conf., 1964; also "Performance Study of a Repetitively Pulsed Two-Stage Plasma Propulsion Engine," Summary Rept., NASA Contract NAS3-3570, Aug. 1964.
36. Larson, A. V., Gooding, T. J., Hayworth, B. R., and Ashby, D. E. T. F., "An Energy Inventory in a Coaxial Plasma Accelerator Driven by a Pulse Line Energy Source," *Paper no. 64-704*, 4th AIAA Electric Propulsion Conf., 1964.

37. Mezger, F. W., "A Constant Current Sheet Velocity Model of the Coaxial Plasma Accelerator," Tech. Information Series Rept. no. R64SD61, General Electric Co., Aug. 1964.

38. Ducati, A. C., Muehlberger, E., and Giannini, G., "High Specific Impulse Thermo-Ionic Acceleration," *Paper no. 64-668*, 4th AIAA Elec. Propulsion Conf., 1964.

39. John, R. R., Bennett, S., and Conners, J., "Experimental Performance of a High Specific Impulse Arc Jet Engine," *Paper no. 64-669*, 4th AIAA Elec. Propulsion Conf.

40. Ducati, A. C., Giannini, G. M., and Muehlberger, E., "Recent Progress in High Specific Impulse Thermo-ionic Acceleration," *Paper no. 65-96*, 2nd AIAA Aerospace Science Meeting, New York, N.Y., Jan. 25–27, 1965.

41. Janes, G. S., "Magnetohydrodynamic Propulsion," Research Rept. no. 90, AVCO Everett Research Laboratory, Aug. 1960.

42. Fonda-Bonardi, G., "Development Potential of the Plasma Engine," *AIEE Paper no. CP62-1291.*

43. Morozov, A. I., "The Acceleration of a Plasma by a Magnetic Field," *Sov. Phys. JETP*, vol. 5, Sept. 1957, p. 215.

44. Petschek, H. E., and Janes, G. S., "Magnetically Driven Shock Waves; Experiments at AVCO," in *Magnetohydrodynamics*, R. K. M. Landshoff, ed. Stanford, Calif.: Stanford University Press, 1957.

45. Josephson, V., "Production of High-Velocity Shocks," *J. Appl. Phys.*, vol. 29, Jan. 1958, pp. 30–32.

46. Blackman, V. H., and Niblett, B., "Experiments Using a Hydromagnetic Shock Tube," in *The Plasma in a Magnetic Field*, R. K. M. Landshoff, ed. Stanford, Calif.: Stanford University Press, 1958.

47. Bostick, W. H., "Plasma Motors: The Propulsion of Plasma by Magnetic Means," in the *Proc. IXth Intern. Astronautical Congr.* (Amsterdam, 1958). Vienna, Austria: Springer-Verlag, 1959, pp. 794–808.

48. Klein, M. M., and Brueckner, K. A., "Plasma Propulsion by a Rapidly Varying Magnetic Field," *J. Appl. Phys.*, vol. 31, Aug. 1960, p. 1437.

49. Miller, D. B., "Acceleration of Plasmas by Inductively Generated Electromagnetic Fields," Ph.D. Thesis, University of Michigan, May 1961; also *ARS J.*, vol. 32, 1962, p. 549.

50. Waniek, R. W., "Inductive High Field Plasma Accelerators," *Paper no. 62-2395*, ARS Elec. Propulsion Conf., Berkeley, Calif., Mar. 14–16, 1962.

51. Penfold, A. S., and Curtis, D. L., "A Single-Phase Induction Plasma Accelerator," *Paper no. 63-012*, AIAA Elec. Propulsion Conf., 1963.

52. Gibbons, E. F., and Miller, D. B., "Inductive Plasma Heating Using a Multi-Turn Coil," Tech. Information Series Rept. no. R64SD76, General Electric Co., Nov. 1964.

53. Phonemann, P. C., Cowling, W. T., and Davenport, P. A., "Interaction of Teaching Magnetic Fields with Ionized Gases," *Nature*, vol. 169, 1952, p. 34.

54. Marshall, J., "Acceleration of Plasma into Vacuum," *Proc. 2nd U.N. Intern. Conf. on Peaceful Uses of Atomic Energy*, Geneva, Switzerland, vol. 31, 1958, p. 341.

55. Miller, D. B., "An Electromagnetic Accelerator and Its Applicability to Acceleration of an Electrical Discharge Plasma," *ASTIA Doc. 162274*, ARDC Conference on Ion and Plasma Research, Oct. 1958.

56. Schaffer, A. B., Huddlestone, R. H., and Meyer, R. X., "Analysis of the Axially-Symmetric Hard Magnetic Piston," Rept. PRL-9-24, Physical Research Laboratory, Space Technology Laboratories, Nov. 1959.

57. Schaffer, A. B., "Hardness of the Axially Symmetric Magnetic Piston," Rept. STL/TR-60-0000-09011, Physical Research Laboratory, Space Technology Laboratories, Jan. 1960.

58. Clauser, M. U., "The Magnetic Induction Plasma Engine," *Rept.* STL/TR-60-0000-00263, Physical Research Laboratory, Space Technology Laboratories, Aug. 1960.

59. Schaffer, A., "Plasma Propulsion with a Pulsed Transmission Line," *Paper no. 60-1534*, 15th ARS Annual Meeting, Washington, D.C., Dec. 5–8, 1960.

60. Penfold, A. S., "Traveling Wave Plasma Accelerator," *Paper no. 61-2130*, ARS Space Flight Rept. to the Nation, New York, N.Y., Oct. 9–15, 1961.

61. Mayfield, E. B., Meyer, R. X., Head, R. M., and Huddlestone, R. H., "Plasma Propulsion by Means of a Helical Transmission Line," *Paper no. 62-2378*, ARS Elec. Propulsion Conf., 1962.

62. Heflinger, L., Ridgeway, S., and Schaffer, A., "Transverse Traveling Wave Plasma Engine," *Paper no. 64-701*, 4th AIAA Elec. Propulsion Conf., 1964.

63. Kolb, A. C., "Propagation of Strong Shock Waves in Pulsed Longitudinal Magnetic Fields," *Phys. Rev.*, 2nd series, vol. 107, no. 4, Aug. 15, 1957, p. 1197.

64. Cann, G. L., "Annular Magnetic Hall Current Accelerator," *Paper no. 64-670*, 4th AIAA Elec. Propulsion Conf., 1964.

65. Hess, R. V., "Experiments and Theory for Continuous Steady Acceleration of Low Density Plasmas," in the *Proc. XI Intern. Astronautical Congr.* (Stockholm, 1960). Berlin: Springer, 1960.

66. Grossman, W., Hess, R. V., and Hassan, H. A., "Experiments with a Coaxial Hall Current Plasma Accelerator," *Paper no. 64-700*, 4th AIAA Electric Propulsion Conf., 1964.

67. Cann, G. L., Marlotte, G. L., and Ziemer, R. W., "A Steady State Hall Current Accelerator," Rept. no. 3160—Final, Electro Optical Systems, NASA Contract NAS3-2500, Oct. 1963.

68. Seikel, G. R., and Domitz, S., "Application of Magnetic-Expansion Plasma Thrusters to Satellite Station Keeping and Attitude Control Missions," *Paper no. 64-677*, 4th AIAA Elec. Propulsion Conf., 1964.

69. Miller, D. B., Gloersen, P., Gibbons, E. F., and BenDaniel, D. J., "Cyclotron Resonance Propulsion System," in the *Proc. Third Ann. Symp. on Eng. Aspects of MHD* (University of Rochester, 1962). New York: Gordon and Breach, 1964.

70. Hendel, H. W., and Reboul, T. T., "Continuous Plasma Acceleration at Electron Cyclotron Resonance," *Paper no. 63-001*, 3rd AIAA Elec. Propulsion Conf., 1963.

71. Ahmed, S. A., and Hendel, H. W., "Space Charge Acceleration of Ions at Electron Cyclotron Resonance," *Paper no. 64-24*, 1st AIAA Aerospace Sciences Meeting, New York, N.Y., Jan. 20–24, 1964.

72. Miller, D. B., "X-Band Magnetic Resonance Plasma Accelerator," *Paper no. 64-702*, 4th AIAA Electric Propulsion Conf., 1964.

73. Miller, D. B., "Continuous Microwave Magnetic Accelerator," Final Rept., NASA Contract 3-3567; also NASA Rept. no. CR-54134, Aug. 1964.

74. Ratcliffe, J. H., *The Magneto-ionic Theory and Its Application to the Ionosphere.* Cambridge, England: Cambridge University Press, 1959.

75. Kelso, J. M., *Radio Ray Propagation in the Ionosphere.* New York: McGraw-Hill Book Co., Inc., 1964.

76. Brown, W. C., "A Survey of the Microwave Power Generation and Rectification Components," presented at the IEEE Energy Conversion and Control Conf., Clearwater, Fla., May 1964.

BIBLIOGRAPHY

Bostick, W. H., "Plasma Motors; The Propulsion of Plasma by Magnetic Means," in the *Proc. IXth Intern. Astronautical Congr.* (Amsterdam, Netherlands, 1958). Vienna, Austria: Springer-Verlag, 1959, pp. 794–808.

Camac, M., Kantrowitz, A., and Petschek, H. E., "Plasma Propulsion Devices for Space Flight," Res. Lab. Rept. 45, AVCO Manufacturing Corp., Feb. 1959.

Kash, S. W., "A Comparison of Ion and Plasma Propulsion," *Proc. IRE*, vol. 48, April 1960, pp. 458–465.

Camac, M., "Plasma Propulsion Devices," in *Advances in Space Sciences*, F. I. Ordway III, ed. New York: Academic Press, 1960.

Evvard, J. C., "Electric Space Propulsion," *Elec. Eng.*, July 1960, pp. 555–563.

Janes, G. S., "Magnetohydrodynamic Propulsion," Res. Rept. 90, AVCO Everett Research Laboratory, Aug. 1960; also AFOSR TN60-955.

Langmuir, D. B., "Electrical Propulsion, State of the Art—1960," *Astronautics*, vol. 5, Nov. 1960, p. 33.

Sutton, G. W., Gloersen, P., "Magnetohydrodynamic Power and Propulsion," *Proc. 4th Biennial Gas Dynamics Symp.: MHD*, Northwestern University, Aug. 1961.

Brewer, G. R., Currie, M. R., Knechtli, R. C., "Ionic and Plasma Propulsion for Space Vehicles," *Proc. IRE*, vol. 49, Dec. 1961, pp. 1789–1821.

Demetriades, S. T., "Plasma Propulsion," *Astronautics*, vol. 7, pt. I, March 1962; also pt. II, April 1962.

Langmuir, D. B., "Electric Spacecraft—Progress 1962," *Ibid.*, pp. 20–25.

Teem, J. M., and Szego, G. C., "Electric Propulsion and Power," *Astronautics and Aerospace Eng.*, vol. 1, Nov. 1963, pp. 98–103.

Stuhlinger, E. "Electric Propulsion in 1964—A Status Review," *Paper no. 64-524*, 1st AIAA Ann. Meeting, Washington, D.C., June 29–July 2, 1964.

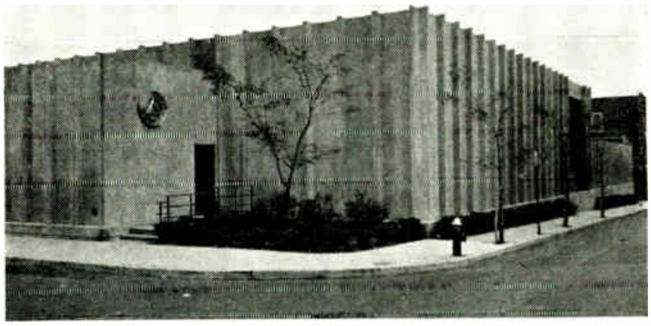
Jahn, R. G., "Electric Propulsion," *American Scientist*, vol. 52, 1964, pp. 207–217.

Kantrowitz, A., "Horizons in Plasma Dynamics," *Astronautics and Aeronautics*, vol. 3, Jan. 1965, pp. 52–65.

Esthetics and electric energy

The architectural design and general appearance of power plants, substations, transmission lines, and other appurtenances have become a prime consideration in the public relations efforts of utility companies

Gordon D. Friedlander *Staff Writer*



There is a saying to the effect that "if an architect designs a building without the help of an engineer, the structure will probably fall down. But if an engineer designs a building without the services of an architect, *the public will tear it down!*"

In recent years many utility companies throughout the United States have gotten the message—by dint of public reaction—that their standard, utilitarian designs for power generating stations, substations, switching stations, and transmission lines would have to be improved in appearance. The residents of suburban communities were particularly vocal in expressing their objections to the unsightly electrical installations and overhead transmission lines literally plunked down in their backyards. The protests included the real, or imaginary, fears that: property values would be adversely affected; the installations would attract lightning; radio and television reception would be impaired; and the hum of the transformers would be a constant annoyance.

In all fairness, however, one must realize at the outset that it is not the writer's purpose to single out our utility industry to bear the onus of public criticism. The recent book by Peter Blake, *God's Own Junkyard*, goes far beyond overhead power lines to include billboards, garish neon-lit hamburger stands, nightmarishly bizarre bowling alleys, grotesque roadside diners, and meretricious shopping plazas—all intent upon achieving "the planned deterioration of America's landscape."

At least in defense of our utilities we can say that their primary concern has been with engineering, functional, and safety concepts, and they have inadvertently—not

Fig. 1 (top). Georgian colonial style of Potomac Electric Power Company's Wostmoreland Substation in Washington, D.C., matches local residential architecture. Fig. 2 (center). Attractive concrete wall enclosure, featuring vertical pilasters, conceals Public Service Electric and Gas Company's Polk Street Substation in Newark, N.J. Fig. 3 (left). Idaho Power Company's unusual substation at Ketchum blends harmoniously with the Sun Valley ski resort environment.

intentionally—overlooked esthetic considerations in a number of cases.

Let's surprise 'em—we'll disguise 'em

It was perfectly natural, therefore, after the utilities ran into the hornet's nest of public opposition, that there was a widespread attempt to accommodate the consumer's outraged esthetic sensibilities by camouflaging the occupancy of electrical facilities, particularly substations. Thus any number of substations began to blend into the local landscapes, and, like Hollywood movie props, these structures were designed with false facades to resemble contemporary ranch houses, stately Georgian-style colonial residences, garden apartment houses, rustic log cabins, and light industrial manufacturing buildings—depending upon the zoning or geographical area in which they were located (see Figs. 1–4).

A number of utility companies have built rather attractive screening walls to conceal substations and switching stations at grade level, both in suburban towns and urban areas. Figure 5 shows one of these interesting solutions.

In some residential areas, landscape architects and the local nurserymen got a big break when substations, such as the one shown in Fig. 6, were completely obscured—at least at grade elevation—by a screen of attractive evergreens. perenniel flower beds. and stockade fences. At first glance, these efforts would seem to have been ideal solutions to make everybody happy, but then it was discovered that a lot of amateur horticulturists lived in these suburban communities. These people took their hobbies so seriously, and were so appreciative of the utilities' concern for beauty, that, under the blanket of the dark, they trundled wheelbarrows to the colorful, flowering oases and transplanted much of the greenery to their private backyards.

In fact, one lighting company engineer related an amusing anecdote concerning countermeasures taken to discourage flower filchers: the shrubbery at one landscaped substation was anchored down by very official-looking, heavy-gauge copper wire. When the nocturnal gardeners' spades struck the sinister wire, the diggers thought sure they had uncovered an underground "hot line" transmission cable—and they promptly fled into the night. Then too, the writer spoke to utilities company officials who ruefully learned that—

You can't kid the kids! The neighborhood youngsters soon discovered an additional advantage, not originally considered by the utilities, in that the attractive landscape screening not only hid the transformers, but also provided excellent cover for petting parties. The humming noises and blazing, all-night illumination in the substations disguised as residences also attracted the kids' curiosities, and they readily deduced that the murmurs were not the animated conversations of guests at "all-night blasts," but that the joints were really jumping with juice, not jive. Following this discovery, the local glaziers—not the utilities—became the happiest group in town.

The 'low-silhouette' substation. To make the landscaping more effective as a screening device, many utilities have redesigned their transformer and switching equipment to cut down on the overall height. Figure 7 shows a good example of a low-silhouette secondary substation in a suburban village. Note that the screen of evergreens and neighboring houses rise above the top elevation of the electric equipment. This photo was

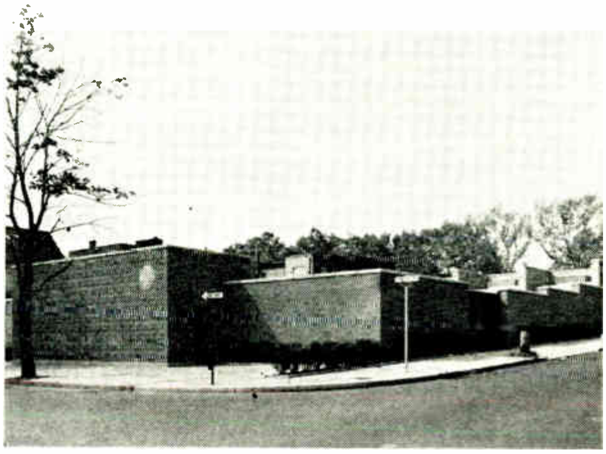
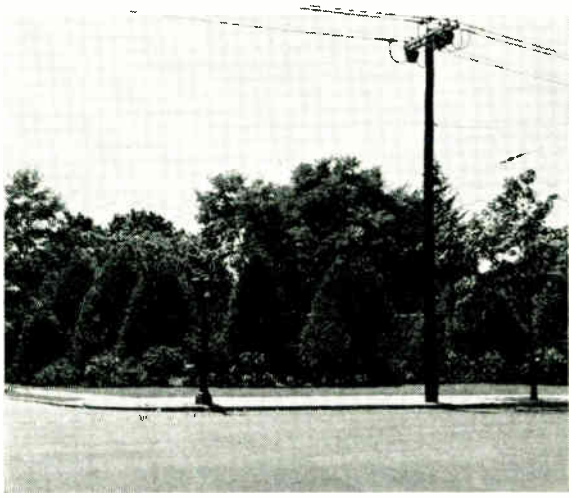
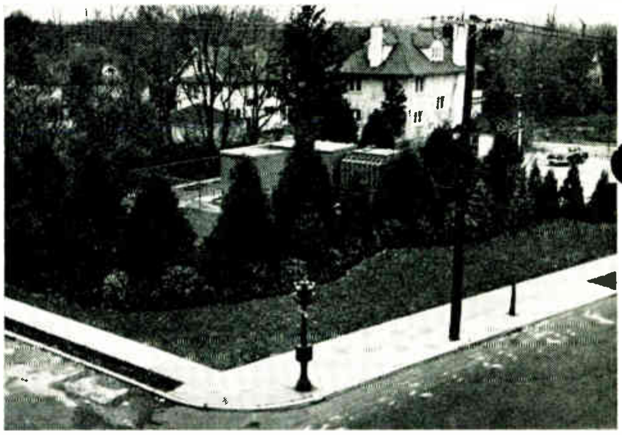
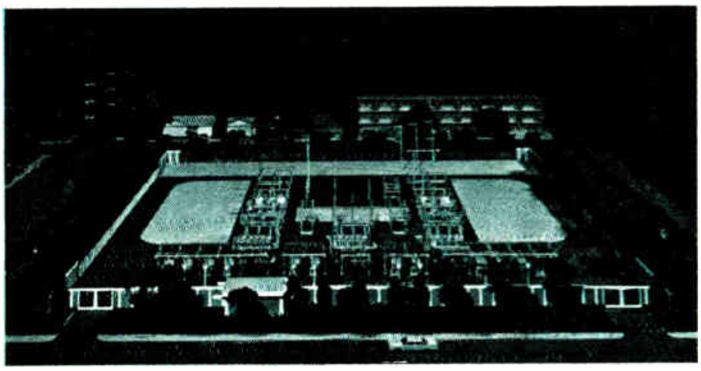


Fig. 4 (top). Florida Power & Light Company's "apartment house" substation at Miami Beach. Fig. 5 (bottom). Brick walls screen Public Service's substation in East Orange, N.J.







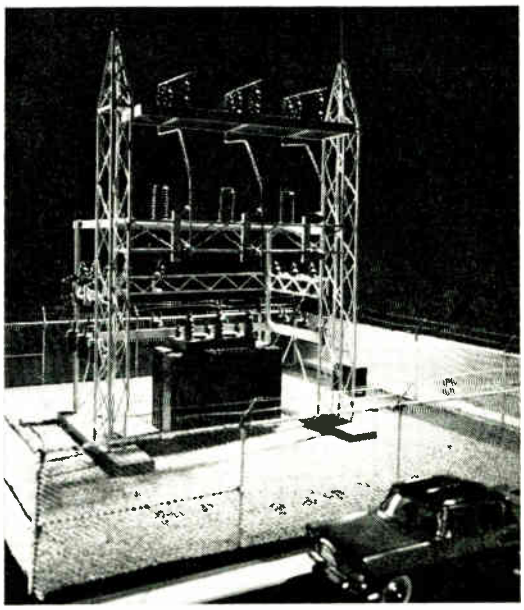
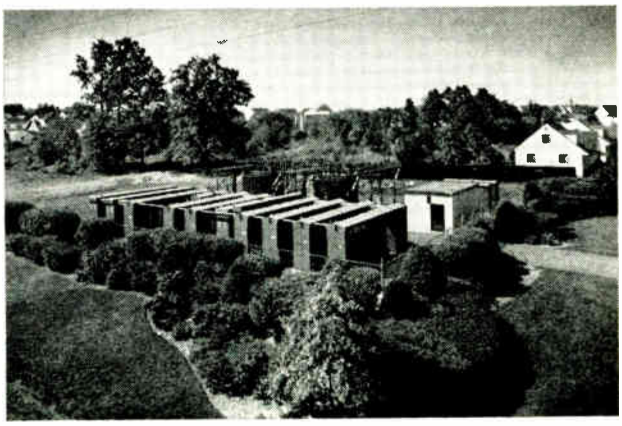


Fig. 6 (top left). Evergreen landscaping hides Consolidated Edison's substation at Douglaston, N.Y. Fig. 7 (top right). Compactness of Douglaston substation is apparent in this elevated view. Fig. 8 (above). Model of a low-profile substation designed for Pacific Gas and Electric Company. Fig. 9 (right). Conventional substation structures utilized "erector set" latticed steel. Fig. 10 (bottom right). Painting equipment in pastel shades complements surrounding landscaping.



taken from the bucket of a "cherry picker," and actually shows the same substation seen from grade level in Fig. 6.

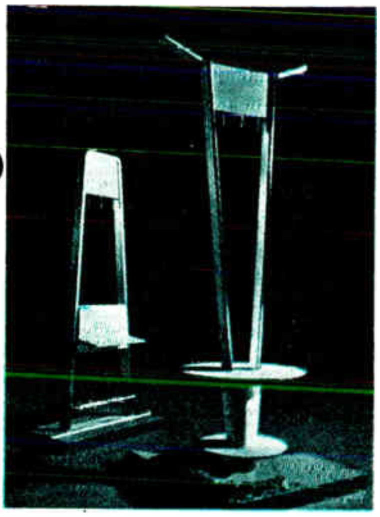
The height of primary substation structures also has been reduced from about 50 to 18 feet in recent years. Figure 8 shows a scale model of a 3-transformer bank of low-profile design, with two incoming 115-kV lines and twelve 12-kV outgoing feeders. While previous designs have made extensive use of latticed steel structures (Fig. 9), many of the new structures utilize tubular steel exclusively for supporting all substation components. Note also in Fig. 8 the use of landscaping and decorative fencing to improve the overall appearance of the facility.

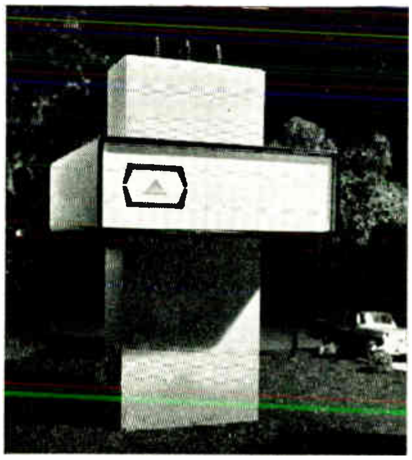
Painting the equipment casings in soft, pastel shades (Fig. 10) has also been effective in blending the transformers harmoniously with the surrounding greenery. And there has been some talk about manufacturing insulators and potheads in more attractive shades than "high-tension brown."

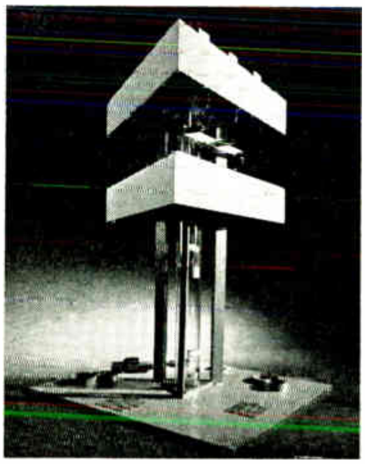
Be electric, not eclectic

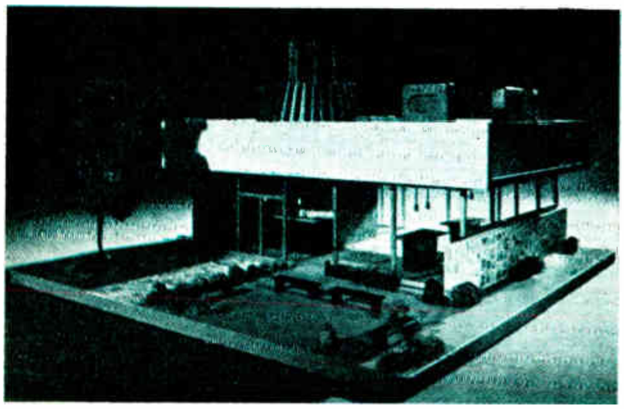
A few months ago, the United States Steel Corporation unveiled what it termed "bold new design ideas . . . [to] help electrical power companies bring their utility structures out of hiding . . ." The promotional literature contended that "the traditional route to community acceptance of the necessary electrical structures has been to put them underground or to hide them in false building shells or behind man-made screens . . ."

The bold look. Thus, reversing the earlier strategy of camouflaging and concealing utility structures, the steel company's venture, called "power styling," advances









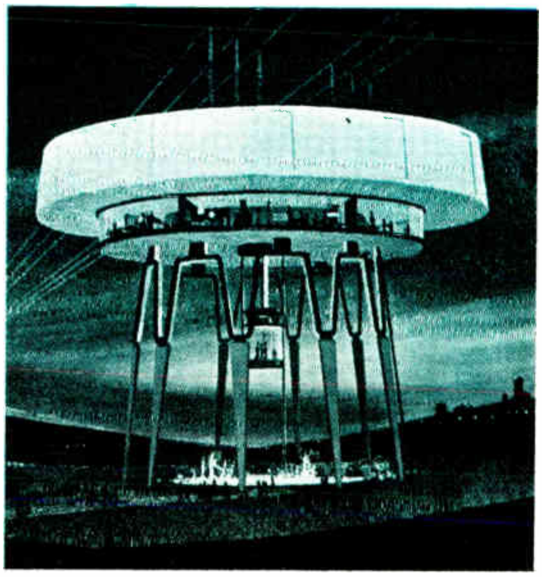


Fig. 11 (top left). Dual-purpose transmission poles could serve as sheltered bus stop and public seating area. Fig. 12 (top center). Model of a proposed "highly compacted substation." Fig. 13 (top right). Proposed "high rise" substation for mid-city areas. Fig. 14 (above). Multipurpose substation could also serve as a community center. Fig. 15 (right). "Way-out" concept of an EHV transmission tower combines office space with fully enclosed transformers.

the concept that ". . . utility structures can and should be bold, handsome additions to the communities which they serve . . . We're taking the structures from behind camouflaging bushes and walls and letting steel help them stand alone on their own merits."

With this manifesto advocating new design approaches, multipurpose and more compact structures, we can see in Figs. 11–15 the imaginative and futuristic trend that is urged by the proponents of power styling. For example (Fig. 11), we are told that a transmission pole can double as a sheltered bus stop or a public seating area, while Fig. 12 shows how the miniaturization of elements could result in the compact, containerlike substation that would be safe enough to be placed on an unfenced lot in a suburban community. Also, a substation module might serve the dual purpose of a community center (Fig. 14).

It was emphasized during a press conference that power styling did not comprise finished engineering drawings, but 85 artist's design concepts included generating stations, diesel-powered units for peak load, transmission and distribution substations, towers, and poles.

While the designs show considerable artistic imagination, many of the concepts have a futuristic appearance that would be more suitable for the New York World's Fair than for, say, Colonial Williamsburg. The practicality of molding electric equipment to accommodate some of the design configurations is open to question.

Notes from the underground

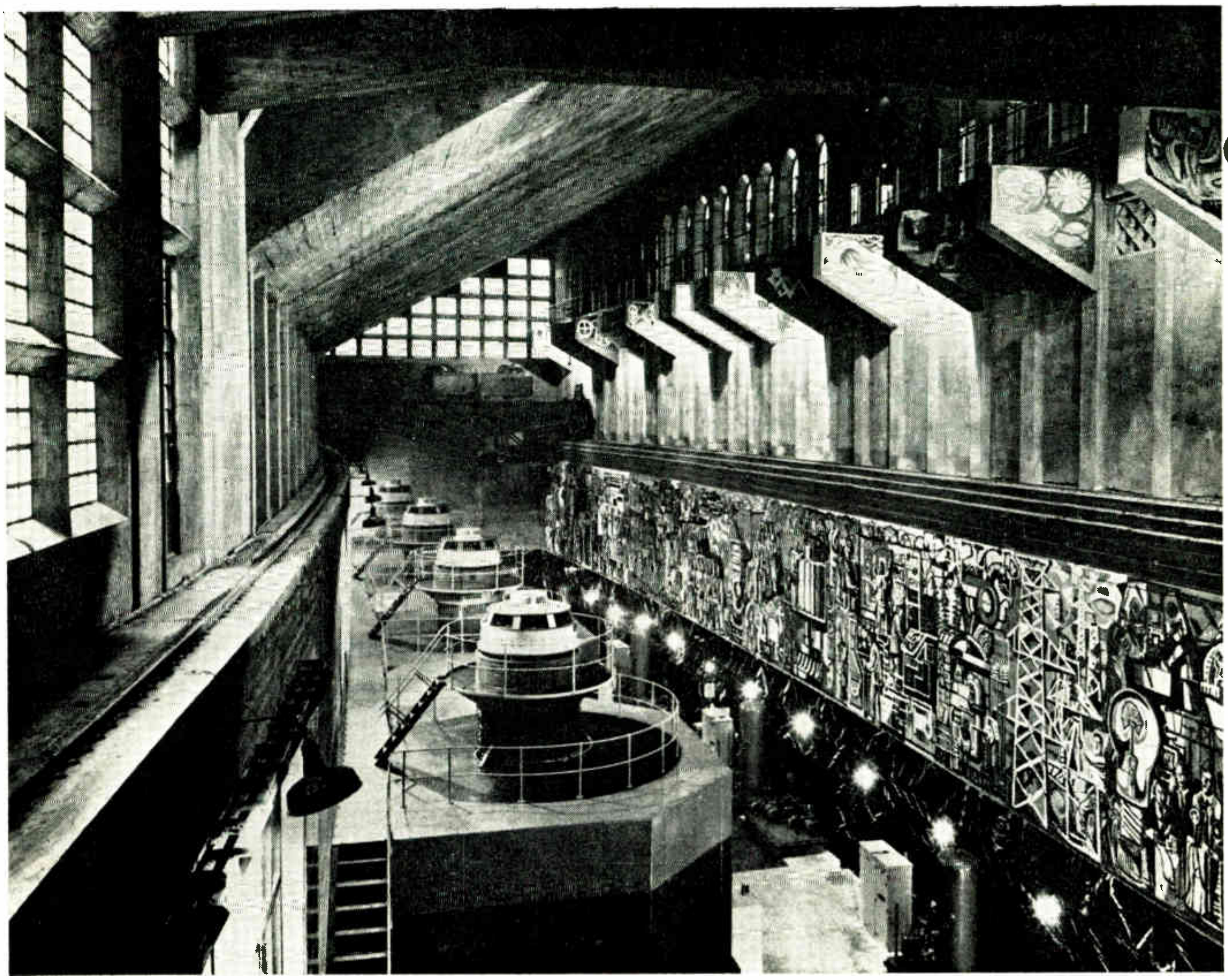
While the underground system is usually the first thought that comes to mind in the elimination of overhead power lines, the cost to achieve this is often prohibitive. Depending upon local soil conditions, the cost to bury distribution lines can run from two to ten times higher than for overhead lines; and for subtransmission lines, this cost ratio is even greater.

The underground distribution system has other disadvantages in that[1]

1. It is not readily adaptable to modification and expansion.

2. Because of the time required to locate an underground fault prior to the restoration of service, comparative reliability to the overhead system is diminished.

3. System modifications and extensions require con-



siderable excavation, with the attendant inconvenience of street obstructions and traffic congestion.

So in answer to the popular public critique, "Why don't the cheapskates shove it all underground?" we can say that, at best, underground distribution is only a partial solution. At worst, it is an overly expensive escape from reality.

And now that we have buried that issue, let's turn to the basic power installation and see what has been done both in the United States and abroad.

Esthetic designs for generating stations

Our European cousins seem to have studied the problem of esthetic architectural design for power stations for quite some time before we became aware of it in the United States. And, in some cases, they have launched a unique, two-pronged effort toward appearance improvement. Reasoning that sound architectural design includes esthetic interiors as well as exterior facades, the European designers have incorporated in some stations extensive mural decoration (as shown in Fig. 16), handsome marble paneling, and structural shapes and masses that are attractive as well as functional.

Although such elaborate decor might seem unwarranted and extravagant at first glance, one must realize that operating personnel must spend many hours of the day in these environments, and certainly artistic and warm surroundings cannot help but provide a boost to employee morale and efficiency.

Figure 17 shows the exterior of the Spanish hydroelectric station shown in Fig. 16, and the impressively beautiful dam that impounds the Salime Reservoir. Note the interesting sculptural relief panels on the downstream facade of the power station, the handsome and functional central counterforts in the dam construction, and how the entire hydro project structure blends into the natural contours and landscaping.

The switching station of the Ponte Novo hydroelectric power plant (Fig. 18) in a deep gorge of the River Navia in northwestern Spain, is situated opposite the power station on a natural peninsula formed by the cut of the river. Here too, the natural contours of the terraced mountainsides are utilized to best scenic and sculptural advantage by means of the grade separations of the access roads. This facility utilizes air-blast circuit breakers to switch power at 165 kV.

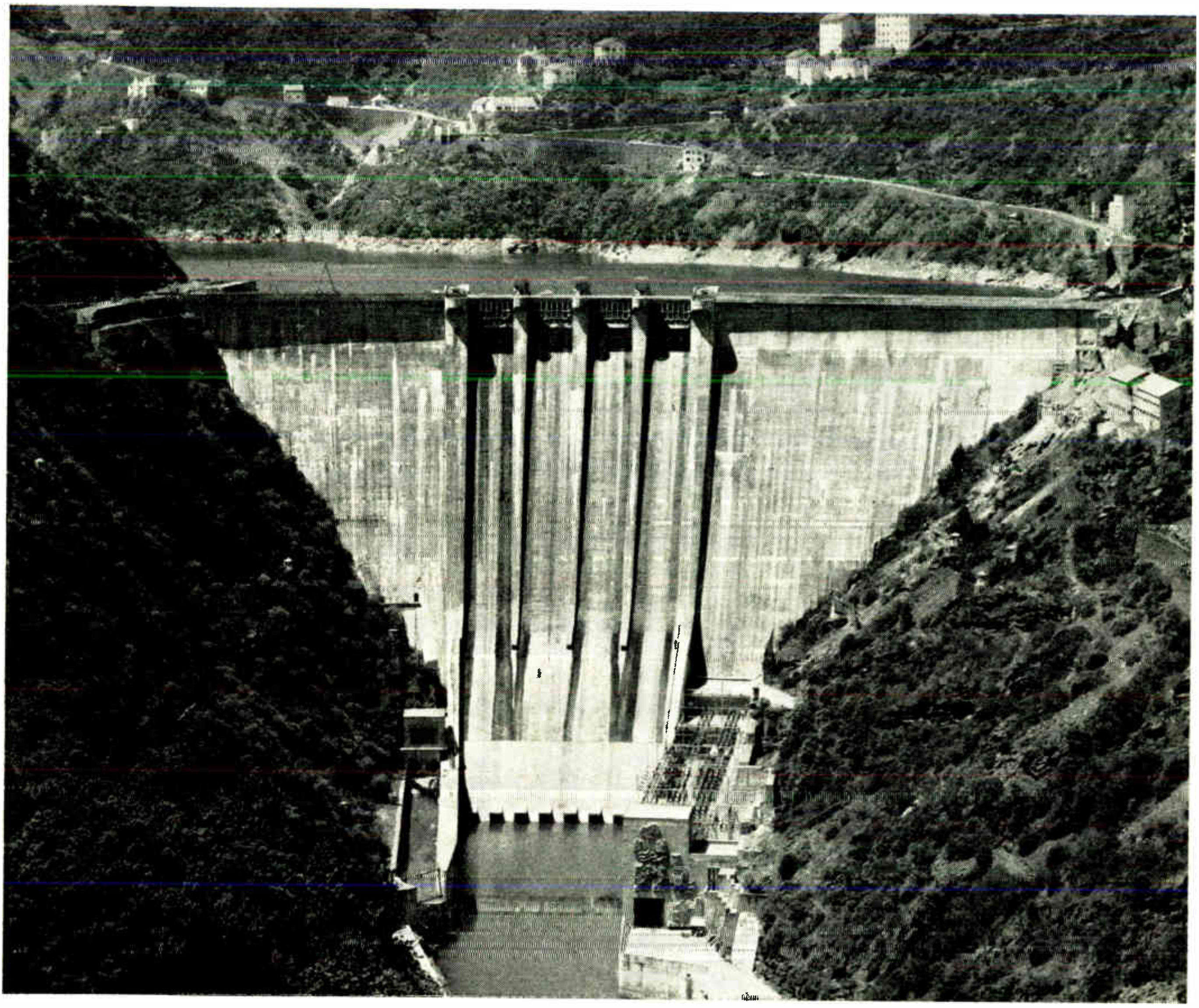


Fig. 16 (left). Generator room of Spanish hydroelectric station features murals and polished marble. Fig. 17 (above). Exterior view of the same station shows sculptural motifs on powerhouse wall.

Figure 19 shows the attractive Fasnakyle Power Station in Scotland. This installation is part of the Mullardoch–Fasnakyle–Affric water power scheme of the North of Scotland Hydro-Electric Board. The random-coursed native ashlar construction was designed to blend and harmonize with the natural beauty of the countryside. The station contains three 33 000-hp vertical reaction, water-turbine generating sets.

As the power station is open to public view from all sides, it would have been difficult to conceal an outdoor transformer and switching station. This equipment, therefore, was installed about 300 yards downstream from the station, where it is less conspicuous.

Another handsome British installation is the Tongland Power Station (Fig. 20) of the Galloway Water Power Scheme. This installation, on the River Dee, is one of five run-of-the-river hydro stations. Like Fasnakyle, its clean lines and simplicity are designed to minimize despoliation of the surrounding countryside.

Finally, Fig. 21 brings us back to our native shores with a striking night shot of a portion of the Public Service Electric and Gas Company's Mercer Station in New Jersey. Here again, the clean lines and functional simplicity of the building siding, glass brick fenestration, the trim housings over the semioutdoor cross-compound turbine–generators, and the novel use of fluorescent lighting fixtures along the handrails complement each other in translating a combination of diverse structural materials to produce an architectural effect that is pleasing, efficient, and thoroughly functional.

But now let's explore some actual "case histories" to see what specific projects are being undertaken by power companies, electric equipment manufacturers, and collaborative ventures of both interests in an attempt to preserve the beauty of urban and suburban areas.

The 'DAPPER' project

About four years ago the General Electric Company[1] accepted the invitation of the Arizona Public Service

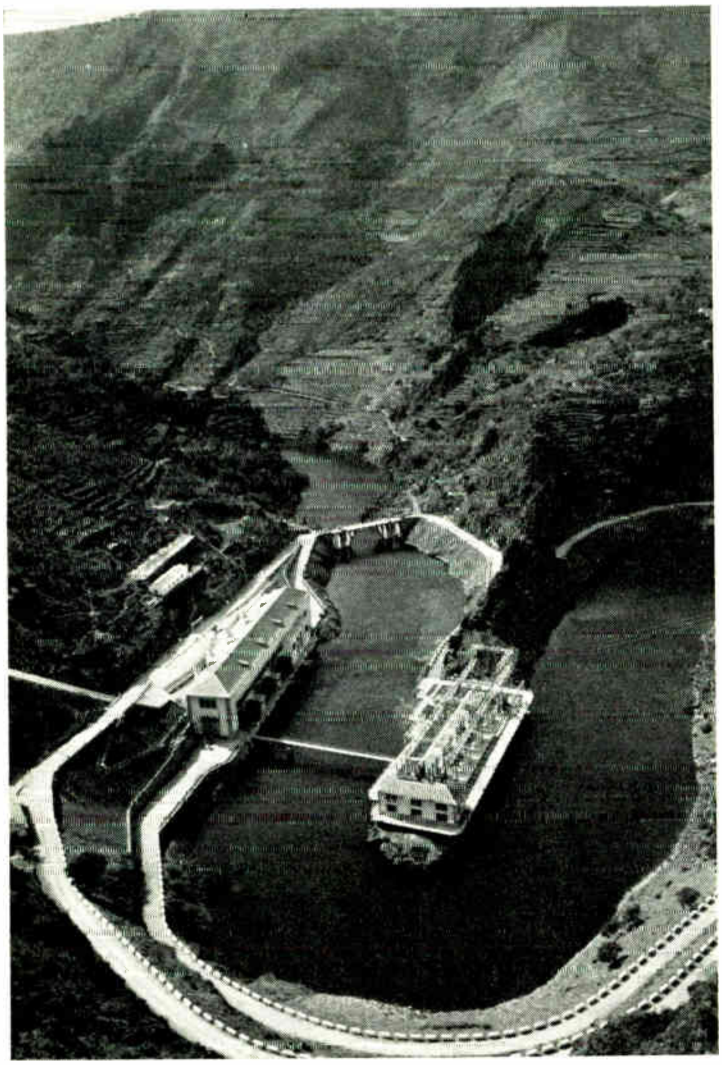
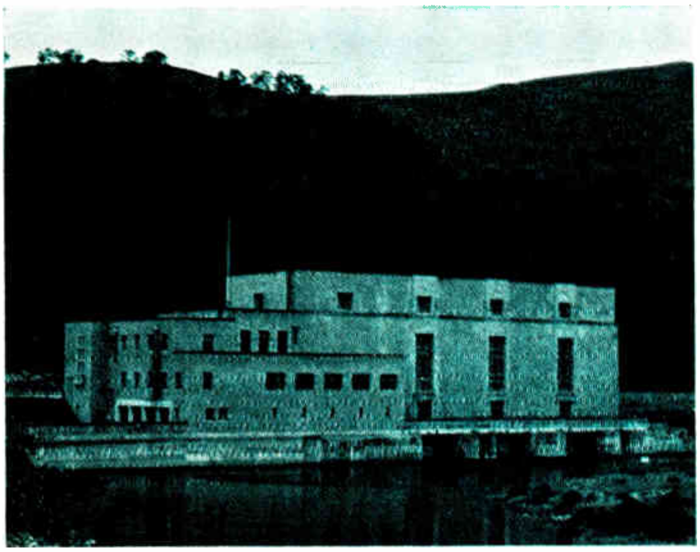


Fig. 18 (above). Spanish hydro plant utilizes natural contours to esthetic advantage. Fig. 19 (below). Scottish power plant has native ashlar construction.



Company to join in a collaborative effort in what was termed "an attack on ugliness."

Teams were formed by both companies to cooperate in the investigation of distribution system appearance from a total system approach. These groups included engineers, operating personnel, architects, and industrial appearance designers, and they focused their attention on both the functional aspects of the utility and the manufacturing phases of possible equipment modification. The project name DAPPER is an acronym for "distribution appearance engineering research."

The initial efforts were devoted to an organized and unrestricted exploration of technically feasible ideas, and economic factors were subordinated in this phase of the project. Many "way out" ideas, including a system for integrating electric service and other utilities into street curbing, evolved in the preliminary work.

The utility company and General Electric established some basic ground rules in their approach. They reasoned, quite logically, that the entire question of appearance is subjective, and, like ladies' hats, what looks good to one person may look awful to another. Thus they decided that first the electrical product, facility, or system should, by appearance, express its primary function. If this could not be achieved, then the product or appurtenance should be made to blend into its environment. And, as a last resort, if the first two objectives could not be attained, the abomination should be hidden.

Theory vs. practice. The collaborating teams soon discovered that the functional design theory looked better on paper than in practice, and that making a distribution system look like what it does was a formidable task. The Arizona topography and geography seemed to militate against this effort. Thus the groups concluded that a more logical approach would be to blend the system into its environment, or to conceal it entirely.

Simplify, integrate, conceal. Project DAPPER quickly developed into a systematic exploration of appearance improvement ideas that related to overhead systems, on-the-ground systems, underground systems, and combinations of all three—all molded to meet the criteria of *simplify*, *integrate*, or *conceal*.

In their investigation of the distribution system problem, it seemed logical to the collaborative teams first to consider the overhead primary main and primary lateral systems because of their many miles of exposure to view. And since the substation is the nucleus from which distribution systems radiate, this type of facility received some prime attention. Figure 22 shows the notable results in improved appearance that were obtained in one instance by combining a low profile substation with desert-blending adobe walls and appropriate landscaping.

Another problem was to redesign the distribution poles esthetically. This was achieved through height reduction, the elimination of unsightly crossarms, and the substitution of streamlined metal construction for the conventional wood pole. In this effort, the project personnel were intrigued by a variation of the design approach used by the Pacific Gas and Electric Company. The P.G.&E. streamlined electric distribution pole is shown in Fig. 23. This is a three-phase main primary (12 000-volt) feeder line that supplies a large suburban subdivision. The basic pole is fabricated of 7-gauge steel; it is 32 feet long and tapers from 8½ inches in diameter at the base to 4 inches in diameter at the point where it flares into a streamlined container that houses a special integral transformer. The pole is erected on the median strip of a divided roadway, and the structure is complete with attractive twin street-lighting brackets.

The sectionalized steel pole of the Arizona Public Service Company (Fig. 24) serves as a feeder pole and integrated street-light support. It is designed primarily for use in commercial areas and residential streets.

Reduced pole height was found to be particularly effective when used in conjunction with rear lot construction in suburban areas. While this approach in suburban areas improved the street appearance, it did introduce certain access, operating, and maintenance problems.

Figure 25 shows how Arizona Public Service has utilized tapered tubular steel poles and horizontal post insulators to construct the double-circuit 230-kV transmission lines along a downtown Phoenix street. While this installation will probably not win any architectural or structural design prizes, it still represents a vast improvement over the massive, latticework delta-section conventional transmission towers.

The third approach in the joint effort—that of concealment—has found considerable favor through the installation of residential subway transformers and underground distribution systems. Although the utility company concedes that there is still a need for further major improvements in design and installation techniques, nevertheless considerable cost economies have been achieved in the underground distribution phases of the project. And for the Arizona installations it is felt that there would be fewer outages due to tornados, ice storms, and possible seismic shock. Other advantages, in addition to appearance, include less need for tree trimming, and front lot access.

In all, Project DAPPER has represented a novel and worthwhile approach to the problems of appearance design. Some concrete results (no pun intended) have been attained, and the collaborative effort may set the pattern for other utility companies that are interested in improving the esthetic appearance of their facilities.

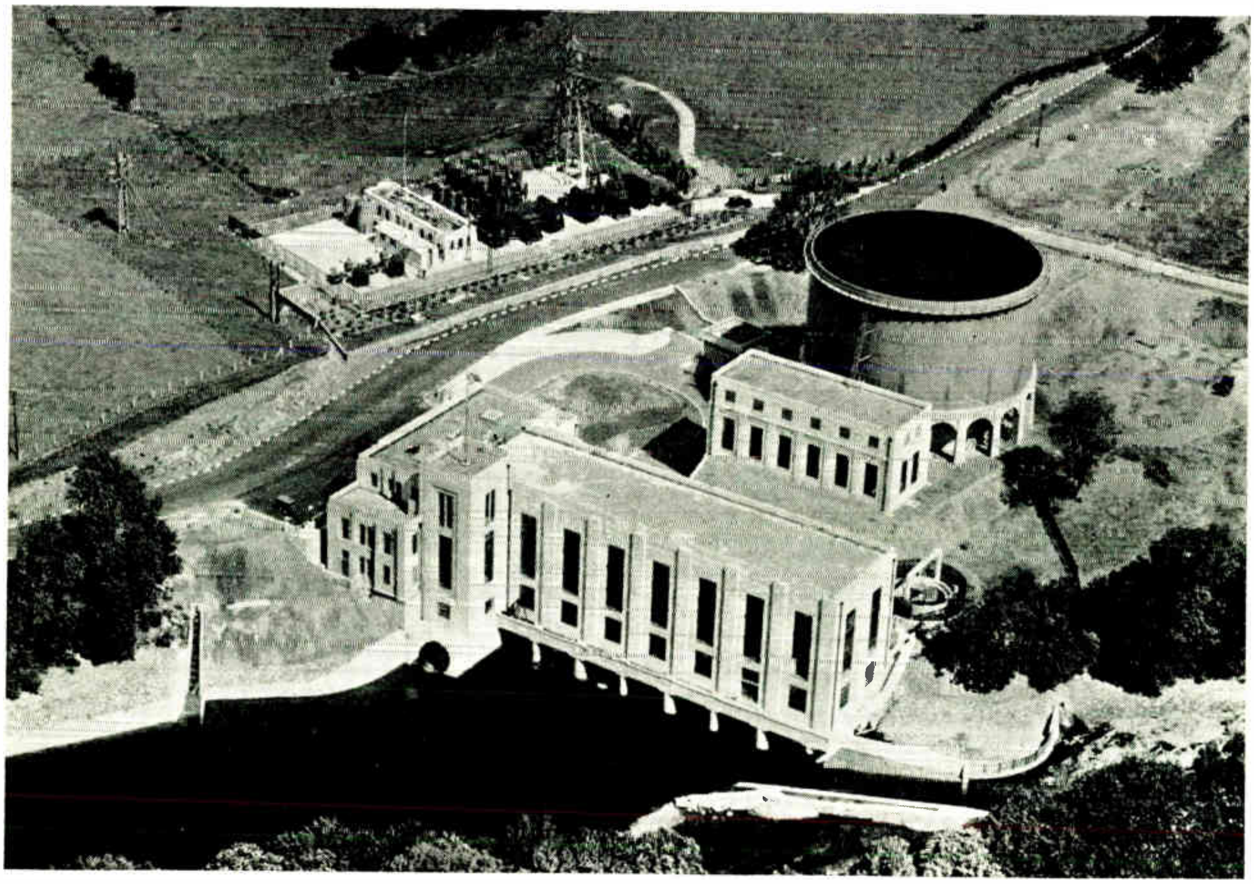
Some 'do's and don'ts' in design and construction

One major eastern utility company has catalogued a comprehensive list of questions, objections, pitfalls, and problems—all gained through prior experience—that are sure to arise before, during, and after the construction of an electrical facility. This compendium also includes a virtual "building code" of *what to do* and *what not to do* to preserve the company image for good public relations.

Positive thinking at power station sites. The four cardinal points in the planning of power stations are:

1. Preserve the existing landscape on the site insofar as possible.
2. Provide some degree of esthetic environment to offset the loss of original landscape.
3. Build at least a good-looking structure.
4. After it is built, provide good maintenance and

Fig. 20. English power station shows clean and compact architectural lines.



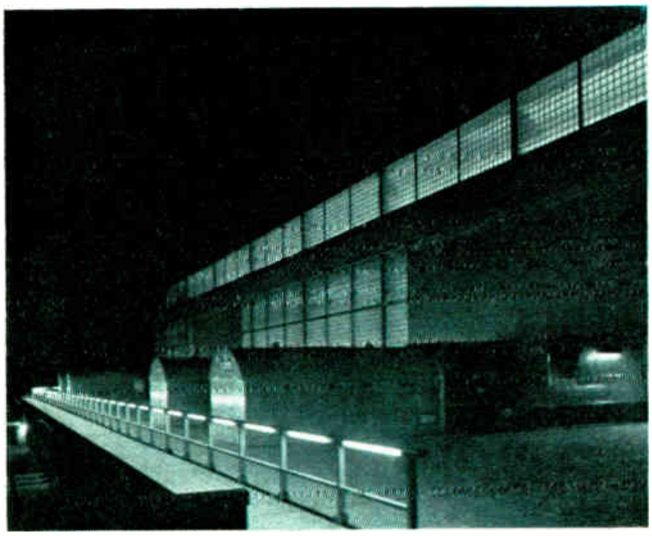
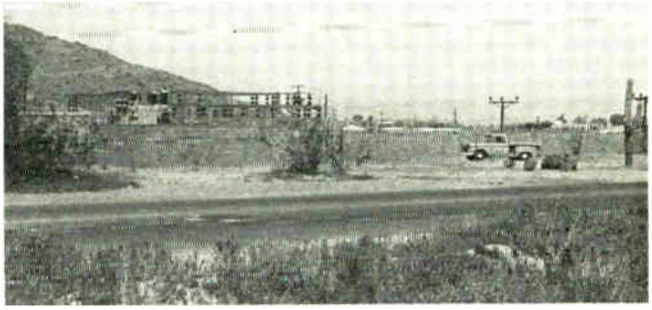
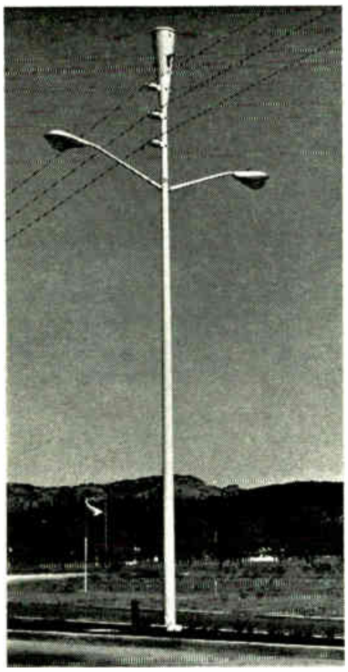
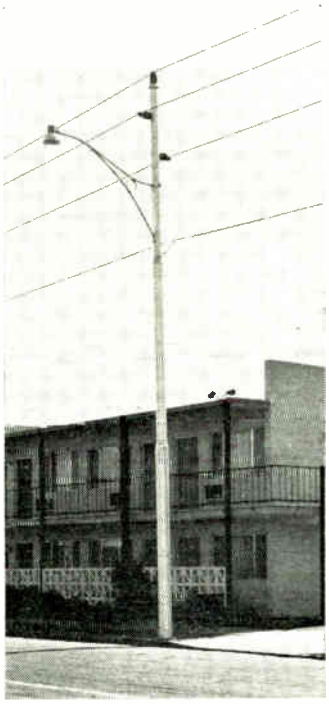
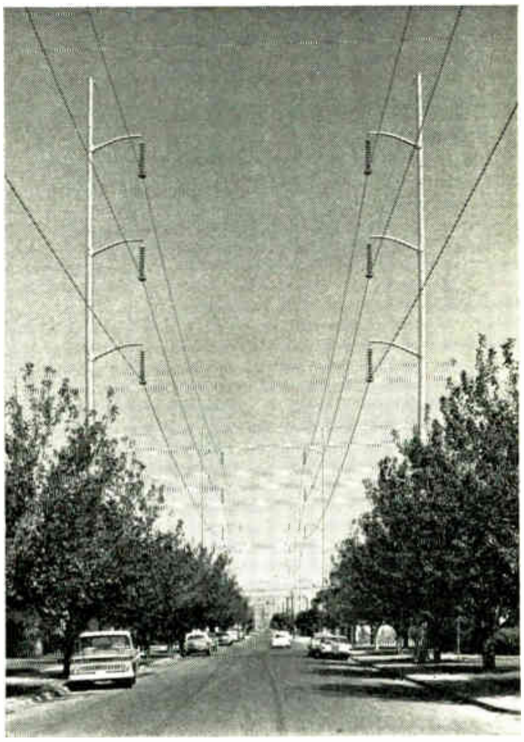


Fig. 21 (left). View of Public Service's new Mercer steam-electric station in New Jersey. Fig. 22 (below). Arizona Public Service's low-profile substation near Phoenix features desert-blending adobe walls. Fig. 23 (bottom left). Pacific Gas & Electric's streamlined distribution pole runs along highway median strip. Fig. 24 (bottom center). Sectionalized steel pole of Arizona Public Service complements contemporary design. Fig. 25 (bottom right). Tapered tubular steel poles carry 230 kV lines along Phoenix street.









avoid noise, dirt, odors, etc., as much as possible.

The rules further stipulate, in the initial planning stages, a recommended—

Method of attack. In the necessary expansion program of the utility's electrical facilities, it is often necessary to acquire new sites. The company has learned—through rueful previous experience—that the selection of an appropriate site can be of paramount importance. Never, but *never*, consider a site where an impasse with a community or a civic group can be predicted. The delaying action of injunctions and litigation can far more than offset any economic or practical advantage. Also, as a rule of thumb, it has been found advisable to avoid taking the last tract of virgin land in a township or community—even though this may be the local swamp, quicksand bog, or poison-ivy patch.

As part of its strategic planning, the company always takes an option on an alternative site, in case difficulties arise in connection with the first choice location.

Objections, demands, and counterattack. While the company's method of attack may be reasonable and considerate, the neighborhood counterattack may include the following demands and objections (an abridged list): don't cut that tree, lower the equipment out of sight, enclose the substation in a false-front house, don't use ugly chain-link fence enclosures, the children may be electrocuted, the landscaping is so meager that it covers nothing but the artist's sketch, etc.

Fig. 26. Sprawling switching station on high rock ledge could make suburban community residents unhappy during and after construction.

It is only fair to say, however, that some of the *don'ts* may be justified. Figure 26 shows an instance where community objection may have some validity. Here, a sprawling switching station has been built on high ground along a rock ledge, close to an arterial expressway. The principal objections to this installation occurred during its construction, at which time the line drilling, rock blasting, dust, and construction noises augmented the usual highway sounds. And, although there is a minimal landscaping cover of evergreens along a portion of the facility's perimeter, there is still much to be desired in the appearance of the total installation.

Some gratuitous PR advice

Experience in public relations has indicated that secrecy or covert deals seldom pay off. People fear most that which they do not know. Therefore, a good company image can be built—along with the facility—by doing everything within reason to be good neighbors. And, by taking the public into its confidence as to future expansion plans and requirements, etc., the utility can preclude much of the public hostility and adverse reaction.

Esthetic criteria are often in the eye of the beholder. A woman may not be a physical beauty in the classic sense, but her charm, wit, and femininity may more than compensate for her physical deficiencies. So too, by means of good public relations, the need for an electrical facility can be explained to the public before, during, and after its construction. Guided public tours of new facilities is an excellent method both to educate the consumer of electricity and to give the public a sense of participation in a vital facet of national growth.

Some final thoughts

The day has long since passed when a utility—or any other special interest—can slash through a forest preserve, blast into a mountain, or despoil a natural scenic site without triggering an outcry of public resentment.

Frank Lloyd Wright believed that the architectural design of a structure should be sincere toward its function and occupancy. In other words, he believed that a school should not look like a motel, the municipal water works need not resemble a commercial building, and it is quite certain he would have felt that electrical facilities should also be esthetically true to their functions.

The collaborative venture of the General Electric Company and Arizona Public Service is commendable in that it represented a pioneering attempt to modify both equipment and facility design to complement each other for the achievement of a worthwhile goal.

Perhaps what is needed most at this juncture is a "new breed" of architectural and engineering designers who are specialists in solving the esthetic problems of power installations, experienced in the spatial and functional requirements of power equipment, and can work cooperatively and collaboratively toward the best solutions.

The author wishes to acknowledge the courtesy and cooperation of the General Electric Co.; Arizona Public Service Co.; Pacific Gas and Electric Co.; Long Island Lighting Co.; English Electric Corp.; Iberduero, S. A.; United States Steel Corp.; Dallas Power & Light Co.; Idaho Power Co.; Potomac Electric Power Co.; *Kaiser Aluminum NEWS* (Figs. 1, 3, 4, and 6); Florida Power & Light Co.; the Banco de Vizcaya; Public Service Electric and Gas Co.; and Consolidated Edison Co., Inc., of New York for providing the illustrations for this article.

REFERENCE

1. Schultz, N. R., "Distribution System Appearance," presented at the Engineering and Operation Sect. Conf. of the Southeastern Electric Exch., Washington, D.C., Apr. 16–17, 1964.

Acoustics of the concert hall

Acoustical measurements of several large halls, together with laboratory experiments, are opening a fresh approach to the design of large concert halls. The energy relationship between early and late sound is found to be unexpectedly critical

T. J. Schultz
Bolt Beranek and Newman, Inc.

The importance of early sound in comparison to the later-arriving reverberant sound heard in an auditorium has been recognized for some time in connection with speech intelligibility. Furduev[1] suggested in 1937 that the "acoustical ratio" (the ratio of "diffuse" to "direct" sound energy) might be an important criterion for the audition of speech in halls. He found, however, that this parameter does not correlate particularly well with the articulation index, an objective measure of the intelligibility of speech.

Ten years later, Maxfield and Albersheim[2] confirmed this result. However, they found that a quantity that they called "liveness" (the ratio of the time integral of reverberant sound energy to direct sound energy) gave predictions which were consistent both with the then-accepted curves of optimum reverberation time in halls and with "loss of speech articulation," provided one chose properly certain arbitrary constants in the equation and also restricted one's attention to seats midway back in the hall. They also determined an appropriate, if not optimum, value of liveness for music by calculating this parameter for seats reputed to be favored by musicians in Carnegie Hall (New York) and in the Academy of Music (Philadelphia). One notes, however, that their liveness parameter may vary through a range of 5:1 with distance from the stage in a given hall; hence, the usefulness of this parameter as a criterion of musical quality is questionable. Either the tolerable range of liveness is so wide—to account for all the good seats in a good hall—that it does not constitute a very sharp index of quality; or, accepting a narrow desirable range for liveness, calculations would predict that, if one seat in a hall is good for listening, most of the other seats in the same hall will be bad.

In 1940 Sukharovskii[3] proposed a "reverberation interference factor" Q_m in terms of which he compared the sound energy which is useful for the intelligibility of speech with energy which is harmful. "Useful sound" is the direct component plus all other sound arriving within the first 50 ms; "harmful sound" is the reverberant sound plus ambient noise in the room. The reverberation interference factor was found to correlate fairly well with speech intelligibility.

In a later refinement of this concept, Golikov[4] integrated the ratio of useful to harmful sound over time, to account for the ballistic character of the ear, and added a factor depending upon the absolute sound pressure level. When this was done, he found good correlation between his coefficient Q, for which he did not propose a name, and published data for the speech articulation index in several halls.

The aforementioned parameters are all calculated quantities; they are expressed in terms of overall sound energy and thus do not take into account any dependence on frequency. Their chief purpose, which has been better fulfilled with each successive refinement, is to predict speech intelligibility in a hall rather than the quality of the acoustics for listening to music.

In 1953, Thiele[5] reported measured results from a series of sound pulse experiments in theaters and radiobroadcasting studios. He observed the ratio of "early" to "reverberant" sound energy, and defined a parameter D, which he called *deutlichkeit* ("definition"):

$$D = \int_0^{0.05s} I(t)dt \Big/ \int_0^{\infty} I(t)dt \qquad (1)$$

where $I(t)$ is the instantaneous overall sound intensity arriving at a given seat location in the hall. Note that Thiele has accepted the 50-ms limit, suggested by Sukharovskii, as the time "boundary" between useful and harmful sound. He found in his measurements that this ratio, for overall sound, varied only 3–5 dB in any one theater and only 8 dB in all the theaters and studios tested. Since he had chosen only well-liked rooms to measure, this narrow range enabled him to deduce from his results a preferred value for the quantity D, which could be taken as a criterion of good speech acoustics in a hall.

Recent measurements of the ratio of reverberant to early sound energy

In the course of studying several recently opened concert halls, we have had an opportunity to extend Thiele's work, measuring the ratio of reverberant to early sound as a function of frequency, as expressed by the following equation:

$$R = \int_{0.05}^{0.4} p^2(t)dt \Big/ \int_0^{0.05} p^2(t)dt \qquad (2)$$

Here, $p(t)$ is the instantaneous sound pressure at a listener's seat position, following the arrival of an impulse from a source on the stage.

Instrumentation. Our analyses were made from tape recordings of the sound picked up by a microphone in the audience area following the explosion of a balloon on the stage. By a combination of time-gating techniques and squaring/averaging circuitry we could measure the energy that arrives at a microphone in the seating area during any desired time interval within the train of reflections following each explosive pulse.

A typical train of sound pressure signals as received by a microphone on the main floor is shown in Fig. 1. The purpose of the pulse-measurement technique is to break this complicated pressure pattern into time packets of energy; for example, we are interested in the energy arriving at the microphone during the first few milliseconds compared with all the energy arriving at later times. For this purpose we use the equipment illustrated in the block diagram of Fig. 2; later on, an explanation will be given of the operation of this circuit. Figure 3 shows the time-gated early-arriving portion of the pressure signal at the microphone; the response of an octave-band filter to this gated signal is shown in Fig. 4. We read out on a meter (or can plot on a graphic level recorder) the total energy contained in the time-gated frequency-filtered pulse.

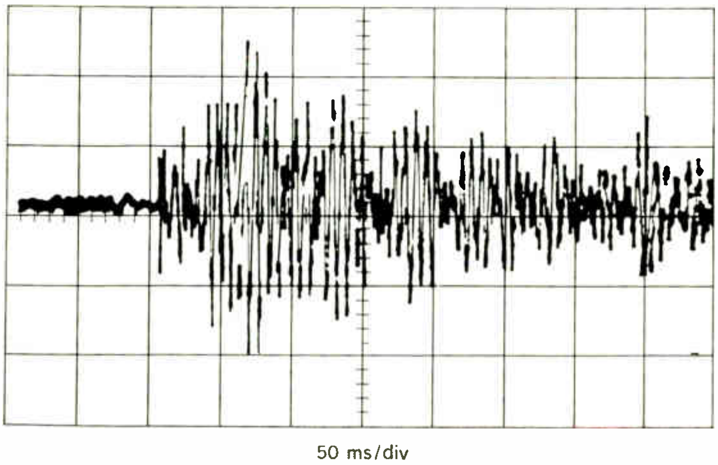
The circuit operation can be seen in greater detail by referring to Fig. 2. Fast-acting relays 1 and 3 are timed by pulse circuitry in the following sequence: Immediately before the arrival at the microphone of the desired signal, relay no. 3 closes for about 1.5 ms, "erasing" the result held in the capacitor C from the previous pulse. As soon as relay no. 3 opens, permitting the capacitor to begin accumulating charge again, relays 1 and 2 then close, thus sending a signal of the desired duration into the octave band filter and the squared filter output into the R-C integrating circuit. At the end of the desired signal, relay no. 1 opens so that no further energy is fed into the filter. However, relay no. 2 remains closed for a total time of $RC/4$ seconds to accept as much of the transient tail of the voltage of the filter as is consistent with a small error due to discharging the capacitor through the squaring circuit. The impedances of the circuit elements shunting the integrator capacitor are high enough that the voltage for each tone burst can be held in the capacitor without significant decay until the next signal is received. A cathode-ray oscilloscope is used to adjust and to monitor the operation of the timing circuits and to aid in adjusting the attenuators in various parts of the circuit.

The equipment was arranged so that we could determine the transmission curve as a function of frequency for any individual sound path—for example, the direct sound, a reflection from an overhead panel array or from the vertical side walls, etc. Alternatively, we could make a frequency plot of (1) the energy arriving at the microphone within the first 50 ms and (2) the energy arriving in the subsequent half-second, which is very nearly the total energy arriving at that position from the reverberant field. These measurements were made for microphone positions in several places in each hall and for several source positions on the stage.

The critical ratio of reverberant energy to early energy was determined as a function of frequency by comparing the curves for reverberant and early energy, respectively, as measured at each seat position.

Relevance to concert-hall symphonic music. In our studies we have been particularly interested in symphonic music rather than in speech and our observations here are restricted to this kind of sound; but confining our interest to music has raised the question of how to evaluate the measured data. For an evaluation of their proposed parameters of merit, previous workers relied on comparison with the articulation index for speech (though, as previously mentioned, Maxfield and Albersheim referred to the public reputation for quality of music in two halls).[2] In the case of music, on the other hand, there is no clearly defined or objectively measurable scale of overall quality. Many more aspects are involved than simple intelligibility, and they are considerably

Fig. 1. Typical train of sound pressure signal received by a microphone on the main floor of a concert hall following an impulse from the stage.



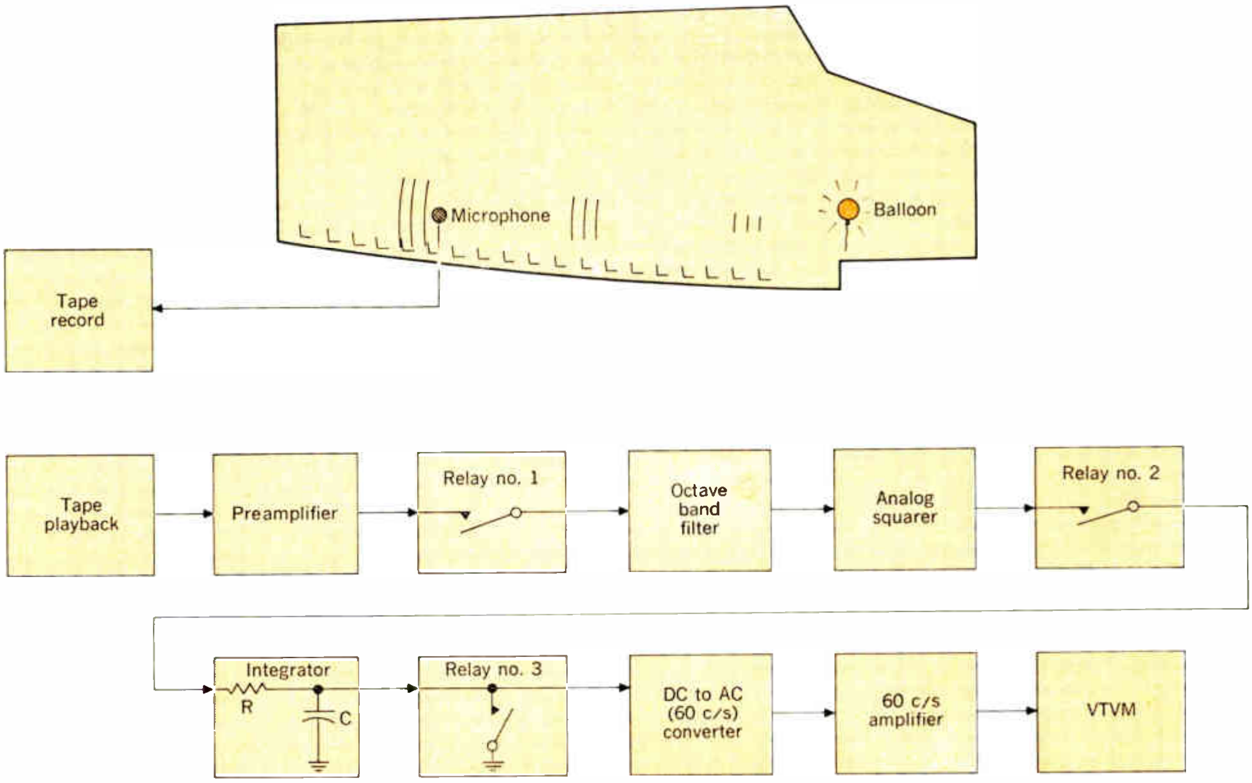


Fig. 2. Block diagram of pulse analysis equipment.

Fig. 3. Time-gated early-arriving portion of the pressure signal at the microphone.

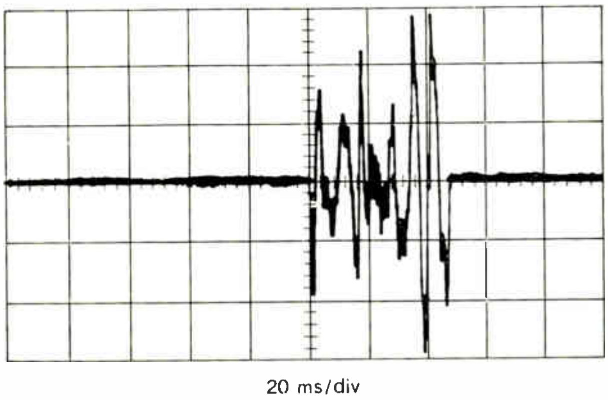
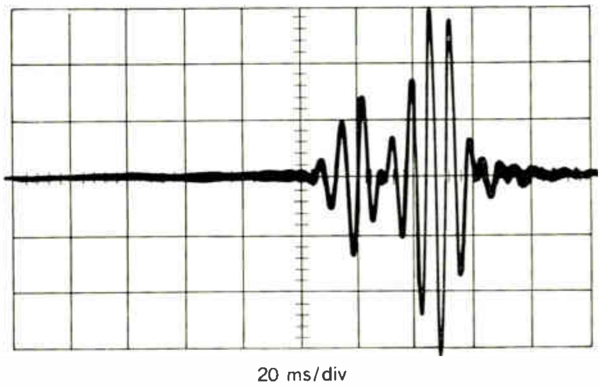


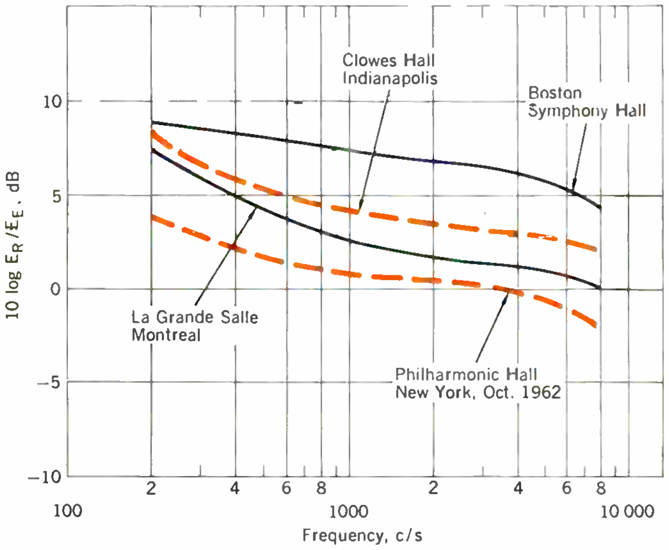
Fig. 4. Response of octave-band filter to the time-gated signal shown in Fig. 3.



more a matter of individual taste. We have felt, moreover, that the public reputation of a hall involves too many variables to be of much help in deciding which aspect of music, as heard at a given seat position, correlates with measurements of a single acoustical variable made at that position. We tried to determine by careful listening some characteristic of the music that increases and decreases with the values of our measured data. This has turned out to be something that we call "running liveness," which is very much akin to "fullness of tone" as described by Beranek.[6] When there is too much running liveness, the music will be "muddy," though full and well blended; when running liveness is slight, the sound is clean and well defined, but dry. We use the word "running" here to emphasize the distinction between this aspect of liveness and that associated with the audible persistence of sound following the termination of the music.

Correlation of measured data with running liveness. Figure 5 shows the logarithmic ratio of reverberant to early sound energy for La Grande Salle in Montreal (opened September 21, 1963); Clowes Hall, Indianapolis (opened October 18, 1963); Philharmonic Hall, New York (as it was in November 1962); and Symphony Hall, Boston (measured in October 1963; hall was built in 1900). All these halls have similar reverberation time characteristics and in each hall the terminal reverberation is audible to about the same degree, but the balance between definition and blend heard in these halls correlates with the measured curves. Boston Symphony Hall, when unoccupied, is too blended, even muddy; for this reason, a heavy curtain is hung across the hall

Fig. 5. Logarithmic ratio of reverberant-to-early energy in several large concert halls.



during rehearsals to suppress the reverberation. On the other hand, Philharmonic Hall in New York seemed to be "overdefined," or too bright, for some tastes. The other two halls fall between these extremes and appear to be well liked. The curves of Fig. 5 correspond to halls that seem to bracket an acceptable range of running liveness; they, therefore, presumably define roughly a tolerable range of the ratio of reverberant to early energy, a spread of only about 10 dB. (The data in Fig. 5 refer to unoccupied halls. If the halls were occupied, the curves would be slightly lower—particularly for Symphony Hall, Boston, where the seats have very little upholstery—and the range between the extremes would be less.)

Figure 6 shows another aspect of the same phenomenon—the rate of growth of sound. In Symphony Hall the first-heard sounds are relatively weak compared with the later reverberant energy, giving the envelope of the curve a softly peaked shape in the first 150 ms; in Clowes Hall (Indianapolis) there is an almost uniform slope; in Philharmonic Hall there was strong early sound, leading to a concave envelope.

Figure 7 represents the log ratio of reverberant/early sound for Philharmonic Hall under three different conditions. At the beginning of the test week in May 1962,[7] there was no simulated audience in the hall, and it was clear that the sound was too live and muddy. At the end of the test week temporary adjustments had been made, and the sound of the hall seemed to be satisfactory.[8,9] However, before the opening of the hall, finishing touches were added that changed the critical energy ratio, with the result that the hall was criticized as too bright or too dry. The three curves of Fig. 7, corresponding to these conditions, again confirm the narrow range between values of this energy balance that lead to excessively muddy and excessively dry sound.

Variation of ratio with distance from stage. Figure 8 shows that there is little variation of the parameter *R* with distance from the stage in La Grande Salle, Montreal; the curves tend to cluster within a very small range. Although the strength of each individual reflection decreases with distance from the source (because of spherical divergence), as one moves farther back into the hall progressively more reflections are received within the first 50 ms, thus keeping the early energy relatively constant. This is consistent with the limited range of *deutlichkeit* found for any one hall in Thiele's data.

Tentative suggestions concerning running liveness.

1. The frequency curve of the ratio of reverberant to early sound tends to be nearly the same for most seats in a hall and may serve to characterize the sound in the hall.

2. The general level of this energy ratio curve correlates with running liveness in the hall, having extremes of

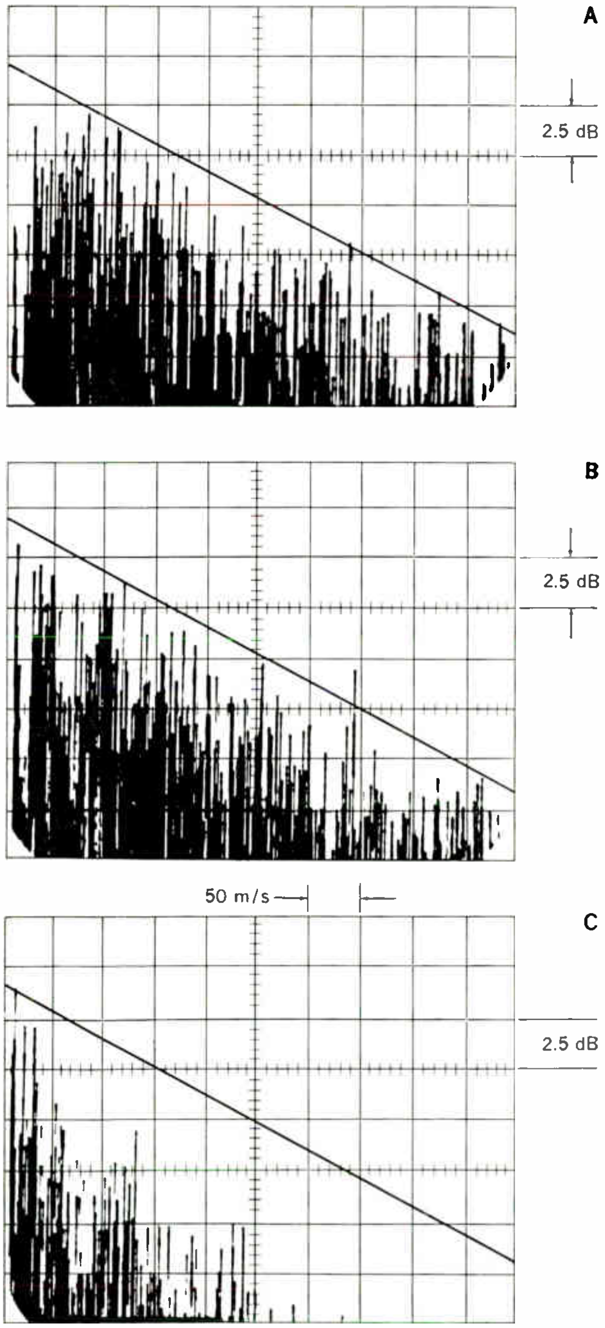


Fig. 6. Rate of growth of sound in several large concert halls, corresponding to the curves of Fig. 5. A—Symphony Hall, Boston; B—Clowes Hall, Indianapolis; C—Philharmonic Hall, New York.

muddiness when the curve lies high on the graph and of dryness when the curve lies near or below the zero line.

3. The range between these extremes in halls suitable for the performance of symphonic music is surprisingly limited, and for good sound may be less than 7 dB.

These suggestions are plausible. For speech, it is well known that we desire maximum clarity. Appreciable liveness reduces the intelligibility and hence the effectiveness of a hall for hearing speech. For music, however, the qualities of clarity and fullness of tone are antithetical (each tends to destroy the other) but *both* are necessary. No wonder, then, that the balance between reverberant and early sound energy is delicate. This balance is the critical acoustical parameter that seems to determine liveness in a concert hall. Its further importance in governing the perceived clarity and warmth of sound will be discussed below.

Cautionary note. Some qualifications to these observations must be pointed out. We have based these suggestions on measurements and listening only in halls of similar size, shape, and reverberation characteristics (those that are typical of much new construction), and we have made our correlation judgments in terms only of symphonic musical material. Moreover, although we have referred our comments to the entire frequency curves of the ratio of reverberant to early sound energy, certain considerations will be discussed later that suggest that the factor of real importance may be not the general "height" of the entire curve with respect to the zero axis but rather a ratio of early sound in a high-frequency range to reverberant sound in a lower-frequency range. We are not at present in a position to refine this energy ratio parameter quantitatively, but will go on instead to point out some related results that clarify the roles of "early" and "late" energy in stabilizing the balance between low- and high-frequency sound in a hall.

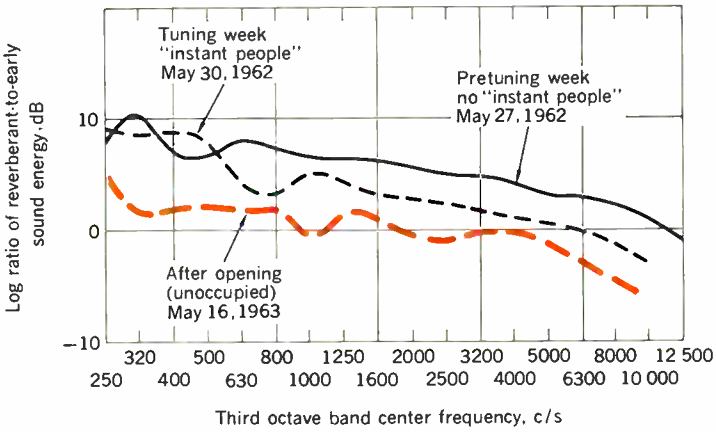
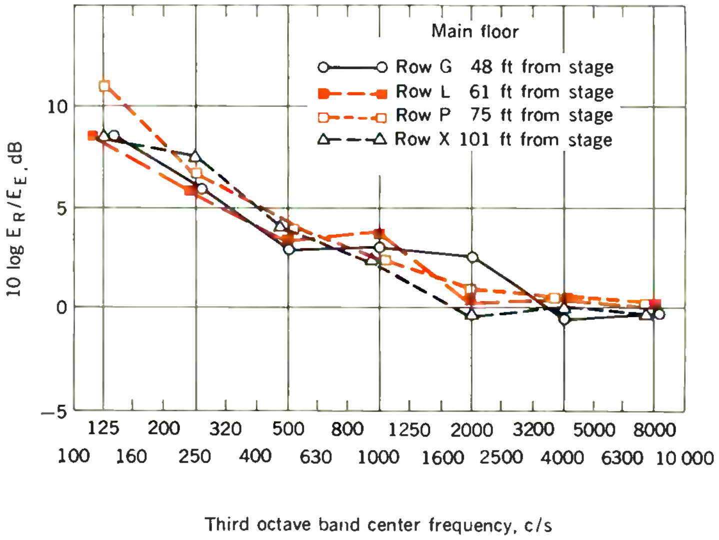


Fig. 7. Log ratio of reverberant to early sound under several conditions in Philharmonic Hall, New York.

Fig. 8. Variation of the parameter R with distance from the stage in La Grande Salle, Montreal.



Roles of early and reverberant sound

Dependence of intelligibility on early sound. Furduev, Maxfield and Albersheim, Golikov, and Thiele clearly felt that the early sound strongly affects the intelligibility of speech in the hall. Also, Beranek[10] has pointed out the importance of early reflections arriving within 20 ms of the direct sound in concert halls, emphasizing that they lend a feeling of intimacy and clarity to the music. In musical terms clarity (intelligibility and definition) concerns: *Which* instrument played? *When* did it speak? *Where* was it? *How* did it articulate?

If it is true, as previous workers have suggested, that intelligibility depends upon the strength of early sound, one wonders whether for music the clarity would suffer from serious gaps in the energy spectrum of the early sound. (We know, for example, that a high degree of intelligibility is preserved in telephone conversations, though there is a severely limited speech spectrum.)

Ragged frequency response in early sound. The question of ragged frequency response is particularly intriguing because there is recent evidence to indicate that the spectra associated with individual paths for early sound in a hall are likely to be very irregular indeed.[11–19] Moreover, it has been shown[16] that the ear responds to a dip in the frequency response curve of pressure in much the same way as a microphone would. Since the early sound in all halls appears to be associated with paths having irregular frequency response,[15,16,21] we are led to inquire what property of the ear permits it to overlook these irregularities, or alternately, what characterizes the halls in which the ragged spectra typical of individual early sound paths go unnoticed.

Simulation tests in the laboratory. We have investigated the effect of certain spectral modifications in the early- and reverberant-sound components by means of "concert hall simulation" tests in our laboratory. The results, described below, are similar to our findings in other simulation experiments conducted in an actual concert hall. (See Appendix I.)

The experimental setup. The experimental setup for the laboratory experiments is shown in Fig. 9. The laboratory simulation tests depended on a specially recorded two-channel magnetic tape; the subject material consisted of opera, organ, and orchestral music. On the first channel, the monaural sound of the performer(s) was recorded in a "dead" space. This signal was played through the "direct" loudspeaker, located in front of and slightly above the listener's position in the audition room (whose reverberation time was about 0.5 second). The direct sound, in addition to reaching the subject's ears directly, was also reflected from nearby surfaces in the audition room to provide several early reflections with various time delays less than 50 ms. On the second channel of the tape was recorded the same monaural sound treated with artificial reverberation, a process involving a special tape recorder, of multiple pickup and rerecord. The reverberant signal did not contain the direct sound or any other sound until approximately 100 ms after the direct sound; then there occurred a realistic, exponentially decaying version of the direct sound of channel no. 1.

The decay rate of the reverberant sound was fixed by the recording on the tape. In each "pickup-rerecord channel" of the artificial reverberation process, the frequency response of the rerecorded signal was sloped to correspond to the differential absorption encountered by the sound at a typical reflecting surface. Thus, the response of the total reverberant signal on channel no. 2 was slightly boosted on the low end and depressed on the high end, as is typical of an actual reverberant field. The reverberated signal was reproduced through a series of six loudspeakers located around the observer's position at different distances throughout the room.

Both the levels and the frequency pass bands of the direct and the reverberant signals were independently adjustable. With both filters set at the flat position, the levels of the reverberant and direct signals could be balanced to yield an aural result at the subject's position that was remarkably like sound in a real hall.

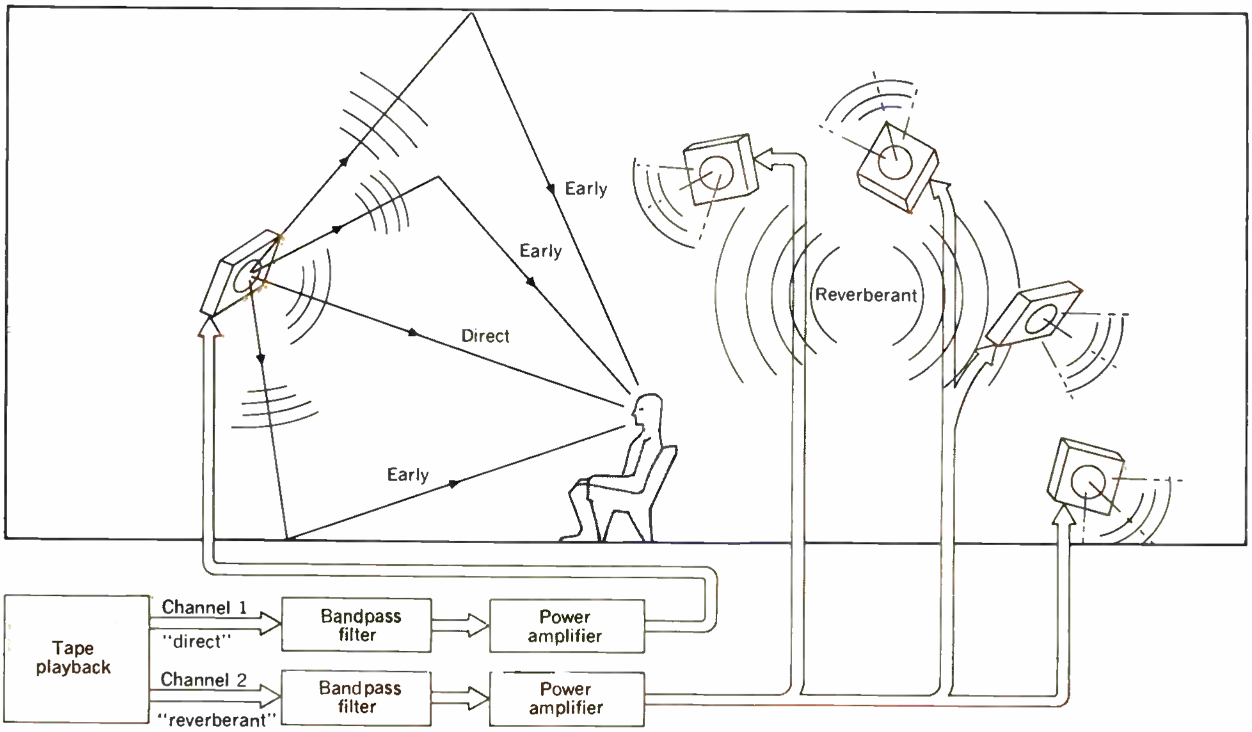
Our first tests used the high-pass filters shown in Fig. 9 to remove low-frequency energy from one channel or the other. Cutoff frequencies of 25 and 250 c/s were available in both the "early" and "reverberant" channels, with 18 dB per octave slope below the pass band. With the high-pass filters adjusted for 25 c/s, essentially the entire audible frequency range was reproduced; switching to the 250-c/s cutoff removed the musical energy below about the middle of the piano keyboard.

Observations concerning early-sound spectrum. With the full-range reverberant and direct energy levels adjusted for pleasing musical balance, the cutoff frequency in channel no. 1 was switched to 250 c/s to eliminate the low-frequency energy in the direct and early sound. Thereupon we usually noted a slight change in the *quality* of the sound, but this change was seldom associated with a difference in spectral balance. Indeed, if we were careful to switch the filter between notes of a musical selection, rather than during a note, even a change in quality was hard to notice!

Paired comparisons. We were very much surprised at the aforementioned results of our own listening, but we wished to obtain more objective results. Accordingly, a test tape was prepared in which 23 paired comparisons were successively presented with various alterations in the spectrum of one or both channels of sound for evaluation by test subjects. For example, the first selection of the pair might be played with normal spectrum in both the direct and reverberant components whereas the second selection of the pair might have all energy below 250 c/s removed from the direct sound. Other alterations involved removing all energy below 250 c/s from the reverberant sound, or removing energy below 250 c/s from the direct sound while weakening the intensity of the reverberant energy by 2 dB (below its usual "balanced" setting, midway in the acceptable range, as later described).

These samples were presented to the test subjects by pairs in a randomly scrambled manner. In each case the subject was asked to indicate whether the second

Fig. 9. Experimental setup for laboratory simulation of concert hall sound.



example of a pair seemed to have "more," "the same," or "less" bass sound than the first.

The subjects' responses confirmed that it is difficult to tell whether or not low-frequency energy is present in the direct sound:

1. When all frequencies below 250 c/s were removed from the direct (and early) sound, the test subjects sensed this as a significant decrease in "bass" only 39 per cent of the time.

Note that, even in a test in which the examples were presented in quick succession for easy comparison, and in which the subjects were warned what to expect, they failed to detect a lack of low-frequency energy in the early signal most of the time! Apparently it is not important that early reflections have a full complement of low-frequency energy; like telephone circuits, the "musical intimacy" and "definition" functions depend chiefly on clear "consonants."

2. On the other hand, when the energy below 250 c/s was removed from the reverberant sound, the test subjects regarded this as a significant decrease in bass 93 per cent of the time.

The perception of "warmth" (or rich bass sound), though apparently independent of the spectrum of the early sound, is lost when the late-arriving reverberant sound is deprived of its low-frequency energy. The ear seems to judge spectral balance in terms of an integration over several hundred milliseconds; it is willing to wait for the reverberant energy before making its evaluation of musical warmth. Thus, the reverberant field can stabilize the overall spectral balance despite low-frequency deficiencies in the early sound.

3. When the reverberant sound was weakened by 2 dB from its initial "balanced" setting and the low frequencies were again removed from the direct and early sound, this was judged 85 per cent of the time to result in significantly less bass. Therefore, if the reverberant sound is expected to compensate for spectral deficiencies in the early sound, it must be present in normal strength. The consequences of "starving" the reverberant field will be discussed below.

Acceptable range for ratio of reverberant to early sound energy. In the second part of our laboratory simulation test, we requested each of the test subjects to make a judgment as to the tolerable range for the balance between reverberant and early sound energies. With the direct (and early) sound set at a comfortable listening level, we asked the test subjects to increase the level of the reverberant signal at will. They were to note the level at which the reverberant sound just became detectable, and then, as the level was continuously increased, the point at which it became obviously excessive.

We found that in fast classical music the average range between "just detectable" and "excessive" liveness was about 10 dB. For slow music, when it was presumably harder to detect the onset of reverberation, the tolerable range was only about 5 dB. These results agree well with the range suggested by the curves shown in Figs. 5 and 7; and they are also consistent with the range found in Thiele's data.

Generalizations. The results of these laboratory simulation tests, taken together with the results found in the actual halls (as previously described), suggest several conjectures concerning concert hall sound:

1. The tolerable range of balance between early and reverberant sound is quite limited; a remarkable change in perceived acoustical quality accompanies a relatively small change in this critical energy balance.

2. When the early and reverberant components are balanced, it is difficult to determine whether or not low frequencies are missing from the "early" signal. Reverberant sound in proper relation to the early sound has the ability to stabilize the perceived spectral balance of sound in a hall, irrespective of low-frequency deficiency in the earlier components of the received signal.

3. Since the early sound does not appear to require low-frequency energy, the early reflections needed for intimacy in a large hall can be returned from relatively small surfaces; larger reflecting panels not only do not add any significant quality to the early sound, but there is the danger that they may upset the critical energy balance by weakening the reverberant component.

Comparison with other listening experiences

It is instructive to test these conclusions against less formal listening experiences (see also Appendix II).

Indoor vs. outdoor sound. Consider first the difference in spectral balance between sound heard out-of-doors and in a concert hall. The sound in a good concert hall is characterized by low frequencies that are emphasized in relation to the high frequencies. Where this bass emphasis occurs it must be attributed to the reverberant component of the sound field rather than to any individual reflection; the reverberant field is made up of sound which has been reflected many times from surfaces that absorb sound differentially, removing more high-frequency than low-frequency energy. It is then not surprising that this reverberant component is closely connected with the perception of satisfying bass sound in a hall.

By contrast, in outdoor concerts (the Esplanade Concerts of the Boston Pops Orchestra and the summer concerts at the Hollywood Bowl, for example) one notices a weakness in the low frequencies whether or not auxiliary amplification has been used.[20]

Also, in a marching band, which nearly always plays outdoors, the lower voices (tubas, sousaphones, trombones doubled with themselves and frequently with euphoniums) are traditionally much more powerful than their indoor orchestral counterparts (cellos, double basses, trombones alone), which are assisted by the low-frequency emphasis provided by a good hall.

Seat attenuation. An important example of the stabilizing role played by the reverberant sound field commonly occurs in connection with a phenomenon recently reported by Schultz and Watters[15] and confirmed by Sessler and West.[21] On the main floor of a concert hall, or indeed in any circumstance where the sound passes at near-grazing incidence over a seated audience, a serious deficiency occurs in the low-frequency sound between 100 and 500 c/s due to the seating arrangement; the maximum attenuation is typically as much as 15 to 20 dB. This deficiency occurs both in the direct sound and in all signals that travel at near-grazing incidence over the audience; consequently, all of the early sound is affected, unless the hall has a very low ceiling. Nevertheless, in many high-ceiling, rectangular halls rich bass sound is heard throughout the main floor. Since this rich bass cannot be attributed to the low-frequency content of the direct or early sound, we believe this to be independent confirmation of our experimental results concerning the role of reverberant sound. (These findings appear to be in conflict with some results deduced from preliminary computer simulation studies by Schroeder, Atal, Sessler, and West.[22] Their results imply that the early sound is more influential than the reverberant sound in determining the spectral balance of music. We believe that their results would have been the same as ours if, in their computer simulation of the reverberant energy, the low frequencies had been emphasized as in the reverberant sound field in typical concert halls.)

Halls with strongly sloped ceilings. The conjectures enumerated in the previous section entitled "Generalizations" help to explain the acoustical difficulties frequently encountered in halls with ceilings that slope steeply downward toward the stage. Although such halls are consistently praised for speech activities, they have often been criticized for large-scale musical performances as being too brilliant and lacking liveness and warmth. Reflections from a steeply sloping ceiling are immediately "grounded" in the audience, where they are perceived as early sound and quickly absorbed, instead of being reflected or diffused into the reverberant field; thus the ratio of reverberant to early sound is low in comparison with the situation in the classical, rectangular concert hall.

It has been shown[10] that early reflections within 10–25 ms of the direct sound are important for clarity and intimacy in a hall, but it is perhaps even more important that the early energy not be excessive for then the reverberant field may be "starved." The argument[14] that one should provide large reflecting surfaces near the sound source to reflect a flat spectrum of early sound to the listener has missed the point, for what is needed in a hall is not a flat spectrum but *emphasized* bass, and this can come only from the reverberant sound field. If the reverberant sound field is deprived of its proper share of the available orchestral energy by the presence of large (or numerous) reflectors which surround the source and reflect large amounts of early energy into the absorbent audience, the reverberant field will fail to develop normally and the hall will lack warmth.

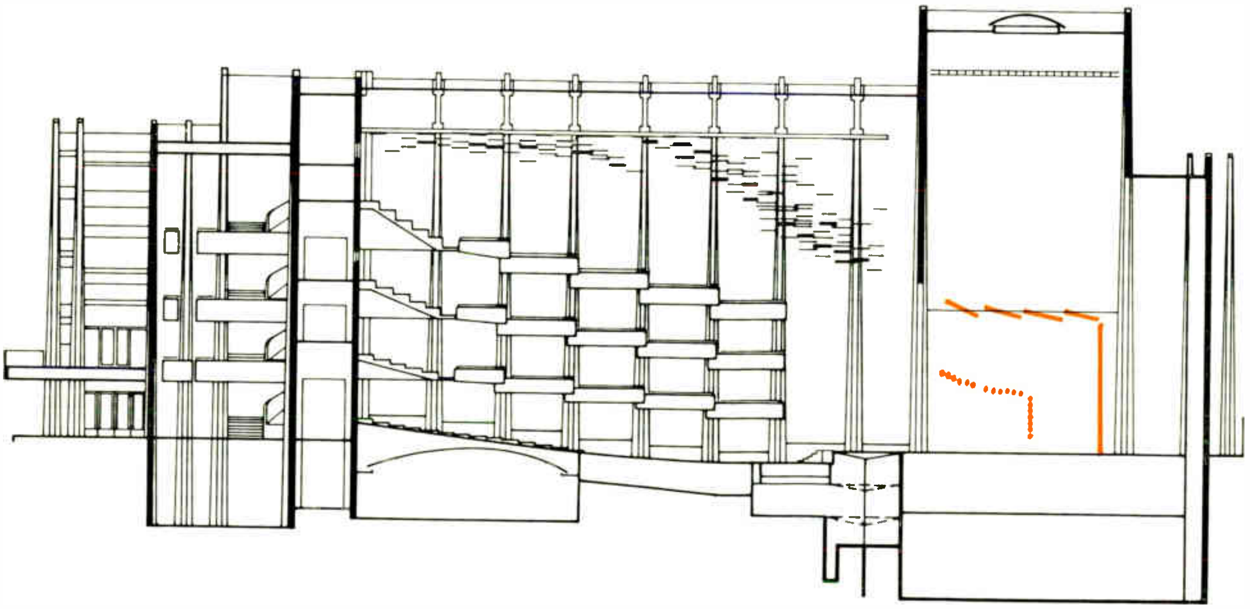
Boundary between direct and reverberant sound. The author recently enjoyed an experience that illustrates the low-frequency potency of the reverberant sound field. He was being guided, with a group of German tourists, through the castle of Ludwig II at Neuschwanstein. On the top floor there is a hall designed for the private performances of opera for the king. The hall is about 35 feet high, 35 feet wide, and 65 feet long, and is virtually empty of furniture but is well decorated with diffusing surfaces.

It developed in the course of the visit that the other tourists were members of a male chorus and their wives. When the guide invited them to try the acoustics of the famous hall, they obliged by singing several selections from a position at one end of the hall near the stage. While they were performing, one could wander freely throughout the hall because there were no seats.

As one moved from the far end of the room and came close to the singers, the bass voices suddenly became weaker. In walking back and forth across a 5-foot-wide boundary, roughly halfway down the room, one could hear the bass voices full and strong if one were behind this boundary in the reverberant field, but hardly at all if one moved closer to the singers into the area where the direct and early sound predominated!

Variable acoustics in Clowes Hall. A further relevant observation was made during the initial acoustical adjustments of Clowes Hall in Indianapolis. The reflecting surfaces of the orchestra enclosure in that hall are motorized for rapid adjustability. The settings of these surfaces as finally chosen for orchestral use (see solid lines in Fig. 10) are appropriate to robust, romantic music: the hall sound is quite live and there is a decided

Fig. 10. Longitudinal section of Clowes Hall, Indianapolis, showing two arrangements of the concert enclosure on stage. The larger enclosure at right (solid lines, in color) is for full orchestra; the smaller area, shown dotted, is for chamber music.



reverberant "tail" to final chords. In a matter of minutes, however, the overhead stage reflectors and the proscenium curtains can be readjusted for chamber music (see dotted lines in Fig. 10) so as to direct more energy toward the audience and less into the upper (reverberant) part of the hall. We have not measured the magnitude of this change but, because of the comparatively limited area of the reflectors, the difference cannot be more than a very few decibels. Nevertheless, the chamber-music adjustment gives this large (2100-seat) hall a small-room sound that is suitable, say, for string quartets. The "big" reverberant quality is suppressed on the main floor and in all except the highest balcony, both in running music and after terminal chords.

Applications to future design of halls

For future design in auditorium acoustics, the previous discussion suggests several interesting possibilities. We believe that it is essential that early sound reflections in a concert hall be present to provide intimacy in musical sound; but we have learned that the early reflections must not be very strong lest their overemphasis lead to an over-brilliant sound. If overhead panels are used to provide early sound reflections, they *need not* be large, because we do not require low frequencies for adequate intelligibility in the early sound; in fact, they *must not* be large (or too dense) or they will "starve" the reverberant sound field, upon which the fullness of tone and warmth of sound appear to depend.

Removing the requirement for large size from the overhead panels permits the acoustical consultant greater flexibility in accommodating the acoustical requirements of the hall to the concept and vision of the architect.

An even more interesting corollary that is currently being explored is the use of overhead panel arrays with variable acoustical transparency. Such panels provide a relatively easy means of achieving large halls with acoustics that are widely and quickly variable to accommodate a range of events from large orchestral forces to small chamber groups, or even speakers without sound reinforcement.

This approach is an advance over the customary method of exposing more or less absorptive material to the auditorium in order to change the reverberation time: first, because the variable-absorption scheme has the disadvantage of being highly frequency-selective, the least change usually occurring at low frequencies where perhaps the greatest change is desired in the reverberant field; second, because each increment of reflecting area added to an overhead panel array both increases the amount of early sound and decreases the strength of the reverberant field, and thus each reflecting element in the ceiling array exercises "double leverage" on the desired change in the acoustics of the hall. (It is assumed that there is a substantial reverberant volume above the ceiling panel array; this volume is excited and communicates with the audience area to a greater or lesser degree as the transparency of the array is changed. Not the *rate of decay* but the *amount of energy* involved in the reverberation process is varied.)

Conclusion

The suggestions presented in this article are not conclusive and it may be a long time before their implications are thoroughly worked out. We do not question the results of the experiments reported here, but the extension of these results to concert hall listening in general can be supported at present only by the agreement between these results and our own extensive listening experience.

In particular, we would like to pursue further the questions raised here with more extensive pulse measurements and the opportunity of careful listening in halls whose acoustical characteristics are a matter of record. Even better, one could wish for ready control of the various acoustical parameters in a hall by means of simulation techniques (perhaps utilizing a computer), plus sufficient time and money to make statistical correlations between subjective judgments and the objectively determined aspects of the sound. In this way it would be possible to test the applicability of the energy-balance concept in a range beyond the limitations presently imposed by the configurations of halls which happen to exist, and to relate this parameter to all the other probably important parameters that have barely been touched on here: the optimum initial time delay (rather than a rough maximum); the desirable fine-scale time structure of early reflection arrival; the role of frequency irregularity associated with "early" paths (this is related to diffusion; how much and what kind is desirable); the direction of arrival of the various components of the early sound.

Whatever changes are ultimately required in the form of the critical energy parameter, it is not likely that the tentative conclusions (under the headings of "Generalizations" and "Applications to future design of halls") will be greatly altered.

One may conclude from the restricted range of tolerable balance between reverberant and early sound that the design problem in a large concert hall is a matter of aiming at a very small target in a very large ocean. It is not a matter for embarassment that our recent research shows the problem to be considerably more difficult than was previously appreciated. It simply warns that in the design of future large halls, provisions for adjusting the reverberant to early energy ratio must be a matter of course until acoustical science achieves considerably greater refinement in its prediction procedures. We should no more expect to be able to hit this particular acoustical goal "on the nose" in designing a concert hall than we would expect to drive a car off the assembly line without allowing for an engine tune-up.

Indeed (and this is distressing to contemplate!), the very narrowness of the tolerable range of the reverberant to early energy ratio suggests that a number of halls in the world may have just missed the mark: they are now perhaps mediocre when, with a change of 1 to 2 dB in this critical energy ratio, they could either become superb—or intolerable. It is our hope that further development of the concepts suggested here will make possible the improvement of existing halls and a "best adjustment" of new halls.

Appendix I

Simulation of sound in Philharmonic Hall. It has been shown[11,13,14,17,18] that the specular reflection from an overhead panel array, such as is sometimes used to provide early reflections in concert halls, may be weak in low-frequency energy. Such a situation is believed to have occurred in Philharmonic Hall in New York City. In December 1962, in order to remedy this low-frequency deficiency, our firm recommended modifications of the ceiling array. (These modifications were consistent with the results reported in references just cited and entailed increasing the effective panel size and removing most of the steps from the surface of the array.)

To test the effectiveness of our recommendations, we set up an experiment in Philharmonic Hall which simulated the sound field perceived by a main-floor listener in terms of three components: (1) direct sound; (2) the reflection from the ceiling panel array; and (3) the reverberant sound. It was our intention to show, by electrically altering the spectrum of the "panel" sound component, the audible effect of spectral changes in the reflection from the panel array.

The experimental setup is shown in Fig. 11. Recorded music was played alternately through two channels. Channel A consisted of a single high-quality loudspeaker, placed in the open on the left-hand side of the stage. Sound from this loudspeaker would excite the acoustics of the hall as would any live source on the stage: it would radiate directly to the listener; it would reflect from the overhead panel array as well as from the vertical side walls; and it would develop the natural reverberation of the hall.

In channel B, three separate loudspeakers were used to simulate independently the three sound components described above:

For the "direct" component, a loudspeaker was positioned on the right side of the stage. It was roofed over with a large shield of plywood faced on the underside with a heavy glass fiber blanket; the stage in front of the loudspeaker was also covered with a glass fiber blanket to minimize reflections into the upper space. Sound from this loudspeaker radiated directly to the observer on the main floor and could also reflect sound to him from the vertical side walls of the hall.

The second loudspeaker was mounted just beneath the ceiling panel array, at the point from which stage sound would have to reflect specularly to reach the observation position in the audience. Since the direct loudspeaker on the stage did not irradiate the ceiling panels, this second loudspeaker could independently simulate the ceiling reflection. The electric signal for this "panel" loudspeaker was delayed 35 ms with respect to the direct loudspeaker, corresponding to the time required for sound to travel from the stage to the panel loudspeaker. Both the level and the frequency response of the panel signal were adjustable.

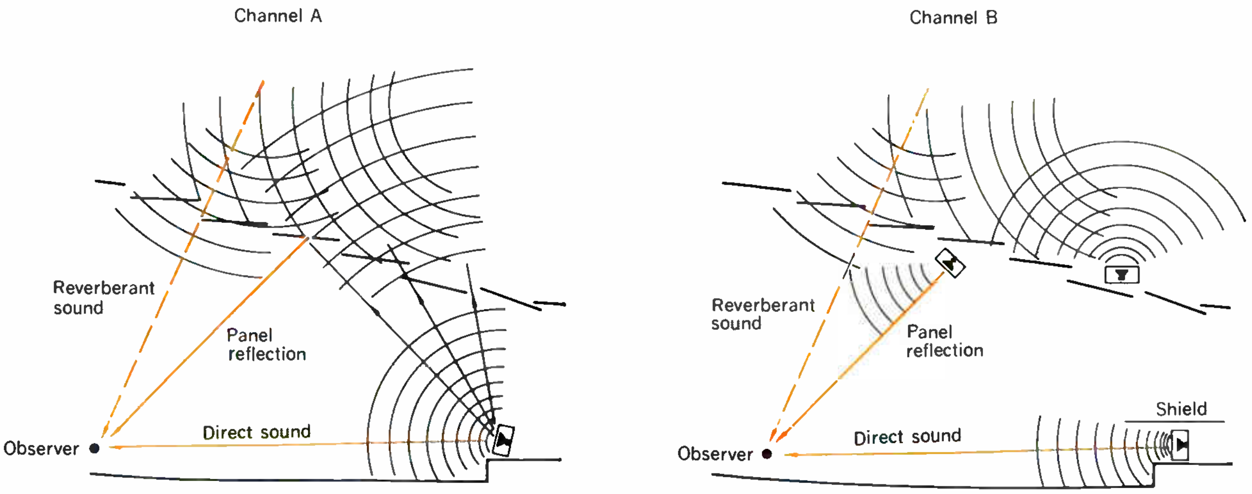
The third loudspeaker, whose electric signal was also delayed 35 ms but whose frequency response remained flat, was located above the panel array and was directed upward, so as to excite only the reverberant hall sound.

Preliminary checks, with each of the three loudspeakers individually excited, indicated that the three components of sound could be independently controlled. The direct loudspeaker excited very little reverberation by reason of its shield. The same was true of the panel loudspeaker because of its directivity, for it was aimed down into the absorptive audience area. The reverberation loudspeaker, on the other hand, primarily excited the reverberant field; its position was difficult to locate by ear.

A necessary preliminary test was to see whether the levels and frequency responses of the three sound components of channel B could be so adjusted as to duplicate the sound of the hall as excited by channel A. If this could be done, it would validate our simulation experiment.

The music to be played in this experiment was recorded in a "dead" room having virtually no acoustical properties of its own; any room sound from the recording studio would obviously confuse the judgment. (This was clearly demonstrated later when we tried to use ordinary disk recordings having normal hall reverberation; under these circumstances channel A and channel B tended to sound alike over a very wide range of control adjustments.) The "dead" music was presented alternately through channel A and channel B. The spectrum of the panel loudspeaker in channel B was initally shaped to give a deficiency at low frequencies similar to that of the panel reflection sound in the hall (Fig. 12).[23] It was then found possible, by level adjustments in the three components of channel B, to produce a sound virtually the same as channel A, thus establishing a "recipe" for the sound

Fig. 11. Experimental setup for three-component simulation of sound in Philharmonic Hall, New York. Signals in upper loudspeakers are delayed 35 ms with respect to "direct" loudspeakers.



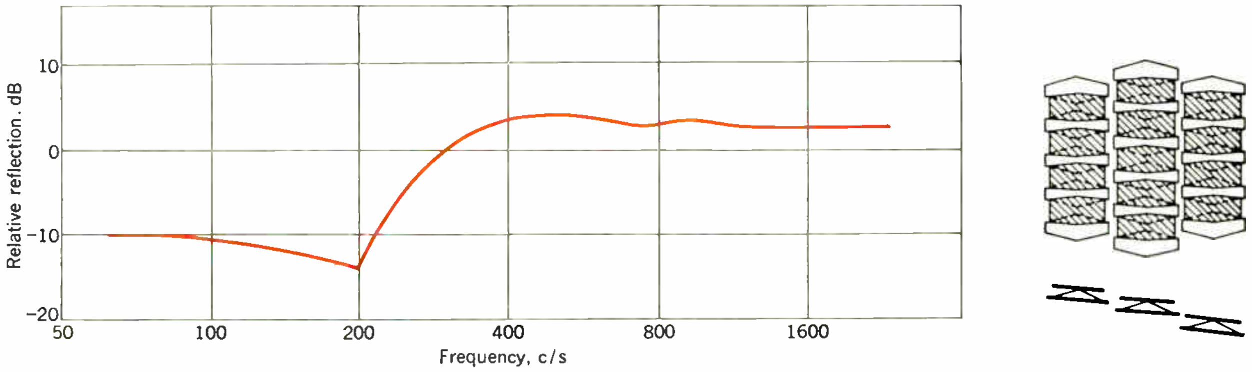
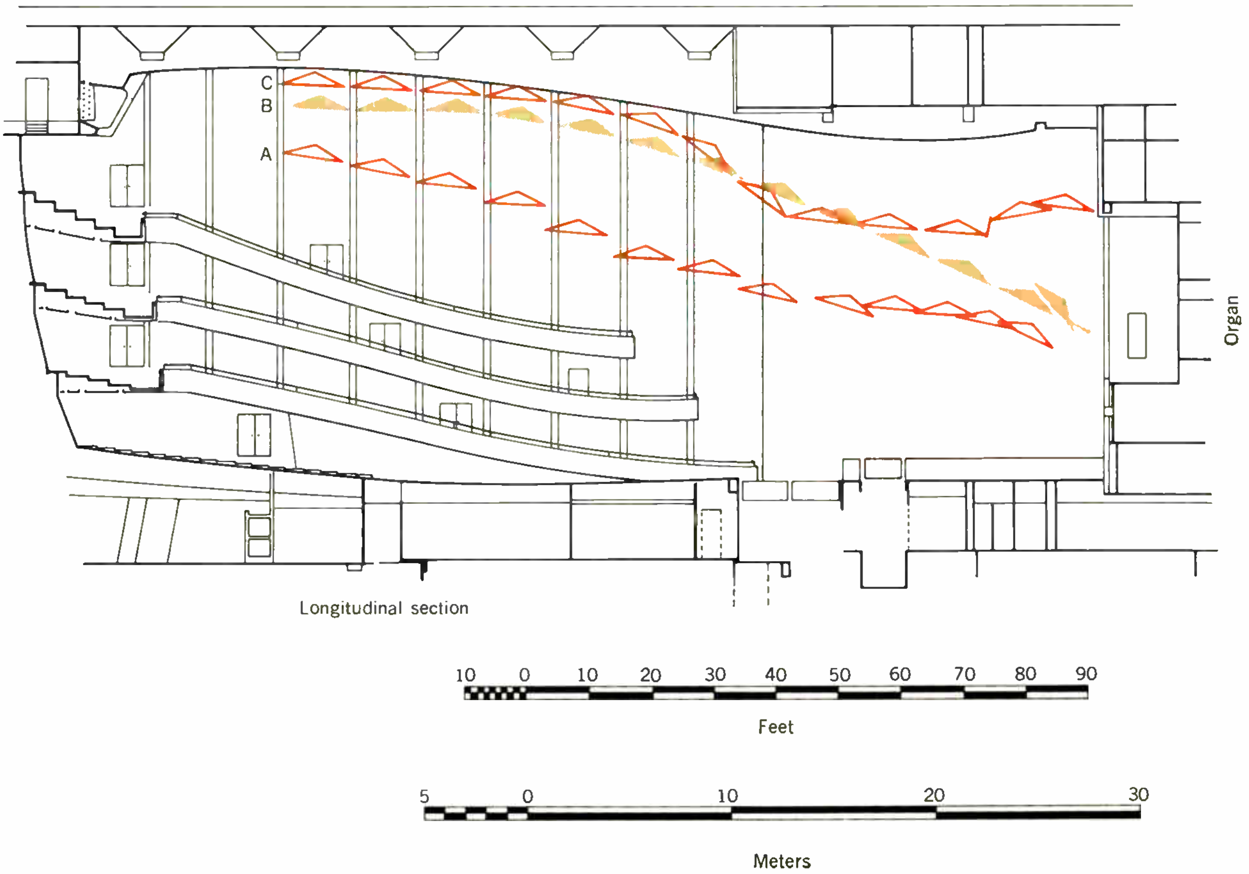


Fig. 12. Deficiency in low-frequency reflectance found in the panel array in Philharmonic Hall, December 1962.

Fig. 13. Longitudinal section of Philharmonic Hall, New York City, showing three configurations (A, B, and C) for the overhead array of reflecting panels as they existed at the opening of the 1962, 1963, and 1964 seasons, respectively.



at the observer's seat position in the hall. The recipes independently determined by four observers agreed within 1 dB of each other, which justified a subjective evaluation in our proposed test of changes in the panel array.

The crucial part of the experiment was the next step: restoring to the panel signal the low-frequency energy which we had removed to simulate the known reflectance of the ceiling array. To our surprise, when we did this, practically no difference was noticeable! Pursuing this unexpected result to an extreme, we inserted a high-pass filter to eliminate from the panel signal all energy below 250 c/s (about the middle of the piano keyboard). Again, with one person switching the filter back and forth between the two conditions, it was difficult for the others to decide whether or not the low-frequency energy was present in the "panel signal." Evidently the "missing bass" problem in Philharmonic Hall was not due to the low-frequency deficiency of the ceiling panel reflection.

In the final part of the experiment, the intensities of the panel signal and the reverberant signal were freely varied by the listener. Surprisingly, the range between barely detectable reverberant energy and obviously excessive reverberant energy was only about 6 dB! With comparatively slight level changes in the "reverberant" sound component of channel B, one could make Philharmonic Hall sound either very dry, quite satisfactory, or very reverberant.

Appendix II

Philharmonic Hall acoustics. Philharmonic Hall in New York offers an unusually good illustration of the views expressed here, for it has had several distinctly different "sounds" without corresponding major changes in the interior configuration. In addition to the three arrangements of overhead panels designated A, B, and C in Fig. 13, corresponding to the conditions of the hall during its first three winter seasons, there was an earlier version at the end of "tuning week" (June 2, 1962) and two summer versions. In no case were appreciable modifications made to the basic shape of the room; the reverberation time remained substantially the same, and the only significant acoustical changes have been in the initial-time-delay gap,[10] the ratio of reverberant to early energy (E_R/E_E), and, to some extent, the diffusion. (Bolt Beranek and Newman, Inc., are not responsible for any of the changes since the official opening in September 1962.)

The sound at the end of tuning week was generally agreed, by the musicians and critics who heard it, to be satisfactory.[8-9] The finishing touches added before the hall opened,[7,24] Fig. 13(A), affected primarily the ratio of reverberant to early sound. Although this ratio was decreased only slightly (see Fig. 7) the hall was judged after opening to be excessively dry though the reverberation time was more than 2 seconds.

The changes of the second year, as shown in Fig. 13(B), entailed closure of most of the spaces between the ceiling panels and raising the panel array, thus increasing the initial-time-delay gap and reducing the excessive clarity. The new *contour* of the panel array decreased the energy in the early sound on the main floor and further reduced the clarity there almost to the point of muddiness in rapid passages. It also focused strong early reflections into the rear of the hall, producing an exciting but unusual sound. Closing the spaces between panels further decreased the ratio E_R/E_E and may explain the decreased subjective liveness of sound. Raising the panel array also exposed the rear corners of the hall and strengthened an echo from this region.

As shown in Fig. 13(C), before the third season the ceiling array was raised still higher, which, together with the closure of the organ opening behind the stage, probably increased the ratio E_R/E_E a bit; this may account for the somewhat greater warmth of sound. It did not decrease the initial time delay significantly below its value for the "B" version of the hall. The sound on the main floor now is considerably less clear; under the balcony overhang on the main floor and in the upper parts of the hall the definition is satisfactory.

Since the opening of the hall the only times when the sound seemed to improve significantly were during the summer seasons, when the upholstered main-floor seating is replaced by hard tables and chairs for the serving of refreshments. This change removed a considerable amount of absorption from the hall and thus strengthened the reverberant energy; also, the added stage decorations may have decreased the early sound energy. Each summer, the hall has received favorable comments; the most noticeable change in the acoustics is the increase in warmth.

It is our hope that eventually the ceiling array can be lowered to favor intimacy once more, and that it can be considerably opened to increase the ratio E_R/E_E and to restore the warmth that we recall in Philharmonic Hall at the end of tuning week.

REFERENCES

1. Furduev, V. V., "A Method of Acoustical Design of Rooms Equipped with Loud Speakers," *Dokl. Akad. Nauk. SSSR*, no. 15, 1937, pp. 313–316.

2. Maxfield, J. P., and Albersheim, W. J., "An Acoustic Constant of Enclosed Spaces Correlatable with Their Apparent Liveness," *J. Acoust. Soc. Am.*, vol. 19, 1947, pp. 71–79.

3. Sukharovskii, Iu. M., "The Effect of Acoustic Conditions in a Room upon Intelligibility of Reproduction," (from dissertation for Moscow Power Institute, Moscow, U.S.S.R., 1940).

4. Golikov, E. E., "The Problem of New Coefficients for Evaluating the Quality of Room Acoustics," *Sov. Phys.-Acoust.*, vol. 2, 1956, pp. 267–279.

5. Thiele, R., *Acustica*, vol. 3, 1953, pp. 291–302.

6. Beranek, L. L., *Music, Architecture & Acoustics*. New York: John Wiley & Sons, Inc., 1962, p. 23 and Fig. 3.1.

7. Beranek, L. L., *et al.*, "Acoustics of Philharmonic Hall, New York, During Its First Season," *J. Acoust. Soc. Am.*, vol. 36, 1964, pp. 1247–1262.

8. *Ibid.*, p. 1254.

9. "Final Verdict: O.K. for Sound," *Time*, June 15, 1962, p. 57; also *Architectural Forum*, July 1962, p. 11.

10. Beranek, L. L., *Music, Architecture & Acoustics. Op. cit.*, chap. 9.

11. Shankland, R. S., "Acoustics of the New Philharmonic Hall," *J. Acoust. Soc. Am.*, vol. 35, 1963, p. 725.

12. Beranek, L. L., "Reply to Shankland's Letter," *Ibid.*, p. 726.

13. Watters, B. G., *et al.*, "Reflectivity of Panel Arrays in Concert Hall," *Sound*, vol. 2, May–June 1963, p. 26.

14. Meyer, E. W., and Kutruff, H., "Reflexions Eigenschaften durchbrockener Decken (Modelluntersucken) an der Reflecktor-anordnung der neuen Philharmonic Hall in New York," *Acustica*, vol. 13, 1963, p. 183–186.

15. Schultz, T. J., and Watters, B. G., "Propagation of Sound Across Audience Seating," *J. Acoust. Soc. Am.*, vol. 36, May 1964, pp. 885–896.

16. Schultz, T. J., and Watters, B. G., "Perception of Music Heard Via Interfering Paths," *Ibid.*, pp. 897–902.

17. Leonard, R. W., Delsasso, L. P., and Knudson, V. O., "Diffraction of Sound by an Array of Rectangular Reflective Panels," *Ibid.*, Dec. 1964, pp. 2328–2333.

18. Veneklasen, P. S., "Acoustical Behavior of Segmented Ceilings (Abstract)," *Ibid.*, May 1964, p. 1010.

19. Sessler, G. M., *et al.*, "Acoustical Measurements in Philharmonic Hall, New York (Abstract)," *Ibid.*, pp. 1011.

20. Steinberg, M., "Music Review," *Boston Globe*, June 30, 1964.

21. Sessler, G. M., and West, J. E., "Sound Transmission Over Theatre Seats," *J. Acoust. Soc. Am.*, vol. 36, May 1964, p. 1725.

22. Schroeder, M. R., *et al.*, "Acoustical Measurements in Philharmonic Hall, New York: Application of Digital Computer Techniques to the Evaluation of the Acoustics of Concert Hall," paper presented at the 3rd Acoustical Conference, Budapest, Hungary, May 1964.

23. Watters, B. G., *et al.*, "Reflectivity of Panel Arrays in Concert Hall," *op. cit.*, Fig. 12.

24. Beranek, L. L., *Music, Architecture & Acoustics. Op. cit.*, pp. 539–540.

This article is an expanded version of a paper presented at NEREM, Boston, Mass., Nov. 4-6, 1964.

We would like to acknowledge our indebtedness to H. Vose Greenough, Cambridge, Mass.; John McClure of the Columbia Recording Company, New York City; and John Kellner of the Aeolian-Skinner Organ Company, Boston, Mass., for making available to us tape recordings of music that had been made in an acoustically "dead" environment. We also wish to thank Mr. Kellner for processing the magnetic tapes that provide dead direct sound on one channel and the reverberant decay on the other channel. Without these rare types of recorded material our simulation tests would not have been possible.

Our thanks are also extended to John Miller, then a student at the Massachusetts Institute of Technology, who conducted and collected the statistics for the laboratory simulation tests.

Performance of interconnected systems following disturbances

Power system behavior immediately following loss of generation is discussed on the basis of the most important system parameters and their effects on overall performance

C. Concordia *General Electric Company*

The concept of electric power system reserve is very well established. It is usually required that in each area there be sufficient spare generating capacity available to supply any reasonably probable loss of generation. However, this provision is ordinarily interpreted as allowing a certain amount of time, of the order of minutes (or sometimes even longer), and requiring a certain amount of dispatching action to cause the reserve generators actually to pick up the load. Thus, even though reserve requirements are sometimes calculated on the basis of keeping the "probability of loss of load" below a specified limit, the question of whether or not the system can survive the first few seconds of emergency operation, so that it will still be in a position to take advantage of its reserve when it becomes available, must be answered by another sort of calculation—namely, a consideration of the dynamical performance of the system immediately following the disturbance.

In order to illustrate the behavior of systems during this critical time and to show which system parameters are the most important in determining their behavior we shall consider various simple examples. We shall discuss principally what happens after a generator has already been lost, for whatever reason. This is the next step, beyond the study of generator stability, in the determination of service reliability.

Frequency drop

As our first example of what happens to system frequency let us consider the case of a power system consisting of ten identical generating units, each loaded to 90 per cent of capacity. If a generator is lost, each of the remaining generators will attempt to pick up 1/9 of the power that was being supplied by the lost generator, or 10 per cent of its own rating. However, the signal to pick up this power will normally come only from a drop in system frequency acting on the turbine speed governors. If the governor regulation, or droop, of each turbine is 5 per cent, then ideally 0.5 per cent (or 0.3 c/s) drop in speed or frequency would occur for each generator to pick up 10 per cent load. But this drop in frequency will result in some reduction in electric load, so that it will not be necessary for each generator to pick up quite 10 per cent load. Figure 1 illustrates the performance in a simple graphical way. The final equilibrium speed is at the intersection of the curves of excess load and of generator pickup versus drop in frequency. If we assume that the load will decrease by 1 per cent for each 1 per cent drop in frequency, it is seen that the actual final frequency drop is somewhat less than 0.5 per cent, being only about 0.475 per cent because of the approximately 0.5 per cent decrease in system load. Thus each remaining generator has to pick up only about 9.5 per cent load. (There may be a further reduction in load if the loss of a generator causes a decrease in load bus voltage, which could result in an even smaller frequency drop. However, we shall not consider the effect of voltage for the present, except to remark that the change in voltage will depend upon how much reactive power the lost generator had been supplying and that the voltage will be restored within a few seconds if it is within the capacities of the remaining generators to do so.)

Let us next consider what would happen in the same system of ten equal generators for a different initial loading pattern. Suppose nine of the generators had been fully loaded, with the remaining one at no load. Then loss of one of the loaded generators would cause a considerably greater drop in frequency, as now all of the generation deficiency will have to be supplied by only one generator, which would have to drop 5 per cent in speed to pick up full load, quite aside from any boiler or turbine load pickup limitations. Now the beneficial effect of the reduction of electric load is much greater, as indicated in Fig. 2. (Note that the excess load is shown in both Figs. 1 and 2 in per cent of the rating of one generator, so the reduction of 5 per cent of total electric load for a 5 per cent drop in frequency is 9 times 5 or 45 per cent of the rating of one generator.) The equilibrium frequency drop is seen to be about 3.45 per cent or 2.1 c/s, which is more than seven times as great as for the first case. We note further that in the first case the system might be said to behave as if it had an effective speed regulation of $0.475/10 = 4.75$ per cent, whereas in the second case it behaved as if it had a regulation of $3.45/11 = 31$ per cent. This demonstrates our first point, which is the importance of having a good percentage of the generating capacity on active speed governor control. (Note that, as a minor point, in the first case, since all machines were only 90 per cent loaded, only 10 per cent of the *remaining* capacity was lost, whereas in the second case, since the lost generator was fully loaded, one ninth or 11 per cent of the remaining capacity was lost.)

Experience has often indicated an effective system speed regulation lying somewhere between these limits, namely about 16 per cent. This corresponds to the bias setting of 1 per cent (a 1 per cent power change for a 0.1-c/s frequency change is equivalent to a 100 per cent power change for a 10-c/s or 16.6 per cent frequency change) commonly used in system tie-line power-frequency control. The limited number of machines with active governors is only one of the factors that cause the effective regulation to be so much greater than the nominal 5 per cent value. Other important factors are the dead band and, in multivalve steam turbines, the rather wide variation in incremental regulation caused by the nonlinear relation of steam flow to valve motion.

The variation of load with frequency is seen to result in a reduction of the effective regulation. The increase in input caused by the speed governors is aided by the decrease in output caused by the load-frequency characteristic. In the first case considered the speed governor regulation of 5 per cent can be paralleled with an equivalent load regulation of 100 per cent, giving a resultant regulation of 4.75 per cent. In the second case the

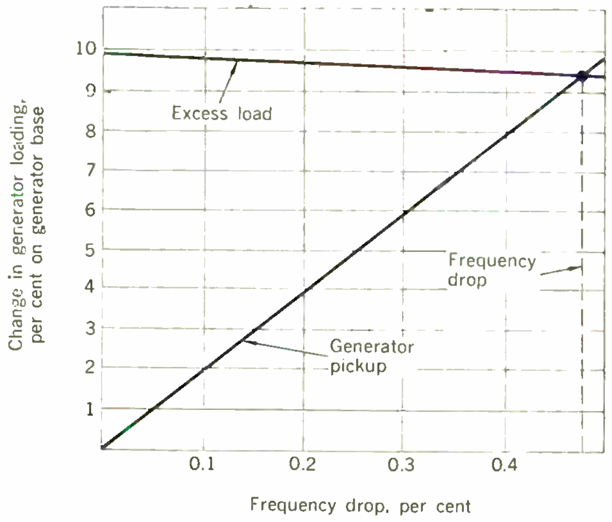


Fig. 1. Frequency drop on loss of generation equal to the reserve capacity, with all of the generators in the system equally loaded.

Fig. 2. Frequency drop on loss of generation equal to the reserve capacity, with 90 per cent of the system's capacity fully loaded.

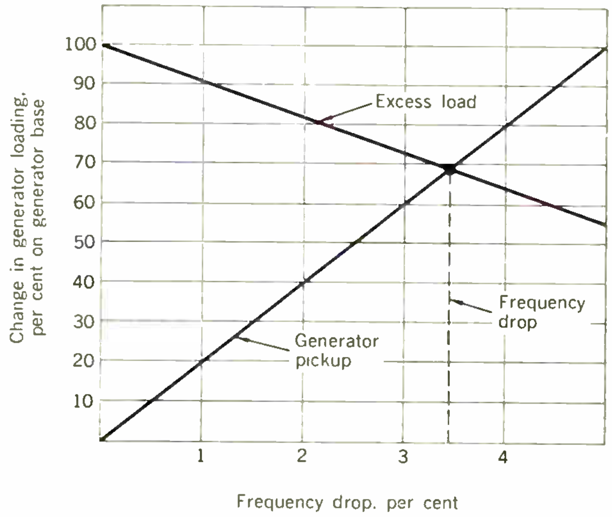
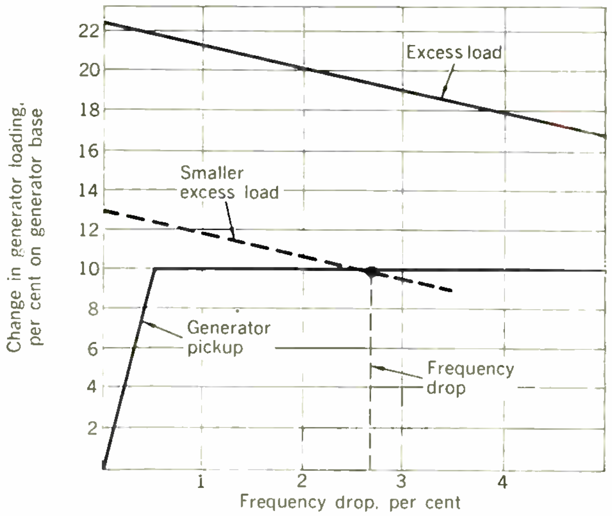


Fig. 3. Frequency drop on loss of generation that is in excess of the reserve capacity.



effective system speed governor regulation of 45 per cent (since only one ninth of the machines are active) is paralleled with the load regulation of 100 per cent, giving a resultant regulation of 31 per cent.

We next consider the effect of losing more generation than the available reserve. Suppose, for example, that in the first case of equal generator loading two generators had been lost, so that only 80 per cent of the original capacity remained to supply the 90 per cent (of the original capacity) load. The initial excess load on each generator is the difference between one eighth of the total load of 900 per cent, which equals 112.5 per cent, and the initial load of 90 per cent, or 22.5 per cent. But each remaining generator can still only pick up 10 per cent of its rating. Figure 3 illustrates that although theoretically there may be an intersection of the excess load and generator pickup curves, as a practical matter we have an intolerable condition and so might have to shed some of the load. However, let us suppose a smaller amount of generation had been lost, so that the initial excess load had not been 22 per cent (or 12 per cent more than the generator capacity) but only 13 per cent (or only 3 per cent more than the generator capacity). Then the dashed line of Fig. 3 shows that the frequency drop would have been less than 3 per cent or no worse than the case of Fig. 2. It is evident that if 3 per cent frequency drop is allowable in an emergency we can, in this particular case, tolerate the loss of about 3 per cent more load than the actual excess spinning capacity. The numbers we have chosen may not be very reasonable, but I wished to illustrate our second point—that there is, or can be, a relation between the required spinning reserve and the mode of operation. For example, if only 0.5 per cent frequency drop had been permissible it would have been necessary to operate as in the case of Fig. 1, even though this might not be the most economical allocation of generation. The alternative would be to increase the excess spinning capacity to an amount many times the amount of the lost generation. In this extreme case it would be out of the question to operate with most of the generators fully loaded as in the case of Fig. 2.

Speed governor response

So far I have said nothing about the type of prime mover or speed governing system, and indeed have neglected entirely the dynamics of the system. As the simplest case let us assume first that all prime movers are nonreheat steam turbines and still neglect the oscillations among the generators. In this case the actual drop in frequency may be as indicated in Fig. 4, which shows the course of the system frequency vs. time curves for the two extreme cases of machine loading illustrated in Figs. 1 and 2, and also for the more usual intermediate case in which the effective system regulation is 16 per cent. We note two interesting features of these curves: first, the minimum frequency is reached only after an appreciable time, which increases as the regulation increases; second, the amount of overshoot decreases as the regulation increases, there being about 60 per cent overshoot for the case of 5 per cent regulation and no overshoot for the case of 31 per cent regulation.

A first consequence is that the actual minimum frequency reached is by no means proportional to the system speed regulation. A second consequence relates to the effect of reheat. At first thought, if we substitute

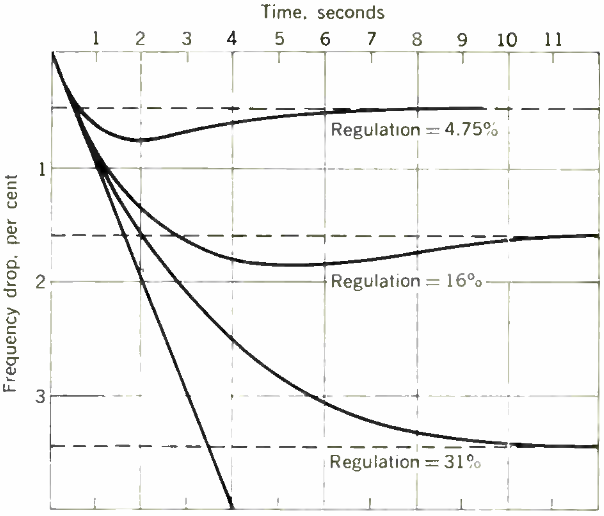


Fig. 4. Frequency drop on loss of 10 per cent of generation, with nonreheat steam turbines as prime movers.

Fig. 5. Frequency drop on loss of 10 per cent of generation, with reheat steam turbines as prime movers.

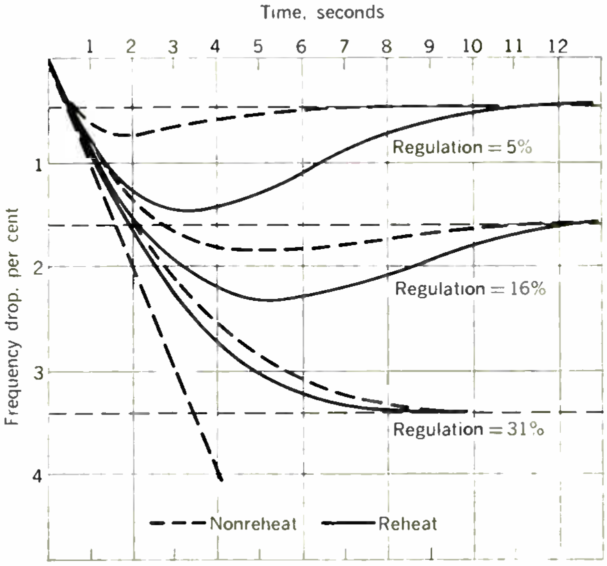
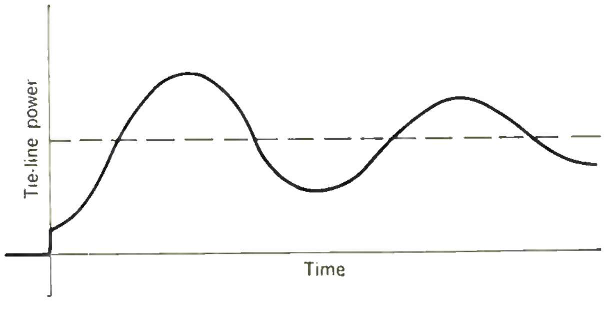


Fig. 6. Typical curve of tie-line power swing vs. time following loss of generation.



ten reheat steam turbines for the ten nonreheat turbines of Fig. 4 we might suppose that the frequency drop would be three or four times as great, since only the portion of the turbine upstream from the reheater responds quickly to control-valve motion. However, as shown in Fig. 5, this is not at all the case. It is quite true that the introduction of reheat limits the initial response of the turbine to the high-pressure portion upstream from the reheater and thus directly responsive to control-valve motion. But since even for the nonreheat case of Fig. 4 the minimum frequency is not reached until about 1.5, 5, and more than 10 seconds, respectively, for the cases of 5, 16, and 31 per cent regulation, and since the reheater time constant is usually less than 10 seconds, an appreciable part of the portion of the turbine downstream from the reheater is effective in limiting the maximum dip. The net result is that, although when all governors are active (5 per cent regulation) the presence of reheat just about doubles the maximum frequency drop, for the more typical case of 16 per cent regulation the maximum drop is only increased by about 25 per cent, and for the extreme case where only one machine is on governor control (31 per cent regulation) reheat makes no difference. This is our third point.

The case of hydraulic turbines is more complex because of the effect of water inertia and the compensating introduction of temporary droop or other stabilizing means into the governing system. I shall not present any detailed curves but merely remark that although the effect on frequency dip may be considerably greater than that of reheat, the relatively long times (seconds) required to reach the minimum frequency still allow time for some reduction of the overshoot. Because it is generally recognized that the response of hydraulic turbine governors to sudden disturbances is considerably slower than that of most steam turbines, attempts have often been made in the past to speed up this response by drastically decreasing the reset time constant (i.e., the time required to go from a large temporary droop to a small steady-state droop) when the generator is connected to the power system. Such attempts will usually do more harm than good, since they will greatly reduce the stability of the governing system. Studies have indicated that in general a broad transient droop and a reset time constant at least twice as great as the water starting time is desirable under all loading conditions.

In some cases steam turbines may be operated with fixed valves and with control through the energy input, steam pressure, or other means. These modes of control have been considered for conventional units (in the form of so-called energy balance control), for variable-pressure units, and for nuclear units. Because of the long time lags in the control loop these control modes may contribute to instability unless they are carefully designed. It is a general principle of automatic control that maximum stability is achieved when all the time lags of the control loop differ greatly from each other, and of course good response can be obtained only if at least part of the response occurs very quickly, as in the conventional direct control of steam flow at a point close to the turbine. However, if it is found impractical to reduce the time lags in order to achieve this quick response it may be desirable to increase them so that the response is very slow, since instability is most likely to occur if the control system time lags are of the same order of magnitude as the inherent lag that results largely from rotor inertia. Then the system regulation over the first several seconds will depend principally only upon the steam units subject to conventional control-valve action. If we consider the idealized case of governors with no dead band and no variations in incremental regulation, we can, at least during normal operation, achieve the same usual overall 16 per cent regulation as at present with only about 25 per cent of total system capacity under fast governor control with 5 per cent droop.

Finally on this subject it should be mentioned that a significant contributing cause to the limiting of overshoot that we have observed is the almost instantaneously acting self-regulating characteristic of the electric load. As noted, a variation of load with frequency of unity (or 100 per cent regulation) has been assumed, and we have seen that the effect of this variation is most pronounced when the governor regulation is large.

Tie-line power swings

I have thought it desirable to review these fundamentals of the behavior of system frequency following loss of generation as a preliminary to considering the effects of interconnecting tie lines. If now we go to the opposite extreme and assume that our system of ten machines is connected by a tie line to another system of infinite generating capacity the situation is completely changed. Since there can be no permanent change of frequency, 100 per cent of the lost generation is eventually supplied through the tie line from the large system, at least until the tie-line power control operates. In addition, because of the oscillation that results from the interaction of the system rotating inertia and the spring gradient formed by the slope of the tie-line torque–angle characteristic there will be an overshoot. This overshoot will not be 100 per cent, but may be as small as 50 per cent because of damping and speed governor action and because the system reactance causes some of the load to be taken up on the tie line instantly (that is, without waiting for the generator rotors of the disturbed system to fall back in angle). Figure 6 is a typical curve of tie-line power swing vs. time. As long as the tie-line stability limit is not exceeded the shape of the curve will look more or less the same but the time scale and the amount of damping will depend upon the tie-line strength. For example, if the tie-line capacity (i.e., the stability limit) is 10 per cent of the system capacity, the period of the swing will be a little more than 3 seconds, and the maximum transient frequency deviation will be about 0.1 c/s for a 5 per cent loss of generation. Although this frequency deviation is enough to cause governor action, the action is attenuated considerably because of the governing system time lags and dead band. For this extreme case it appears that governor action is unimportant except for its contribution to damping. We shall see later, however, that in the general case governor action may be very important.

Extremely large interconnections

Although an infinite system may seem extreme it is not very far from being realized in the eastern part of the United States, where any one system is a very small part of the total interconnection. Thus it may be of interest to make some further observations. First, if the tie line can support all of the generation deficiency for a few seconds it can in principle support it for as long as we please. Thus each system of the large interconnection has its own reserve, not because it would otherwise suffer a "loss of load" but rather because it finds it desirable to restore its tie-line schedules and to take care of its own load. Each system contributes its share of the total reserve of the interconnection, but sometimes a generator is considered a part of its reserve capacity even though it may not actually be running.

Second, if the strength of the tie is no greater than the largest generator (with a margin to take care of the overshoot) then the tie must initially have been very lightly loaded if it is not to be lost as a consequent event. If it had been importing power and had therefore become overloaded and tripped as a result of loss of generating capacity, this is equivalent to increasing the size of the largest generator. In this case the tie can do either good or harm, but it cannot be neutral; or to put it in another way, we cannot count the same tie-line capacity twice, for both economy loading and reserve assistance.

Third, the tie-line strength must bear some relation to the size of the largest generator. If it is smaller than this generator, the tie line will obviously trip out whenever the generator is lost unless it is used only for exporting power. If the tie line is too much larger and we load it up very much beyond the capacity of the largest generator it itself will become in effect a new largest generator, which may be lost. (This last remark applies only to a single tie line, whereas the previous remarks are applicable regardless of the number of physical lines that are paralleled.)

Fourth, the tie may be said to *permit* us to operate the system with the most economic allocation of generation, which we might not otherwise be able to do without materially affecting the emergency performance. More generally, there are significant mutual effects among economic loading, reserve capacity, economy interchange, and generator size that should be taken into account when determining the optimum size of an interconnection.

Fifth, from a technical standpoint there may not always be a clear distinction between a tie line connecting two different power systems and an internal transmission line. If we take this point of view and consider that all interconnections are of adequate capacity and reliability (for example, two or more lines), then even a generator of 1000 MW is less than 0.7 per cent of the total system capacity of about 150 000 MW. This percentage is an order of magnitude smaller than that usually found optimum in reserve studies.

Interconnected systems

As the next step in our analysis of interconnected system behavior let us consider the more general situation, in which all of the systems are finite, and take as our first example the simplest case of two systems connected by a tie. In this case, when a generator is lost on one of the systems both of the changes previously discussed will occur. There will be a reduction in frequency as well as a change in tie-line power interchange. If the systems are equal in all respects—in capacity, inertia, effective speed regulation, and loading—then when a generator is lost on one system, only about half of the lost generation will be supplied over the tie and the frequency drop will correspondingly be reduced to about half. Returning to the simple graphical representations of Figs. 1 and 2, we observe in Figs. 7 and 8 the corresponding curves of excess load and generator pickup vs. frequency for the overall interconnected system.

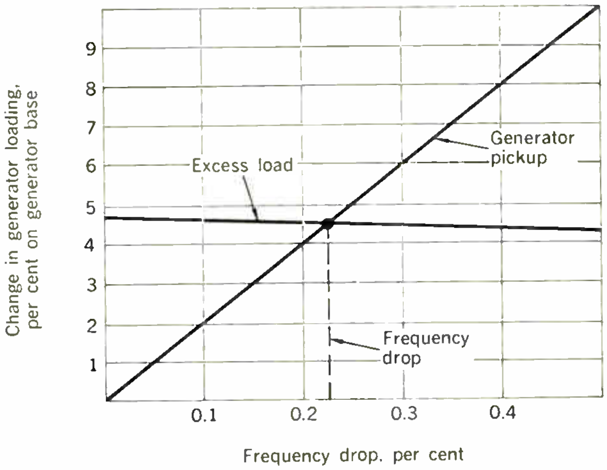
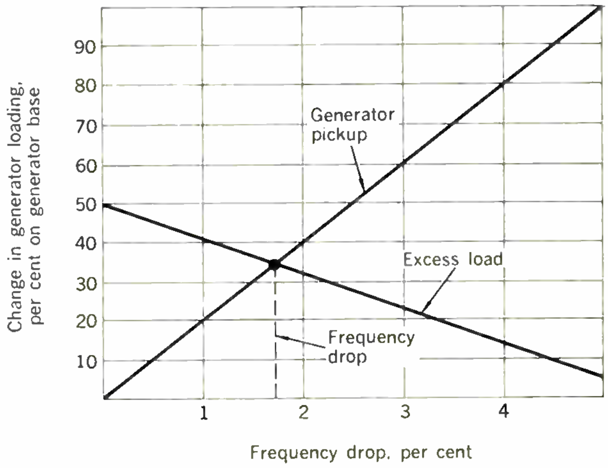


Fig. 7. Frequency drop on loss of generation equal to one half of reserve capacity; all generators equally loaded.

Fig. 8. Frequency drop on loss of generation equal to one half of reserve capacity; 90 per cent of capacity fully loaded.



The shape of the resulting tie-line power swing is the same as in Fig. 6 but now for a tie line of 10 per cent capacity the period of the oscillation is only about 2¼ seconds and the equilibrium value of power about which the oscillation occurs is only about 50 per cent. It may be worthwhile to discuss briefly the factors that determine this equilibrium value, because it may have an appreciable effect on the tie line's stability limits.

In order to calculate the amount of tie-line flow we may first calculate the drop in frequency by equating the total turbine output as a function of speed governor droop and initial loading to the total electric load, which is also a function of frequency. Then at this new reduced frequency we can calculate either the excess of turbine output over electric load for the undisturbed area, or the excess of electric load over turbine output for the disturbed area. (These two calculations should result in the same number.) The disturbed area is aided not only by the

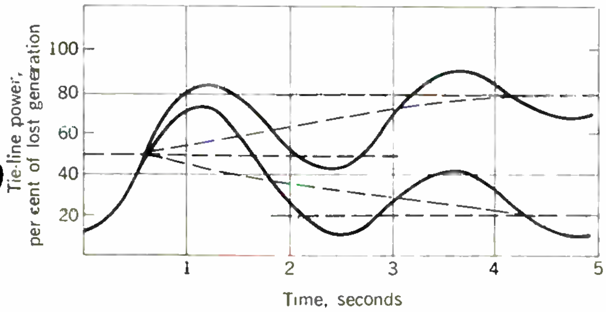


Fig. 9. Tie-line power swing following loss of generation. Upper curve—Loss in high-regulation area. Lower curve—Loss in low-regulation area.

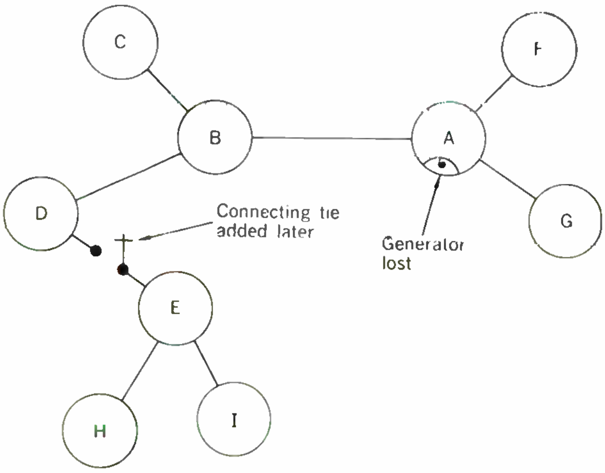


Fig. 10. Effect of remote ties.

increase in generation, but also by the reduction in the electric load, of the undisturbed area; in fact, it may have difficulty distinguishing between the two effects. Note that in the case of Fig. 7 the undisturbed area contributes somewhat more than half of the lost generation, since even though the loads in the two areas remain equal, more generators remain under governor control in the undisturbed area. In the case of Fig. 8, however, the undisturbed area contributes exactly half of the lost generation.

We next consider the case in which the capacities and inertias of two interconnected areas are alike but the effective speed regulations are widely different. Now we suddenly realize that we have been considering only the effective speed regulations and capacities and have paid no attention to the relative values of inertia. Suppose one area has an effective regulation of 10 per cent and the other of 40 per cent, resulting in an overall regulation of 16 per cent. Figure 5 indicates that with a regulation of 16 per cent the overall system deceleration has been completely arrested by about 5 seconds. Therefore, by this time, which is at the end of about two cycles of the tie-line power oscillation, the division of generation—and thus the tie-line power about which the oscillation will occur—has been established as depending upon the effective regulations. On the other hand, the first cycle may depend principally upon the relative inertias of the two areas. If the loss of generation takes place in the area having the 40 per cent regulation the picture of tie-line power might look something like the upper curve of Fig. 9, whereas if the loss of generation occurs in the area having 10 per cent regulation, it might look like the lower curve. We are now getting into the region where generalizations may be dangerous, and thus we should calculate directly the specific case of interest.

Certain general observations may be pertinent, however. First, although the peak of the first power swing is determined principally by the inertias, even this swing is affected to some degree by the system's speed governors. Second, the second power swing is already determined principally by the speed regulations of the two areas. We note for instance that in the upper curve of Fig. 9 the second power peak, which occurs only after more than 3 seconds, is larger than the first because of this regulation effect. Third, the relative values of the area speed regulations appear to be more important than the individual absolute values in determining the tie-line power swings.

Multiarea systems

In actual practice each of the two areas will themselves probably consist of several interconnected areas connected by tie lines. The first consequence is that there are many natural frequencies of the system, quite aside from the relatively high natural frequencies corresponding to the oscillations among individual machines of one area that we have been neglecting so far. Therefore, although most curves of power swings that we have seen do indicate that one frequency is predominant, actually there are always several modes of oscillation and the magnitude of the initial power peak will be affected by the location of the lost generator in the system; that is, it will depend somewhat upon the particular area in which the disturbance originates.

Second, the amount of load picked up by a tie between two electric utility companies can change because of new interconnections made between two entirely different companies. For example, Fig. 10 shows areas A and B connected through a single tie line, and also areas A, F, and G and areas B, C, and D interconnected as indicated. Each area may represent a different electric utility company. If a generator is lost in area A and if all the areas are of about equal capacity then, since there are three companies on each end of the tie line, one half of the amount of lost generation will be picked up on the tie between A and B. However, if later on company D decides to connect to company E, which is in turn interconnected with H and I, then there are six areas with twice the former capacity on the left side of the tie and still only three on the right-hand side. Now if a generator is lost by company A, two thirds of the lost generation will be picked up on the tie line. Thus the dynamic performance of an interconnection must be restudied periodically even if no change occurs in the tie itself, in order to make sure that changes made by other companies, perhaps thousands of miles away, have not materially affected its behavior.

Third, in the study of interconnection stability following loss of generation it is often necessary to consider a fairly extensive system in some detail, not only in order to include the effect of other interarea oscillations on the maximum power swing in the tie line with which we are concerned but also to make sure that some other system

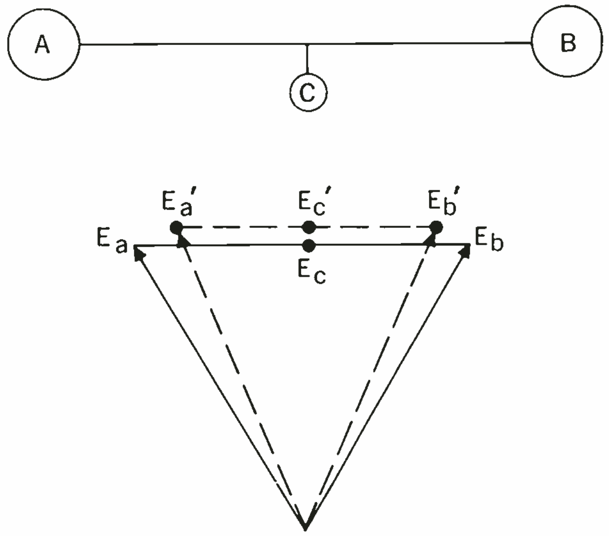


Fig. 11. Voltage changes caused by tie-line power swings.

tie does not become overloaded and open, and thus affect the tie-line power by changing the relative amount of generating capacity on the two sides of the tie.

Fourth, when we speak of the amount of generation on either side of the tie we must consider the total interconnection. Even though the tie-line strength may be relatively large in terms of the immediately adjacent areas, it may be small in terms of the total interconnection. The resulting natural period of the tie-line oscillation may be 5 or more seconds, so in some cases even the first peak of the power swing is not reached until after 2 or 3 seconds.

We have so far discussed the performance of interconnected power systems primarily as if they were systems of many masses and (electrical) springs. We have emphasized the importance of governor characteristics but have not discussed electrical factors other than synchronizing torque, except briefly in connection with the sudden initial change in tie-line power evidenced in Figs. 6 and 9. However, there are several other aspects of the electric system which, although they may not be of primary importance, are still significant as far as stability is concerned. These include generator excitation, system damping, and electric load characteristics.

Generator excitation

Automatic generator voltage regulators and excitation system characteristics are important primarily because, with the long times involved in tie-line power swings, voltage regulator action is necessary to maintain the general system voltage level. This action has a direct effect on the amount of electric load and thus on the amount of power that will appear on the tie line; that is, electric load usually varies directly with voltage as well as with frequency. It is evident that for this purpose it is primarily the mere presence of voltage regulators, as well as the adequacy of the exciter ceiling voltages to maintain full terminal voltage at the load buses, and not the rapidity of response, that is significant. Theoretically, excitation has also a direct effect on all synchronizing torques and thus on the tie-line stability limit. However, we usually must hold the system voltages somewhere near normal, and thus are not free to change the excitation entirely as we please. Moreover, because the tie-line reactance is so much greater than the internal reactance of the generators, there is only a much diluted effect on the tie-line steady-state stability limit.

If the system consists of several interconnected areas covering a large region and if power is generally flowing in one direction, so that an appreciable angular difference exists between the two extreme areas, then the areas near the center of the system will experience a voltage oscillation roughly in phase with the angular (or tie-line power) oscillation, the voltage decreasing as angle (or tie-line power) increases. Figure 11 illustrates an extreme case of this situation, with an area C of relatively small capacity at the middle of a tie line between two major areas A and B. The voltage E_c of area C will increase to E_c' as the angle between A and B decreases, as shown in the lower part of the figure. It is also evident that the frequency and phase angle of area C will undergo very little, if any, change during the oscillation.

It may be difficult to hold the voltage of area C constant by excitation control, primarily because of the rather large generator-field time constants. For example, if the period of oscillation is 3 seconds, the component of field current produced by changes in field voltage may lag this field voltage by about 80°. Thus very little additional lag in the voltage regulating system would cause the regulator to aggravate, rather than correct, the voltage swings. Response of the regulating system to rate of change of system voltage would seem almost necessary to obtain effective performance. Although these voltage changes may not be objectionable for a short time following a severe system disturbance, they may be intolerable if they persist in the steady state, as has sometimes been observed in the case of weak and heavily loaded ties.

System damping

System damping arises from many sources: prime movers, speed governors, electric loads, circuit resistance, generator amortisseurs, and generator excitation. For two or more generators that are closely coupled electrically, the amortisseur is the most important source of damping. Two generators paralleled directly at their terminals have a rather high natural frequency, and oscillations between them are damped almost entirely by their amortisseurs. Phase lag in the turbine speed governors may be so great that the governors produce negative rather than positive damping, the electric load hardly changes since the load bus is likely to be at the center of gravity of the oscillation, and the inherent variation of prime-mover torque with speed is small compared with the amortisseur damping.

However, for oscillations of power on a relatively weak tie line between two large systems the situation is almost completely reversed. The amortisseur damping becomes very small (decreasing almost inversely as the square of the total effective circuit impedance as viewed from the machine), the negative damping produced by circuit resistance may become significant, and only the inherent load and prime-mover damping remain. The governors may or may not produce some positive damping, their phase lags depending on the natural frequency of the tie-line oscillations. For instance, if the variation in turbine torque produced by the governor lags the speed by a half second, as might be the case for a steam turbine, then even with no dead band the damping produced will be positive only if the period of oscillation is greater than 2 seconds. For a hydraulic turbine the component of damping due to governor action may be negative for any period of oscillation less than about 10 seconds. The net damping is usually very small, perhaps only 5 per cent of critical damping.

The case of long-distance transmission from a generating station to a large system lies somewhere between these two limits. Especially near the steady-state stability limit, all sources of damping become important.

Steady-state stability and tie-line power control

We have discussed so far the performance of interconnected systems only during the first few seconds following loss of a generator. However we have noted that in one of the cases considered (the upper curve of Fig. 9) the second peak of the tie-line power swing was greater than the first. This leads naturally to the question as to whether the initial transient swings are necessarily the most severe criteria of tie-line stability. The answer is "no." It cannot be assumed that if a system can successfully survive the violent first swing without losing synchronism it will be stable in the resulting steady state. Thus steady-state stability for the condition following the disturbance must be checked. Eventually, of course, the tie-line power control will intervene to restore the original tie-line power, if it is within the capability of the generators in the affected area to pick up all the lost generation. However, there is a period after the first swing, but before the tie-line power control has acted appreciably, during which the tie may be lost because of steady-state instability.

The tie-line power-frequency control of the area in which the loss of generation occurs will receive a signal to increase generation as soon as the tie-line power changes. However, the maximum rate at which any prime mover input can be changed by such control may be typically only about 5 per cent of rating per minute, which is only 0.1 per cent per second. If every machine in the area is controlled, this same percentage rate also applies to the area as a whole. Expressed as a percentage of the 10 per cent tie-line rating that we have been considering as an example, this becomes 1 per cent of tie-line rating per second. This case is extremely optimistic, and it is much more likely that only a fraction of the machines will be under control. It may thus be unwise to depend on tie-line power control having accomplished very much to relieve the tie-line loading until after 20 or 30 seconds have elapsed. This is of course in line with the usual philosophy of applying tie-line power-frequency control so that it will not prevent all interconnected areas from coming to the aid of any particular area with a temporary generation deficiency, its primary function being the control of frequency and power (and sometimes the economic allocation of generation) in normal operation.

However, in a few cases high-speed response, for limited changes in generation, has been used in tie-line power-frequency control. If we take as our example a system in which 20 per cent of the generation capacity is equipped with tie-line control having a maximum rate of response of 100 per cent of rating per minute up to 16 per cent of capacity, then in terms of our 10 per cent tie-line rating the maximum rate of reduction of tie-line power is about 3 per cent per second up to a maximum change of about 30 per cent in 10 seconds. This action would slightly reduce even the first power swing and would considerably relieve the steady-state stability problem, but by the same token would require that the disturbed system furnish more of its own immediately available spinning reserve.

Since tie lines are often installed, at least in part, to reduce reserve requirements, it would seem desirable to consider very carefully the economic balance between, on the one hand, increased reserve capacity and operating limitations to insure adequate capacity margin in the generators subject to the high-speed signal and, on the other hand, a somewhat stronger tie. Moreover, if extremely high speeds of response are desired for emergency it may not always be desirable to utilize these high speeds except during the emergencies (and except in the direction of increasing generation), so it becomes necessary to have a foolproof way of determining when an emergency exists. This may not always be an easy task.

The tie-line power-frequency controls in the other interconnected areas will momentarily receive a signal to decrease generation. If their frequency biases are set to match the area's speed-regulation characteristics, however, this signal will disappear after the several seconds required for the overall system frequency to drop to its new equilibrium value; thus, very little change in generation will result from this action.

If the frequency biases are not set to match the area speed regulations, the tie-line power-frequency controls in the undisturbed areas may continue to act, sometimes causing overshoots in frequency or in tie-line power that may persist for several minutes. Such action has been observed on many occasions. We might say that whatever these controls do is in principle wrong, because they are not supposed to do anything.

Although tie-line power-frequency control may not have a direct effect on interconnected system behavior immediately following a disturbance, it has had a major influence on the trend toward interconnections. A large number of independent power systems that are interconnected by tie lines of relatively small capacity, as in the United States, could not operate satisfactorily even under normal conditions without automatic tie-line power-frequency control. For example, if tie-line capacity is only 2 per cent of that of either of the two areas interconnected, then to keep the random tie-line power fluctuations within 20 per cent of tie-line capacity, which is certainly not negligible, requires that the total generation in each area be continually matched to the load in that area to within 0.4 per cent of the total capacity. Manual dispatching would seem very difficult in such a case. Automatic dispatching, however, has usually permitted tie-line capacities to be based on what is needed for economic interchange of energy and for reserve in emergencies, and thus to be economically desirable, without having to be large enough to stand the large random fluctuations that might result from manual control. Even with automatic control, random power fluctuations of some magnitude will still occur. Detailed discussion of these fluctuations is outside of our present subject, so I shall merely remark that they have been shown in many cases to be very roughly proportional to the square root of the area capacities.

While we are on the subject of long-time effects I should point out that our discussions of frequency drop have been based on the assumption that the power capacities of the prime movers were independent of frequency. This statement is true only for a relatively short time. In the case of steam turbines, the steady-state capability may drop as much as, or possibly even more than, the drop in electric load. The actual amount appears to vary greatly. Some electric utilities have reported being able to carry peak load by dropping frequency, while others have reported twice as much drop in capability as in load. The loss in capability will occur, if it does occur, only after the stored energy in the boiler has been dissipated; it depends primarily on the low-frequency and possibly low-voltage characteristics of the auxiliaries.

Tie-line faults

As stated earlier, losing a tie, if it had been importing power, is something like losing a generator. But if other ties to the same external areas remain, then there is no net loss of generation to the system as a whole, and thus no frequency drop. The problem is one of tie-line stability, and the remaining ties must be able to withstand the resulting power swing and remain stable in the resulting steady state with increased loading.

If the remaining ties are found to be unstable, it may sometimes be possible to prevent loss of these ties by dropping some generation in the sending area. This should be the minimum necessary, and cannot in any case exceed the ability of the receiving area to pick up the load without undue frequency dip. In addition, the tie-line power-frequency control must be temporarily blocked or the tie-line power immediately rescheduled, in order to prevent this control from eventually loading the line beyond its steady-state limit. The amount that can be dropped and the benefit that can be obtained depend very much on the particular case. Careful coordination with the available spinning reserve in the receiving area is required.

Direct-current tie line

It would hardly be appropriate to discuss the performance of interconnected systems without at least mentioning dc ties. I shall very briefly point out what I consider to be the distinguishing features of dc ties, as contrasted with ac ties, from the point of view of system disturbances.

First, let us consider the case of two areas connected by a dc tie. If a generator is lost in either area, the dc tie will, in principle, take no action unless it is told to do so. This is the major and striking difference between dc and ac ties. Actually, however, there may be some momentary effect. For example, if the disturbed area has been importing a scheduled power and if the loss of the generator causes a slight drop in system voltage, then with the usual practice of very rapid primary control of rectifier current and with inverter voltage limited by the receiver system ac voltage, the reduction in ac, and thus of dc, receiver voltage will cause a momentary reduction in imported power, until it is brought back to the scheduled value by the power control. If the disturbed area has been exporting power, a slight disturbance in ac voltage will not produce any change in power. Of course it is not necessary that the control be of power. For example, the dc tie to the island of Gotland has operated to control frequency on the island, allowing the direct current to vary. Similarly, a dc tie between two areas could be controlled by a sort of tie-line power-frequency control, with the frequency bias made to depend not on the absolute frequency of either area but rather on the difference in frequency between the two areas. It would then behave somewhat, but not exactly, like an ac tie, responding to differential frequency rather than to differential angle. Since a frequency difference is required to change the tie-line power flow, the frequency drop in the undisturbed system cannot be as great as that in the disturbed system, so the two areas cannot be made to pick up the lost generation quite in proportion to their regulating capacities, as would be the case with an ac tie. Also, there would not be the same tendency for the two systems to oscillate against each other. It should be pointed out that it is not always self-evident that we want the tie to respond to disturbances. In contrast to an ac tie, if a dc tie line does not respond, and is not depended upon for support in emergencies, it can be as small as we please without danger of its being lost as a consequent event.

Second, let us consider the case of two areas connected by both a dc and an ac tie. If a generator is lost we cannot depend on a difference in frequency as a signal to change dc power, since the ac tie will hold the two areas in synchronism. Perhaps the simplest concept, if we want the dc tie to participate in assisting the disturbed area, is to control the dc tie-line power in rough correspondence with the ac tie whenever a sufficiently large disturbance occurs. In theory we might want the dc tie-line power to depend on the angle between the two areas but, since this may be rather difficult to measure, we might use instead simply the ac line current (together with a periodic check on the sign of the angle). We cannot of course use the ac line power as a signal since power does not exhibit consistent behavior near the stability limit, and we certainly would not want the power on the dc tie to simulate that on the ac tie if the two systems go out of synchronism.

As we have seen, the dc tie has no significant inherent response characteristics of its own, but it can be made to respond rather rapidly to control, and thus it can be employed most effectively during emergencies. However, it may present problems of gathering the proper intelligence so as to distinguish, with satisfactory accuracy, between normal and abnormal conditions.

Conclusion

I have attempted here to provide some insight into the dynamic behavior of interconnected electric power systems following disturbances by discussing what I believe to be the most significant system parameters. The subject is vast, so I may have rambled a bit. However, I have been guided in the selection of topics by the questions that have arisen over many years of contact with the problems involved.

The opinions expressed are my own, and some may disagree; but I hope that this article at least will establish a basis for further discussion.

Essentially full text of a paper presented at the Pacific Coast Electrical Association Engineering and Operating Conference, Los Angeles, Calif., March 18–19, 1965.

Magnetoelastic waves —

new mechanisms for energy transport

Magnetic and magnetoelastic wave propagation provides a means for achieving relatively long, continuously variable delay times in compact microwave structures in which single crystals of ferromagnetic insulators are employed

George P. Rodrigue *Sperry Microwave Electronics Company*

Recent research on microwave resonance phenomena has led to the discovery of the existence of high-Q microwave acoustic modes of vibration. These modes were initially found to exist in highly perfect single crystals of yttrium iron garnet.[1] Subsequent investigations have shown that microwave acoustic oscillations or vibrations can exist and propagate in many crystals with greater or lesser amounts of attenuation. At room temperature, yttrium iron garnet (YIG), ruby (Al_2O_3), rutile (TiO_2), and magnesium oxide (MgO) are low-loss microwave acoustic materials. At liquid-helium temperatures, many crystals—in particular, quartz crystals—exhibit very low loss propagation of microwave acoustic signals.

Microwave acoustics refers simply to elastic vibrations at microwave frequencies; such vibrations might be referred to more succinctly as phonons. It was only recently discovered that coherent phonons can be excited, propagated, and detected in solid crystalline materials at frequencies well into the microwave region, at least to the X band. Aside from the purely scientific interest in this new means of propagating microwave signals, there is considerable practical interest because of the low velocity of propagation of elastic waves in solids and the resultant long time delays that can be achieved in physically short single-crystal materials. Beyond this consideration, moreover, research in microwave acoustics has shown the existence of an entirely new means of propagating microwave signals.

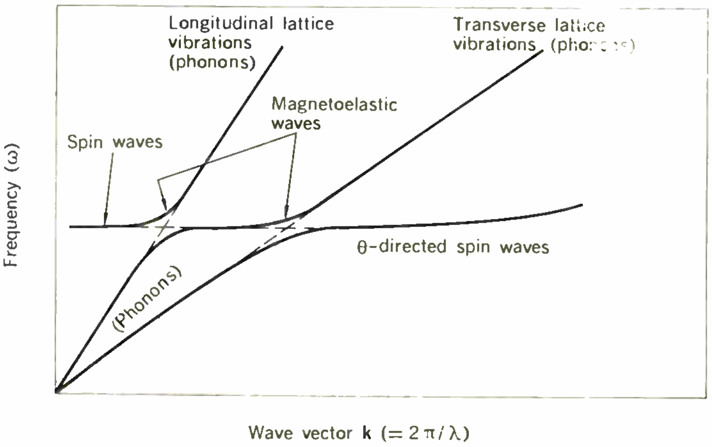
Heretofore, microwave signals have been propagated in the form of electromagnetic energy or as the vibrational energy of microwave phonons. But work on YIG led to the discovery of the propagation of magnetic waves in solid crystals. The propagation of such magnetic waves was first observed in 1962 and reported by Eshbach.[2] Today we know that microwave signals can be propagated as electromagnetic waves, microwave acoustic waves or phonons, or magnetic waves or magnons. Furthermore, in the crossover region between the spin wave and phonon dispersion curves, these waves form admixtures or magnetoelastic waves that take on some of the properties of both magnetic and elastic waves.

Magnetic waves of long wavelength are commonly called magnetostatic waves, while shorter wavelength modes are spin waves.[3–5] The distinguishing feature of the magnetic and magnetoelastic waves is that their velocities of propagation can be varied and controlled by an external magnetic field. Thus it is possible, for the first time, to control the transit time of a microwave signal electronically or with a biasing field. Since the velocities are relatively low, the technology now exists for achieving very long and controllable delays of microwave signals in relatively short physical dimensions. It is possible, for example, to obtain single-transit delays of the order of 1 to 10 μs in crystals less than a centimeter in length.

Characteristics of propagating modes

The dispersion relations for both spin waves and phonons are shown in Fig. 1, where frequency is plotted as a function of wave vector **k** ($= 2\pi/\lambda$). The fact that the phonon-dispersion curve is a straight line indicates that acoustic or vibrational waves propagate without dispersion—i.e., with a frequency-independent velocity—throughout the microwave region. This velocity is deter-

Fig. 1. Spin-wave and phonon-dispersion curves showing relation between frequency and wave vector. Strong coupling region between elastic and magnetic waves is indicated by the dashed lines.

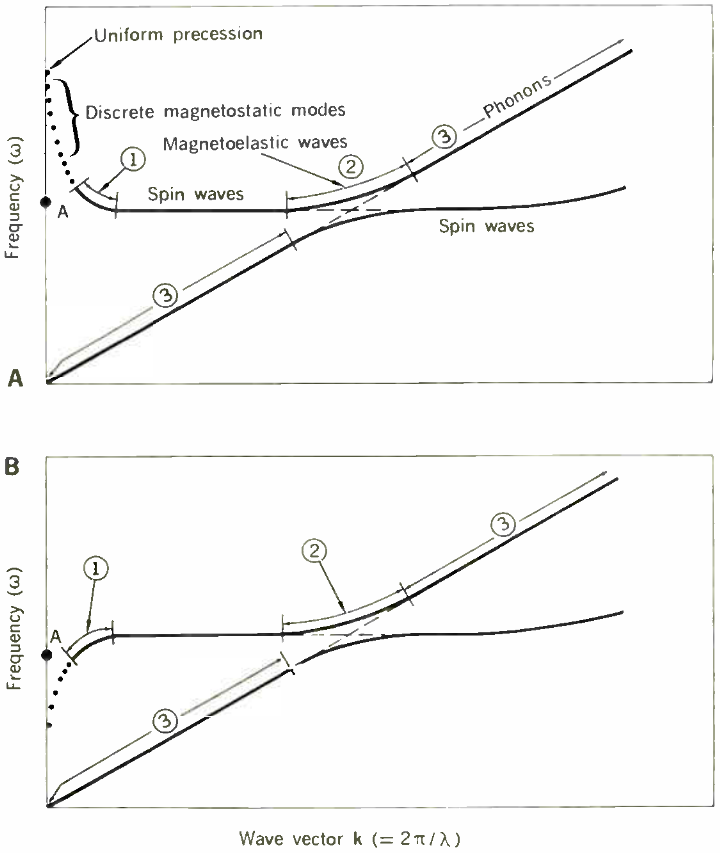


mined by the elastic constants of the material, and differs for longitudinal and transverse waves, as indicated in the figure. The dispersion curve for magnetic waves is parabolic, and, since the group velocity of any of these waves is given by the slope of this curve, their velocity of propagation is a function of frequency; that is, group velocity $v_g = \partial\omega/\partial k$.

It can be seen in Fig. 1 that in the crossover region of the dispersion relations the waves have identical frequencies and wavelengths and are strongly coupled, so essentially complete conversion frequently occurs between propagating spin waves and phonons. It is in this heavily coupled region that the spin waves and pure acoustic waves form the admixtures or magnetoelastic waves.

The general form of the curve of Fig. 1 would be similar for various geometric shapes of magnetic materials. For different specific shapes, however, the curves assume important differences in the long-wavelength (low **k**) region. For these modes the boundary conditions are important, and the wavelengths are comparable to the dimensions of the samples. The dispersion curve for an axially magnetized rod is shown in Fig. 2(A) and for an axially magnetized disk in Fig. 2(B). The long-wavelength region for the axially magnetized rod has been treated specifically by Fletcher and Kittel.[6] Magnetostatic waves are relatively long—of the order of 0.01 cm or more; the shorter spin waves are 100 microns or less.

Fig. 2. Dispersion curves for an axially magnetized rod (A) and disk (B). Only one phonon branch is shown for the rod, because it is assumed that either longitudinal or transverse waves are excited and propagated.



At any point along these curves the group velocity is given by the slope of the curve, and thus a wide variation in group velocities can be obtained for these two shapes. The negative slope of the magnetostatic region for rod geometry corresponds to backward traveling waves.

In practice the operating frequency is generally fixed, as at point A of Figs. 2(A) and 2(B), and the dispersion curve for magnetic waves can be raised or lowered with respect to this operating frequency by varying the applied magnetic field. Increasing the applied field raises this curve with respect to the frequency, and decreasing the field lowers the curve. Of course, the phonon branch is invariant under the application of an external field.

If the operating frequency corresponds to point A in Figs. 2(A) and 2(B), the velocity of propagation of a magnetic wave can be varied over wide ranges by controlling the position of the dispersion relation with respect to this frequency. In region 1, near the elbow of the dispersion curve, the velocity of propagation (or slope of the ω vs. **k** curve) varies rapidly with the applied field, so that the delay time will vary markedly for small changes in applied field. In region 2, the slope changes more gradually and the velocity (or time delay) is found to be less sensitive to the applied field. In region 3, pure acoustic or phonon propagation occurs, and the delay time is then independent of the applied field or frequency.

Thus, in a given crystal of fixed physical dimensions, the transit time of a propagating magnetic or magnetoelastic wave can be controlled through an applied external magnetic field that controls the velocity of propagation. Depending on the operating region used, the transit time can be made to vary either rapidly or slowly with field; and, by selection of the proper geometry, the sign of this dispersion can be either negative or positive. In the pure-phonon region (region 3) the velocity is completely independent of field.

Excitation of magnetic and elastic waves

At microwave frequencies, pure acoustic waves can be excited by transducer techniques extended from the lower-frequency VHF region. Microwave acoustic transducers normally employ piezoelectric materials that couple the electric field of the microwave signal to a vibrational wave, or magnetostrictive materials that couple through the RF magnetic field. In the former case, the free end of a quartz rod may be used, or a thin quartz transducer may be operated on a high harmonic of its fundamental frequency. In the second case, a thin film of a ferromagnetic material may be applied to the delay medium. When the film is biased to the vicinity of ferromagnetic resonance, the precessing magnetization will couple energy through magnetostriction to a vibrational wave that then propagates through the delay medium.

The principal difficulty in converting electromagnetic microwave energy to acoustic form is that of matching the wavelength of 3-mm waves to the very short wavelengths of the microwave acoustic waves. Since wavelength is equal to velocity divided by frequency, the very low velocities of propagation encountered give rise to acoustic wavelengths measured in microns. Thus very thin films or plates are required for efficient transducer action. Evaporated or electroplated magnetic films can be applied to crystals such as sapphire, with thicknesses of about one half an acoustic wavelength; but the coupling of the RF fields to such films is normally weak. Thin quartz plates with fundamental frequencies above 100 Mc/s are excessively fragile, and microwave operation on a high harmonic provides a narrow-band response. Transducers of this type are at best relatively inefficient, of the order of 10^{-3} at microwave frequencies. Of course, it is possible to increase efficiency at some sacrifice in bandwidth.

In the case of magnetic or magnetoelastic propagation, the transducer action is accomplished directly through ferromagnetic resonance in the crystal material. It is not necessary to rely on magnetostrictive coupling, because the propagating modes of the magnetization are themselves biased to resonance and coupled directly to the electromagnetic field.

The materials used for magnetic propagation are ferromagnetic insulators. Because the wavelengths are extremely short and the materials used must be dimensioned perfectly down to a half wavelength, the requirements are very stringent. Only single-crystal materials can be applied. The grain boundaries of polycrystalline materials have thicknesses of the order of an acoustic wavelength and cause prohibitively large reflections or scattering of the wave. Even in terms of single-crystal material, the requirements are severe. Only the most highly perfect crystals can be used, and only two known magnetic insulators are available with a suitable degree of single crystal perfection. These two materials are YIG and lithium ferrite, together with doped derivatives of these materials. Even with these substances, crystal quality is a very serious problem. Both materials are opaque to light, and it is thus impossible to inspect their quality by any means other than microwave acoustic propagation. Quartz, ruby, and rutile, on the other hand, can be investigated easily by optical means. This lack of an auxiliary method of checking crystal quality makes material selection a problem.

The point of generation of the magnetic wave inside a given sample will depend on the internal magnetic field existing in the sample. Excitation will occur at that point where magnetic modes of the specific applied frequency are biased to resonance. The wavelength of the mode excited will then be determined by the dispersion relations sketched in Figs. 1 and 2.

Because of demagnetizing effects, the field inside a magnetic sample is a function of the applied external field, the geometry of the sample, and the position inside it.[7] The internal field of an axially magnetized rod is sketched in Fig. 3(A), and Fig. 3(B) shows the same curve for an axially magnetized disk. In either case, generation will occur at the point inside the sample where the effective internal field has the proper value to bias a magnetic mode to resonance at the operating frequency. These are the points denoted by ω/γ of Figs. 3(A) and 3(B), and in these cases generation and detection of the propagating magnetic wave would occur at X_1. As the externally applied field is raised, the internal field is also increased. An increase in applied field causes the point of generation X_1 to move toward the surface of the rod X'_1 and toward the center of the disk.

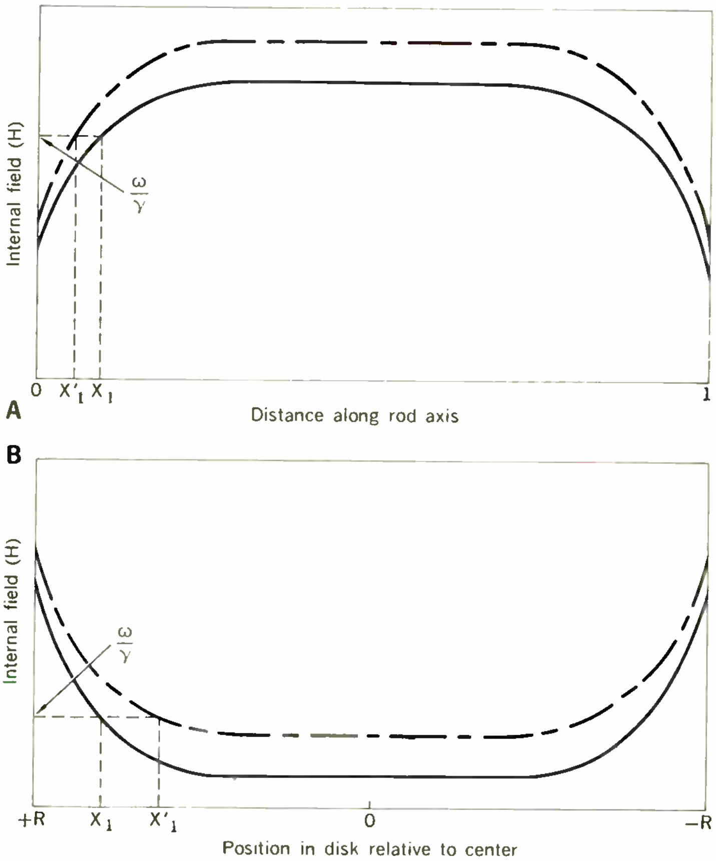
The change in X_1 provides a second means of varying time delay. Varying the externally applied magnetic field controls the point of excitation and detection in the sample. The path length, and consequently the transit time, of the propagating wave is also controlled.

To summarize, two causes of the observed variation in delay time with applied field have been described: the field dependence of the velocity of propagation of the magnetic wave, and control over path length between the points of generation and detection of these waves.

Some very clear oscilloscope traces of pulse propagation in these dispersive modes have been obtained at X-band frequencies and liquid-helium temperatures by Damon and Van de Vaart of the Sperry Rand Research Center.[8] Similar propagation has been observed at the Sperry Microwave Electronics Company at lower frequencies at room temperature, though the losses at room temperature are substantially greater. Oscilloscope traces of magnetostatic pulses propagating in an axially magnetized rod of YIG are shown in Fig. 4, and Fig. 5 shows similar data obtained on an axially magnetized disk. These waves are the long-wavelength, highly dispersive modes of region 1 of Fig. 2. The pulse delay varies by more than 20 μs for a field change of approximately 2 oersteds. Also seen in these photographs is a broadening of the delayed pulse due to the very highly dispersive nature of the delay mechanism. The strong dependence on field is accompanied by an equally strong dependence on frequency, and the different frequency components of the input pulse are each delayed by slightly differing times.

Oscilloscope traces obtained from magnetoelastic propagation in the rod and disk are shown in Figs. 6 and 7. These modes, which are the shorter-wavelength modes of region 2 in Fig. 2, exhibit a delay that is far less sensitive to the applied field. Because they are much less

Fig. 3. Internal field of an axially magnetized rod (A) and disk (B). The dashed curve shows the effect of raising the external field slightly.



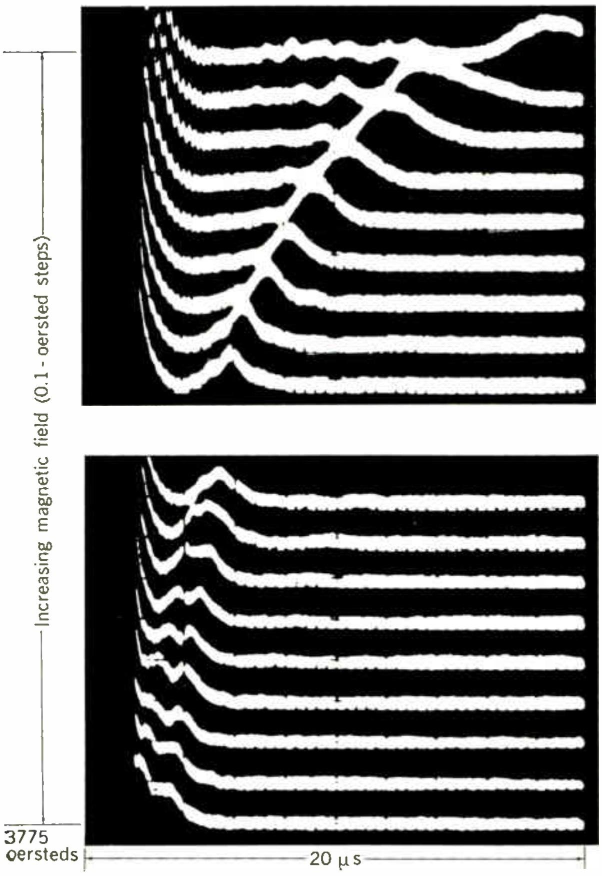


Fig. 4. Oscilloscope traces showing variation in delay with applied field for propagation of magnetostatic modes in an axially magnetized rod.

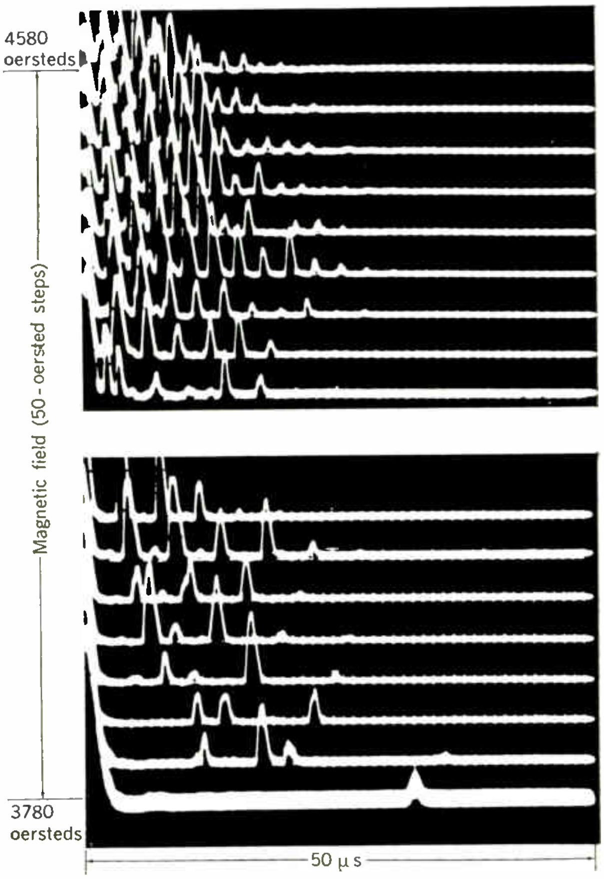
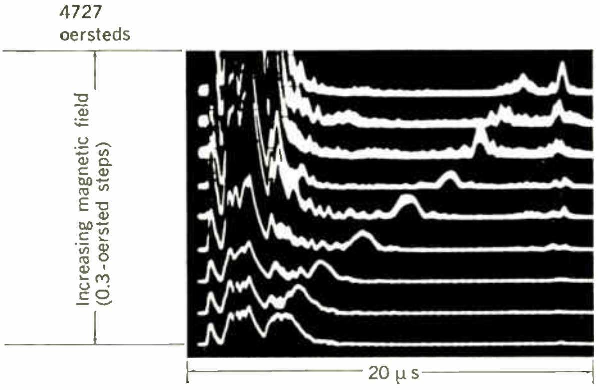


Fig. 6. Oscilloscope traces showing delay from magnetoelastic propagation in a rod in the X band and at liquid-helium temperature. Delay is a weaker function of the field than in the magnetostatic region.

Fig. 5. Oscilloscope traces for an axially magnetized disk. Sign of dispersion is opposite to that of Fig. 4. Data were obtained in the X-band range.



dispersive, the output pulse is not broadened as in the case of magnetostatic propagation. The lowest trace on each of these figures shows a single-pass pulse, whereas other traces show outputs obtained from pulses making more than one transit between generation and detection points.

Applications of solid-state delay lines

Although the overall loss of present solid-state delay lines is relatively high, pure phonon devices compare favorably with other microwave delay lines, i.e., with coiled cables or strip lines. In fact, for delays of 1 μs or more, it is possible to obtain a longer delay time per decibel of loss in pure phonon propagation than can be obtained with the more conventional techniques. Thus the microwave phonon devices are already supplanting conventional microwave delay lines. These devices supply delays ranging from 1 μs up to about 80 to 100 μs. Their very small physical dimensions are an advantage in airborne and space applications. An output signal from one such device operating at room temperature and L-band frequencies is shown in Fig. 8. The time between pulses corresponds to the time required for one round trip of the acoustic wave in the rod; in this low-loss material, outputs are visible out to about 200 μs.

Pure acoustic, nondispersive delay devices can be applied to target simulators for radar testing and calibration. In countermeasures, such delay lines can be used to produce false range and velocity information, and they might be used in the control of beam direction from plane antenna arrays. Since the field-variable delay line also exhibits frequency dispersion, it could be used in pulse compression radar systems.

Conclusion

Magnetic and magnetoelastic wave propagation provides a new energy-transport mechanism that can be

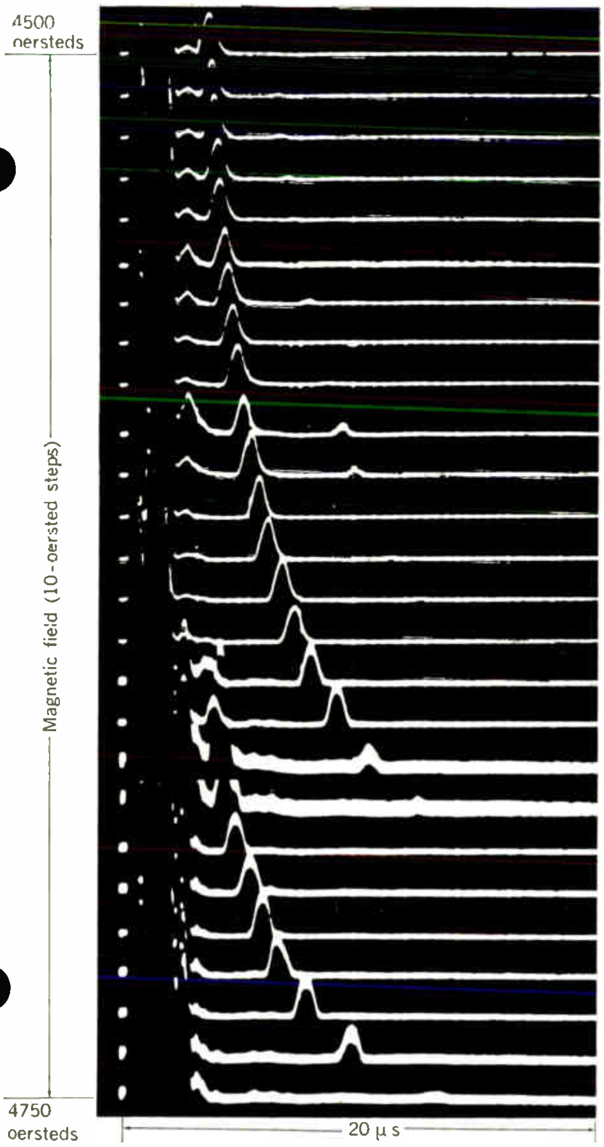


Fig. 7. Oscilloscope traces of magnetoelastic wave propagation in an axially magnetized disk of yttrium iron garnet (the same material used in Fig. 6). The sign of dispersion is opposite to that of the rod.

used to realize relatively long, continuously variable delay times in compact microwave structures employing single crystals of ferromagnetic insulators. Although the technique has been established, several problems remain. The reproducibility of present garnet crystals leaves much to be desired. Only relatively small crystals are available, and these frequently contain imperfections that seriously affect their use in microwave acoustic propagation. Some new or improved technique of growing these crystals is sorely needed, and, lacking this, it is necessary to improve the methods of crystal selection.

A second problem, of course, is the low transducer efficiency encountered. In most applications, insertion losses below 5 dB are desired, and today's losses of 60 to 100 dB are acceptable only in test equipment. Although the resonant magnetic modes are more efficient transducers than thin films or plates, their efficiencies are still only about 10^{-2} to 10^{-1}.

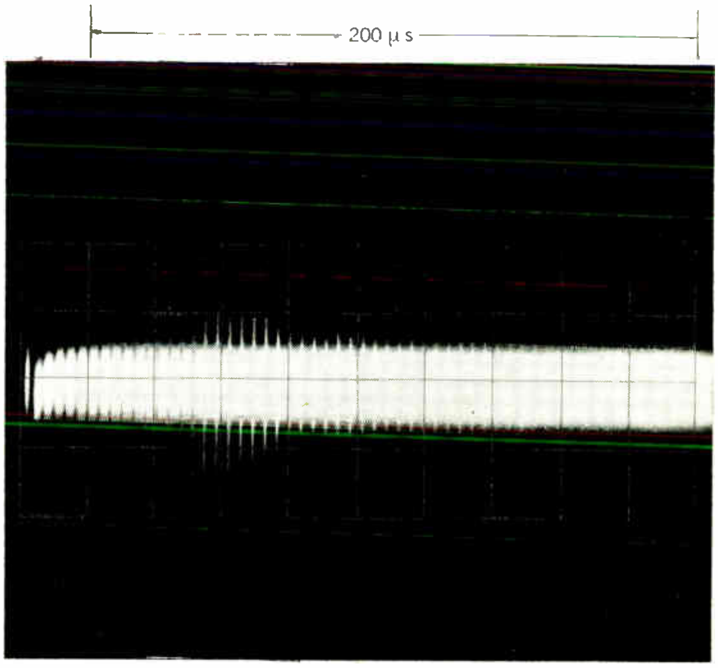


Fig. 8. RF output pulse train from typical delay line.

Finally, the variable delay of the propagating magnetic wave is usually accompanied by considerable amplitude modulation, and frequently by spurious delayed pulses. The spurious pulses probably arise from internal mode conversion in the crystal. For most practical applications it would be necessary to improve the fidelity of the delayed pulse and to eliminate spurious responses. These problems can best be overcome by study of the effect of crystal orientation and perfection on mode purity.

In spite of the remaining problem areas, the technique has been proved feasible, and its application promises the realization of continuously variable time delay and significant reductions in the size of microwave delay lines.

Essentially full text of an article that originally appeared in *Sperry Engineering Review*, vol. 17, Winter 1964. Reprinted by permission.

REFERENCES

1. LeCraw, R. C., Spencer, E. G., and Gordon, E. I., "Extremely Low Loss Acoustic Resonance in Single-Crystal Garnet Spheres," *Phys. Rev. Letters*, vol. 6, June 1, 1961, pp. 620–621.

2. Eshbach, J. R., "Spin-Wave Propagation and the Magnetoelastic Interaction in Yttrium Iron Garnet," *Ibid.*, vol. 8, May 1, 1962, pp. 357–359.

3. Walker, L. R., "Magnetostatic Modes in Ferromagnetic Resonance," *Phys. Rev.*, vol. 105, Jan. 15, 1957, pp. 390–399.

4. Damon, R. W., and Eshbach, J. R., "Magnetostatic Modes of a Ferromagnetic Slab," *J. Appl. Phys.*, vol. 31, May 1960 (suppl.), pp. 104S–105S.

5. Lax, B., and Button, K. J., *Microwave Ferrites and Ferrimagnetics*. New York: McGraw-Hill Book Co., Inc., 1962, pp. 170–180.

6. Fletcher, P. C., and Kittel, C., "Considerations on the Propagation and Generation of Magnetostatic Waves and Spin Waves," *Phys. Rev.*, vol. 120, Dec. 15, 1960, pp. 2004–2006.

7. Sommerfield, A., *Electrodynamics*. New York: Academic Press, Inc., 1952, p. 78.

8. Damon, R. W., and Van de Vaart, H., "Dispersion of Long Wavelength Spin Waves from Pulse-Echo Experiments," *Phys. Rev. Letters*, vol. 12, 1964, p. 583.

IEEE Reports for 1964

Introduction

B. M. Oliver, President

As the IEEE enters its third year, it becomes my privilege to present to the membership the statistical profile of our activities during 1964, presented to me by the Secretary and Treasurer, and to offer a brief evaluation of our general standing.

The information reported by the Secretary and Treasurer, which covers in rather extensive detail our organizational, editorial, and financial activities, reflects the continuing process of merger of the former separate organizational units of the AIEE and the IRE. With respect to the many difficult problems attendant upon such a merger, and with regard to the many accomplishments of 1964, I am pleased to extend our membership's special thanks to Junior Past President Clarence H. Linder and to the Headquarters Staff of the IEEE for their devoted efforts.

As Secretary Pratt's report points out, total membership declined slightly in 1964, from 154,509 to 153,978 members, owing largely to a 16 per cent drop in Student grade membership. It is interesting to note, however, that membership in grades above Student grade actually increased by 3.2 per cent, and all other organizational categories increased substantially. At the end of the second year of merger, Sections had gone from 181 to 183, Subsections from 38 to 65, Group Chapters from 346 to 406, and Student Branches from 260 to 270.

Secretary Pratt's report also outlines many of the major changes in our editorial activities that came about in 1964. The new IEEE SPECTRUM was launched at the beginning of the year, ELECTRICAL ENGINEERING was discontinued, a few new Group TRANSACTIONS were established in areas not previously served by such publications, and the PROCEEDINGS was placed on a subscription basis. The job of merging our publications is now completed, although we do not consider the present pattern to be permanent. Changes will occur as our Groups merge and shift their scopes.

Editorially, as Secretary Pratt's report shows, 1964 was a year of action and change. The highlight of our refreshed editorial activities was undoubtedly the launching of SPECTRUM. This new magazine, cutting as it does across the whole range of our members' interests and needs and directly furthering the IEEE's scientific, literary and educational purposes, has already demonstrated its capability of being a major integrating and unifying force for the IEEE. And we should realize that SPECTRUM has only begun to explore its potential in terms of its scope, editorial excellence, and influence. In all, the 1964 publishing program resulted in more than 2100 papers and 1000 letters running to a total of over 23,000 pages.

Another important activity in 1964 was the installation of the new IEEE Computer Center at UEC. This new facility, as was detailed in SPECTRUM for last December, should maximize our efficiency in the handling of many routine jobs incident to the operation of an organization as large as ours. The initial phase of conversion of many operations to the computer has been completed. As soon as tests show that completely reliable performance is available, we will convert to computer operations.

Treasurer Herwald's report, which has been incorporated into this introduction, shows that the IEEE sustained an overall deficit in 1964, as had been anticipated. This deficit is due directly to special nonrecurring expenses detailed in the Auditor's report that follows. It is noteworthy that although it had been anticipated that we would again incur a small operating deficit in 1964 our normal operations (aside from the nonrecurring expenses) actually resulted in a surplus, owing to a healthy advance in income and a reduction of expenses. Income increased by over one-half million dollars from 1963, and operating expenses decreased by over $100,000, giving us a total improvement over 1963 of more than $600,000. Net results from operations showed a surplus of $223,700 as compared with a $424,109 loss during 1963, which in part reflects the fact that many duplications of effort and expense incidental to our first year of merged operations have been progressively eliminated.

While this trend is encouraging, it is important that we remember that many inflationary forces are at work, which are steadily increasing the costs of the goods and services purchased by the Institute. Thus, when the planned economies made possible by the merger are fully implemented, we must expect the cost trend to reverse. Some evidence of this is already appearing in our 1965 operations.

Special nonrecurring expenses during 1964 included: $167,000 to relocate Headquarters and to dispose of obsolete equipment; $175,000 contribution to the UET (United Engineering Trustees) to reflect IEEE's share of the capital cost of the United Engineering Center in proportion to the increased membership resulting from merger; $196,000 to provide for computer installation and record conversion cost, including all cost of initial programming, consultant fees, forms, and personnel.

Although no major changes in the basis of investing our funds were instituted during 1964, certain prudent changes in our holdings to keep pace with market developments led to profits of $67,618 on sale of securities. At year end, the value of securities held by the IEEE shows an unrealized appreciation of $205,000.

Also during 1964, the 79th Street property of the Institute was contracted for sale, a transaction that was completed early this year. At the time of permanent investment of the funds from the sale of the buildings, our total investment portfolio and policy will be reviewed to insure proper use of these assets.

However, I must bring to the attention of the members the fact that there are two important aspects of our financial situation that remain unsettled. I refer to reduced advertising revenue and to the question of taxation of exhibition income.

Income from advertising revenues has steadily declined from premerger 1962 levels. While this kind of decline is generally prevalent, and although our situation is being studied carefully, it is unlikely that advertising revenues will contribute a substantially larger amount to Institute operations for some time. A sharp recovery to the level of last year is unlikely.

Clarence H. Linder's report to the members last July informed the IEEE members that the Internal Revenue Service has taken the position that the IEEE is subject to taxation on the net income realized from the IRE's and the IEEE's exhibition, which is held as an integral part of the annual International Convention. The principal steps that have been taken in regard to this pending tax matter are as follows:

(1) On February 20, 1964, the IEEE was requested by the Service to file tax returns and pay tax with respect to its income for all calendar years commencing with 1951.

(2) In April of 1964, the IEEE was advised that, due to a recent Revenue Ruling, only the period 1951 through 1953 would no longer be under consideration.

(3) In May of 1964, legal counsel was authorized by the Board of Directors to proceed to secure a judicial determination of the question of IEEE's alleged liability for the "test year" 1954.

(4) In June of 1964, a tax return for 1954 was filed and taxes of approximately $15,000 were paid. Immediately thereafter a claim for refund was filed for the entire $15,000.

(5) In March of 1965 the Service completed its audit of the 1954 return and proposed adjustments which resulted in the assessment of approximately $54,000 of additional taxes, which were paid and with respect to which a claim for refund was subsequently filed.

(6) In April of 1965, the local District Director's office attempted to repudiate its earlier position exempting the years 1951–1953 [see (2) above]. This is being opposed and technical advice is being sought from the National Office of the Internal Revenue Service.

(7) If the Internal Revenue Service is successful the IEEE would be required to pay interest at the rate of 6 per cent per year on any taxes from the original due date thereof.

We have been informed that it is unlikely that the Internal Revenue Service will approve the claims for refund and, accordingly, it will undoubtedly be necessary for us to take this matter to the federal courts to secure a final adjudication. It is the intention of the management of the IEEE to oppose vigorously the Internal Revenue Service on their stand since we strongly believe that it is incorrect. We feel that the annual exhibition is and has always been substantially and essentially in furtherance of the purposes of the convention and of the IEEE. It is extremely doubtful, however, that this court action can be initiated before the end of 1965, and the earliest we can hope to have any determination would be in the spring of 1966.

The IEEE membership should be aware that unless these two potential deficiencies—reduced advertising income and Federal income taxes—can be overcome, some other sources of revenue or an increase from the existent sources will be required to generate the funds to balance the budget.

In view of this situation, I have recently appointed a special committee of your Directors to study the long-range financial trends of Institute operations. This committee consists of Vice President Shepherd, Chairman; Vice President Blackmon, Secretary Pratt, Treasurer Herwald, and Past President Linder. This committee will make an initial report to the Board of Directors in August of this year. The members of the Institute will be informed in these pages of the results of this study.

Report of the Secretary—1964

Haraden Pratt

To the Board of Directors
The Institute of Electrical and
Electronics Engineers, Inc.

Gentlemen:

The Report of the Secretary for the year 1964, the second year of operations of the merged IEEE, is presented herewith.

Your attention is directed to the growth of 3.2 per cent in membership grades above the Student grade. A reduction of 16 per cent in student membership offsets this gain resulting in a slight drop of total membership during the year.

Attendance at the International Convention declined with a reduction in the number of exhibitors. Attendance was off 11 per cent and exhibits were down 26 per cent from the peak year of 1962. However, over that same period of time, space occupied went up 5 per cent and the number of papers presented increased 10 per cent.

During the year, the space on the main floor of the Engineering Center, which had been reserved for the new computer, was prepared to receive this machine, which was installed and placed in operation for personnel training and programming preliminary to regular functioning early in 1965. Also, two additional floors in the building were fitted out so that the staff and facilities at the Fifth Avenue buildings could be moved shortly after the first of the year.

There appear to be no unresolved organizational problems brought about by the merger requiring preferred attention and the energies of your Staff can now be devoted to better and more efficient operations for the future welfare of the Institute.

Respectfully submitted,
Haraden Pratt
Secretary

February 28, 1965

Section A—Membership

Table I gives the distribution of the membership by grade and by percentage and Table II gives the geographical distribution. Of a total of 3772 life members, 513 are contributors to the Life Member Fund, and 3259 are noncontributors.

Section B—Section and Subsection activities

At the end of 1964, the number of IEEE members residing in 102 countries around the globe was 153,978. Of these, all but 3567 lived within the territory of an IEEE Section or Subsection. The distribution of Sections and Subsections is indicated in Table III.

I. IEEE membership by grade, by percentage, December 31, 1964

Grade	Number of Members	Percentage
Honorary (H)	8	
Fellow (F)	2,595	1
Senior Member (SM)	26,182	17
Member (M)	87,435	57
Associate (A)	13,682	9
Student (S)	24,076	16
Total	153,978	100

II. Geographical IEEE membership distribution, December 31, 1964

Region	Number of Members	Percentage
1	39,005	25
2	25,881	17
3	13,564	9
4	17,748	12
5	12,896	8
6	30,456	20
Subtotal	139,550	91
U.S. possessions	...	
U.S. overseas military	818	1
Subtotal	818	1
7	6,597	4
8	3,438	2
9	3,575	2
Subtotal	13,610	8
Grand total	153,978	100

III. Distribution of Sections and Subsections

	Sections	Subsections
United States	151	64
Canada	16	1
Abroad	16	
Total	183	65

A major activity of many Sections and the larger Subsections is the publication of a local monthly Bulletin to fulfill the need for announcing to the Section member the increasing activities of the Section, including (1) Section Meetings, (2) Group Chapter Meetings, and (3) Technical Group Meetings. Fifty-seven of the Sections and Subsections now issue these monthly publications.

The number of meetings reported to Headquarters during the year was 1262 by Sections, 338 by Subsections, 865 by Group Chapters, and 325 by Technical Groups, for a total of 2790 local meetings.

Section C—Report of technical activities (Groups and related activities)

1. Mergers and new groups. If the 1963 report of technical activities was characterized by the gross picture of the merging of two great societies to form the IEEE, 1964 has been characterized by the detailed merging of the technical entities.

The 35 Groups in being on January 1, 1965, might be divided into three categories: (1) those inherited from IRE and unchanged by any merger with a former AIEE entity; (2) those that are a merger of a former IRE Group with one or more former AIEE Technical Committees, and, in one case, with an entire Division; and (3) new Groups formed by the transition of Technical Committees, or Divisions, to Group status. The year 1964 saw one other merger development of equal significance to those mentioned above; namely, the merging of mature, established Groups. Four Groups—Aerospace, Aerospace and Navigational Electronics, Military Electronics, and Space Electronics and Telemetry—have developed a detailed plan for merger; the four Administrative Committees individually adopted the plan and the Groups' membership are currently balloting (over 95 per cent favorable) on adopting and implementing the plan. Several other Groups with related technical interests are examining the possibility of merger; and the five Groups interested in communications are coordinating their overall plans through a Council, established as a subcommittee of the Groups Committee.

2. Group membership. A simple measure of the vigor of the IEEE Groups is the count of members, regular and Student, and Affiliates. The consequences of the difficulties of merging AIEE and IRE membership lists at the management level must have contributed in large measure to the setback in the growth of Group membership that was apparent in 1963. A distinct resurgence in the last third of 1964 has brought membership levels back approximately to the December 1961 levels. This is no cause for complacency, however, because if the annual rate of growth for the five-year period ending December 1961 were projected to December 1964, the IEEE Groups would still be found to be lagging. Neglecting this projected growth, one may find some interesting characteristics in the pattern of memberships for the three categories of Groups previously described. The Groups that have not merged with any Technical Committee or Division have memberships slightly below the 1961 level. The second category, Groups that merged with a Technical Committee or Division, average 5 to 10 per cent above the 1961 level. In the third category, two of the new Groups have been in existence long enough to show meaningful membership data. The Aerospace Group started with about 300 members from its origin in AIEE and has had more than a fivefold increase. The Power Group has passed 7000 members and, incidentally, has acquired more Chapters (50) than any other Group. If one adopts the member–subscriber list for the former bimonthly, POWER APPARATUS AND SYSTEMS, as being equivalent to the voluntary decision to join the Group and pay the annual fee, then the Power Group has seen a more than threefold increase. The experiences of the Aerospace and Power Groups deserve special attention because mergers of Technical Committees or Divisions with existing Groups appear to have produced only modest influxes of new members.

3. Evaluation—publications and meetings. Statistics on publications, major meetings and conferences, and Student Branches appear elsewhere in this Report. In the last part of 1964, some penetrating questions have been raised concerning the quality and timeliness of papers published in the Groups' TRANSACTIONS. The relation of paper publication to proper presentation at a conference and the criteria and procedures for accepting papers either for publication or for conference presentation are involved in these questions. The premerger Groups handled publications and conferences quite differently than did the premerger Technical Committees and Divisions. Another unanswered question from 1964 is whether those Groups that now encompass former Divisions in their entirety should continue to follow the Division practices. Answers for the questions will be sought in 1965 through the joint efforts of the Technical Activities Board and Editorial Board, and the Officers and Directors.

Progress was made toward clarification of the role of Groups in sponsoring conferences on special technical subjects and the role of Sections (and Regions) in sponsoring so-called general meetings. A simplified set of rules and procedures has been developed whereby the IEEE, through the General Manager, will control the general course of its diversified activities, while permitting the greatest possible flexibility and adaptability. IEEE's strength lies in its members. IEEE must be prepared to accept innovation and to prosper with the continuously changing pattern of member interest and activities.

4. Technical Operations Committee (TOC). At their September 23, 1964, meeting, IEEE's Executive Committee authorized establishment of a Technical Activities Board (TAB) to be effective January 1, 1965; and appropriate changes in IEEE Bylaws were made by the IEEE Board at their meeting in October. The new TAB is based on consolidation of the technical activities conducted by the organizational entities of the Technical Operations Committee (TOC) and by the Groups Organization. A consolidated Technical Activities Secretariat has been organized to serve TAB under the direction of Dr. Richard M. Emberson, formerly Groups Secretary.

The new TAB Organization was under way by mid-1963 and continued through December 1964 and included the participation by TOC's six General Committees [including the IEEE Standards Committee with its ten Ad Hoc Committees and jurisdiction over 23 Technical Committees (Standards) and their 112 Subcommittees] plus its six Divisions consisting of 69 Technical Committees and 320 Subcommittees.

TOC's Technical Committees and Subcommittees have continued to be active through 1964 in the technical programs presented at IEEE's International Convention, the National Electronics Conference (NEC) in Chicago, and the Winter Power Meeting. Many of the Committees and Subcommittees have been responsible for the 1964 program of 40 Special Technical Conferences sponsored either solely by TOC entities or jointly with Groups or with associated societies. Many of the Conferences published Proceedings.

The IEEE Standards program continued under the coordination of the Standards Committee and the Standards-generating entities of the Technical Committees and Groups. During 1964, 16 IEEE Standards were published, and five were in process of balloting as the year ended. In addition, 46 Standards proposals were submitted to IEEE by outside organizations for our concurrence. Two Recommended Practice documents, "Electric Systems for Commercial Buildings (IEEE 241)" and "Electric Power Distribution for Industrial Plants (IEEE 141)" were published. Staff work was begun on an alphabetically arranged volume of "Definitions of Electrical Terms," which IEEE will publish.

5. The Joint Technical Advisory Committee (JTAC). The Joint Technical Advisory Committee, sponsored by IEEE and EIA (Electronic Industries Association), held a total of six meetings during 1964. The Sixteenth Anniversary Dinner was held in May 1964 at the Waldorf-Astoria Hotel, New York City.

5.1 Radio Spectrum Administration—Subcommittee 62.1. Under the chairmanship of Philip F. Siling, JTAC set up a Subcommittee to revise its 1952 publication "Radio Spectrum Conservation," together with its 1959 Supplement, taking present-day and future needs of spectrum conservation into consideration. Mr. Siling was assisted by a host of eminently qualified experts and "Radio Spectrum Utilization, 1964" is now available.

5.2 Electromagnetic Compatibility—Subcommittee 63.1. Since 1961 JTAC has endeavored to stimulate the interest of engineers associated with nonmilitary items in the increasing technical and economic problems of their own electromagnetic compatibility. In November 1963, JTAC established a Subcommittee on Electromagnetic Compatibility, under the chairmanship of Richard P. Gifford, to explore pertinent areas and to initiate educational and remedial studies. This Subcommittee will submit a Progress Report to the Office of Emergency Planning early in 1965.

5.3 Microwave Relay System Reliability—Subcommittee 63.2. In FCC Docket No. 15130, adopted July 24, 1963, the FCC referred to an earlier JTAC report submitted by request in which JTAC recommended FCC adoption of a policy permitting use of frequency diversity in all cases except where local interference would result. JTAC recommended that a carrier frequency separation of at least 5 to 10 per cent should be maintained to obtain full benefits of the use of frequency diversity. The Docket further stated that although JTAC provided the Commission with pertinent analysis and commentary on the relative merits of diversity techniques, the Commission still lacked sufficient data to permit the issuance of considered opinions on this method of achieving reliability, at the cost of spectrum space. JTAC established a Subcommittee on Microwave Relay System Reliability, under the chairmanship of Dr. William H. Radford, in November 1963 to reply to Docket No. 15130. Membership is composed of representation from the user group, equipment manufacturers, and the research area. A liaison representative from the FCC attended the four meetings held during 1964. A report will be submitted to the FCC early in 1965.

5.4 Mobile Radio Services—Subcommittee 64.1. On March 26, 1964, the FCC adopted Docket No. 15398 and terminated its inquiry into the allocation of frequencies between 25 and 890 Mc/s. This Docket is an inquiry into the optimum frequency spacing between assignable frequencies in the land mobile service and the feasibility of frequency sharing by television and the land mobile service. It did not limit inquiries from interested parties but was "hopeful that technical groups such as the Joint Technical Advisory Committee (JTAC) and Electronic Industries Association (EIA) will respond . . ."

JTAC established a Subcommittee on Mobile Radio Services on May 21, 1964, under the chairmanship of Dr. John A. Pierce, to respond to this Docket and resolved that "... while Section 4 has been called to JTAC's attention, Section 4D should have priority." JTAC considered that in order to submit a comprehensive report, the individual interests of both the television broadcasters and the land mobile services are necessary. Frank Marx of ABC and Waldo A. Shipman of Columbia Gas System Service Corporation were appointed to head these two groups respectively, serving as vice chairmen of the Subcommittee. In June 1964, JTAC advised the FCC that a study limited to channel sharing within the VHF television band would be only of limited value, and that it would be desirable to conduct the study throughout the entire allocated television spectrum, both UHF and VHF. Subcommittee membership has been drawn from both the television broadcasters and the land mobile service. Five meetings were held during 1964. It is anticipated that a report will be submitted to the FCC by April 1, 1965.

6. The International Radio Consultative Committee (CCIR). The Executive Committee of the U.S. National CCIR held five meetings during 1964, at which the U.S. Study Group chairmen submitted progress reports. Major attention has been given to detailed preparation for the 1965 Plenary Assembly, and the U.S. responses to studies formulated at the Xth Plenary Assembly are being submitted to the International study groups prior to submission to the XIth Plenary Assembly.

7. The International Scientific Radio Union (URSI). The U.S. National Committee of the URSI held two meetings during the Spring URSI/IEEE Meeting at the NAS, Washington, D.C. Together with The American Geophysical Union and The American Astronomical Society, URSI jointly sponsored a Symposium on Solar-Terrestrial Relationships, held at the Department of the Interior Auditorium, Washington, D.C., April 20 and 21, 1964.

8. The IEEE Intersociety Relations Committee. The IEEE Intersociety Relations Committee met five times during 1964.

One of the ISRC's major efforts is the evaluation of IEEE participation in the activities of outside organizations. During 1964 a systematized method of appointing IEEE representatives to outside organizations was formulated. This policy on appointment included the recommendation of a Headquarters file on all appointees, which would include a yearly report by each representative on the activities of each respective committee.

The ISRC, in coordination with the Education Committee, is in the process of recommending amendments to the Constitution and Rules of Procedure of the Engineers' Council for Professional Development. It is estimated that this study will be completed early in 1965.

To assure uniformity in joint conferences, the ISRC was instrumental in drawing up a "Model Charter for Intersociety Conferences." It recommended that all future intersociety conferences be based on this "model charter."

The ISRC is working closely with the State Department in order to set up guidelines that will enable earlier issuance of visas to facilitate the attendance of Russian engineers at major IEEE conventions. This work is being done in conjunction with the Russian Popov Society.

The IEEE, on recommendation from the ISRC, appointed representatives to 22 organizations during 1964.

Currently the ISRC is preparing a proposed policy on the use of IEEE membership lists for recommendation to the Executive Committee.

Section D—Report of editorial activities, 1964

General. In contrast to 1963, which was a year of study and deliberation regarding future editorial plans, 1964 was a year of action and change. Without a doubt, the highlight of the year was the January appearance of IEEE SPECTRUM. This new magazine, which is general in nature and primarily educational in content, serves the entire IEEE and goes to all members with the exception of Student members. After only a year of publication, SPECTRUM has firmly established itself as a major integrating and unifying force for the IEEE and the electrical and electronics engineering profession.

Also of major import was the implementation of the decision to continue the PROCEEDINGS OF THE IEEE by placing it on a paid subscription basis. It is encouraging to note that the 1964 subscriptions to this research-oriented journal were in excess of 55,000.

Considerable progress was made during the year in merging the former publications of the AIEE and IRE. Several new Group TRANSACTIONS were established in areas not previously served by this publication medium. At the same time, all former publications, with the exception of ELECTRICAL ENGINEERING, were continued without interruption or substantial change in character or quantity. ELECTRICAL ENGINEERING was discontinued, having been replaced by SPECTRUM.

The total 1964 IEEE editorial program, excluding the translated journals, resulted in the publication of more than 2100 papers and 1000 letters, for a total of over 23,000 editorial pages during the year. This last figure represents a slight increase in the number of pages published in journals and a decrease in the pages of preprinted papers.

To keep the Editorial Board in close touch with the complex and expanding editorial activity of the IEEE, a Board member was given responsibility to oversee and report on each of the following: PROCEEDINGS, SPECTRUM, Group TRANSACTIONS, translated journals, STUDENT JOURNAL, and information retrieval. Boards of Consultants, modeled after that in existence for the STUDENT JOURNAL, were established under the Editorial Board member responsible for PROCEEDINGS and SPECTRUM.

The year 1964 saw the retirement of Charles S. Rich from the Headquarters editorial staff after 34 years of dedicated service to the AIEE and the IEEE. He carried with him the esteem and best wishes of his many friends and associates.

Proceedings of the IEEE. The policy of publishing high-level, research-oriented papers of broad interest in the PROCEEDINGS was continued. Although the philosophy was adapted that the coverage of this journal be expanded to include all areas pertinent to the IEEE, few nonelectronics papers were submitted for consideration during 1964. The year was highlighted by the appearance of two special issues dedicated to the thriving fields of Cryogenic Electronics and Integrated Electronics and one special issue covering all phases of Project West Ford.

The number of regular papers submitted for publication consideration during 1964 and their disposition remained about the same as in the past, viz., 281 papers were received of which 31 per cent were accepted, 32 per cent were referred to the TRANSACTIONS Editors for consideration, and 37 per cent were rejected. The number of letters published showed a modest increase, being 513 as compared to 506 for 1963, and 407 pages were devoted to this quick method of announcing important research results.

During the year the PROCEEDINGS carried a total of 1845 editorial pages and 659 pages of advertising and other noneditorial material, making a grand total of 2504 pages published.

IEEE SPECTRUM. The 1964 editorial year began with a flourish with the successful launching of IEEE SPECTRUM in January. During late 1963 and early 1964, the Headquarters editorial staff was augmented by an art director and two staff writers to make this major undertaking possible.

The majority of the 69 articles published in SPECTRUM were solicited from authors acknowledged to be outstanding in the various subject areas covered. A few articles were voluntarily contributed and three were staff written. Of the 2560 pages published, 1389 were devoted to technical and editorial matter and 1171 consisted of advertising and other noneditorial material.

TRANSACTIONS. The TRANSACTIONS, both Bimonthly and Group, again encompassed a major share of the IEEE publication activity. During 1964 there were 31 Groups which published TRANSACTIONS, and these accounted for 114 issues totaling 12,119 pages. These figures include the publication output of the Power Group, which was formed from a TOC Division on July 1, 1964.

The three Bimonthly TRANSACTIONS produced 19 issues made up of 3020 pages. These figures do not include those issues of the IEEE TRANSACTIONS ON POWER APPARATUS AND SYSTEMS published after the formation of the Power Group, but do include an 880-page Special Supplement to that TRANSACTIONS, which was printed to eliminate the 1963 backlog of papers.

It is worthy of note that this year two TRANSACTIONS, those of the Electron Devices Group and the Power Group, became monthly publications.

IEEE Student Journal. The bimonthly student magazine of the IEEE continued to serve the Student membership during 1964. It provided its more than 25,000 readers with 288 pages of technical and other career information, including 43 articles.

Translated Journals. The IEEE continued its program of translating and publishing four Russian and two Japanese technical journals. This program is carried out with the support of the National Science Foundation. The year 1964 saw the appearance of 4308 pages translated from the Russian and 1394 pages from the Japanese. Advance tables of contents of issues to be translated were carried in SPECTRUM, as were signed critical reviews of selected papers which had been published.

Special Publications and Preprints. The papers presented at the IEEE International Convention held in New York in March resulted in publication of a ten-part CONVENTION RECORD totaling 2577 pages, as compared to the 1963 total of 1988 pages.

In addition, eight Special and Technical Conference Publications were issued comprising 1156 pages. Finally, a total of 217 papers, amounting to 3312 pages, were individually preprinted in photo-offset form for six meetings and conferences.

Section E—Major meetings and conferences

The IEEE, its Regions, Sections, and Groups, sponsored or cosponsored 85 major technical meetings and conferences during 1964. The high point of the year was the annual International Convention in March, which attracted 66,541 members and visitors to New York for a five-day program of technical papers and four days of exhibits.

Section F—Student Branches

Eleven Student Branches were established during 1964, raising the total to 270, 17 of which are in Canada and six in Latin America and Europe. The new Student Branches and the IEEE Sections in which they are located are as follows: University of California, Los Angeles (Santa Monica Bay), California Western University (Santa Monica Bay), Eastern Ontario Institute of Technology (Ottawa), Escuela Tecnica Superior de Ingenieros de Telecomunicacion (Spain), Franklin University (Columbus), Grove City College (Sharon), Manitoba Institute of Technology (Winnipeg), Northern Alberta Institute of Technology (Northern Alberta), Pennsylvania Military College (Philadelphia), Queen's University (Bay of Quinte), and Sacramento State College (Sacramento).

Price Waterhouse & Co. audit report

Price Waterhouse & Co.

60 Broad Street
New York 10004
March 9, 1965

To the Board of Directors of
The Institute of Electrical and Electronics
Engineers (Incorporated)

In our opinion, subject to the final determination of the Institute's income tax liability, if any, as referred to in Note 3, the accompanying statement of financial position, the related statement of income and operating fund and the statement of changes in restricted funds present fairly the financial position of The Institute of Electrical and Electronics Engineers (Incorporated) at December 31, 1964 and the result of its operations for the year, in conformity with generally accepted accounting principles applied on a basis consistent with that of the preceding year. Our examination of these statements was made in accordance with generally accepted auditing standards and accordingly included such tests of the accounting records and such other auditing procedures as we considered necessary in the circumstances.

Price Waterhouse & Co.

THE INSTITUTE OF ELECTRICAL AND ELECTRONICS ENGINEERS (INCORPORATED)

COMPARATIVE STATEMENT OF FINANCIAL POSITION

	December 31, 1964	December 31, 1963
Operating Fund		
Current assets:		
Cash	$1,228,256	$ 565,111
Marketable securities, at cost, market value $3,485,000 (1963—$3,280,000)	2,469,762	2,489,552
Accounts receivable, net of provision for doubtful accounts	179,849	130,660
Note receivable, current portion	31,824	128,279
Prepaid expenses, inventory, etc.	279,668	300,230
Total current assets	4,189,359	3,613,832

Less—Current liabilities:		
Accounts and accrued expenses payable	704,448	547,106
Funds held for the use of professional groups	407,114	255,049
Deposit received on sale of real property	215,000	
	1,326,562	802,155
Deferred income:		
Dues	1,068,204	567,715
Subscriptions	408,819	388,606
Convention	620,575	544,190
Other		4,904
	2,097,598	1,505,415
Total current liabilities	3,424,160	2,307,570
Working capital	765,199	1,306,262
Note receivable, 6%, installments due after 1965	121,656	
Fixed assets:		
Land and buildings, at cost (Note 4)	1,641,455	1,641,455
Office equipment and leasehold improvements, at cost, less accumulated depreciation and amortization $336,958 (1963–$263,041) (Note 4)	533,089	427,982
	2,174,544	2,069,437
Operating fund balance (accompanying statement)	3,061,399	3,375,699
Property Fund		
Advance to United Engineering Trustees, Inc. (Note 2)	265,000	265,000
Restricted Funds		
Cash	63,797	53,858
Marketable securities, at cost, market value $148,300 (1963—$141,000)	98,231	97,718
Restricted funds balance (accompanying statement)	162,028	151,576
Total funds	$3,488,427	$3,792,275

THE INSTITUTE OF ELECTRICAL AND ELECTRONICS ENGINEERS (INCORPORATED)

COMPARATIVE STATEMENT OF INCOME AND OPERATING FUND

	For the year ended December 31, 1964	1963
Income:		
Membership entrance fees and dues	$1,912,743	$1,868,407
Advertising	1,392,744	1,397,263
Convention and technical conferences	1,127,145	1,106,008
Subscriptions and publications	1,118,428	723,532
Investments, including gain on sale of securities	210,090	105,753
Miscellaneous other	63,248	83,521
Total income	5,824,398	5,284,484
Expenses:		
Exclusive of salaries shown below:		
Section, group, and branch support	376,999	383,159
Advertising sales	441,287	438,242
Publication printing and sales items	1,366,045	1,452,375
Convention and technical conferences	848,641	902,059
General and administrative expenses	978,147	1,054,173
Salaries	1,589,579	1,478,585
Total expenses	5,600,698	5,708,593
Excess of income over expenses for the year	223,700	(424,109)
Less—Special charges:		
Provision for computer installation and record conversion	196,000	
Provision for relocation and disposal costs (Note 4)	167,000	
Contribution to United Engineering Trustees, Inc. (Note 4)	175,000	
	538,000	

Income (expenses) for the year and, in 1964, special charges transferred to operating fund	(314,300)	(424,109)
Operating fund balance, January 1	3,375,699	3,799,808
Operating fund balance, December 31	$3,061,399	$3,375,699

THE INSTITUTE OF ELECTRICAL AND ELECTRONICS ENGINEERS (INCORPORATED)

STATEMENT OF CHANGES IN RESTRICTED FUNDS FOR THE YEAR ENDED DECEMBER 31, 1964

Restricted fund	Fund balance January 1, 1964	Receipts from contributions and marketable securities	Disbursements for awards and related costs	Fund balance December 31, 1964
Life Member Fund	$ 55,051	$10,089	$ 745	$ 64,395
International Electrical Congress—St. Louis Library Fund	6,685	138	137	6,686
Edison Medal Fund	12,469	990	547	12,912
Edison Endowment Fund	8,254	267		8,521
Lamme Medal Fund	9,331	345	315	9,361
Mailloux Fund	1,087	47	43	1,091
Volta Memorial Fund	20,168	782	1,750	19,200
Kettering Award Fund	2,273	43		2,316
Browder J. Thompson Memorial Prize Award Fund	5,480	140		5,620
Harry Diamond Memorial Prize Award Fund	1,070	40		1,110
Vladimir K. Zworykin Television Award Fund	5,233	112		5,345
W. R. G. Baker Award Fund	8,588	390		8,978
William J. Morlock Award Fund	5,044	185		5,229
W. W. McDowell Award Fund	10,088	371		10,459
William D. George Memorial Fund	755	50		805
Total	$151,576	$13,989	$3,537	$162,028

NOTES TO FINANCIAL STATEMENTS

NOTE 1: The unfunded past service liability at December 31, 1964 under the Institute's noncontributory pension plan for its employees was approximately $106,300.

NOTE 2: In accordance with a Founder's agreement between the Institute and the United Engineering Trustees, Inc. the Institute has agreed to permanently maintain its principal offices in the United Engineering Center, which in 1965 will involve a lease payment of approximately $180,000. The $265,000 advanced to United Engineering Trustees, Inc. is repayable only out of available reserve funds on dissolution of United Engineering Trustees, Inc. and carries interest at an annual rate of 4%.

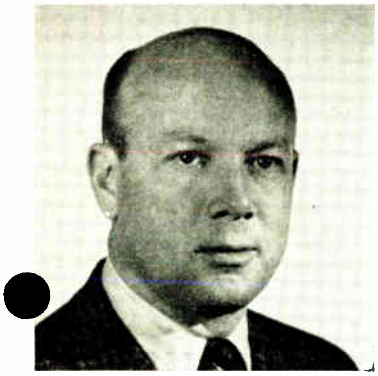
NOTE 3: On February 20, 1964 the Institute was notified by the Internal Revenue Service that the Institute's annual convention involved the operation by the Institute of an unrelated trade or business and that the net income therefrom, if any, is subject to federal tax. If the Service's position, which is applicable to 1954 and subsequent years, were ultimately sustained, the amount of potential liability for taxes and interest would be material.

The Institute has filed a tax return with respect to the test-year 1954 and a claim for refund in the amount of the taxes shown to be due thereon. The Institute intends, through its legal counsel, to continue to contest the imposition of the proposed tax until a final judicial determination is made.

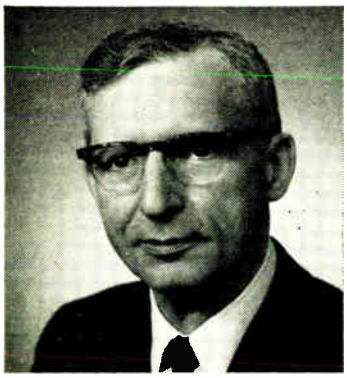
NOTE 4: On February 5, 1965 the Institute sold its three buildings located at 79th Street and Fifth Avenue, and is in the process of selling the furniture and other equipment which had been located in these buildings. The Institute has provided $167,000 to cover the cost of moving its personnel and remaining assets from these buildings to the United Engineering Center, and to cover its expected loss on the assets being sold. In addition, the Institute contributed $175,000 to the United Engineering Trustees during 1964 to reflect its share of the capital costs in proportion to the increased membership resulting from the merger of AIEE and IRE.

Authors

David B. Miller (M) received the A.B. degree in physics in 1952 from Colgate University and the M.S. degree in physics in 1953 from the University of Michigan. In 1953 he joined the General Electric Company in Schenectady, where he worked on the development of gas-discharge devices, and in 1954 he transferred to the X-Ray Department in Milwaukee, where he did design and development work on high-voltage X-ray, electron-beam, and gas-discharge tubes. In 1956 he resumed his graduate studies at the University of Michigan while working as assistant research engineer at the university's Research Institute. He received the M.S.E. degree in 1960 and the Ph.D. degree in 1961, both in electrical engineering. Since 1961 he has been with General Electric's Missile and Space Division, where he is concerned with research and advanced development studies of electromagnetic plasma propulsion systems. He is also adjunct professor at Pennsylvania State University's Graduate Engineering Center, King of Prussia, Pa.



T. J. Schultz attended the University of Rochester's Eastman School of Music, University of Missouri, University of Texas, and the U.S. Naval Academy. He received the M.S. degree in 1947 and the Ph.D. degree in 1954, both in acoustics, from Harvard University. Prior to joining Bolt Beranek and Newman Inc. in 1960, he served as an instructor at the U.S. Naval Academy, research physicist at the Naval Research Laboratory, instructor and research fellow in acoustics at Harvard, and assistant chief of the Acoustics Section at Douglas Aircraft Company. He has worked in the fields of acoustical instrumentation, architectural acoustics, and electromechanoacoustic transduction theory and application, and in problems of autocorrelation and cross correlation. He has been a consultant to various firms in such areas as electronics and acoustics, calibration and testing of phonograph pickups, and design of aircraft soundproofing. He is a Fellow of the Acoustical Society of America and a member of Tau Beta Pi, Eta Kappa Nu, and Sigma Xi.



C. Concordia (F) has been with the General Electric Company since 1926, and is at present consulting engineer with the company's Electric Utility Engineering Operation. His work has been concerned principally with the dynamic analysis of electric machinery, interconnected power systems, and automatic control systems, including power system voltage, speed, tie-line power, and frequency control. In particular he has been active in the application of analog and digital computers as aids in the solution of these and other engineering problems in such diverse fields as centrifugal compressor aerodynamic design and power system transient overvoltages. He is the recipient of General Electric's Coffin Award (1942) for his contributions to the analysis of wind-tunnel electric drives and AIEE's Lamme Medal (1962) for his achievements in the development of electric machinery.

Mr. Concordia holds six patents and is the author of more than 70 technical papers and of a book on synchronous machines.

George P. Rodrigue (M) is a research staff consultant in the research section of the Sperry Microwave Electronics Company in Clearwater, Fla. He joined the company in 1958 as a senior staff engineer and was assigned to studies of parametric amplification. At the present time he is primarily concerned with solid-state materials and their applications to microwave components. He received the B.S. degree in physics in 1952 and the M.S. degree in physics in 1954 from Louisiana State University, and the Ph.D. degree in applied physics from Harvard University in 1958. Prior to joining Sperry he was engaged in research work on the preparation and resonance properties of garnet materials and on formation of ohmic and rectifying contacts to silicon.

Dr. Rodrigue has had a number of papers published in technical journals and has a patent pending on low-noise parametric amplifiers. He is a member of Sigma Pi Sigma and Sigma Xi.

What keeps SYLVANIA ahead of the other 95%? = Engineers who keep ahead of the other 95%.

(In 1964 General Telephone & Electronics Corporation ranked 25th among 500 DOD prime contractors engaged in research, development and test work. Sylvania Electronic Systems provides government systems management for GT&E.)

Our engineers enable us to successfully compete for a major share of new contracts based on their diverse electronic capabilities . . . from initial research to installation and training services . . . designed to meet government defense and space requirements.

In turn, SES management strives to fulfill a two-fold responsibility to the engineering staff—by supporting all necessary activities focused on the acquisition of important new contracts . . . and by providing a working environment that frees each engineer to concentrate his talents and professional interests on his assignment—without needless administrative or procedural distractions. Cross-fertilization of ideas, so important to the success of major programs, is enhanced by the organization of our labs into small informal groups. Overall, SES has an environment which has inspired a record of important achievements, with more impressive ones on the way.

Our list of current projects and assignments reads like a who's who of major military and government funded electronics programs. Their diversity is just as meaningful as their individual importance. (It takes both to stay ahead of the other 95%.) At present they include: ground electronics equipment for Minuteman missile sites • research and development in electronic warfare field • electronic security systems • ASW systems • special purpose airborne computers for incorporation into U.S. Air Force large scale electronic systems • laser systems • design of spaceborne electronic and optical systems for the Orbiting Astronomical Observatory.

Opportunities at All Locations of Sylvania Electronic Systems

ADVANCED SYSTEMS PLANNING
(Suburban Boston). Defines opportunities and prepares plans for business in new markets and product areas.

Appointments in: Communications Switching • Communications Theory • Space Information Handling Systems.

The APPLIED RESEARCH LABORATORY
(Suburban Boston). Central Research Facility at Waltham, Mass.

Research Assignments in: Pattern Recognition Techniques • Laser Research & Applications • Research in Communications Techniques • Physics of Radio Propagation • Computer Systems.

CENTRAL OPERATION
(Suburban Buffalo). Laboratories in Williamsville, N. Y. Production facilities in Buffalo, N. Y.

R&D Assignments in: Weapon System Communications • HF Communications Systems • Microwave Communications Systems • Communications Systems Requirements Analysis.

EASTERN OPERATION
(Suburban Boston). Laboratories at Waltham and Needham, Mass. Production facilities at Muncy, Pa. and Needham, Mass.

R&D Assignments in: Radar & Sensor Systems & Techniques • R & Digital Microcircuitry • Antenna Systems • Command & Control Systems • Advanced Information Systems Design • Machine Language, Management Information Systems, Real Time Systems & Analysis • Digital Computers • Systems Simulators & Trainers • Communications Switching Systems • Display & Instrumentation Systems • Digital Control Systems.

PRODUCT SUPPORT ORGANIZATION
(Suburban Boston). Headquarters at West Roxbury, Mass.

Technical Assignments (domestic and overseas) in support of present and future electronic systems including all phases of: Siting • Installation • Operation • Spares Provisioning • Logistics • Checkout • Integration • Maintenance • Training.

WESTERN OPERATION
(Suburban San Francisco). Laboratories at Mountain View, Calif. Production facilities at Santa Cruz, Calif.

R&D Assignments in: Electronic Warfare & Collection Systems • Geophysics Propagation (Acoustics) • Missile Analysis • ECM Systems • Signal Identification Systems • Operational Analysis • Broadband Antenna Systems • Signal Processing (Servo) Systems • Transmitter, Transceiver & Receiver Systems • Microwave Device Development • Laser Systems.

Please forward your resume indicating location and specialty area of interest, to Manager of Professional Staffing, Dept. 10F, Sylvania Electronic Systems, Division of Sylvania Electric Products Inc., 40 Sylvan Road, Waltham, Mass. 02154.
An Equal Opportunity Employer.

Please advise us if you wish to receive the latest issue of "The SCANNER" . . . Sylvania's internal publication designed to keep technical staff members abreast of developments in the military and space electronics fields.

GT&E

GENERAL TELEPHONE & ELECTRONICS
Total Communications from a single source through

SYLVANIA ELECTRONIC SYSTEMS