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IEEE spectrum

features

departments

THE INSTITUTE OF ELECTRICAL AND ELECTRONICS ENGINEERS, INC.

IEEE spectrum

the cover

This month's cover illustration is a representation of the way a portion of the sky would appear if our eyes were sensitive to radio waves rather than to light. The contours indicate the equivalent brightness temperature of the sky background; the light and dark areas represent, respectively, strong and weak radio emission. Although the science of radio astronomy is only 33 years old, it has greatly increased our knowledge of the universe and changed many of our theories about it. Many of the remarkable advances in this field are described in the article by John D. Kraus beginning on page 78 of this issue.

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Reflections

75 years ago

Accumulators in Electric Lighting. "One of the commonest, and perhaps the simplest applications of accumulators to lighting work is found in their employment in connection with direct isolated plants in factories, office buildings, etc. In illustration of the method of applying accumulators in such cases, we may select as a type of this class of lighting one of those office buildings common in New York and other large cities. This building, we may assume, has already been, or is about to be, wired for 500 16-candle, 100-volt, ½-ampere lamps on the multiple-arc plan, and is to be provided with a 125-volt, 200-ampere dynamo; it being calculated that more than 400 lamps will rarely be lighted simultaneously. We are not specially concerned with the power plant, and will simply assume that it is of ample capacity, it being remembered that such buildings are usually steam heated, and therefore, offer favorable conditions for the operation of a plant of the character under consideration. Now it can be deduced from experience that, during the day, from say nine o'clock in the morning until about sunset, only a limited number of lights will be burned in certain dark corners of the building, and that as twilight and darkness come on the load will gradually increase, reaching a maximum at a certain hour depending upon the season; subsequently the load will decrease, finally reaching a minimum after the janitor and his assistants have finished their cleaning operations, which load will probably be maintained for the remainder of the 24 hours. It is evident that a direct plant operating under such conditions would necessitate the employment of two forces of men, either one or two in each, and would, moreover, be running under exceedingly uneconomical conditions for a large part of the time. Let us now consider in what manner accumulators may be added to this plant in order that it may supply the variable load for 24 hours daily, while at the same time dispensing with the services of one staff of men and reducing the running time of the engine to eight hours.

"It has been shown in a general way how the load varies during 24 hours; but in order to ascertain the capacity of the accumulators required, it will be necessary to assume, though only approximately, somewhat more precise figures. Say that the load is as follows:—

"From 9 P.M. to 9 A.M., 20 lamps = 120 ampere-hours.
"From 9 A.M. to 4 P.M., 200 lamps = 700 ampere-hours.
"From 4 P.M. to 6 P.M., 400 lamps = 400 ampere-hours.
"From 6 P.M. to 9 P.M., 50 lamps = 75 ampere-hours.

"An inspection of the above schedule shows that for 12 hours out of the 24, only 20 lamps, or 10 amperes, are used, while for three hours more only 50 lamps, or 25 amperes, are required; and a simple calculation proves that a set of accumulators having a capacity of 200 ampere-hours will be amply sufficient to maintain the light lamp load for 14 hours out of the 24. If the dynamo is started at 8 A.M. and operated until 6 P.M., while maintaining the required number of lamps during that period, it will still have surplus current for charging the battery as follows:—

"From 8 A.M. to 9 A.M., 190 amperes for 1 hour.
"From 9 A.M. to 4 P.M., 100 amperes for 7 hours.

or 890 ampere-hours, an available capacity vastly in excess of the requirements. Now, if during the eight hours in which the dynamo is operating, the accumulators are charged at the rate of 30 amperes, in that period they will receive a total charge of 240 ampere-hours. According to the schedule, the maximum output required from the battery will be 185 ampere-hours, whence it follows that the charge received by it is more than ample, even after making the customary allowance of 20 per cent for loss by conversion; and the desired result has been accomplished." (G. B. Prescott, Jr., "Some Methods of Regulating Accumulators in Electric Lighting," *Trans. AIEE*, vol. VI, Nov. 1888-Nov. 1889, pp. 439–485.)

50 years ago

Playing by Ear. "The use of a polyphase alternating current source to energize the oscillating circuits of a radio transmitter is not new in the art. Eisenstein in his patents has clearly shown how this may be accomplished. For example, in his United States Patent Number 991,837, filed in August 1905, he shows a three phase transmitting arrangement in which each phase energizes thru corresponding transformers three separate oscillating circuits having a common inductance directly connected in the aerial circuit. By this arrangement, Eisenstein hoped to accomplish several important results. First of all by greatly increasing the number of discharges per cycle in each phase, he desired to obtain a continuous or nearly continuous excitation of the antenna. This, he said, would enable him to use the arrangement for telephony. The greatly increased spark frequency meant a greatly increased total energy in the radiating circuit without an increase of the potential to which it would be charged. Eisenstein furthermore appreciated the many advantages to be obtained thru a satisfactory secrecy system. He claimed that he could produce this by using different wave lengths in the several discharge circuits, and that because of the high spark frequency (perhaps entirely beyond the limit of audition) the signals would be inaudible in a telephone.

"Eisenstein unquestionably had the correct idea. At that time, however, shock excitation methods had not been disclosed to the art. The open spark-gaps which Eisenstein of necessity had to employ made the success of his much cherished plan impossible.

"It was not until the year 1913 that

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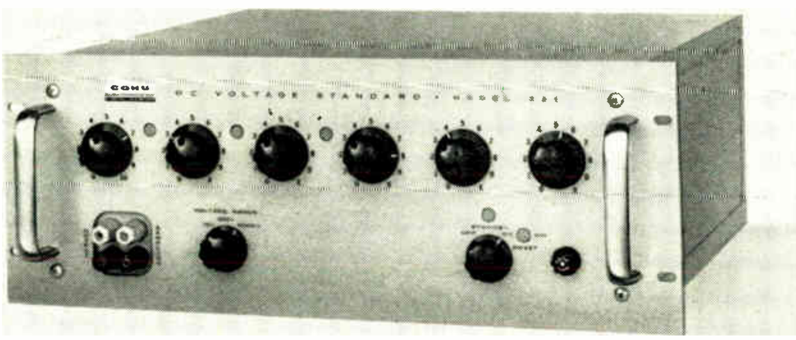
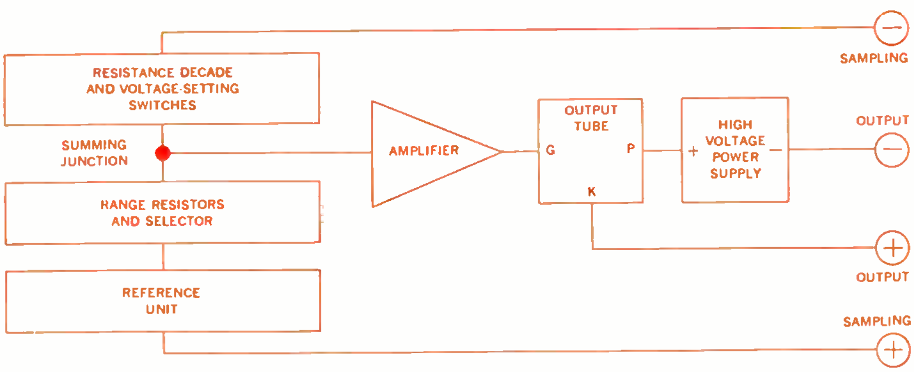


diagrammatic view:



engineer's view:

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For more information on advertisements use the reader service card an opportunity presented itself of thoroly demonstrating the practicability of employing a polyphase alternating current. Stirred on by a patent situation which apparently gave to one radio company the sole right to use a high spark frequency in the transmitter, in conjunction with practical methods of reception used today, a three phase, 500 cycle generator of 7.5 kilowatt capacity was constructed. Preliminary tests made in the laboratory with the use of a dummy aerial showed sufficient promise to warrant the making of further tests on a more extensive scale and in connection with a radiating antenna.

"Thru the courtesy of the Navy Department, a series of tests were conducted last November, using the New York Navy Yard antenna. The apparatus consisted of three 2 kilowatt panel radio transmitters each individually energized by the separate phases of the 7.5 kilowatt 500 cycle three phase generator. The primaries of the low frequency or power transformers were connected in delta for convenience. The secondary of each oscillation transformer was connected in series with the antenna and ground.

"As in almost every test of this kind there was some speculation as to the results that would be obtained. A casual inspection suggests at once that the effect of allowing these three practically independent quenched primaries to act on a single secondary oscillating circuit, will be to produce a 3,000 sparks per second tone in the telephone. The primaries would be expected to discharge 1-3000th second apart, and as the energy in all the primaries is immediately transferred to the common antenna circuit, there should be produced three sets of 1,000 spark wave trains evenly interspaced. It was expected that the maximum voltage produced by the three phases in the antenna circuit would be the same as that produced by one phase acting alone; and that the power input would be tripled, thus increasing by the $\sqrt{3}$ current produced by a single phase in the antenna circuit; and similarly for two phases that the tone would be 2,000 per second and the current increased by the $\sqrt{2}$.

"But as is usual in experiments of this kind, the preliminary speculations as to results and difficulties to be met were quite in error.

"The radiation did not increase in the ratio of $\sqrt{3}$, and the generator to antenna efficiency dropped from 61.9 per cent to 36.2 per cent. The sound produced in a wave meter telephone had no tone characteristic, but was arc-like in nature.

"It was at about this stage, that owing to the tester's inability to discriminate between a 500 and 1,000 spark tone, a set of observations was unintentionally made with the sets adjusted to the lower spark frequency. This series of observations gave a noticeably higher efficiency with the three phases operating together than any previous series of observations. The experienced ear of Mr. Frank Hinners, who was called in to check up the work, quickly noted the difference in pitch due to the diminished spark frequency. It was this fortunate mistake that at once suggested that the time interval between primary circuit discharges might affect the efficiency in some way or other." (E. J. Simon and L. L. Israel, "The Operating Characteristics of a Three Phase 500 Cycle Quenched Spark Transmitter," *Proc. IRE*, Sept. 1914, pp. 217–234.)

Inductive Interference. "The formation of the Joint Committee on Inductive Interference was the outgrowth of certain differences involving power, communication and railroad interests which were brought to the attention of the Railroad Commission of California. As an alternative to contesting the issue at that time it was agreed by the power and communication companies, with the approval of the Commission, that a joint investigation should be made to obtain certain information essential to a proper solution of the difficulties. The Commission desired that the matter be thoroughly investigated before passing upon the general principles involved in these difficulties. To this end a general conference was called to select representatives to form a 'Joint Committee' empowered to conduct test, experiments and investigations, the results of which would serve as a basis of recommendations for rules and regulations, to be issued by the Commission, tending to minimize inductive interference and physical hazard arising from parallelism of different classes of circuits. This conference was held December 16, 1912. As a result, the Joint Committee on Inductive Interference, representing the Railroad Commission and railroad, power, and communication interests of the State, was organized and authorized by the Railroad Commission of California to conduct the desired investigation.

"The following paragraphs summarize very briefly the principal results accomplished to date. These statements of results are accompanied by brief explanatory comment upon the conclusions reached. The reasons for and explanations of these conclusions are given in more detail in the appendices to which reference is made.

"*1. Interference to telephone circuits under normal operating conditions of power circuits arises almost wholly from the harmonic voltages and currents of the power systems.*

"This is due chiefly to the fact that the frequencies of the harmonics generally present in the voltages and currents of power systems cover a considerable portion of the range of the voice frequencies, particularly those frequencies at which telephone instruments and the human ear are of maximum sensibility. Extraneous currents of frequencies approaching the average voice frequency have a more injurious effect upon telephone conversation than currents of lower frequencies.

"*2. The effect of induction of the fundamental frequency on telephone circuits is comparatively unimportant unless it is of magnitude sufficient to constitute a physical hazard.*

"This is due to the fact that the fundamental approaches to the lower limit of audible frequencies, at which the telephone and the human ear are not efficiently responsive.

"*3. Interference to telegraph and other signaling circuits is due principally to the fundamental and lower harmonics.*

"Telegraph receiving instruments are relatively insensitive, as compared with the telephone, to the higher harmonics, but are sensitive to disturbances of lower frequencies, such as the fundamental and lower harmonics which more nearly approach the normal operating frequency of such circuits.

"*4. The power circuit currents and voltages may be divided into two factors: balanced and residual, of which, for equal magnitudes, the latter in general produce the greater inductive interference.*

"Residual currents and voltages act inductively in a similar manner to single-phase currents and voltages acting in a circuit composed of the line conductors in parallel with earth return, which is a condition favorable to very large induction. Moreover, such a circuit which includes the earth as one side cannot be transposed. Transpositions in the power circuit cannot reduce the inductive effect of residuals except as they reduce the magnitudes of the

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For more information on advertisements use the reader service card residuals themselves, which they do in some cases. The inductive interference arising from such currents and voltages can be reduced only in the case of metallic circuits such as telephone circuits, by transposing these circuits. It is therefore important that the telephone circuits be transposed at frequent intervals throughout parallels and carefully balanced throughout their entire length and that the residual currents and voltages be kept sufficiently small to give negligible induction in telephone circuits so arranged.

"*5. Inductive interference to communication circuits, arising from the balanced voltages and currents, can in a large measure be prevented by means of an adequate system of transpositions applied to both power and communication circuits (assuming the latter are metallic) and located with due regard to each other.*

"This is accomplished partly by creating mutually neutralizing inductive effects in neighboring lengths of each side of the communication circuit or circuits by transposing the power circuit, and partly by equalizing the inductive effects on the two sides of the communication circuit or circuits by exposing each side equally to the influence of the power circuit by transposing the communication circuit.

"*6. Abnormal conditions and at times switching operations produce transient disturbances of a very severe character.*

"This is due to the fact that abnormal conditions almost invariably give rise to residuals of large magnitude, often including high harmonics. Abnormal occurrences incident to electrical power transmission do not give warning of their occurrence, and since they cannot be produced artificially on transmission systems without subjecting the apparatus to great risk or danger, it has been deemed unwise to attempt any experimental tests of these effects. This conclusion is therefore drawn from general experience and data of actual occurrences collected by the Committee." ("Report by the Joint Committee on Inductive Interference to the Railroad Commission of the State of California," *Trans. AIEE*, vol. XXXIII, Part II, June-Dec. 1914, pp. 1441–1508.)

25 years ago

Business and Government. "No one can face the developments of the last few

An Invitation to Join the New Power Group

Congratulations to the men and women of Power who pitched in to make a huge success of the first Power meeting in early February. The meeting budget was based on 1500 attendees, yet 2500 registered. Everyone seems to agree that the technical program was splendid. Despite the large number of sessions (49) and parallel committee meetings, the sessions were better attended than in most General Meetings of the past. Local arrangements, including the Awards luncheon and the dinner dance, were extremely successful.

The IEEE Group on Power cannot take any credit for this performance since it did not take over until July 1 of 1964. However, it has gained inspiration from this success. As was reported earlier in SPECTRUM, the open-forum meeting which was held during the Winter Power Meeting was attended by 500 power oriented members of the IEEE, and the Power Group organizational plans were unanimously endorsed.

The TRANSACTIONS ON POWER APPARATUS AND SYSTEMS has now been accelerated to a monthly schedule in order to provide the members of the Power Group with the best possible publication service. A large number of Power Group chapters have already been formed, and we have every reason to expect that at least 10,000 members will sign up. The drive for membership is now on. All of you who have indicated a primary interest in power should have received by now a request to join up. Let's make this drive as successful as the Winter Power Meeting and its open forum.

C. A. Woodrow

Chairman,
IEEE Power Group

years and not be aware that that is one of the greatest problems in America. There was a time, if I can clearly read the history of my country, when the primary business of government was to do what men could not do for themselves. Now there seems to be a tendency to let government do whatever government may aspire to do. Business finds itself in competition with its government at so many turns nowadays that one really wonders whether government proposes to take over the whole field of business. It is interesting to review the story of Egypt, and of Assyria, and of Babylonia, and of Greece, and of ancient Rome. All that happened to those countries should lead us to pause. We have had our constitutional government for only 150 years. We are a young nation as civilization is chronicled, and yet we are following the tendencies that have cracked up all the civilizations referred to. They cracked up economically. They rolled up tremendous debts from which they could find no release. In our own country we have piled up a tremendous debt. Our government has entered into fields of competition with scores of its industries. There is a growing disposition to center more and more of our activities in Washington. I don't argue that the government cannot run the railroads or the telephones. I am aware that the government can operate the power business. The government, too, can furnish us with food and clothing, if it chooses. But once the government does all these things, American democracy becomes a memory.

"Let me illustrate out of my own field. Certainly there the government has overreached its original boundaries. In the name of a yardstick experiment it has plunged into a program with the Tennessee Valley Authority which threatens to socialize the whole power program. You hear no more of the yardstick these days. Evidently it has been lost in the schemes of reforestation, of flood control, and of social rehabilitation. Let's look at a concrete example. The government is faced with the problem of flood control, or of reclamation. In the natural course of its development it must build a dam. A natural result is the production of power. I have no quarrel with the program up to that point; but when the power is produced, what need is there for the government to set up its own agency for distribution when to do so it must destroy agencies that have already done the work of pioneering and of building up the territory? Does the government say, "The costs are out of line?" Certainly these costs can be determined and controlled without crucifying existing institutions. Does the government say, "We must extend service to the frontiers?" Certainly that is a worthy purpose. But the government, again, can do this work of reaching out to the far corners either by way of gifts or by way of subsidies to agencies already established. In the American scheme of things it is always fine to see that we have an umpire to see that the game is played fairly. It is an American practice in baseball, basketball, tennis, and football. But when Uncle Sam aspires to play left halfback on the football field—when he takes the ball under his arm and heads toward the goal—at the same time presuming to be the umpire—sooner or later that practice will develop into a rotten game.

"In order that this may not stand as a mere negative criticism, may I close this discussion with a few constructive suggestions which, in my judgment, will promote the relationship between government and business:

"First, let the government concern itself with problems that everybody will agree belong to it, such as national defense, highway construction, reforestation, and the preservation of law and order.

"Second, let it withdraw from activities in which it finds itself in competition with private agencies already established and doing a creditable job.

"Third, if it desires to extend benefits and services, let the government do so through agencies that have already been built up in the spirit of American industry and that to date have made this country possible, and that now propose to sustain it.

"Fourth, let the government cease its industrial indictments and its appeals to class animosities.

"Fifth, let the government set industry free to expand not in words only, but in performances that make its words ring true."

"Much has been said in recent years about driving money changers from the Temple. I am aware of that quotation. But it does not represent its Author at His best. That same Man, under the stress of a very vexing situation, declared as He meditated: 'He that is without sin, let him cast the first stone.'" (A. S. Bennion, "Human Relationships," *Electrical Engineering*, Sept. 1939, vol. 58, no. 9, pp. 371–73.)

Andromeda galaxy (M31), at a distance of about two million light years. However, the two strongest radio sources (Cygnus A and Cassiopeia A) defied identification with optical objects until 1951. In that year Graham Smith at Cambridge, England, obtained a precise position for Cygnus A, which he communicated to Walter Baade of the Mt. Palomar observatory.[8] Dr. Baade took long-exposure photographs with the 200-inch telescope and at Smith's position found a peculiar, faint object which has been identified as a galaxy at a distance of 600 million light years.[9] Cygnus A has a radio power output of 10^{38} watts. If it were ten times as far away it would still be a relatively strong radio source but near the limit of detection of the largest optical telescopes. This spectacular result suggested that radio astronomy might play a leading role in the exploration of the most distant parts of the universe and gave a fresh impetus to the subject.

Subsequently, Baade and Minkowski[9] identified the strongest radio source, Cassiopeia A, with faint wisps of nebulosity at a distance of about 11 000 light years. These appear to be the gaseous remnants of a supernova, like the Crab nebula, but one in which the explosion is now thought to have been more recent. The stellar explosion resulting in the Crab nebula was witnessed by Chinese astronomers in 1054 A.D. (910 years ago), whereas the Cassiopeia A explosion is believed to have occurred about 250 years ago. However, there is no record that it was observed visually, no doubt because it is farther away than the Crab nebula and would have been much fainter and also because it took place in a part of the sky that is heavily obscured from visual observation by gas and dust in our own galaxy.

Radio emission from sources like Cygnus A and Cassiopeia A, and from the sky background, can be detected over a wide range of frequencies. This radiation is said to be of the continuum type. The possibility of a single-frequency, or line, radiation from interstellar hydrogen at 1420 Mc/s was reported by van de Hulst[10] of Leiden, Netherlands in 1945. In 1951 Ewen and Purcell[11] at Harvard detected the line in emission, and in 1954 Hagen and McClain[12] at the U.S. Naval Research Laboratory detected the line in absorption. The great importance of the hydrogen line is that both the amount of neutral hydrogen and its radial velocity can be measured. The velocity is calculated from the Doppler shift of the radiation from the rest frequency (1420 Mc/s). Neutral hydrogen gives off no visible radiation and so cannot be detected by optical means.

Fig. 1. Grote Reber's meridian-transit radio telescope.

This was the status of radioastronomy about ten years ago. Since that time new findings have come so rapidly that it is difficult to recount them in chronological sequence. Accordingly, our present state of knowledge will be described in terms of the types of objects or the phenomena involved, with emphasis on the most recent results; radio telescopes and observational techniques will then be discussed.

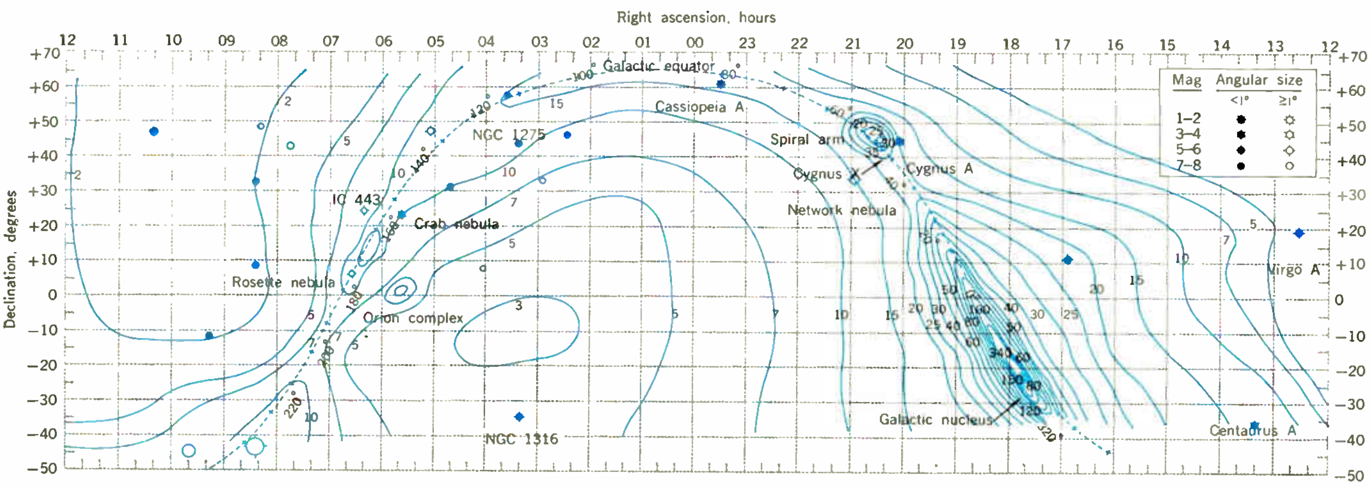
The radio sky

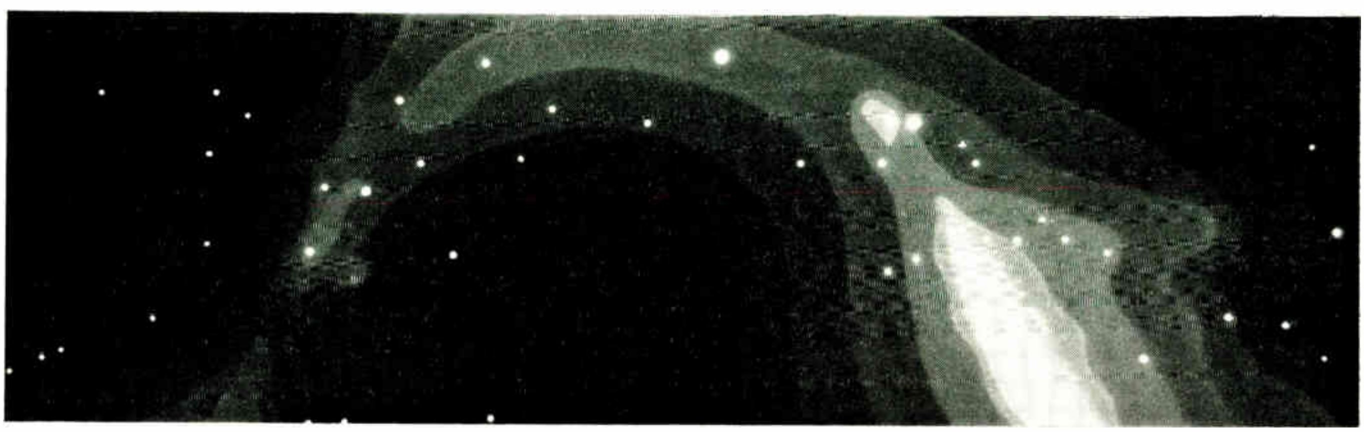
The appearance of the "radio sky" at 250 Mc/s is shown by the map of Fig. 2.[13] The coordinates are declination (north–south) expressed in degrees and right ascension (east–west) expressed in hours (24 hours = 360°). The contours indicate the equivalent brightness temperature of the sky background, and the small circles show some of the stronger discrete radio sources. The contours are in units of 6°K above the coldest parts of the sky (about 80°K near the galactic poles). Thus, contour 7 is at a temperature of 122°K—that is, 7 × 6° + 80°. The discrete sources are on a relative magnitude scale (4 dB per magnitude) with smaller magnitudes for stronger sources, analogous to the magnitude scales used for optical stars.

If the contour map of Fig. 2 is converted to shades of black and white, the presentation of Fig. 3 is obtained. It shows how the sky would appear if our eyes were sensitive to radio waves instead of to light. The white areas indicate strong radio emission and the dark areas weak emission. The bright points are the discrete radio sources. These are sometimes called "radio stars," although none shown on this map correspond to any optical star. The broad band of emission arching across the picture corresponds to the plane of our galaxy with the nucleus or center of our galaxy at the lower right. The presentation in Fig. 3, as in Fig. 2, is a Mercator projection. One may visualize the true (spherical) projection by imagining the right and left edges of Fig. 3 to be joined behind one's head while the upper edge is pulled over the top. From the center of a sphere whose inside surface is covered in this manner by Fig. 3, the bright band or plane of our galaxy would appear to be a strip running all the way around the sphere like the rim of a wheel with one's head at the hub.

A further insight into Fig. 3 may be obtained by reference to the simplified sketch of our galaxy shown in Fig. 4. The galaxy consists of an aggregation of billions of stars (about 10^{11} stars) arranged like a great flat wheel turning slowly in space. There is a complex central region with a number of spiral arms extending outward. The overall diameter of the system is about 100 000 light years and the wheel makes one revolution in about 300 million years. The earth and solar system are situated in one of the spiral arms at a distance of nearly 30 000 light years from the center. From our position in the galaxy the strongest radio background emission comes from the center of the galaxy. There is also a strong band of radiation everywhere in the plane of the galaxy. In the Cygnus direction we are looking inward along a spiral arm and observe a peak of radiation (near +40° declination and 20 hours right ascension in Fig. 2). In the direction of the

Fig. 2 (top.) Map of the radio sky at a wavelength of 1.2 meters, made with the Ohio State University 96-helix radio telescope. Fig. 3 (bottom). Map of Fig. 2 converted to shades of black and white, showing how the sky would appear if our eyes were sensitive to radio waves instead of light. The broad arch of radiation comes from the plane of our galaxy. The bright dots represent "radio stars."





Crab nebula (+21° declination and 5.5 hours right ascension) we are looking almost directly away from the galactic nucleus or in the anticenter direction. Directions perpendicular to the plane of the galaxy correspond to the galactic poles or the coldest regions of the sky.

Discrete radio sources numbering in the thousands have now been located. As larger telescopes go into operation this number continues to increase. A hundred or so of these sources have been identified with optical objects. These may be divided into three groups: objects in the solar system, objects within our galaxy, and extragalactic objects; see Table I. In the solar system, the sun, the moon, and the nearer planets have been observed with radio telescopes. Radio sources in our own galaxy, but outside the solar system, are of three principal kinds: (1) ionized hydrogen clouds, (2) neutral hydrogen clouds, and (3) supernova remnants. Outside our galaxy, radio emission from many other galaxies has been detected: observations of the Andromeda galaxy and the Cygnus A galaxy have already been mentioned. It is convenient to divide these extragalactic radio objects into "normal" galaxies, whose radio power output is much less than the optical power output (Andromeda is an example), and "abnormal" or "radio" galaxies whose radio power output is more nearly equal to or even more than the optical power output (Cygnus A is an example).

Spectra

Ground-based radio astronomical observations can be made over a nominal frequency range from about one centimeter to some tens of meters. The short wavelength limit is caused by molecular absorption and the long wavelength limit by ionospheric reflection. This relatively transparent region of the earth's atmosphere is sometimes called the "radio window." Before the advent of radio astronomy most of our knowledge of the external universe came from observations through another transparent region of the atmosphere referred to as the "optical window." The relation of these two principal windows to the entire electromagnetic spectrum is shown in Fig. 5. Whereas the optical window is only one octave wide

I. Discrete radio sources

Object	Spectral Type	Spectral Index (n)
Solar system sources:		
Sun	Thermal at less than 3 cm but complex at longer λ	−2 to +2
Moon	Thermal	−2
Mercury, Venus, Mars	Thermal	−2
Jupiter	Thermal at less than 3 cm but complex at longer λ	−2 to +5
Galactic sources:		
Ionized hydrogen clouds		
Orion nebula	Thermal	−2 to 0
Neutral hydrogen clouds	Line at 21 cm	
OH clouds	Line at 18 cm	
Supernova remnants		
Cassiopeia A	Nonthermal	0.8
Crab nebula (MI)	Nonthermal	0.3
Flare stars	Nonthermal	?
Extragalactic sources:		
Normal galaxies		
M31	Nonthermal	0.5
Radio galaxies		
Cygnus A	Nonthermal	0.6 to 1.0 (curved)
Virgo A	Nonthermal	0.8
(Virgo A jet)	Nonthermal	0.3
3C295	Nonthermal	0.4 to 0.9 (curved)
Quasars		
3C273	Nonthermal	0.3
3C147	Nonthermal	0.2 to 0.8 (curved)

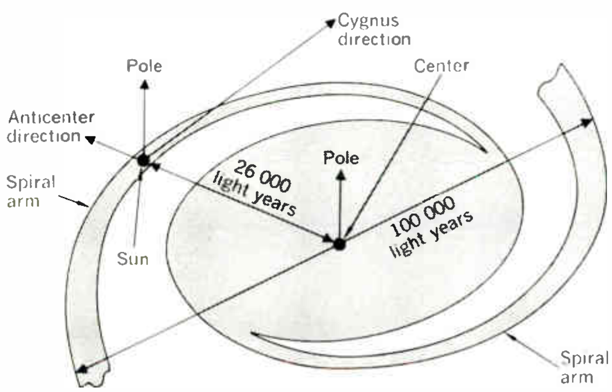


Fig. 4. Simplified sketch of our galaxy. Pole direction is perpendicular to plane of galaxy.

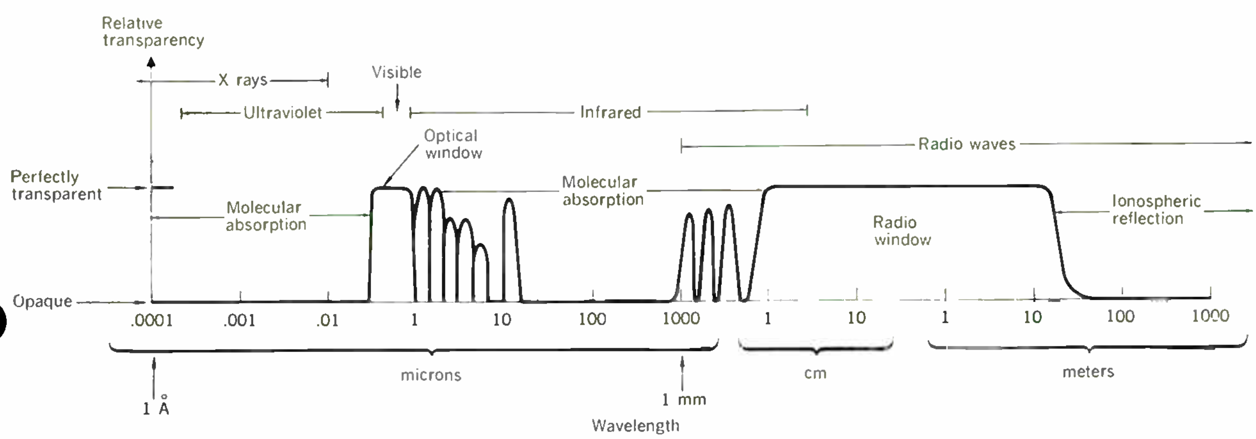


Fig. 5. Electromagnetic spectrum showing the transparent regions or "windows" in the earth's atmosphere. The ordinate gives the relative transparency of the atmosphere (including ionosphere), ranging from perfectly transparent to completely opaque.

(factor of 2 to 1) the radio window is many octaves wide (2000 to 1). By measuring the strength of a radio source over as much of this range as possible, the spectrum of the source may be determined. Measured spectra of several radio sources are shown in Fig. 6(A). The ordinate is the flux density in janskys or watts per square meter per cycle per second. Sources like Cassiopeia A and Cygnus A have spectra in which the flux density falls off with frequency, but for objects such as the moon and Mars the flux density increases with frequency. Different emission mechanisms are responsible for the two types of spectra.

According to the Rayleigh-Jeans law the flux density of an object at a wavelength λ in the radio spectrum is given by

$$S = \frac{2k}{\lambda^2} \int\int T \, d\Omega \qquad (1)$$

where k is Boltzmann's constant ($= 1.38 \times 10^{-23}$ joules per deg K). In Eq. (1) T is the equivalent black-body temperature, the integration being carried out over the solid angle subtended by the object. If the temperature is uniform over the source, this equation reduces to

$$S = \frac{2k}{\lambda^2} T \Omega_s \qquad (2)$$

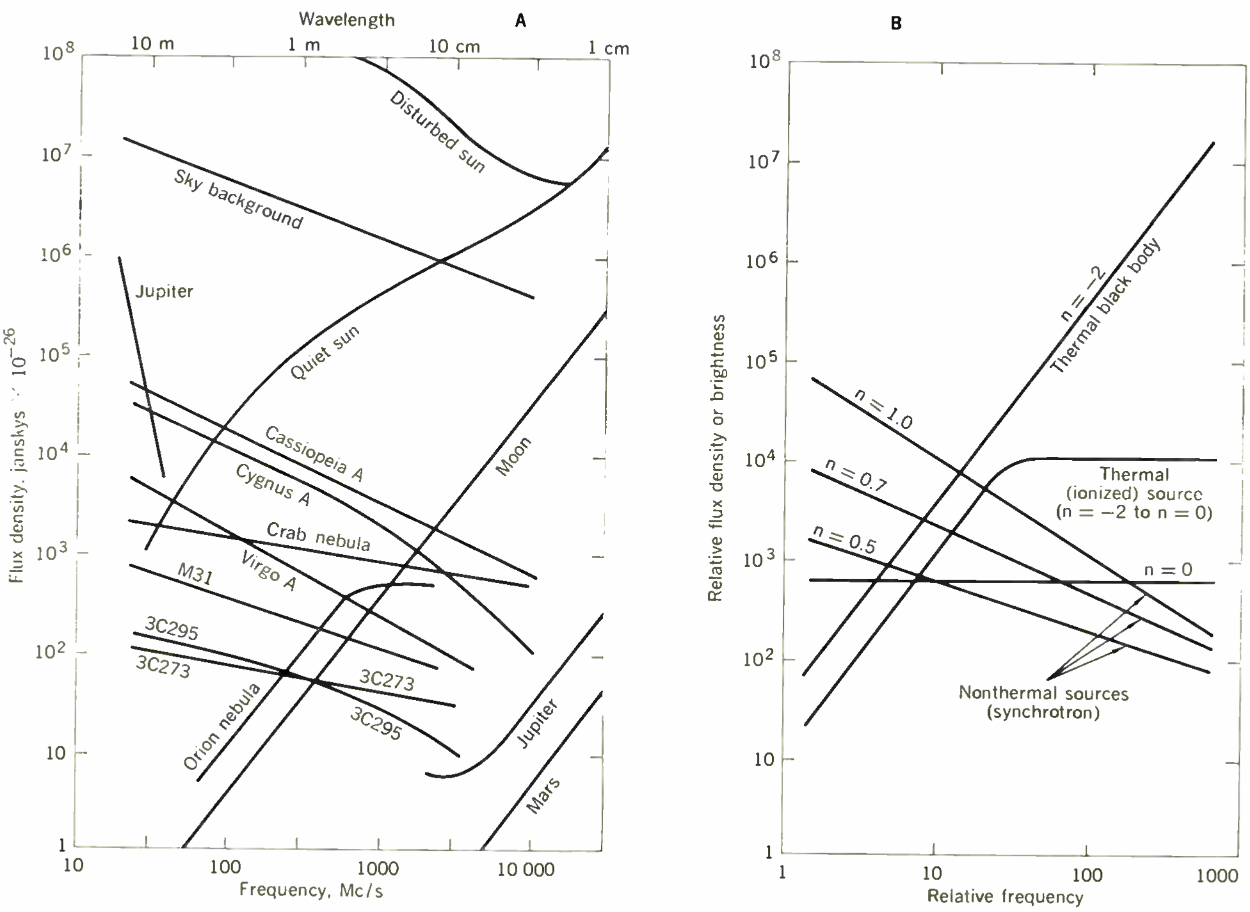
where Ω_s is the source solid angle. If T is constant the flux density varies inversely as the wavelength squared, and if the variation of S with wavelength is expressed by the relation

$$S \propto \lambda^n \qquad (3)$$

where n is the spectral index, then in this case $n = -2$. This variation is characteristic of the thermal radiation from a black body. If the slope of the $n = -2$ line in Fig. 6(B) is compared with the slopes of the moon and Mars spectra in Fig. 6(A) we may conclude that the radiation of these two solar system objects results from *thermal* emission. The oppositely sloping spectra of Cassiopeia A and Cygnus A suggest an entirely different mechanism, so these sources are referred to as *nonthermal* types. Although the spectra of these sources are not quite straight, the spectral index over most of the frequency range is about $+0.8$. The spectral index for most nonthermal sources lies between $n = +0.3$ and $n = +1$, with an average value near $+0.7$. Calculated spectra with indexes of $+0.5$, $+0.7$, and $+1.0$ are illustrated in Fig. 6(B).

It was proposed by Shklovsky[11] that the synchrotron mechanism was responsible for the emission from nonthermal radio sources. High-energy electrons moving with the relativistic velocities of cosmic rays in magnetic fields will radiate with this nonthermal type of spectrum.[15] Synchrotron radiation should also show strong linear polarization. This phenomenon has now been observed

Fig. 6. A—Representative spectra of various radio sources. B—Calculated spectra for various values of spectral index (n).



in many radio sources[16,17] and it is universally accepted that the synchrotron mechanism is responsible.

In the case of some objects, such as the Crab nebula, optical radiation is also due to the synchrotron mechanism, with electron energies of about 10^{11} electron volts. In the radio spectrum the indicated electron energies in this exploded star or supernova remnant are about 10^9 electron volts and a magnetic field of about 10^{-4} gauss must be present.[18] This value is about ten times the magnetic field believed to be present in interstellar space. The abundance of relativistic electrons also suggests that the Crab nebula is a strong source of cosmic rays.

The spectrum for the Orion nebula, shown in Fig. 6(A), appears to be of the thermal type ($n = -2$) at low frequencies, but it becomes flat at higher frequencies. This nebula is a large hydrogen cloud about two light years in diameter and at a distance of about 1500 light years. The hydrogen is ionized by the ultraviolet radiation from a hot stellar source at the center of the cloud. Radio radiation is by a thermal mechanism in which free electrons passing near protons are accelerated, and therefore are caused to emit. The effective temperature is given by

$$T = T_c(1 - e^{-\tau}) \qquad (4)$$

where T_c is the temperature of the hydrogen cloud and τ is the attenuation in nepers (1 neper = 4.3 dB) of a wave passing through it. The attenuation τ is referred to by astronomers as the "optical depth." If the cloud is dense ($\tau \gg 1$), T is constant ($= T_c$), and from (2) and (3) the spectral index $n = -2$, as for a true black-body radiator. This situation holds for the Orion nebula at low frequencies; however, at higher frequencies τ, being proportional to λ^2, becomes small ($\tau \ll 1$) and T becomes a function of the wavelength ($T = T_c\tau$ or $T \propto \lambda^2$). Introducing T with this wavelength variation into (2) yields a spectral index $n = 0$. Under these conditions the spectrum is flat.[19]

A calculated spectrum with $n = -2$ at low frequencies and $n = 0$ at higher frequencies is illustrated in Fig. 6(B) for comparison with the measured Orion nebula spectrum in Fig. 6(A). Such bent spectra characterize the radio emission from ionized hydrogen clouds. These clouds are referred to as emission nebulosities and are common close to the plane of our galaxy.

The map of the radio sky in Fig. 2 was made at 250 Mc/s. The temperature at the coldest parts is about 80°K. With increase in frequency it drops to about 2°K at 1000 Mc/s, whereas with a decrease in frequency it rises to about 40 000°K at 20 Mc/s. This corresponds to a 2.5 power variation of temperature with wavelength, and introducing this relation into (2) yields a spectral index $n = 0.5$ for the sky background. The inference is that the background radiation, produced by a blend of unresolved discrete sources and/or a continuous distribution, is to a large extent attributable to synchrotron radiation. Integrating the background radiation over the entire sky to give its flux density results in the spectral curve shown in Fig. 6(A).

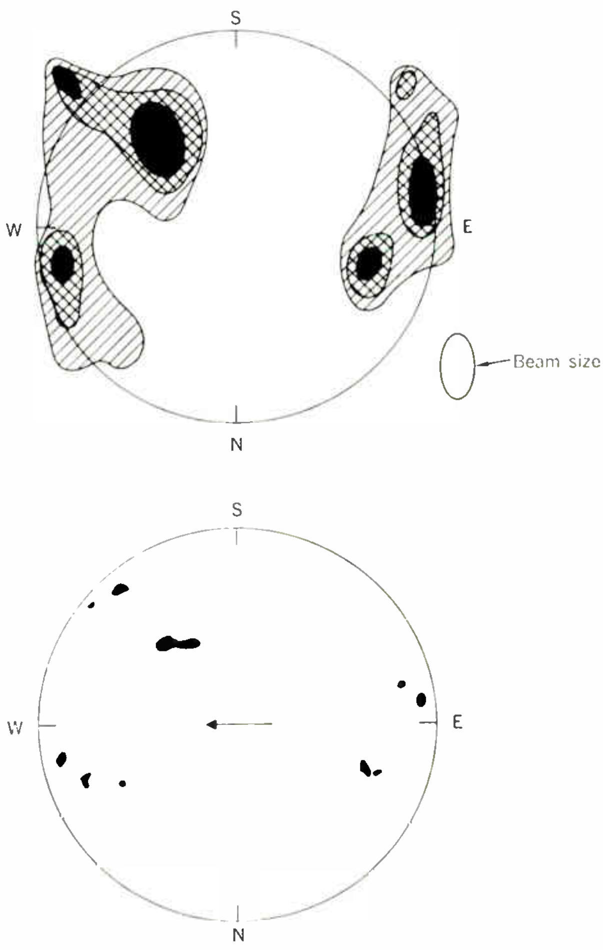
The sun

Radio emission from the sun exhibits the spectrum shown in Fig. 6(A). At the highest frequencies in the figure the emission is characteristic of a thermal black-body radiator ($n = -2$). At lower frequencies, however, the situation is more complex and the flux density at a given frequency may vary widely from a very small amount during quiet conditions to a maximum amount that may be a million times stronger during disturbed conditions.

Solar emission may be conveniently classified as emission from the quiet sun and from the disturbed sun. The latter, in turn, may be divided into a slowly varying component and a rapidly varying component characterized by bursts of emission. The quiet-sun emission is of the thermal type and at a wavelength of a centimeter or less originates near the 6000°K surface or photosphere. At about 10 centimeters it originates from 40 000°K regions at the base of the corona, and at wavelengths of 1 to 10 meters it originates in the corona from regions at temperatures of 1 000 000°K.

The slowly varying component is also of the thermal type but comes from regions around and above sunspots and tends to fluctuate with the sunspot number. This component is prominent in the 3- to 60-cm wavelength region. A radio picture of the sun made with a crossed-interferometer array at 21 cm by Christiansen, Mathewson, and Pawsey,[20] is presented in Fig. 7 (top). At 21 cm the emission is predominantly the slowly varying

Fig. 7. Regions of 21 cm (continuum) radiation from the sun (upper) and visual appearance of the sun showing sunspot areas (lower). Regions with the heaviest shading in the upper sketch have the strongest radio emission.



component.* The close association of this component with sunspots is well illustrated by comparing the radio picture with the visual appearance of the solar disk at the bottom of Fig. 7, which shows the sunspot areas. All of the radio-emitting regions are associated with sunspot groups, even in the case of the radio region above the southeast limb where no spots are visible. A few days later, because of the sun's rotation, a spot group appeared around the limb at this position. The radio picture clearly shows that much of the radio emission originates from regions situated well above the photosphere or visible disk of the sun.

The bursts of emission, which characterize the rapidly varying component, are sporadic and complex. They commonly appear in association with chromospheric flares, and a variety of nonthermal mechanisms of the plasma, synchrotron, and possibly Cerenkov types are also involved. Wild has classified them into five types, some of which are circularly polarized.[21,22] The emitting regions may rise at velocities of 1000 or 2000 km/s to great heights in the corona above the flare location.[23] Particles ejected from the sun during such flare-burst phenomena may travel outward to the earth, producing a variety of geomagnetic, auroral, and ionospheric effects. A solar-eruption sequence is shown in Fig. 8.

Although radio emission and also optical emission (during solar eclipses) from the corona have been observed at heights of more than one solar radius, the presence of the corona can be detected at distances of 15 to 20 solar radii from the sun by its influence on radio waves from the Crab nebula which is occulted—that is, covered —by the sun's corona each June.[24,25]

The moon and the planets

The moon was first detected at radio wavelengths by Dicke and Beringer[26] in 1946 on a wavelength of 1.25 cm. Observations over several months by Piddington and Minnett[27] showed that at this wavelength the emission is that of a thermal black-body radiator at 200°K with a small variation over the lunar cycle. This relatively constant temperature at radio wavelengths contrasts with a temperature range of 100° to 350°K during the lunar cycle at infrared wavelengths. This difference is interpreted to mean that the radio emission comes from below the lunar surface where the temperature is more constant, whereas the infrared radiation comes from the surface layer, which warms and cools with the lunar cycle. From more detailed studies of this type, much has been learned about the characteristics of the lunar surface and subsurface.[28]

The planet Mercury was detected in 1960 by Howard, Barrett, and Haddock at a 3-cm wavelength.[29] A temperature of 400°K was measured and from this it was inferred that the surface toward the sun was at a temperature of 1100°K, which is greater than the infrared temperature. The discrepancy may imply a higher internal temperature of Mercury, perhaps due to radioactive heating.

The first detection of Venus was at wavelengths of 3 and 9 cm in 1956 by Mayer, McCullough, and Sloanaker.[30] The radiation corresponded to that from a thermal black body at 600°K. Later measurements over a wider range of wavelengths indicated a temperature of about 600°K at wavelengths greater than 3 cm. At shorter wavelengths the temperature decreased, and was found to be about 350°K at 0.5 cm. These observations are interpreted as indicating an extensive atmosphere and high surface pressures.[28]

In 1956 Mayer, McCullough, and Sloanaker detected both Mars and Jupiter at a 3-cm wavelength.[31] Mars appears to radiate as a thermal black body at 218°K. At 3 cm Jupiter also appears to radiate as a thermal source at a temperature of 145°K. However, measurements at 10 cm and longer wavelengths deviate so much from the expected thermal behavior that a nonthermal mechanism must also be involved. It has been postulated that at these longer wavelengths there is synchrotron emission from relativistic electrons trapped in radiation belts around Jupiter that are similar to the Van Allen belts around the earth. If the synchrotron mechanism is responsible, the radiation should show linear polarization; this has been observed at 31 cm by Radhakrishnan and Roberts.[32]

At still longer wavelengths, in the 10- to 20-meter range, all of the Jovian radiation appears to be nonthermal. At these wavelengths the radiation is sporadic, fluctuating when present, and often very intense. Radio power outputs of the order of a million megawatts are indicated. It was this decametric radiation that was discovered at 22 Mc/s by Burke and Franklin in 1955.[33] The radiation appears to come from one or more sources on the planet. The fluctuations tend to correlate with the planet's rotation, and observations over a number of years give a period of 9 hours 55 minutes 29 seconds This differs significantly from the period determined by tracking a visual feature. The radio period is also subject to small abrupt changes, the interpretation of which is not clear.[34] The decametric radiation may show strong circular polarization, usually of the right-handed variety. The thermal nature of the Jupiter radiation at centimeter wavelengths, as well as its more complex and highly fluctuating nature at longer wavelengths, is reminiscent of the solar spectrum.

Of the planets beyond Jupiter, Saturn is the only one that has been detected at radio wavelengths. Measurements have been made at 3 and 10 cm. There is also some inconclusive evidence of emission from Saturn at decameter wavelengths.

Galactic radio emission

Radio emission from within our galaxy but outside the solar system may come from several types of discrete sources: (1) supernova remnants, such as Cassiopeia A and the Crab nebula with nonthermal spectra, and prominent at longer wavelengths (2) ionized hydrogen clouds, such as the Orion nebula, with thermal spectra, and prominent at shorter wavelengths, and (3) neutral hydrogen clouds emitting at the hydrogen line (21 cm). In addition there is a background of emission, which may consist of unresolved discrete sources or a more or less continuous distribution in the galactic plane of ionized hydrogen and also relativistic particles moving in magnetic fields.

Observations of the 21-cm (1420-Mc/s) line radiation, caused by the hyperfine transition in the ground level of the neutral hydrogen atom, have enabled radio astronomers

* The wavelength of the neutral hydrogen line emission is 21.4 cm (1420 Mc/s). Although Christiansen's solar measurements are at a frequency near the hydrogen line, they are representative of the solar continuum radiation, and involve no neutral hydrogen emission.

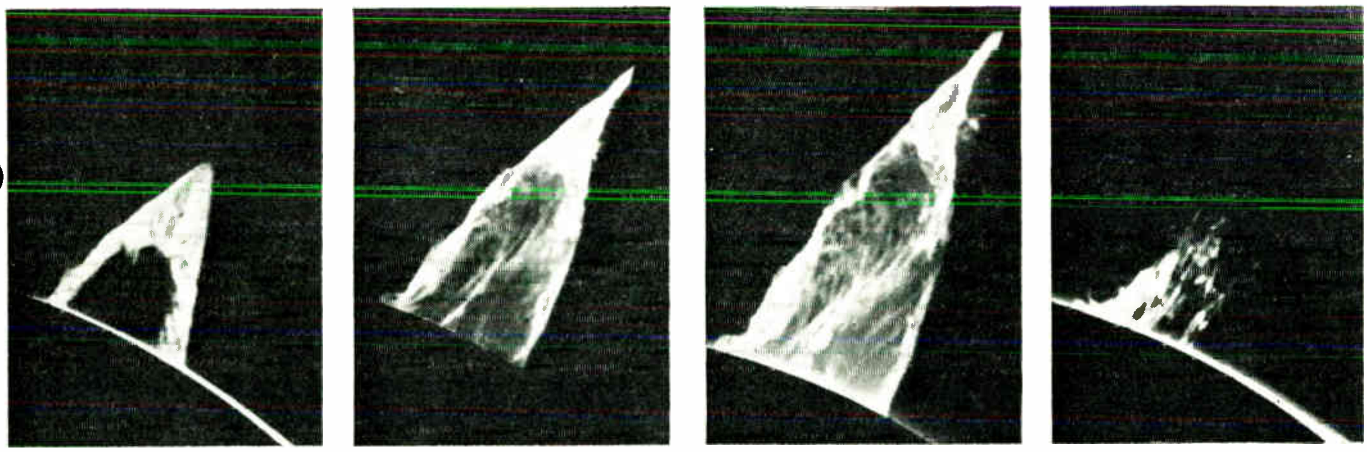


Fig. 8. Solar eruption of April 11, 1959, photographed by Joseph Klepesta at Prague, Czechoslovakia. The four photographs show the progress of the event from beginning to end. The second, third, and fourth photographs were taken 10, 44, and 48 minutes after the first one. Matter was ejected from the sun at about 400 km/s during the event. Such phenomena may be accompanied by strong radio emission.

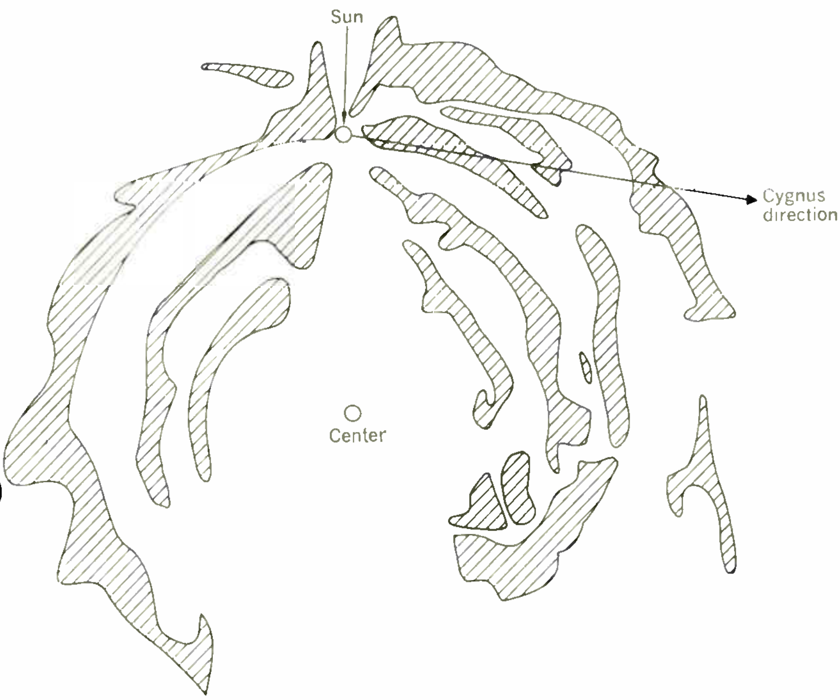


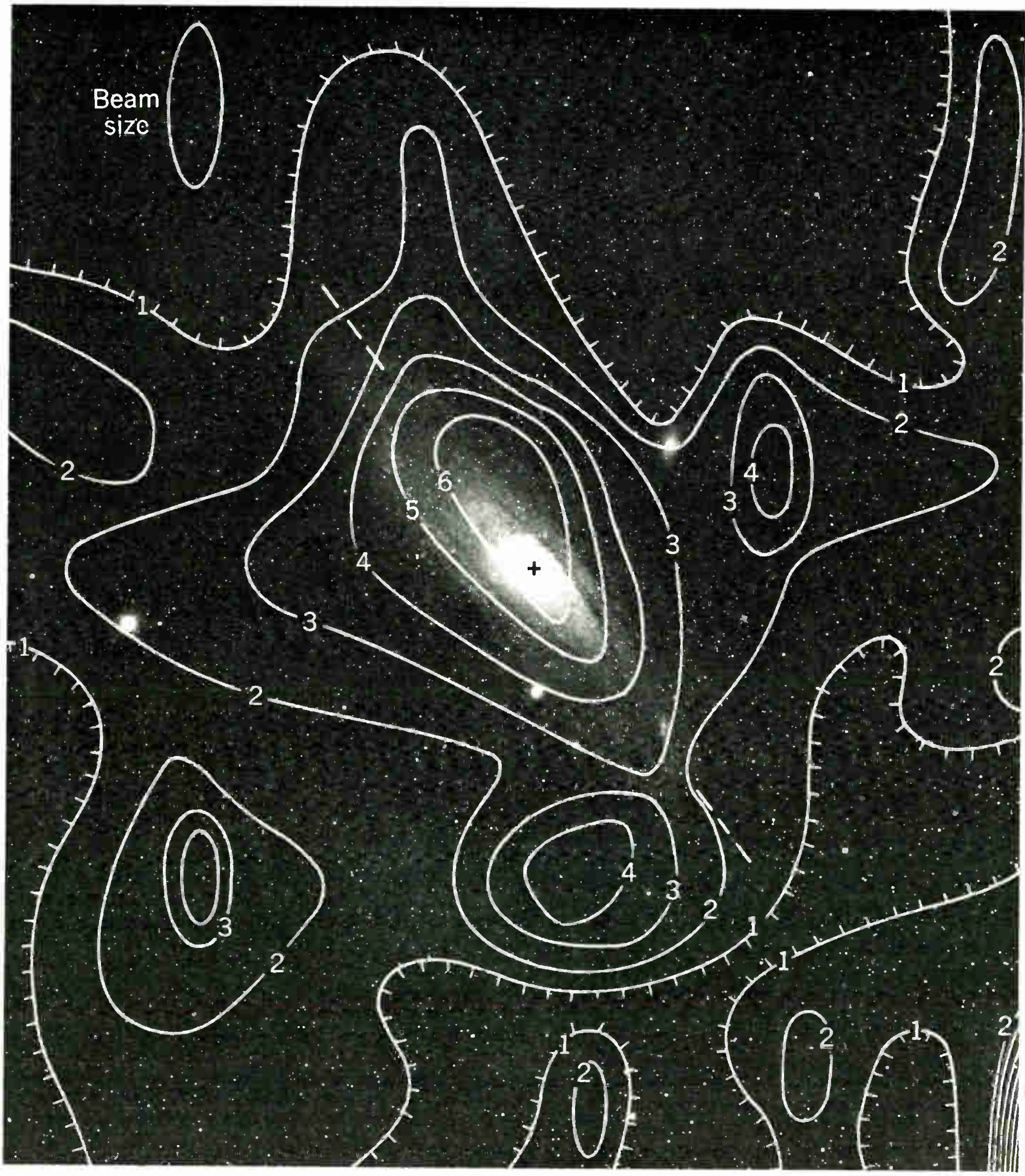
Fig. 9. Distribution of neutral hydrogen in our galaxy, showing its complex spiral structure. Shaded areas correspond to the regions of greatest hydrogen concentration as deduced from observations that were made at 21 cm.

to deduce for the first time a picture of the spiral structure of our galaxy. From profiles of intensity versus frequency (or radial velocity) it is found that in some directions the neutral hydrogen is moving toward us and in other directions away from us, with velocities up to several hundred kilometers per second. From such observations around the galactic plane and a suitable velocity-distance model, it is possible to construct an approximate map of the distribution of neutral hydrogen in our galaxy. Such a picture, assembled from Dutch and Australian observations, is presented in Fig. 9.[35,36] Portions of the galactic plane either below or too close to the horizon for observations in the Netherlands were mapped by the Australians, and vice versa. In the broadside view of Fig. 9, the center of our galaxy is nearly 30 000 light years away from the sun. Fig. 9 shows more detail and irregularity in the structure of our galaxy than are indicated in the oversimplified sketch of Fig. 4.

In directions near the galactic center the radial velocity due to galactic motion tends to approach zero and becomes confused with radial velocities due to local turbulences. Hence, a sector towards the galactic center is left blank in Fig. 9. In spite of this problem, observations of the galactic nucleus (Sagittarius A) at the hydrogen line and also in the continuum indicate the existence of a remarkable structure at the center of our galaxy.[37] There appears to be a small thermal nucleus—that is, an ionized hydrogen source—at the center of a flat disk and ring of neutral hydrogen, with all three components (nucleus, disk, and ring) imbedded in a nonthermal source consisting of a region of magnetic field and relativistic electrons. Regions near the center show both high rotational velocity and rapid expansion radially outward from the nucleus. The reasons for this complex structure are not known, but some astronomers suggest that the structure is the result of an explosion in the nucleus in an earlier epoch.[36]

The great value of the hydrogen line inspired numerous

Fig. 10. Radio contours at 1415 Mc/s superimposed on a Perkins Observatory photograph of the great Andromeda galaxy (M31). Radio measurements were made with Ohio State University's 260-foot radio telescope. Contour interval is 0.05°K.



attempts to detect other lines, such as the 92-cm line of deuterium. All were unsuccessful, however, until Weinreb, Barrett, Meeks, and Henry[38] detected the 18-cm line of the hydroxyl (OH) radical in 1963. The "line," which is actually a close doublet, was observed in absorption by noting the decreases in intensity of Cassiopeia A at or close to 18 cm caused by absorption of OH over the path between the earth and Cassiopeia A. Absorption by neutral hydrogen over the same path was observed in 1954.[12] Although a single transition of the OH molecule at 18 cm is much more intense than a single transition of the neutral hydrogen atom, the OH molecules are much less abundant and, accordingly, more difficult to detect. Over the Cassiopeia A path the neutral hydrogen atoms are 20 million times as abundant as the OH molecules.[39] Australian observations indicate that in the direction of the galactic center this factor is much less. They also find curious concentrations of OH near the nucleus that differ significantly in radial velocity distribution from the neutral hydrogen concentrations.[40]

Both the 18- and 21-cm lines permit the observation of constituents of the interstellar medium that were previously undetected. Studies of each line and intercomparisons between the two open new areas for investigation that may become even more fruitful, and complex, if still other molecular lines are detected.[39]

Mention should also be included of another possible type of discrete galactic radio source. Occasionally large increases have been observed in the optical brightness of a number of red dwarf stars, called flare stars. The brightenings are thought to be similar to solar-type flares but perhaps far more violent. Since solar flares commonly are accompanied by large radio flux increases at meter wavelengths it is thought that similar radio outbursts might occur during a red dwarf flare.[41] The nearest flare stars are about a million times as far away as the sun, so the flux density would be small, near the limits of detectability. Nevertheless, flare star watches have been in progress for several years at Australian and British radio observatories in cooperation with optical observers.[42,43] Violent flares are both rare and unpredictable, and observations of the star, to be significant, must be made simultaneously at both radio and optical wavelengths. The observational program is still in an early phase but evidence is accumulating that flare stars are detectable, but sporadic, radio sources.[43]

Extragalactic sources

We turn now to the radio sources situated outside our own galaxy—that is, the extragalactic sources. The space outside our galaxy is populated by billions of other galactic systems, each containing billions of stars of its own. These galaxies vary widely in size, form, and distribution, but a typical galaxy may be some 50 000 light years in diameter and the spacing between galaxies several million light years. A hundred or so radio sources have been identified with external galaxies and as more accurate radio positions are obtained it is likely that many more presently known radio sources will be identified with such objects.

Extragalactic radio sources may be divided broadly into two groups: "normal" galaxies and "radio" galaxies. The normal galaxies have radio power outputs of the order of 10^{32} watts, while the power output of the radio galaxies may be as much as a million times greater; see Table II.

II. Power output of astronomical objects

Object	Optical Power, watts	Radio Power, watts
White dwarf star	10^{23}	?
Sun	4×10^{26}	10^{12}
Supergiant star	10^{31}	?
Supernova remnant	10^{29}	10^{28}
Normal galaxy (10^{11} solar masses)	10^{37}	10^{30} to 10^{32}
Radio galaxy	10^{37}	10^{34} to 10^{36}
Quasar	10^{39}	10^{37}

The great Andromeda galaxy (M31) is an example of a normal galaxy. It is one of our nearest neighbors, at a distance of 2 million light years, and has a size and spiral structure similar to our own galaxy's. Radio contours of M31 measured with the Ohio State University radio telescope in the continuum at 1415 Mc/s are shown in Fig. 10 as superimposed on a Perkins Observatory photograph of the galaxy.[44,45] Although the radio contours conform roughly with the optical object, there are significant differences. Thus, the radio contours suggest projections that have no optical counterpart and the radio center (small circle) is displaced from the optical nucleus (small cross). Our own galaxy, the Magellanic clouds, and the nearby galaxy M33 are also of the normal type.

Since they have a relatively small power output, only a few of the nearer "normal" galaxies have been detected by radio. Most of the identified extragalactic radio sources are the more powerful radio galaxies. For example, the radio source Cygnus A is associated with a distant galaxy, about 600 million light years away. Curiously, the radio emission does not come from the optical galaxy but from two regions situated symmetrically to either side at a distance of about 100 000 light years. The double nature of this radio object is typical of many other radio galaxies.

One of the problems involved in the radio galaxies is that of the large power outputs (10^{38} watts in the case of Cygnus A). The tremendous magnitude of this power may take on more significance if we note that the radio wave energy radiated by Cygnus A in just one millionth of one second is sufficient to supply all of the world's electric power requirements for all purposes (light, heat, mechanical work, etc.) at a million times the present rate for the next 10 million years. (In the United States alone the average power usage is 100 million kW.) Assuming a lifetime for Cygnus A of one million years, a short time by astronomical standards, the total energy output in radio emission would be 10^{51} joules. Assuming that the galaxy has a mass of a billion suns, the total energy that could be obtained if all of the mass were converted at 100 per cent efficiency into energy (by Einstein's relation, $E = mc^2$) is 10^{56} joules. Although this is more than the total radio energy radiated, the radio emission, as in Cygnus A, comes from outside the optical galaxy, where no visible matter exists, and must involve synchrotron radiation from regions with high-energy particles moving in magnetic fields. Since the synchrotron mechanism is not very efficient in converting particle energy to radio energy, it is something of a puzzle to explain what keeps the radio source going. Thus, if the conversion of mass to particle energy and the conversion of particle to radio energy were each somewhat less than one per cent efficient, the entire mass energy of the galaxy, at the rate of three suns

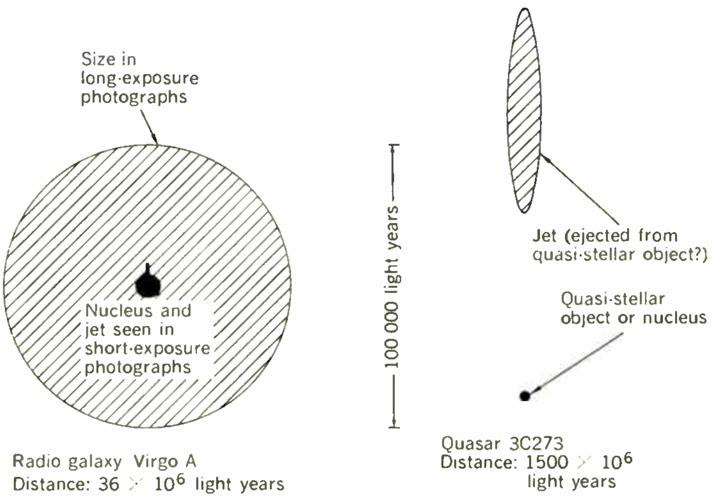
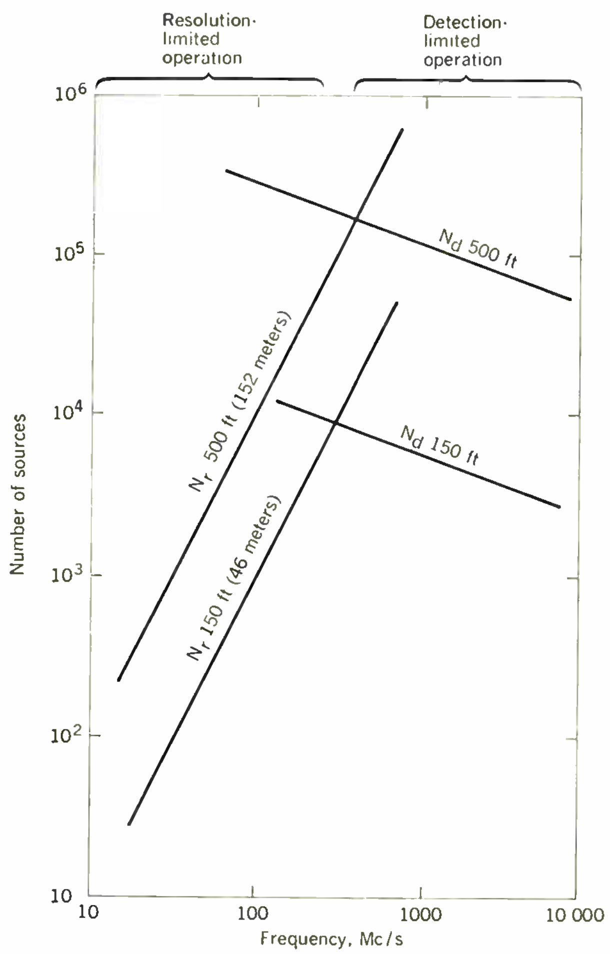


Fig. 11. Radio galaxy Virgo A with small jet near the nucleus and quasar 3C273 with huge jet 100 000 light years from the nucleus. The sketches are based on Mt. Palomar photographs and both are approximately to the same scale.

Fig. 12. The number of sources that a radio telescope can resolve (N_r) and the number it can detect (N_d) as a function of frequency, for telescope apertures with diameters of 150 and 500 feet. The maximum number of sources that a telescope can both detect and resolve occurs where the lines cross ($N_r = N_d$).



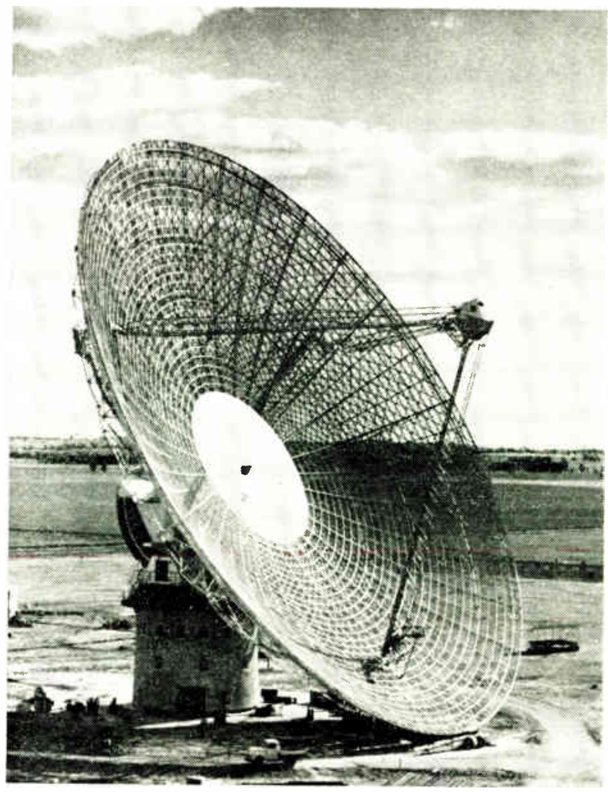
per day for a million years, would be required to account for the radio output.

The appearance of Cygnus A and that of other radio galaxies suggests that violent explosions may have occurred in the central regions during some earlier epoch. The radio galaxy Centaurus A has a structure suggesting more than one explosion. In addition, photographic evidence has been obtained for an explosion in the nucleus of the galaxy M82.[46] In the case of M87 (Virgo A) a jet of optical emission is seen to extend radially outward from the center of the spherically shaped galaxy, as in Fig. 11. Baade showed that the light from this jet has a strong, linearly polarized component, which implies synchrotron radiation; this, in turn, implies relativistic particles and magnetic fields.

The situation in the case of 3C273 is even more curious.* As indicated in Fig. 11, it has a small bright nucleus with an enormous jet at a large distance. An optical red shift of the nucleus, corresponding to a recessional velocity of 15 per cent of the speed of light, has been measured. A distance of about 1.5 billion light years is implied. The radio power, mostly from the jet, is 10^{37} watts; however, the optical power output of 10^{39} watts, almost entirely from the small bright nucleus, is 100 times that of a standard galaxy. The nucleus is hardly 1/10 the diameter of a standard galaxy. Its small size resembles a star image, and it has been described as a "quasi-stellar radio source" or "quasar."[47, 48]

* The source 3C273 is source number 273 in the Third Cambridge (3C) Catalog of Radio Sources, compiled at the University of Cambridge, England.

Fig. 13. Commonwealth Scientific and Industrial Research Organization's 210-foot-diameter radio telescope at Parkes, Australia. (Photo courtesy J. L. Pawsey.)



About a dozen of these objects have been found. Burbidge[49] points out that Seyfert-type galaxies, ones with small bright nuclei, have some similarity to quasars. He suggests that through evolutionary processes a Seyfert galaxy might eventually develop into a quasar. To account for the large energies required in such objects, Hoyle and Fowler have postulated the formation and collapse of extremely massive superstars involving ten million solar masses with energy released by nuclear or gravitational mechanisms.[48,50] In the latter stages of the collapse, as the radius decreases, the gravitational energy output becomes dominant.

Another quasar, 3C147, has an indicated velocity of recession almost half that of the velocity of light and is at the greatest measured distance, some 4000 million light years, of any known object.

Radio telescopes

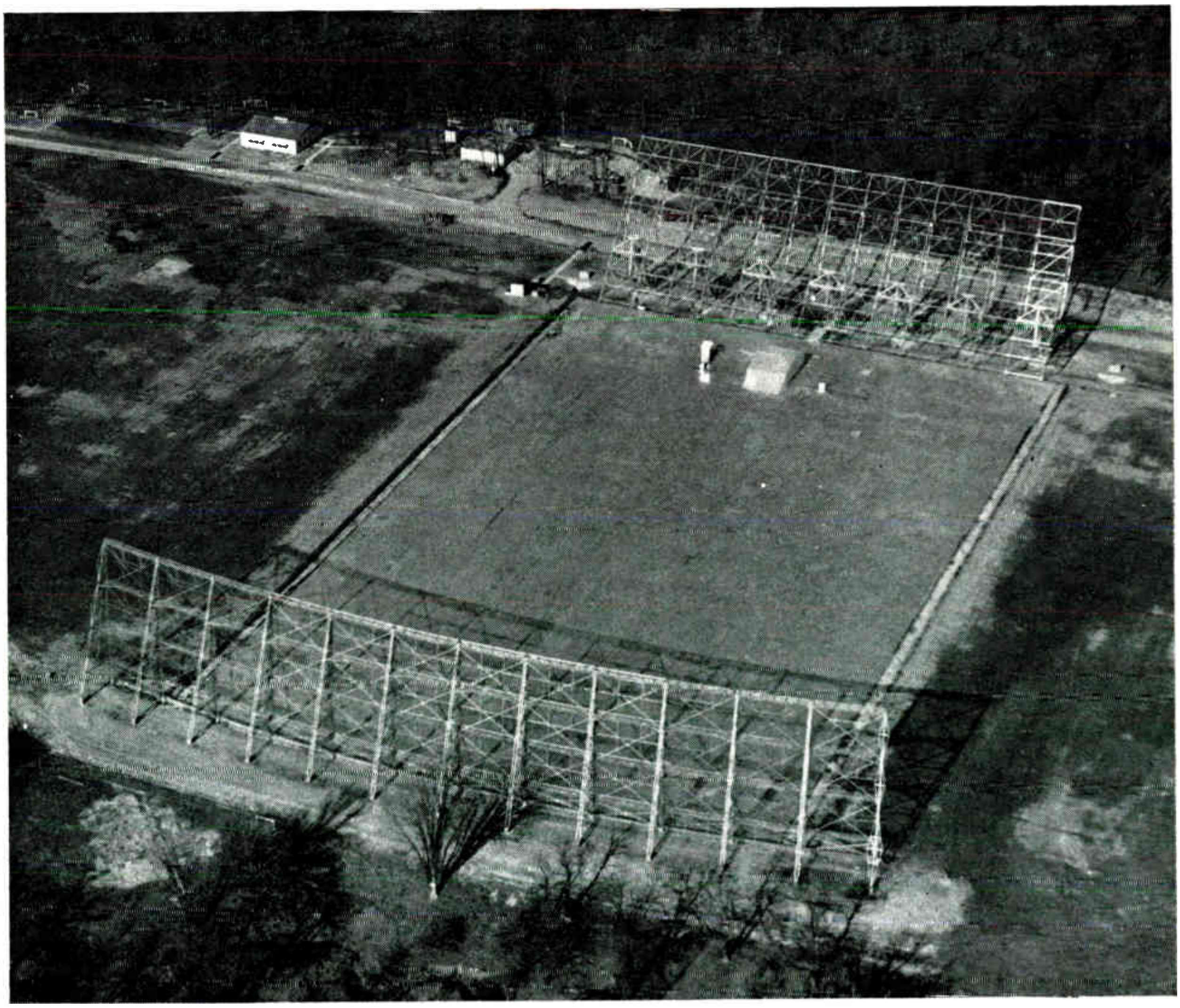
A radio telescope consists basically of an antenna and a receiver–recorder system. The antenna collects and focuses the waves from a celestial radio source in the same way that the lens of an optical telescope focuses the light from a star. The radio energy is then conveyed to a receiver–recorder analogous to the photographic plate in an optical telescope.

In order to observe a radio source, a radio telescope must be capable of both detecting and resolving it. The resolution is a function of the size of the telescope antenna aperture measured in wavelengths. Ideally the number of radio sources a telescope, able to scan the entire sky, can resolve is equal to the sky solid angle (4π) divided by the solid angle of the antenna beam. This is the same quantity that antenna engineers call the directivity D of the antenna. Thus, the number of sources N_r that a telescope can resolve is given by

$$N_r = D = \frac{4\pi}{\Omega_A} = \frac{4\pi}{\lambda^2} A_e \qquad (5)$$

where Ω_A is the antenna beam solid angle, A_e is the antenna effective aperture, and λ is the wavelength.[51]

Fig. 14. The 260-foot standing parabola tiltable flat reflector radio telescope at the Ohio State–Ohio Wesleyan Radio Observatory, Delaware, Ohio. (Photo by Tom Root.)



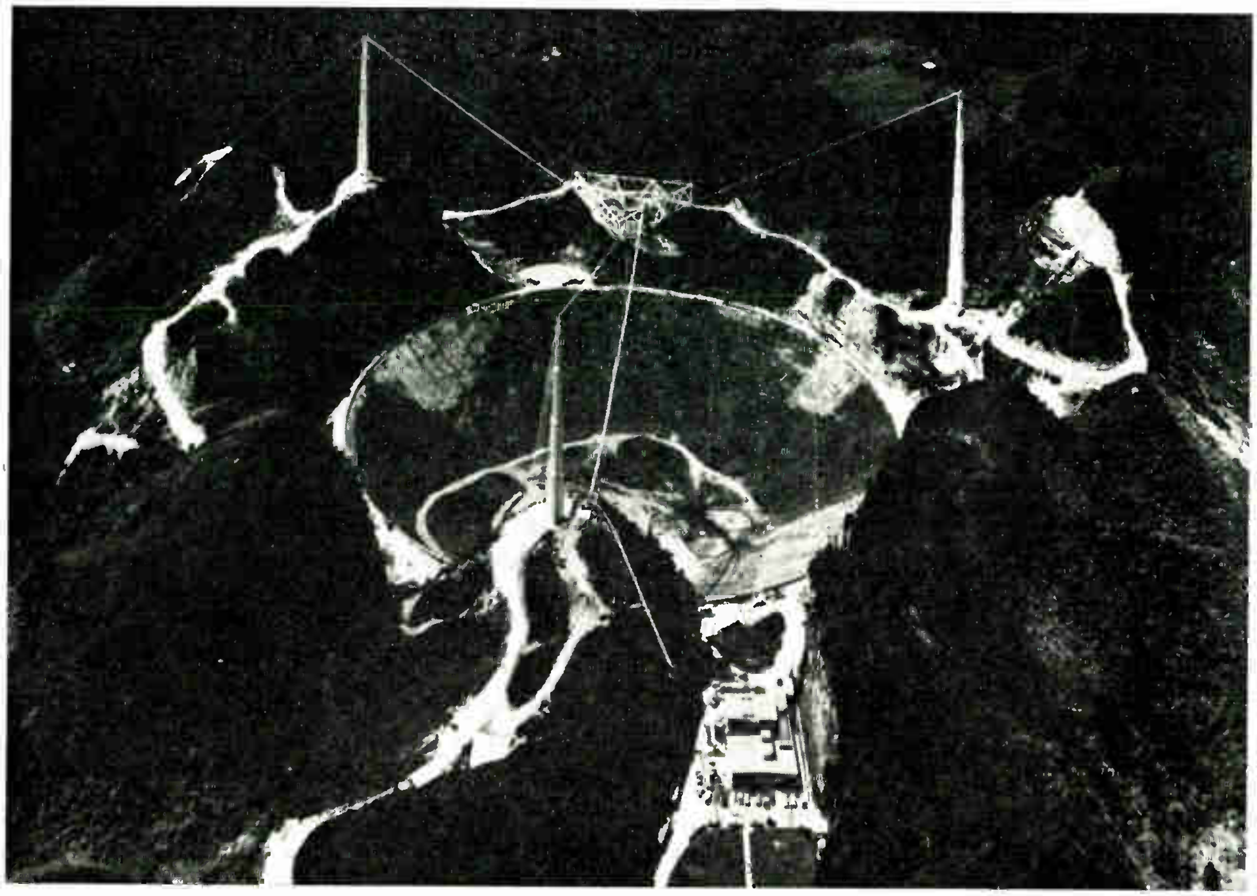
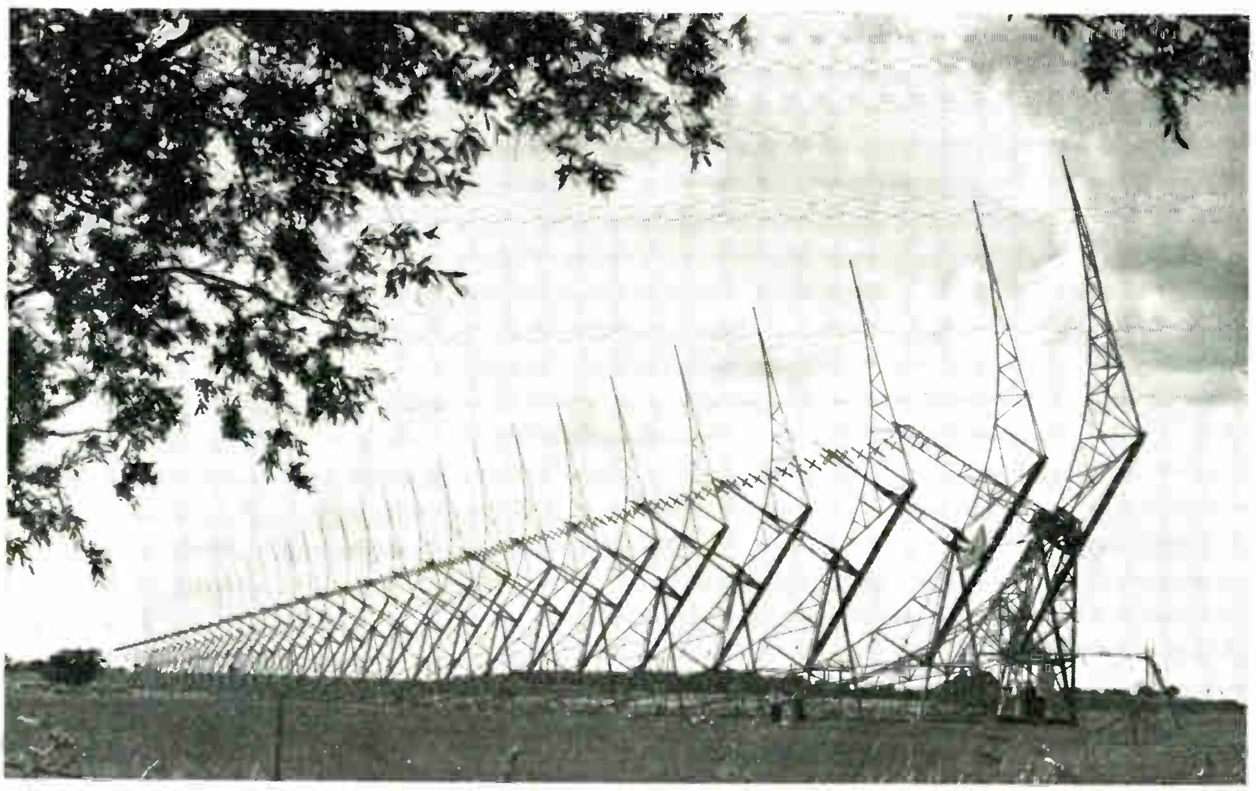


Fig. 15. The 1000-foot-diameter spherical dish antenna of Cornell University and the U.S. Air Force at Arecibo, Puerto Rico. (Photo courtesy W. E. Gordon.)

Fig. 16. A 178-Mc/s aperture synthesis array at the University of Cambridge, England. The array is 1450 feet long east–west. A smaller array is mounted on tracks and can be moved 1000 feet in the north–south direction. (Photo courtesy Martin Ryle.)



In practice, the number of sources that can be resolved unequivocally may be only a few per cent of this figure. However, (5) establishes an upper limit.

The number of radio sources N_d that a telescope can detect is dependent on the telescope aperture, the receiver characteristics, and the flux density of the radio sources. If a number of arbitrary assumptions about the receiver and sources are made, a relation for N_d can be obtained, with the result as shown in Fig. 12. Here the number of sources that radio telescopes having circular apertures 150 and 500 feet in diameter can both resolve and detect is presented as a function of the frequency. The graph indicates that, in principle, there is a frequency, where $N_d = N_r$, for which a maximum number of sources may be both detected and resolved for a given size telescope. At lower frequencies the telescope tends to be resolution limited and at higher frequencies it tends to be detection limited.[51] This discussion is considerably oversimplified, but it does bring out, for example, that at a wavelength for which a radio telescope is resolution limited it may be uneconomical to increase the sensitivity (N_r is already less than N_d). On the other hand, it may be worthwhile to increase the resolution by rearranging the aperture area into some other configuration, such as a Mill's cross, so as to make N_r approach N_d.

Radio telescopes appear in a great variety of both antenna and receiver types. Any antenna classification is arbitrary, but it is convenient to divide telescope antennas into completely steerable, partially steerable, and fixed types. Telescopes of the first category can be steered, in two coordinates, to any point in the sky above a certain horizon angle. The large telescopes at Jodrell Bank in Manchester, England, are of this type. The 50-foot precision aluminum parabolic dish antenna at the Naval Research Laboratory, Washington, D.C., and the new 210-foot parabolic dish at Parkes, Australia (Fig. 13), also belong to this group.[52]

Partially steerable telescopes may be turned in one coordinate, usually declination, with the earth's rotation used for the right ascension scan. Telescopes in this category are the new 300-foot parabolic dish at Green Bank, W. Va.,[52,53] the standing parabola tiltable flat reflector telescope of the Ohio State University (Fig. 14),[54] and the similar but larger French telescope.[52,55] This instrument, just completed at Nancay, France, is the largest movable-structure radio telescope in the world.

Fixed telescopes may be regarded as those whose main structure is mechanically fixed, but whose beam may be steered by electrical means or by movement of the feed. Examples of this type are the Mill's cross telescopes at Sydney, Australia, the new 1000-foot-diameter Arecibo, Puerto Rico, antenna (Fig. 15), and the University of Illinois antenna. The Mill's cross has two arms, one north–south and the other east–west, each giving a fan beam.[56] The two fan beams are multiplied, giving a pencil beam at the intersection of the two fans. Phase adjustments of the dipoles making up the north–south arm permit beam steering in declination. The sensitivity of the telescope (and N_d) is a function by the physical area of the two arms of the antenna. However, the resolution of the arrangement (and N_r) is a function of the lengths of each arm (L_1 and L_2) and is proportional to the product of the two arm lengths (L_1L_2). This telescope differs from the others described in that the aperture area (L_1L_2) is only partially filled by the antenna structure. The ratio of the actual aperture to the area L_1L_2 is called the filling factor. Although the resolution is porportional to the area L_1L_2 the sensitivity is a function of the actual aperture (L_1L_2 times the filling factor).

The Arecibo antenna (Fig. 15) consists of a 1000-foot-diameter fixed spherical reflector or wire screen anchored in a large depression in the ground.[52] A movable line feed corrects for aberration and permits beam tilt of 20° from the zenith. The feed system and associated focal point structure, weighing 600 tons, is suspended by cables from three towers. The Illinois antenna has a fixed 400- by 600-foot cylindrical parabolic reflector resting on the ground with a horizontal elevated north–south line feed.[52,57] The beam can be steered in declination by phase adjustments in the line feed.

Another approach to the resolution problem is to separate the antenna into two or more parts. The basic arrangement of this type consists of two antennas of equal size separated by a distance D, usually in the east–west direction, providing a simple interferometer. A system of this kind with two 90-foot-diameter parabolic dish antennas mounted so the separation of D can be varied has been used successfully at the Owens Valley radio observatory of the California Institute of Technology to measure the size of many radio sources.

The output of a simple two-element interferometer is proportional to one Fourier component of the sky brightness distribution. By making measurements with different spacings, the Fourier transform (as a function of D) can be determined. By Fourier inversion, the sky brightness distribution can be obtained to about the same detail as with a continuous antenna of aperture equal to the maximum spacing D, used with the interferometer. With small individual elements and large maximum spacing the resolution of an interferometer may be high but the filling factor and sensitivity are low. A separate measurement is required for each spacing so that more time is required to obtain the distribution than with a continuous aperture. Thus, the interferometer takes longer to obtain a given amount of information, but since it is a partially filled aperture it costs less to build.

The interferometer technique has been extended by Ryle and his associates at Cambridge University, England. For example, a continuous aperture that is long in the east–west direction (L_1) but narrow in the north–south direction is used as one element of an interferometer (Fig. 16) with a smaller aperture that can be moved along a north–south track over a distance L_2 as the other element.[58-60]

If a series of observations is made with the movable element at different stations, the two-dimensional sky brightness distribution can be deduced, in principle, by this method of "aperture synthesis" to a detail comparable to that from a filled-aperture antenna of area L_1L_2. Observational data are stored and processed by an electronic computer. A still further development of the interferometer idea by Ryle involves two or three steerable dish antennas that track a sky region for an extended period while the earth's rotation changes the interferometer base-line orientation.[61]

Interferometers with more than two units—that is, multiple-unit types—have been developed extensively by Christiansen in Australia.[62,63] In his design the dipole arrays of the arms of a Mill's cross are replaced by east–

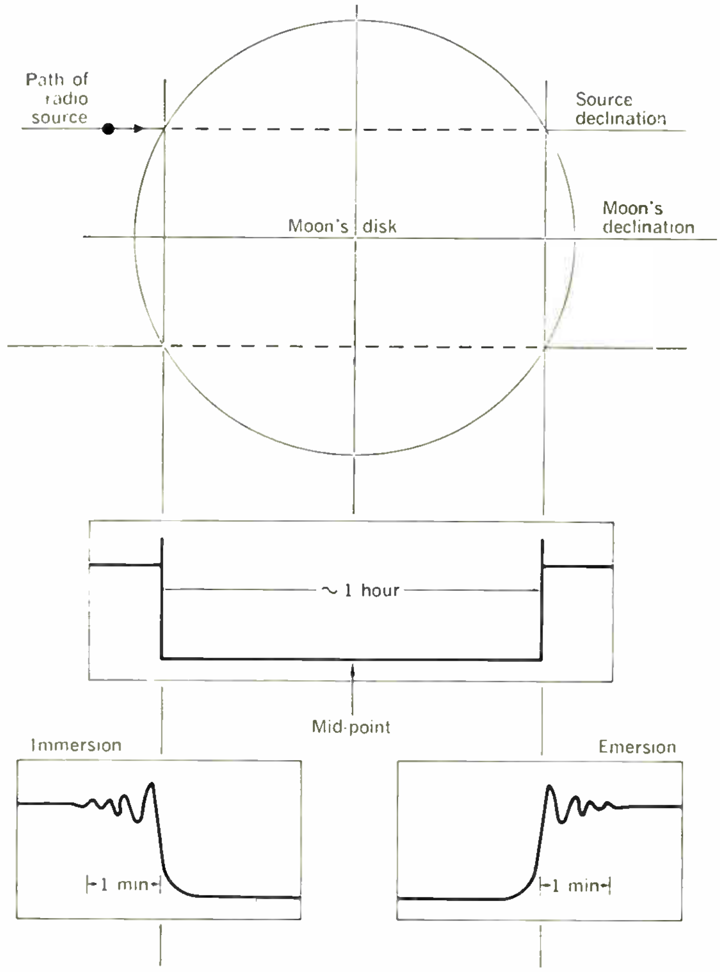


Fig. 17. Linear occultation geometry (top), radio telescope record (center), and immersion and emersion parts of record, to expanded time scale, showing diffraction-type pattern (bottom).

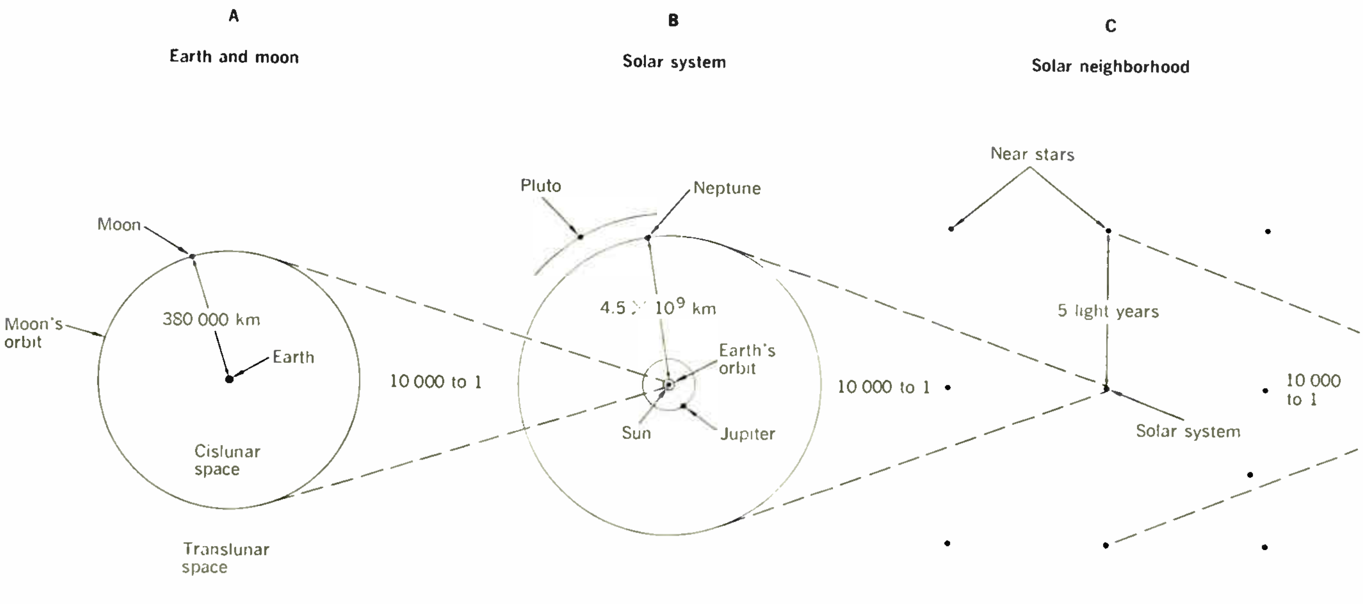
west and north–south rows of steerable dish antennas.

Instead of using a cross configuration, Wild is building an array of one hundred 40-foot steerable dishes deployed along a circle two miles in diameter.[64,65] This array and that of Christiansen are designed primarily for solar observations.

In Europe a Benelux radio telescope project is under way in which plans call for a cross antenna with about one hundred 100-foot-diameter steerable dish antennas in north–south and east–west arms about one mile long. In the U.S.S.R. a number of large radio telescopes have been built in recent years.[66] These include a 70-foot-diameter steerable dish of precision construction that can be operated at wavelengths of one cm and less, and a large Mill's cross array that uses a long cylindrical parabola, similar to the Cambridge antenna of Fig. 16, for the east–west arm. In Tasmania, Reber has constructed a fixed dipole array about one km in diameter for operation at hectometer wavelengths (2 Mc/s).

Another technique that is proving to be a powerful tool for radio source size and position measurements is that of lunar occultation. When the moon passes in front of a radio source its disk occults the radio source, and a record, as in Fig. 17, may be obtained. From the duration of the occultation the declination of the source with respect to the moon's declination can be deduced, the ambiguity in source declination north (above in the figure) or south of the moon's declination being resolved, for example, if an approximate position by other means is available. The right ascension of the source corresponds to the moon's right ascension at the mid-point of the event. The moon's position is accurately known and it drifts across the sky background at a sufficiently slow rate (50 minutes of right ascension per day or about ½ second of arc per second of time) that position determinations of the order of one second of arc are readily possible. Quasars appear optically so much like ordinary

Fig. 18. Six sketches of the universe, progressing from the earth–moon system (A) to the entire observable universe (F). Object at greatest known distance is quasar 3C147, nearly half way to the celestial horizon in (F).



stars that positional accuracy of this order is needed to tell which of the many stellar objects in a region is the radio source. Hazard, Mackey, and Shimmins[67] used this lunar occultation technique with the Australian 210-foot telescope to determine the position of the quasar 3C273 to an accuracy of one second of arc and also to deduce the source size and structure to a similar precision. The source size is obtained from an analysis of the Fresnel diffraction fringes of the record. To get the same detail at a wavelength of one meter without the help of the moon would require a radio telescope with a 100-mile aperture.

To apply the lunar occultation technique the radio source must be followed for as much as about one hour, so a steerable beam telescope is required. Consideration is being given to the construction of very large steerable-dish-type radio telescopes specifically for lunar occultation source size measurements of as weak radio sources as possible. If the radio sources measured are sufficiently uniform in physical size, the measured angular size may be used to determine their distance. This information, in turn, can be used to test various cosmological theories about the distribution of galaxies in space.[68]

The synchrotron mechanism tends to produce linearly polarized radiation. If a radio source is found to have a nonthermal spectrum and significant linearly polarized radiation, the evidence is strong for a synchrotron mechanism in the source. For polarization measurements a symmetrical antenna system is desirable. By rotating a linearly polarized feed in such an antenna the degree of linear polarization can be deduced. Extensive measurements of this type have been carried out on discrete radio sources.[16, 17, 69] Polarization measurements of the galactic background radiation have also been made which permit deductions concerning the galactic magnetic fields.

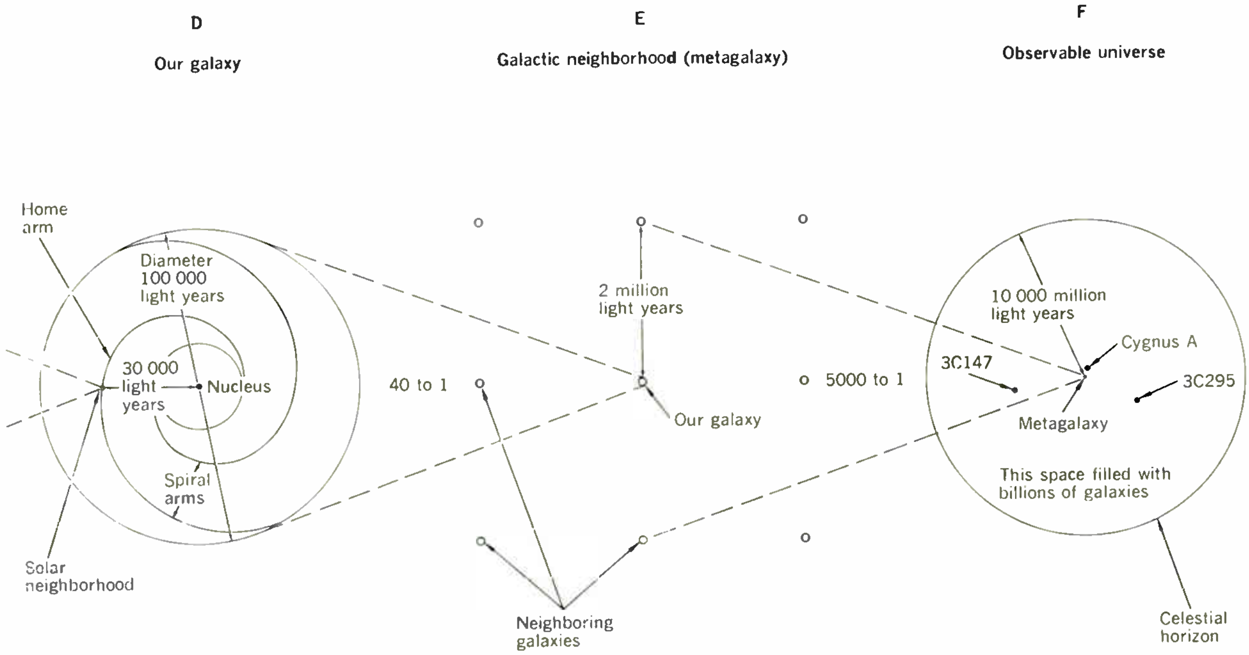
Radio telescope receivers

The sensitivity of a radio telescope is a function of its aperture and minimum detectable temperature T_{min}. The latter depends on the system temperature T_s and receiver characteristics as given by

$$T_{min} = \frac{k_1 T_s}{\sqrt{n \Delta f t}} \qquad (6)$$

where n is the number of independent observations, Δf the predetection bandwidth, and t the postdetection time constant.[70] The quantity k_1 is a constant, of the order of unity, that depends on the particular type of receiver used. The system temperature T_s is the sum, mainly, of the receiver temperature and the antenna temperature. At meter wavelengths the sky background temperature and, hence, the antenna temperature may be hundreds or thousands of degrees, so a low-noise (and low-temperature) receiver is not required. However, at microwave and centimeter wavelengths the sky background temperature drops to a few degrees Kelvin and the use of parametric and maser amplifiers is worthwhile. Of course, the antenna temperature at centimeter wavelengths will, generally, be higher than the sky temperature because of side-lobe pickup from the ground, which is at about 300°K. Thus, good antenna design may be required to keep the antenna temperature down. Receiver temperatures of 10°K or less can be obtained with masers and liquid-helium-refrigerated parametric amplifiers, temperatures of about 50°K with liquid-nitrogen-cooled parametric amplifiers, and 100° to 200°K with ambient-temperature parametric amplifiers.

The 1415-Mc/s contour map of M31 in Fig. 10 was measured by use of a liquid-nitrogen-refrigerated parametric amplifier giving a 50°K receiver temperature.[71] With an antenna temperature of 60°K (so that the system



temperature is 110°K), a bandwidth of 5 Mc/s, and a time constant of 10 seconds, the minimum detectable temperature from (6) is 0.01°K. Three records were averaged ($n = 3$) and $k_1 = \pi/2$. The contour interval in the map of Fig. 10 is 0.05°K and the maximum temperature near the center of M31 about 0.3°K. It is obvious that a low system temperature is essential for mapping such weak objects as M31 at 1415 Mc/s.

The future

In little more than a decade radio astronomy has greatly increased our knowledge of the universe and changed many of our theories about it. With larger antennas and lower-temperature receivers now under construction and planned for the near future, this rapid pace of discovery will doubtless continue at an accelerated rate.

Radio telescopes possess unique advantages for the study of the most remote parts of our universe. The farther into space we probe the farther back in time we look, so observations of very distant objects should provide knowledge about the evolution and destiny of our universe.

Radio telescopes are also powerful research tools for nearer objects, including those in the solar system. It may be said that radio telescopes have the potential of a full coverage in distance of our universe. Space probes and manned exploration should develop into important techniques for more direct studies of the moon and objects in our solar system. However, the extension of these direct methods beyond our solar system is a matter of the distant future if, indeed, trips to the stars are ever possible at all.

The very small prospective range of probes and manned space travel compared to radio telescopes is illustrated by the idealized diagram of our universe presented by the six sketches of Figure 18. Figure 18(A) shows the earth–moon system. Figure 18(B), which shows the solar system, is reduced with respect to the first one by a factor of 10 000. In 18(C) the solar neighborhood is shown in an idealized manner. The reduction of this sketch from 18(B) is also 10 000 to 1. Figure 18(D) is a simplified representation of our galaxy with the solar neighborhood about 30 000 light years from the center of the galaxy; again the reduction is 10 000 to 1. Figure 18(E) is an idealized picture of our galactic neighborhood or metagalaxy. The reduction from the previous sketch is 40 to 1. Figure 18(F) is an elementary representation of the observable universe bounded by the "celestial horizon" with a radius of about 10 billion light years from our galaxy at the center. A uniform expanding universe is assumed with the velocity of expansion equal to the velocity of light and the red shift infinite at the horizon.

The space inside the celestial horizon contains, perhaps, 100 billion (10^{11}) galaxies, with an average intergalactic spacing of several million light years. A typical galaxy may contain some 100 billion stars, so the universe may contain 10^{22} stars. The overall scale reduction of the last sketch of Fig. 18 with respect to the first one is 2×10^{17}.

Whereas radio telescopes can penetrate far out in the region of Fig. 18(F), close to the celestial horizon about 10 billion light years away, man has not yet covered the interval in 18(A) or one light second, and probes have functioned only to the inner parts of 18(B), or one light hour. This tremendous difference in range capability may take on more significance if expressed in units of common everyday experience. Thus, for example, if the range of radio telescopes is scaled down to, say, 10 000 miles (New York to Sydney), then the distance of the nearer planets is only a few millionths of an inch. It is apparent that the universe is very large and that our present knowledge represents only a small beginning.

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The 'Quoddy question—time and tide

For the third time in thirty years, a major effort is being made toward the realization of the sixth wonder of the modern world, the Passamaquoddy Tidal Power Project

Gordon D. Friedlander *IEEE Spectrum*

Since the dawn of recorded history, man has been intrigued and puzzled by the phenomenon of the ocean tides that are caused by the gravitational pull of the moon and sun. About every four weeks—at the time of the new moon—the sun and moon lie in the same direction from the earth; and, fourteen days later, at the time of the full moon, these bodies lie in opposite directions. When either condition occurs, once every two weeks, the lunar and solar gravitation forces supplement each other to produce maximum, or "spring" tides. When the moon is at its quarter phases, however, the sun and moon subtend a right angle to the earth, as shown in Fig. 1. Their gravitational pulls oppose and partially neutralize each other, and produce minimal tidal ranges—or "neap" tides—that are only one third as high as spring tides. And when the moon is either new or full, and simultaneously in perigee, the tidal range is unusually great.

In mid-ocean, the water rises vertically, and then subsides as each tidal lift passes. But when the tidal bulge reaches a shore, it decelerates in the coastal shelf, and the water is forced horizontally inland under the differential in hydrostatic head, piling up on the shore and then ebbing. The geographical configuration of the coast line largely determines the height to which local tides will reach. On exposed oceanic headlands the tidal range may be 6 to 8 feet, while in landlocked seas such as the Mediterranean, where a higher rate of surface evaporation is also a factor, the tidal range is negligible. Because of this higher evaporation, the level of the Mediterranean is about 5 feet lower than that of the Atlantic Ocean. Thus, strong currents surge eastward through the Pillars of Hercules, and are accelerated by the Venturi effect of the constricted and attenuated Straits of Gibraltar.

In certain areas of oceanic coastal waters, notably around Nantucket and Martha's Vineyard, there are "nodes" where the tidal range is imperceptible. But in funnel-shaped embayments and estuaries that shelve from shallows out toward the open sea, the water piles up as it is concentrated forward into the ever-narrowing bays, and strong tidal currents are created. Such conditions cause the extreme tidal phenomenon of the Bay of Fundy, the body of water between the Canadian provinces of New Brunswick and Nova Scotia—the site of the world's greatest tidal range.

Some historical background

For centuries imaginative people have harnessed the potential power of the tides in a very limited manner. In the 11th century, small tide mills were used to grind corn in England and other Western European countries. In the 18th century, "Slade's Mill" in Chelsea, Mass., was built to grind spices. The mill, consisting of four water wheels, developed about 50 horsepower, and was driven by the hydrostatic head created when a minor estuary was dammed to trap water at high tide.

With the advent of hydroelectric power, many potential tidal power sites throughout the world have been investigated and studied. These sites, in addition to the Passamaquoddy Bay area on the border between the State of Maine and the Province of New Brunswick, include the tidal estuary of the River Severn, England; the la Rance estuary in Brittany; Mont St. Michel in northwest France; the Gulf of San José, Argentina; and the Bay of l'Aber Vrach in Brittany.

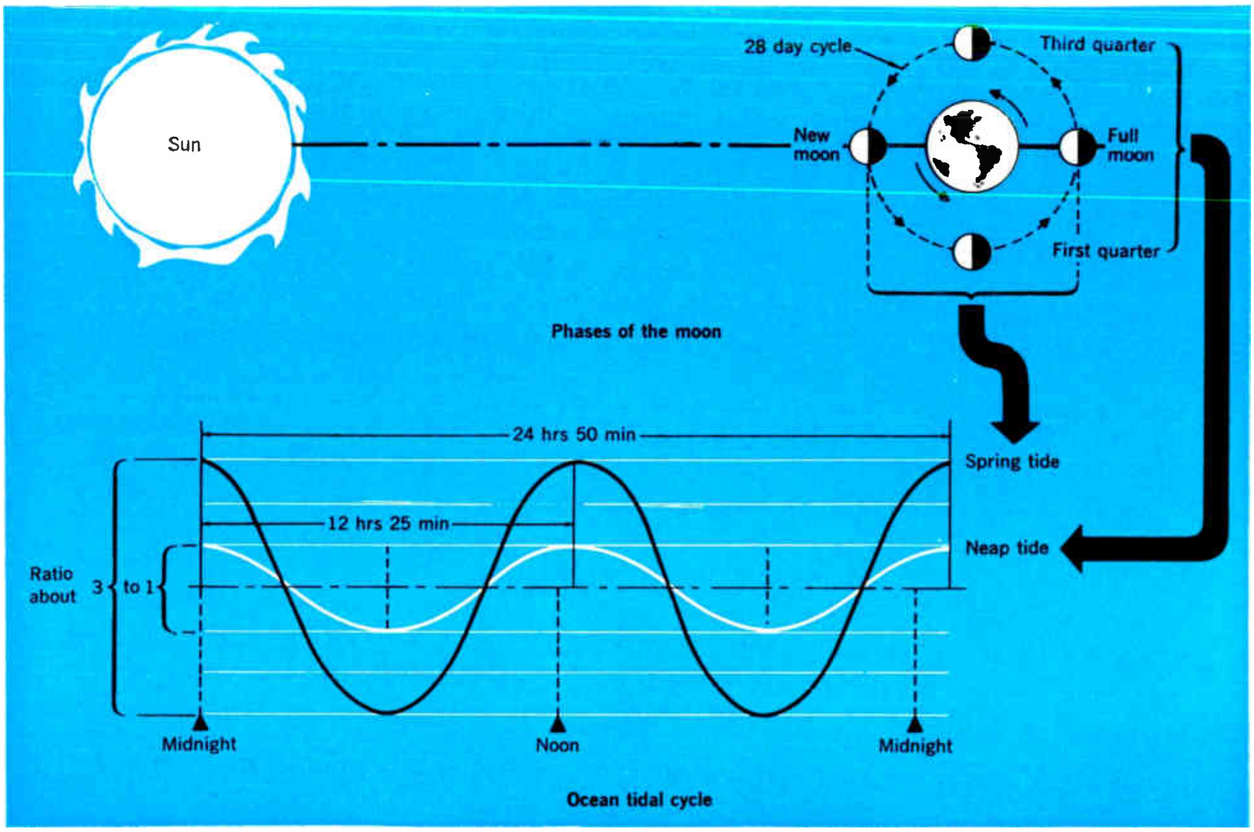


Fig. 1. Diagrams of the phases of the moon, and their effect—in conjunction with the sun—upon the ocean tides.

Hydroelectric power generation from the great tides of the Bay of Fundy has been the subject of intense interest to American and Canadian engineers for almost 50 years. At Burntcoat Head, in the upper reach of the Bay of Fundy, spring tides reach an extreme range of 50 feet between ebb and flood. And the tidal range in Passamaquoddy and Cobscook Bays, the site of the proposed tidal project, varies from a minimum of 11.3 feet at neap tide, to a maximum of 25.7 feet at spring tide—with an average of about 18.1 feet. It is estimated that during each tidal cycle, about 70 billion cubic feet of sea water enters and leaves the two bays.

Back in 1919, a Canadian engineer, W. R. Turnbull, proposed the production of hydroelectric power from the huge tides at the head of the Bay of Fundy. In 1945, the Burntcoat Head site was investigated by Canadian engineers, and they came to the conclusion that the project was economically unfeasible.

In the 1920s, an American engineer, Dexter P. Cooper, made the first large-scale study of potential power production that envisioned the utilization of both Passamaquoddy and Cobscook Bays. He proposed that each bay be enclosed by a series of earth dams, with provision for navigation locks and regulating gates, to form a "two-pool" tidal project. The water discharge thus made available by the difference in hydrostatic heads, would be channeled through turbines located between the two pools. But enthusiasm for this ambitious project—as well as monetary support—waned during the financial collapse of 1929.

Then, in 1935, the U.S. Government, as part of its far-reaching public works program, initiated the development of a single-pool project to utilize only the waters of Cobscook Bay on the United States side of the international boundary line. But as the result of determined Congressional opposition, plus other economic factors, work on this scheme was suspended in 1937, when Federal appropriations were discontinued. The surveys, investigation, and construction of three small dams, completed by the Army Corps of Engineers, proved to be of great value, however, to subsequent investigations.

Spurred by the continued American and Canadian interest in the potentialities of the 'Quoddy scheme, and the sense of urgency to exploit all possible sources of electric energy, an International Joint Commission was formed in 1948 to review all previous reports, and to estimate the cost of conducting a comprehensive study to decide conclusively the engineering and economic feasibility of a large-scale, two-pool international tidal power project in Passamaquoddy and Cobscook Bays. The International Joint Commission (IJC) report, completed in 1950, led directly to the extensive surveys and recommendations of 1956 to 1959.

The two-pool plan—how it works

From comparative studies and investigations of a number of single-pool and two-pool plans, the conclusions clearly indicated that the most efficient utilization of the tidal potential for power production lay in the adoption of the latter scheme, in which the 101-square-mile area of Passamaquoddy Bay would form the high pool, and the 41-square-mile area of Cobscook Bay would form the low pool. This plan, of course, would require the full participation and cooperation of the United States and Canadian Governments, since virtu-

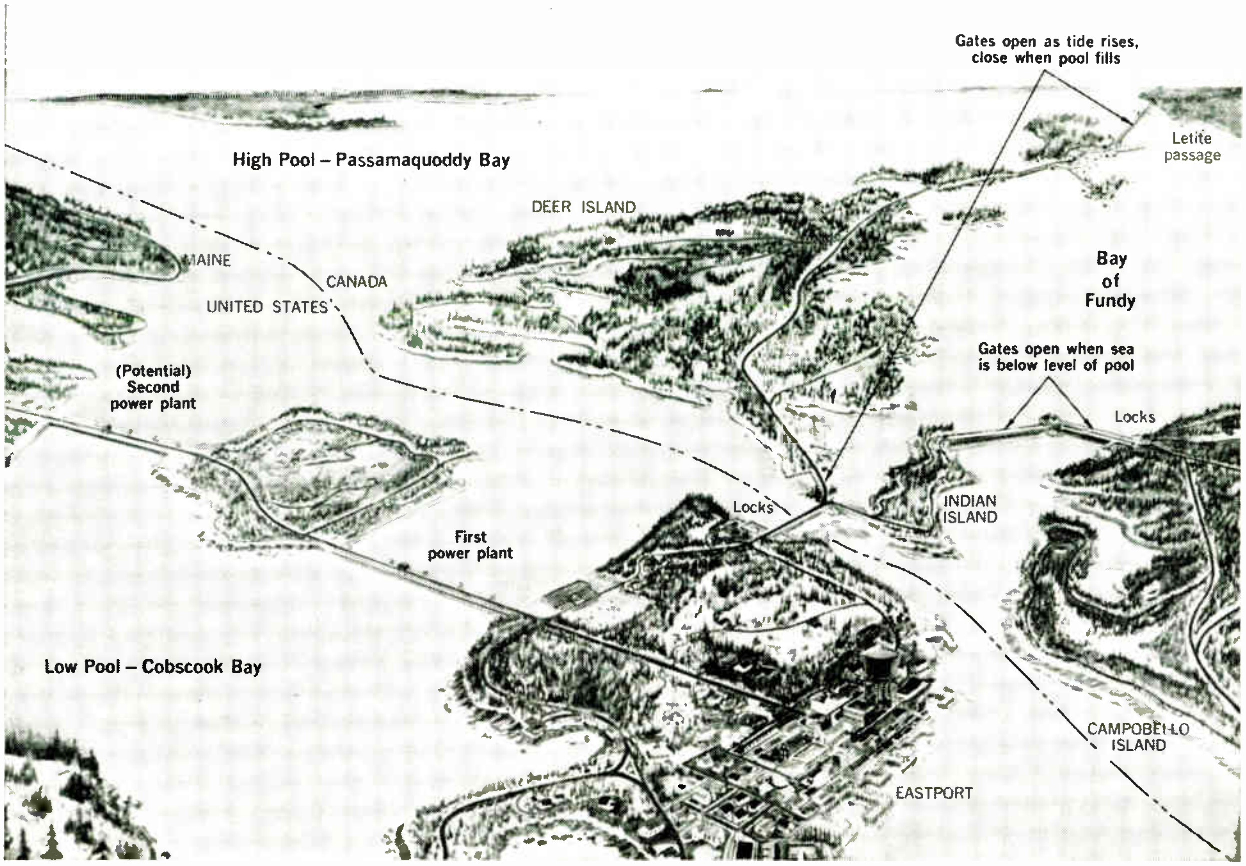


Fig. 2. Oblique aerial view of the Maine–New Brunswick coastal area, showing the locations of the proposed Passamaquoddy power plants, dams, and appurtenances.

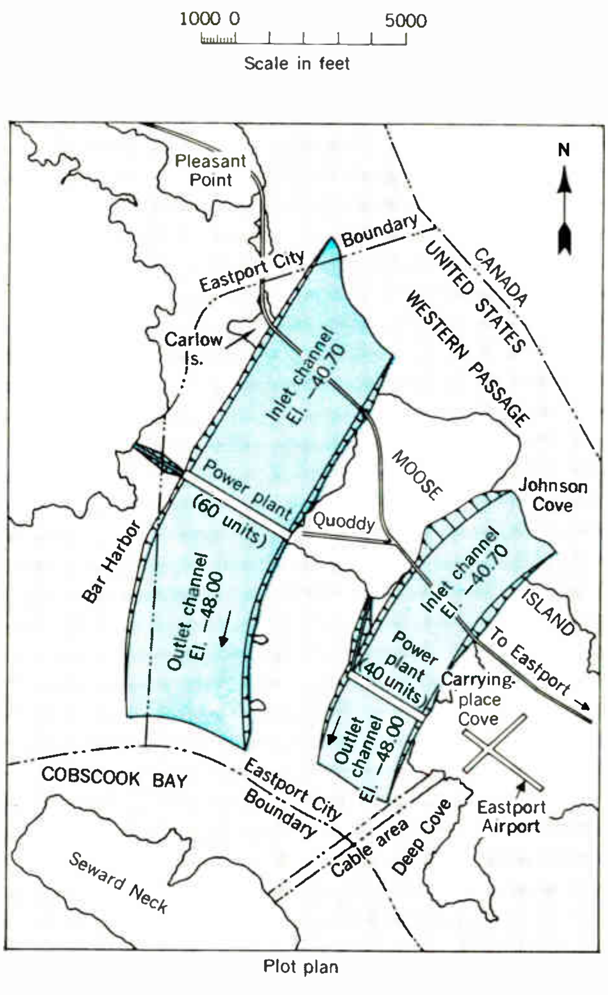


Fig. 3. Plan of the geographic area for the proposed first and second power plants. Note that the arrangement selected in the report utilizes 50 units in each plant instead of 60 and 40 units as shown on the map.

ally all of Passamaquoddy Bay lies within the Province of New Brunswick.

Referring to the Fig. 2 aerial oblique, 40 filling gates would be located in the Letite Passage between the Bay of Fundy and Passamaquoddy Bay, and 50 filling gates would be built at Deer Island Point between Indian River and Western Passage. These 90 filling gates would open as the tide in the Bay of Fundy rises, and would close when the high pool—Passamaquoddy Bay—is filled to the flood tide level of Fundy. The impounded water in the high pool would be channeled through the 50-unit turbogenerators of the first proposed power plant located at Carryingplace Cove, and eventually to the 50 additional power units to be located in a second power plant between Moose and Carlow Islands (see Fig. 3).

The 70 billion cubic feet of water transferred to Cobscook Bay, the low pool, would be discharged back to the Bay of Fundy through 70 emptying gates situated between Pope and Green Islets, when the level of Fundy drops below the level of the low pool.

There would be four navigation locks for the accommodation of present and projected shipping requirements, probably located at Little Letite Passage, Western Passage, and in Quoddy Roads. Figure 2 also indicates the approximately seven miles of rock-filled dams that would have to be built to achieve the formation of the two pools.

The latest Department of the Interior proposal envisions the installation of two 50-unit power plants, of 500 MW each, and located at the sites just mentioned. If operated at 15 per cent above rated capacity for short periods during spring tides, the total output of the tidal power plants could reach 1150 MW.

Some construction details

The power plants have been conceived as semiexposed reinforced concrete structures (see Fig. 4). Access to the turbogenerators and other equipment would be provided through rolling hatches located over each 10 000-kW unit. A 320-ton-capacity gantry crane would travel over the hatchways for the installation and maintenance of the generator units, and a 100-ton-capacity gantry crane would be used to install and service the turbines.

The generators would be protected by weatherproof housings on the power house deck. All control equipment, operating galleries, and cable and piping runs would be located within the structure as shown in Fig. 5. Emergency gates at the upstream end, and bulkhead gates at the downstream end of the waterway would permit dewatering for inspection and maintenance.

The 50 turbogenerator units of each powerhouse would be placed in a reinforced concrete monolith 55 feet wide by 188 feet long in the direction of flow—as indicated in Fig. 5—with the bottom of the draft tube about 92 feet below the powerhouse deck.

All metal parts of the powerhouse, and all other components of the tidal project exposed to salt water would be protected from corrosion by the use of corrosion-resistant alloys, protective coatings, and cathodic protection.

The design of an economical 50-unit powerhouse for the first construction phase that would be of minimum length to fit the available site, and capable of handling a tremendous volume of discharge, indicates the use of the largest possible turbines. Thus, the turbines planned for the project would be the fixed-blade propeller type, with a throat diameter of 320 inches, and a speed of 40 r/min. Because of the low average head of 18.1 feet, the large turbines would be directly connected to generators with a relatively low rating of 10 000 kW each.

The 50 turbogenerators of the first power plant would be connected, in banks of seven and eight, to six 90 000 kVA transformers located on the upstream side of the powerhouse, and connected to the switchyard by oil-filled, high-voltage cables. Transformers would operate at 230 kV for supply to the United States, and 138 kV for supply to Canada.

Powerhouse operation would be fully automatic. The wicket gate setting of each turbine would be automatically controlled at a predetermined opening, dependent upon the gross head of the plant. Synchronizing, loading, and the starting and stopping sequences of each power unit would be controlled automatically by computers and would be based upon tidal predictions. A central control board, permitting the fully automatic or manual control of all units, would be located at the center of the powerhouse.

. . . And some construction problems

The two-pool project requires the construction of almost seven miles of rock-filled dams. With tidal velocities as high as 10 feet per second during the 26-foot spring tides, the difficulties of building sufficiently watertight tidal dams—some portions of them in water depths ranging from 125 to 300 feet—and closing these dams in the face of restricted and greatly increased tidal velocities that would range up to 20 feet per second, presents engineering and design problems that are without precedent. To assist in the solution of these problems, leading hydraulic engineering and soil me-

Fig. 4. Architectural rendering of a proposed power plant at Passamaquoddy. Note the large gantry cranes that would serve for the installation and maintenance of the turbogenerator units.

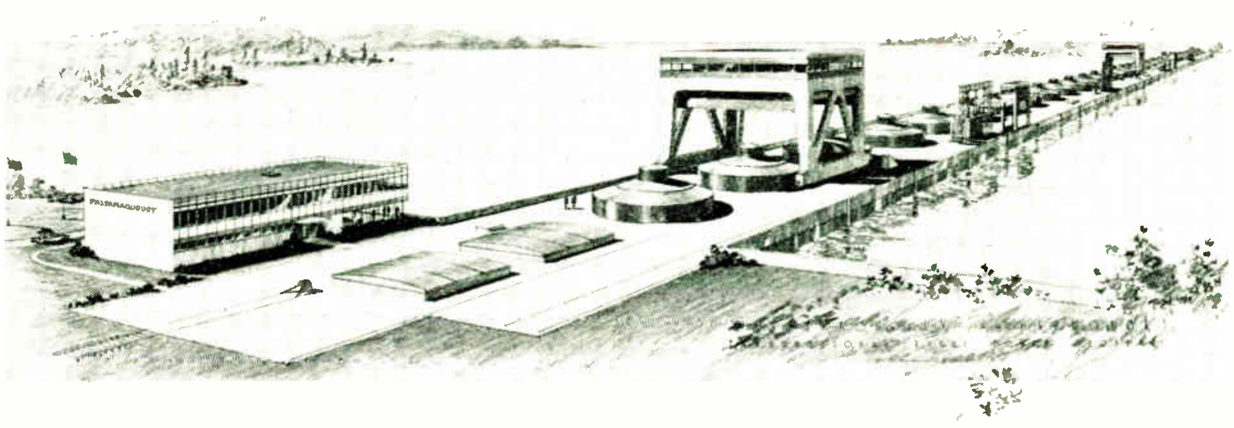
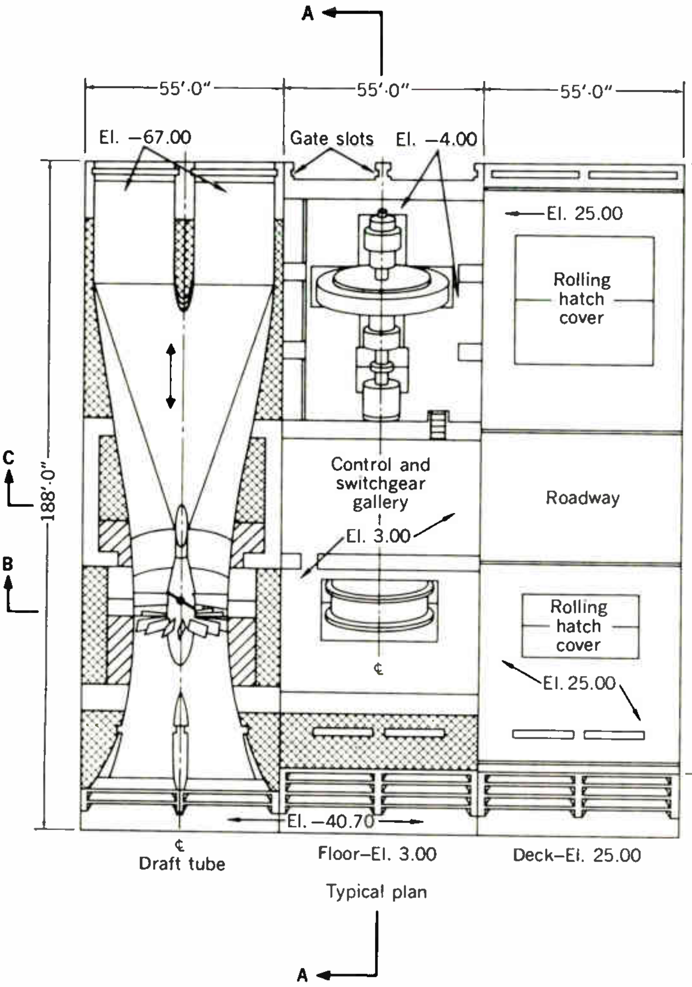


Fig. 5. Plan and sections of typical turbogenerator unit of the 50 proposed for each power plant.



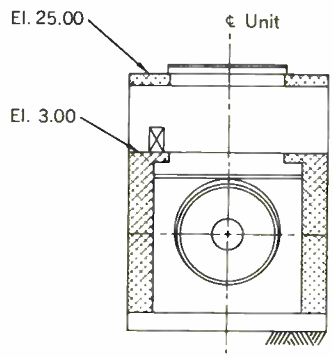
Concrete symbols
- Cast in place
- Cast in place or precast option
- Second stage

UNIT DATA

Generator .... 10 000 kW

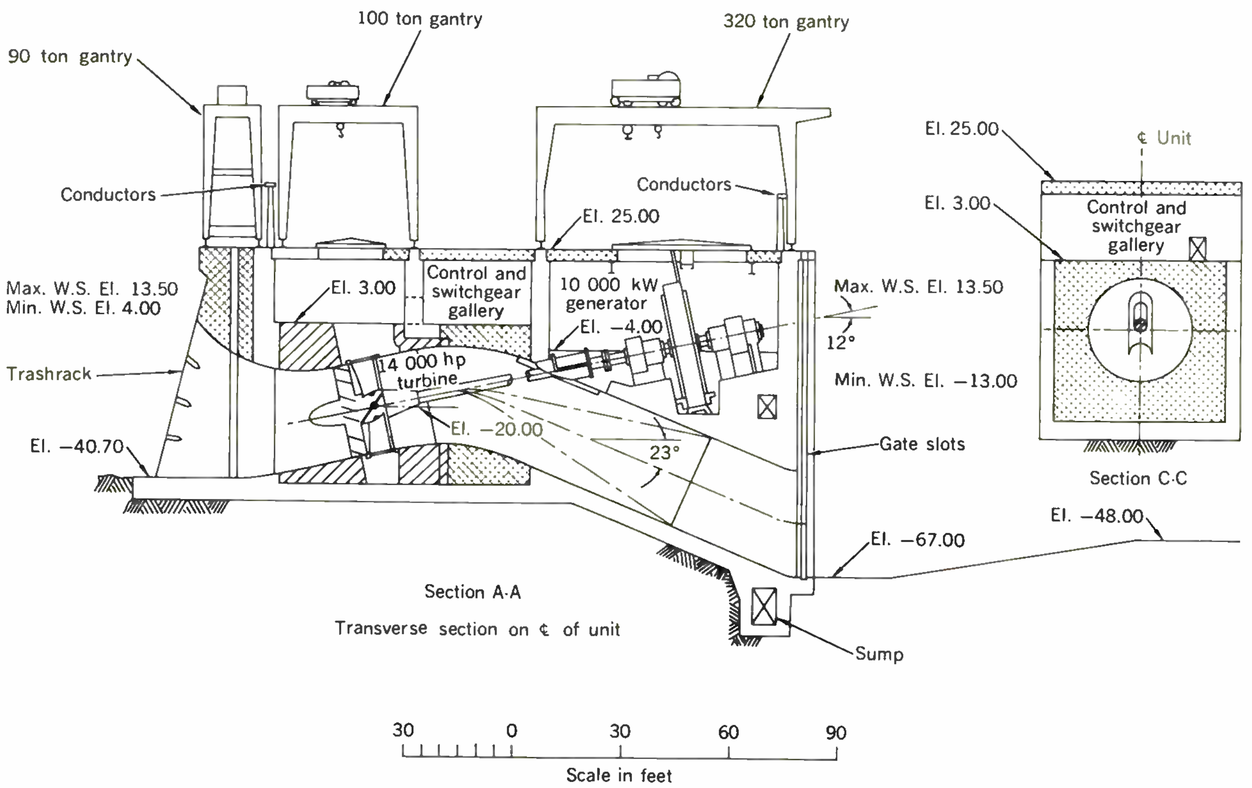
Turbine, adjustable pitch propeller type
- Horsepower 14 000
- Speed .... 43.4 r/min
- Head .... 13.2 ft
- Q .... 11 000 ft^3/s

Cranes
- One 320 ton gantry each power plant
- One 100 ton gantry each power plant
- One intake gate gantry crane with one pair of emergency-type intake gates for each ten units.



Section B-B

(Propeller blades not shown)



chanics specialists were consulted, and scale-model studies were made of the hydraulic characteristics of deep tidal dams to determine the most practical and economical methods of construction.

Soundings and core drillings revealed that bottom conditions in Passamaquoddy and Cobscook Bays vary widely from areas of exposed bedrock to clay overburden that is more than 100 feet thick. The 35 700 linear feet of tidal dams would be located, insofar as practicable, on foundations of bedrock, or granular material, to avoid the clay overburden. The tidal dams, as shown in the Fig. 6 cross section, are composed of a clay core that is supported by flanking dumped-rock fills, and are designed to permit the greatest possible use of material excavated from the gate structures, navigation locks, and the powerhouse.

It is planned to use the greater portion of some 17 million cubic yards of clay, excavated from the site of the Carryingplace Cove powerhouse, for the clay cores of the dams that are situated in water depths up to 125 feet. About 2900 linear feet—almost 8 per cent of the total length of the tidal dams in the project—would be located in water depths of 125 to 300 feet below mean sea level. At these greater depths, a granular core would be placed by special bottom-dump buckets. With the exception of these deep, granular core sections, all the tidal dams could be built with conventional land and marine equipment.

Construction of the dams would be scheduled to permit direct placement of the material excavated from the powerhouse, navigation locks and gates without costly stockpiling. And to overcome the problem of greatly increased tidal currents caused by the Venturi effect during closure of the dams, the 160 emptying and filling gates would be constructed first, and then operated to handle part of the tidal ebb and flood, thereby reducing the quantity of water passing through the closure sections.

Cofferdamming. Cofferdams of several different types—depending upon the depths to be dewatered—would be erected prior to the excavations for the foundations of the powerhouses, the filling and emptying gates, and navigation locks. The cofferdam designs include earth embankments, log cribs with timber sheathing, earth-filled cylinders, and sheet-steel piling. Construction of the emptying gates in Head Harbour Passage would entail an embankment cofferdam 120 feet below mean sea level, under a head of 75 feet when pumped out. The construction of such huge cofferdams, built to withstand water pressures far greater than those anticipated for the tidal dams, is one of the major engineering and erection problems of the tidal project.

Filling and emptying gates. The project plans include 90 filling gates (see Fig. 7), 40 in Letite Passage, and 50 between Western Passage and Indian River. In the reach between Pope and Green Islets, 70 emptying gates, similar to the filling gates, but set at a lower elevation, would empty the lower pool.

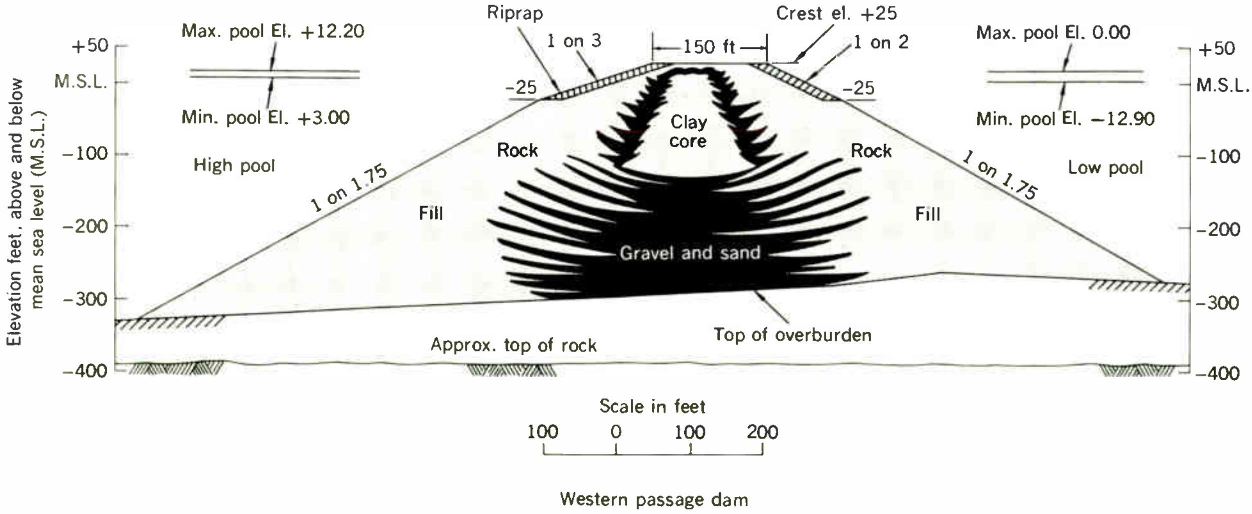
A comprehensive study of all types of gates led to the recommendation of a 30 ft by 30 ft vertical-lift, steel gate set in a Venturi throat. This type would permit maximum discharge for a given gate area.

Navigation locks. Four navigation locks are anticipated for the accommodation of present and future water-borne traffic in the two bays. Two locks, one at Little Letite Passage and the other at Quoddy Roads, would have clear dimensions of 95 ft by 25 ft by 12 ft, to pass fishing vessels. The two other locks, one at Head Harbour Passage, immediately east of the emptying gates, and one at Western Passage, north of Eastport, would have clear dimensions of 145 ft by 60 ft by 21 ft, to pass vessels larger than present traffic.

The Navy barges in

The IJC report of 1961 indicated that a large portion of the project cost is involved in the deep-water structures in Western Passage, Indian River, and Head Harbour Passage. In view of its experience in deep-water construction, the Navy Bureau of Yards and Docks reviewed the IJC report, and concluded from its review that because of the thoroughness and up-to-date applications of latest engineering technology in the investigations, no major breakthroughs in construction could be offered. In the Bureau of Yards and Docks report, however,

Fig. 6. Cross section of typical earth- and rock-fill tidal dams that would be required to form the two pools.



there are references to the possibility of future utilization of nuclear energy explosions for the major excavation areas.

Also, the Navy suggested that if the project generates sufficient interest to justify the use of further study efforts in the planning stage, the following items might be investigated:

1. Greater control accuracy for the deposit of the dam core material which may be achieved by utilization of hinged trunks or tremies on bottom-dump barges. This method may prevent fill material scatter and lateral displacement of fill by swift currents.

2. The possibility of using flat-decked barges, equipped with articulated tremies into which bulldozers on the decks could push materials.

3. Alternative methods of transport for the core materials such as cableways and belt conveyors, and the placement of these materials by hydraulic dredge, with submerged pipelines and discharge.

4. The possibility of further refinement in the widths and design slopes of the dam cross sections, with a view toward the reduction of the total quantities required.

Don't raise the bridge—lower the river

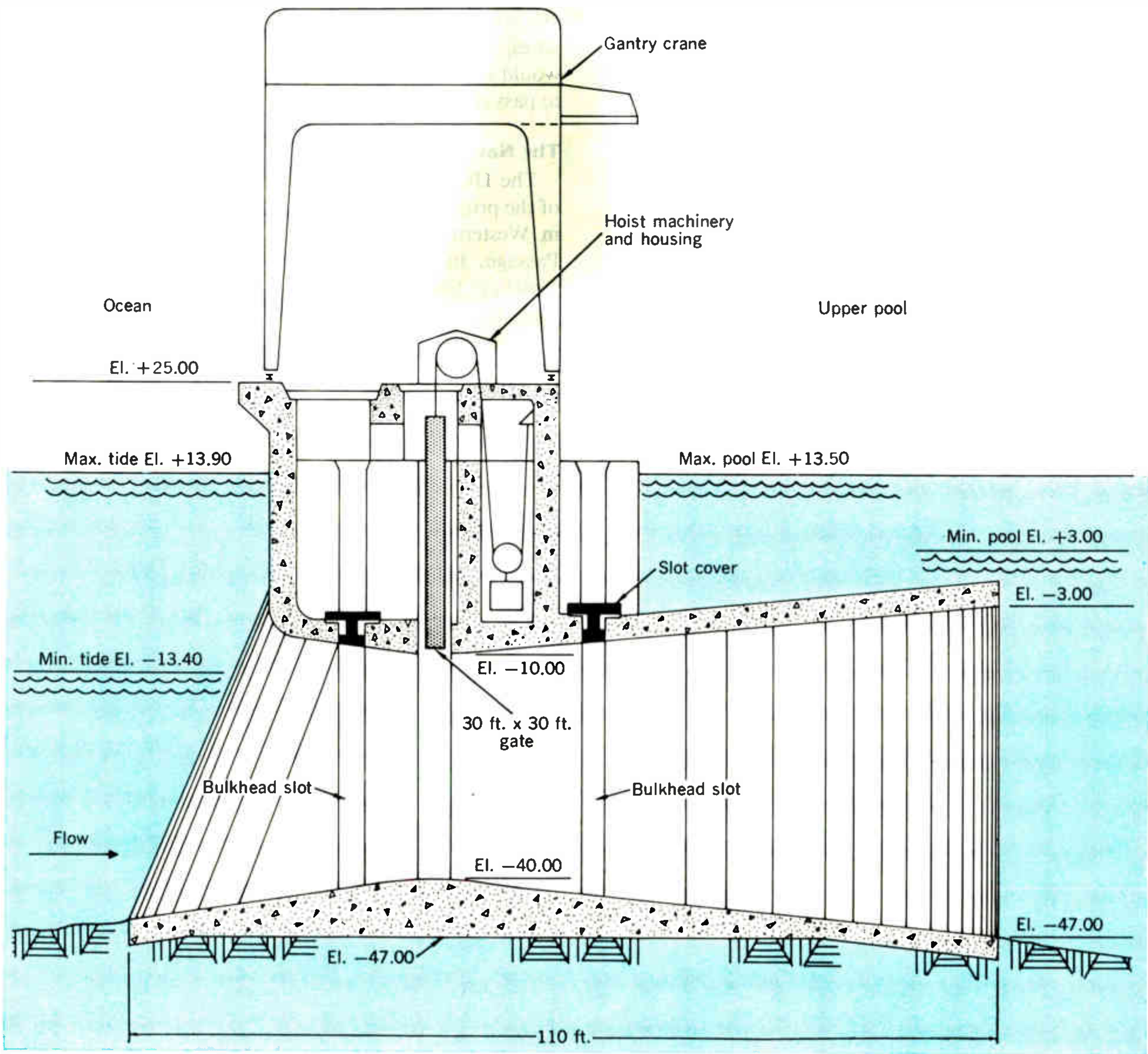
To pick up the chronological thread of historical background we must here revert to 1956, when the International Passamaquoddy Engineering Board was appointed by joint agreement between the United States and Canadian Governments. This board subsequently found that a tidal power project could be built and operated in the area, and that a two-pool arrangement—similar to that already discussed—would be best suited for the site conditions.

Following this appraisal, the most comprehensive study and analysis was initiated. The investigations consumed almost five years. Then, on April 4, 1961, the IJC reported that: "It is evident that construction of the tidal power project by itself is economically unfeasible by a wide margin.

"In short, the Commission finds that the tidal project, either alone or in combination with auxiliary sources, would not permit power to be produced at a price which is competitive with the price of power from alternative sources."

The IJC further recommended that *development of the project be viewed as a long-range possibility when other*

Fig. 7. Cross section of typical vertical-lift filling gate is shown in submerged Venturi setting.



less costly energy resources available to the area were exhausted. And the Commission emphasized that economic feasibility of the project might be affected by future changes in the costs and benefits considered in the evaluation.

However, the late President Kennedy, on May 20, 1961, requested the Secretary of the Interior to review and evaluate the IJC report and, upon completion of this review, the President asked the Secretary to advise as to what changes in fuel, engineering, and financing cost might render the project economically feasible.

Another report—another proposal

As a result of President Kennedy's instructions to Interior in May 1961, a new group, called the Passamaquoddy–Upper St. John Study Committee, had a Load and Resources Study made in December 1961. This study clearly indicated that the project would be feasible if developed as a peaking power plant of 1000-MW capacity, instead of the 300 MW envisioned in the IJC report. And the study also made observations in reference to new types of horizontal turbines, operation of the tidal power project as a peaking plant, integration with other forms of hydro and thermal power generation, and interconnection with electric utilities systems in the United States and Canada.

In the Public Works Bill for fiscal year 1963, Congress appropriated the sum of $200 000 for the Secretary of the Interior to perform the basic studies required to determine the validity of the peaking power concept for the 'Quoddy project. These studies are now complete.

Auxiliary power sources

Each tide at 'Quoddy would fill the high pool of the project regardless of the amount of water used to generate energy in the previous cycle. Unused water would be wasted. In this respect, the tidal power project is somewhat similar to a "run-of-the-river" hydro plant in which no storage is available. Thus, energy generated by a two-pool tidal plant must take full advantage of the ebb and flood of the tides. Because electricity is generated as the tides occur—rather than when the power market requires it—modification of this fluctuating output to meet demand is essential to the power plant operation.

As illustrated in Fig. 8, the output of the two-pool project would vary with the ebb and flood periods. Coupled with the additional variations in the tidal range from spring to neap tides, and the 50-minute difference between the lunar and solar days, this variable output contrasts sharply with the normal pattern of power demand. Hourly, weekly, and seasonal demands for power reflect activity patterns. Therefore, daily variations in demand, or load patterns, follow the solar cycle, which is out of phase with the lunar cycle. At times, then, the peak demand for power may coincide with minimum output from the tidal power plant.

For load-carrying purposes, power from the tidal project is limited to the capacity it can furnish under the most adverse conditions. All output in excess of this capacity is not dependable for serving loads. Thus, all excess energy would have value only as nonfirm or secondary energy. Therefore, to make the maximum output of the tidal power plant dependable, this output must be firmed by an auxiliary source of power.

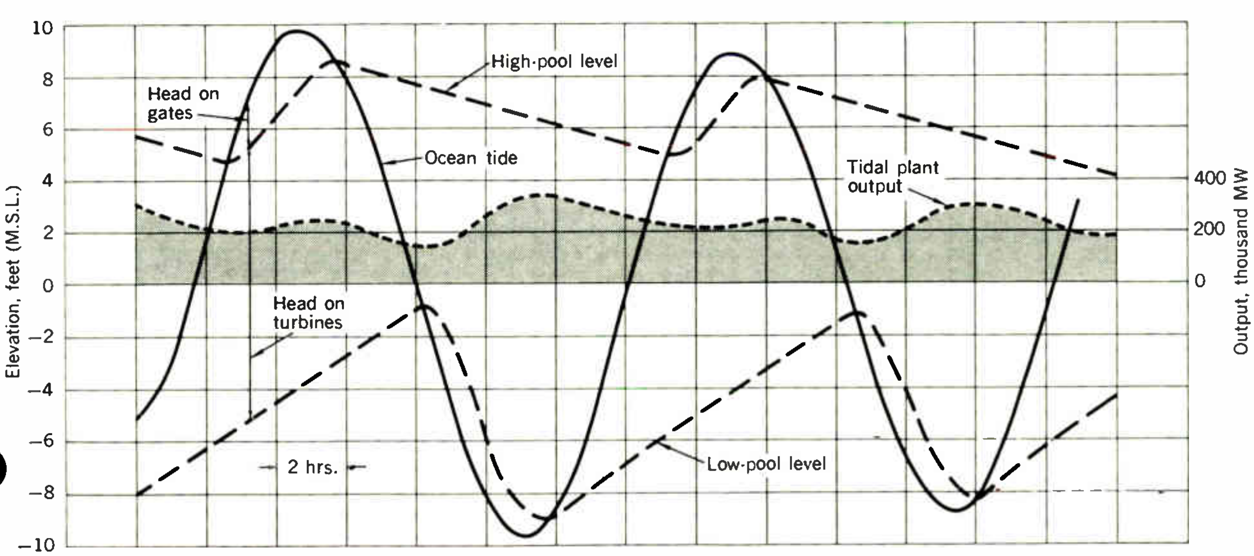
Nevertheless, Interior claims that the two-pool plan would be readily adaptable to a peaking operation, and the prime consideration is for the two pools to be operated to provide the maximum amount of head on the turbines at the start of each peaking period. Interior's operating plan for Passamaquoddy as a peaking power plant involves the following basic steps:

1. Filling the high pool through the filling gates to the maximum height the tide will permit.
2. Retaining the water in the high pool until power is required—then releasing the water through the power plant to the low pool.
3. Releasing the water in the low pool to the ocean through the emptying gates whenever the tide is below the level of this pool.

St. John River hydrologic studies

About two years ago, the Government conducted hydrologic studies of the St. John River to evaluate the practicality of a coordinated power project with 'Quoddy. Such coordination would be valuable to integrate a large

Fig. 8. Output curves for a two-pool tidal plant operation.



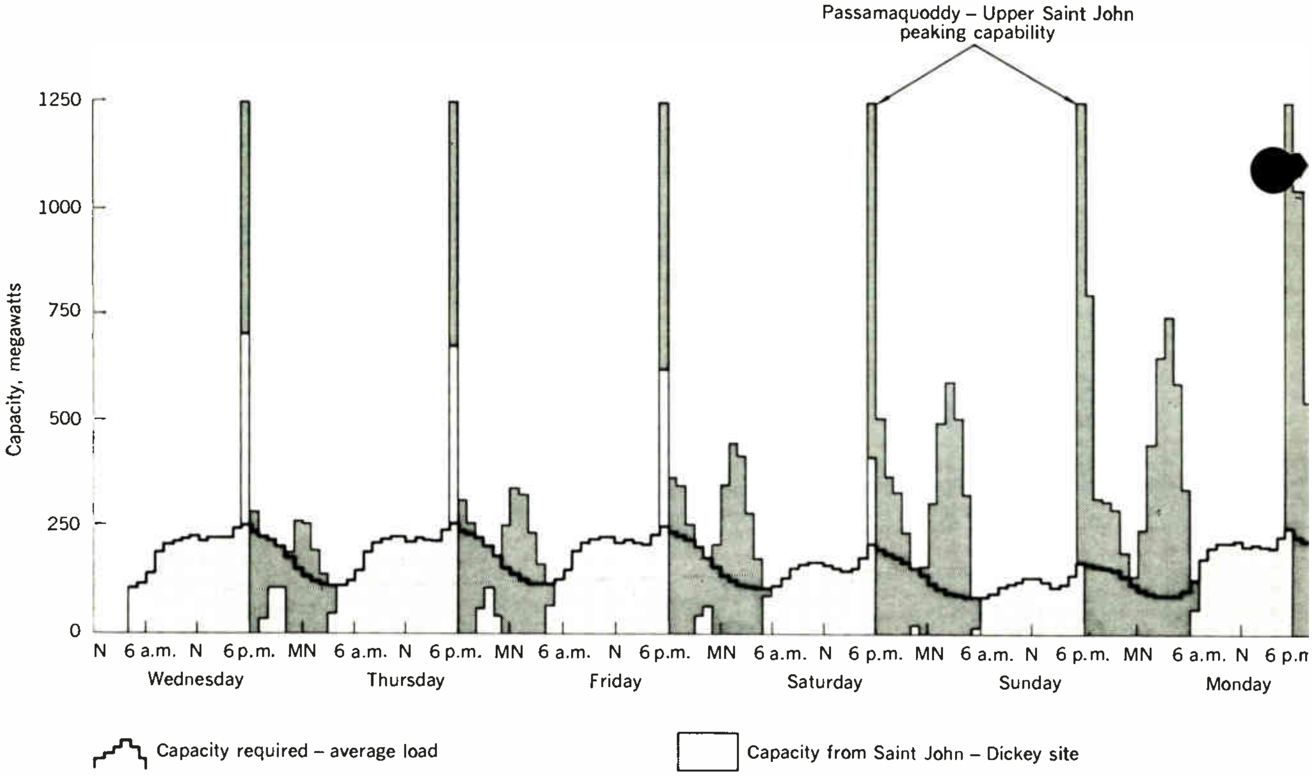


Fig. 9. Graph showing the coordinated operation of the 'Quoddy project with the proposed Dickey power plant. The chart is based on a capacity of 1000 MW at 'Quoddy and 750 MW at Dickey.

part of the tidal off-peak energy with the St. John energy, thereby permitting the utilization of the combination as firm energy. And the Government engineers felt that additional installed capacity could be provided in the river plant to meet the peaking requirement for the increased firm energy—and to bolster the tidal peaking capability during neap tides.

For these studies, pertinent stream flow records for the Allagash River and St. John River, at Dickey, were extrapolated back to September 1929 by correlation with other stations. The records were then used to derive monthly runoff values for possible dam sites at Big Rapids, Dickey, Rankin Rapids, and Lincoln School. Mass curves of runoff vs. time, prepared for the main storage sites, indicated that the critical low runoff period on the St. John River extended from July 1955 through March 1958. Figure 9 illustrates the coordinated operation of the Passamaquoddy Tidal Power Project with the proposed Dickey power plant. The chart is based on an installed capacity of 1000 MW at 'Quoddy, and 750 MW at Dickey. This would provide a dependable capacity of 1250 MW, of which 250 MW from Dickey is usable as load factor power, and 1000 MW as dependable peaking capacity.

The reregulation dam

A hydroelectric plant operating to provide a load with sharp peaking characteristics requires a reservoir down stream to assure as nearly continuous flow as possible. The reregulating reservoir must have sufficient storage capacity to accommodate large influxes of water. Thus, a power plant such as the one proposed at the Dickey site would require a reregulating reservoir located at the Lincoln School site. But the water level for this reservoir would be restricted to an elevation that would not encroach upon the tail water from the Dickey plant. However, sufficient reservoir capacity at Lincoln School would have to be provided for the necessary reregulation of the water released from Dickey.

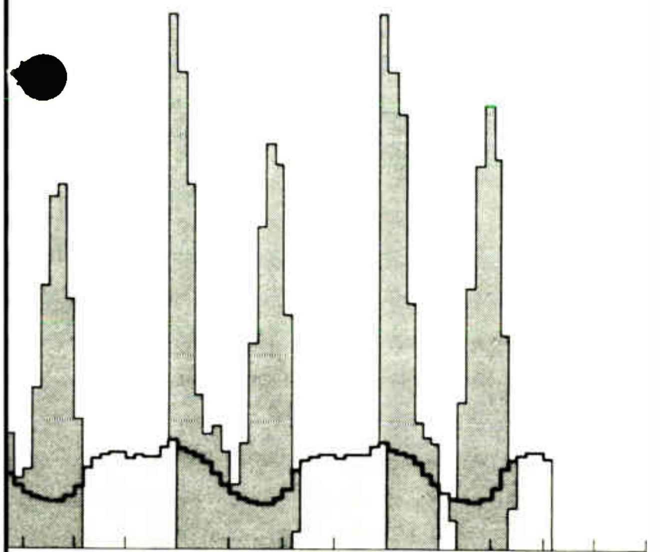
Interior states that further studies are required for the precise location of the Dickey plant site, and the probable discharge from this plant. No cost estimates were included in the recent study to cover the cost of the reregulating reservoir installation.

Flood control—fish and wildlife

It is Interior's contention that the storage of water on the Upper St. John will afford almost complete regulation of the river above the proposed Dickey Dam, and substantial flood-control protection will be provided for the Lower St. John River. But in this connection, the following paragraph quoted from the 1961 IJC report seems to be a bit contradictory:

"*Flood Control.* Damages from floods occur with some regularity along the St. John River, and the damages would be reduced by an upstream storage project. The extent of these annual damages, as indicated . . . is a substantial loss to the area, but very small compared to the power benefits of the projects being considered. Flood-control benefits which might accrue would have only a small effect on the benefit–cost ratio of the tidal project and its auxiliary, therefore, further study in this direction was not undertaken."

In reference to fish and wildlife, the IJC report contains the following information from the Bureau of Fish and Wildlife in reference to downstream benefits in this category:



". . . Based on this review and the discussions [we] conclude that further studies of the marine fisheries or sport fisheries and wildlife as they would be affected by construction and operation of the Passamaquoddy project would not be required at this time."

Recreational and economic benefits

Last—but not least—Interior claims that the 'Quoddy–St. John venture would produce numerous recreational and economic peripheral benefits. The economic advantages would:

1. Enhance the fisheries of New England through the removal of existing small and inefficient hydro projects that now block the migration of anadromous fish.

2. Improve the sagging economic status of northeastern Maine through the creation of many job and work opportunities.

3. Protect for all time the great scenic beauty and recreational values of the Allagash River.

Interior believes that the principal tourist attraction would be the tidal project itself, and recommends the construction of a visitor center with adequate parking facilities, picnic areas, boat-launching sites, and frequent scenic roadside overlooks.

The 'spring tide' of opposition

As might be expected, the investor-owned private utility companies in New England regard the 'Quoddy project as anathema to their interests, and irked by the contradictory aspects of the IJC report of April 1961, and subsequent events, have made their opposition known to the public and to Congressional representatives.

In the view of the utility industry's articulate spokesmen—and there are many—some of the most glaring flaws in the voluminous file of Government reports are the many conflicting statements, contradictions, and ambiguous recommendations. In some instances these inconsistencies are contained in the same report, while in other instances later reports seem to contradict and nullify their predecessors.

And to compound the confusion, the IJC, within its report of April 1961—and despite a statement to the contrary—somehow found the combination of the 'Quoddy Tidal Power Project and incremental capacity of the Rankin Rapids site to be most feasible, and observed that changes in economic considerations, markets for power, technological changes, and advances in construction and equipment, could result in greater economic feasibility.

Meanwhile, back at the Rance . . .

While the surveys, investigations and controversy pro and con on the subject of 'Quoddy continue on this side of the Atlantic, the dream of harnessing the tides for electric power is about to come true in France with the imminent completion of the la Rance power project in Brittany—one of the world's best tidal sites. Although the French project is not nearly so ambitious in scope or power production as that envisioned for 'Quoddy, the thrifty and practical French have managed to design—and are constructing—24 turbogenerator units, each of 10 000-kW capacity.

This site was visited by an Interior Department Assistant Secretary and members of his staff in 1963. A portion of their report is quoted:

"This project is presently the largest tidal project under construction in the world. It will have an initial power installation of 240 megawatts in 24 turbine sets, and could have an ultimate installation of 320 megawatts. It is being built at an approximate cost of $80 million, and represents the continued effort of French engineers over a 20-year period to harness the energy of the tides at St. Malo. The site is ideal for the construction of such a tidal project because it is a narrow estuary with a tidal range of 13½ meters (that is roughly 44 feet). The la Rance Tidal Project is operated for peaking capacity or energy. Since the units are reversible, it is designed to take whatever advantage of the tides for generation to fit into the power loads of the French electric system.

"The la Rance Tidal Project which is under construction certainly inspires the officials and engineers of the Department of the Interior who have been concerned with the review of the Passamaquoddy Tidal Power Project and the St. John River. Every effort will be made to quickly obtain authorization and make plans for construction of the Passamaquoddy Project coordinated with the St. John River."

La Rance will have an initial mean annual output of 544×10^6 kWh, operating under an average head of 18.5 feet. This quantity is possible because of the most recent advances in the design of low-head propeller turbines. And this means that la Rance will be among the twelve most powerful hydro stations in France.

River la Rance flows into a long, broad estuary (see Fig. 10 map) that opens into the English Channel at St. Malo. The dam and power plant are situated about 2½ miles upstream from the town. At the powerhouse site, the Rance estuary is about 2500 feet wide, and maximum depths are 42.6 feet beneath mean low water. The dam proper has a length of about 2300 feet, and is approximately 85 feet high from river bed to crest. The dam is of the gravity type, and is of hollow, reinforced concrete construction.

The power unit comprises 24 bulb-type Neyrpic horizontal-axis turbines, with each alternator having a maximum capacity of 10 000 kW (see Fig. 11). These unique machines, which double in duty as turbogenerators and pumps, were developed just in time to assure the economic feasibility of the plant project. Had the conventional, or Kaplan type, vertical-axis turbines been selected, power could be generated only on the ebb tide.

The horizontal-axis machines are set directly in the line of flow. They are completely submerged, and have the unusual property of being able to generate power with the water flowing in either direction. Thus, functioning as pumps as well as turbines, they can be utilized to generate power on both the ebb and flood tides. The Fig. 12 graphs illustrate the pump-generator cycles. The pumping function can be used to raise the reservoir levels above those normally attained, thereby increasing

Fig. 10. Map showing the location of the la Rance tidal estuary power project in France.

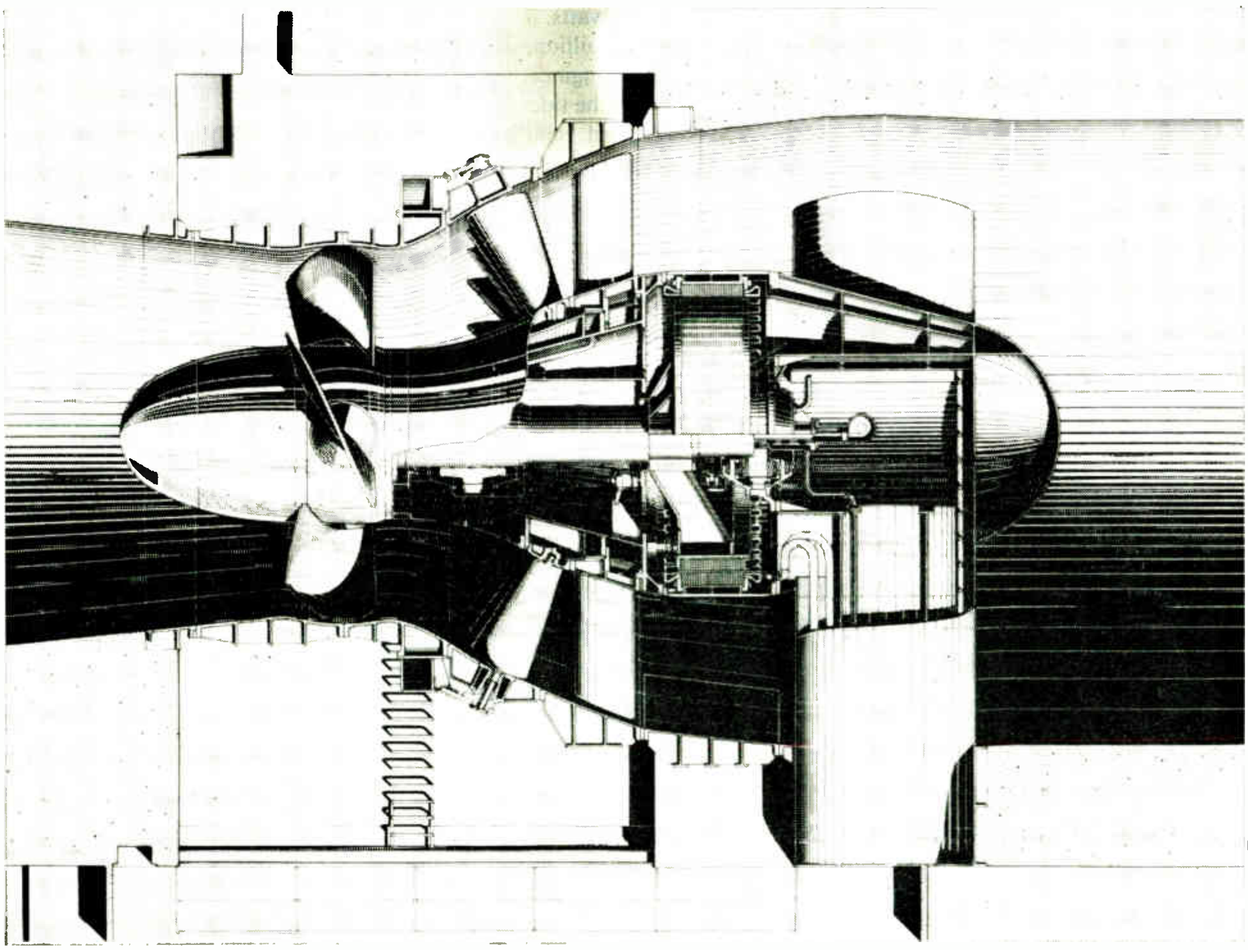


Fig. 11. Diagrammatic cross section of a typical horizontal-axis, bulb-type turbine that is being installed at la Rance.

the head available for the turbines. This feature can produce an additional 130 million kWh per year. And, as the turbines are mounted horizontally, the head loss caused by the size of the installation is minimized.

Streamlined access tubes in the bulb turbine housings are used for inspection and the protection of the power cables. The 24 bulb-type turbines might seem to be an inordinately large number of relatively small machines, but several advantages accrue—the effective head is greater on a small machine; one unit out of service has little effect on the total output; small "monobloc" units can be removed and replaced in a matter of hours; and finally, since a large number of machines have to be manufactured for this and subsequent stations, the cost per megawatt can be reduced by assembly-line methods of production.

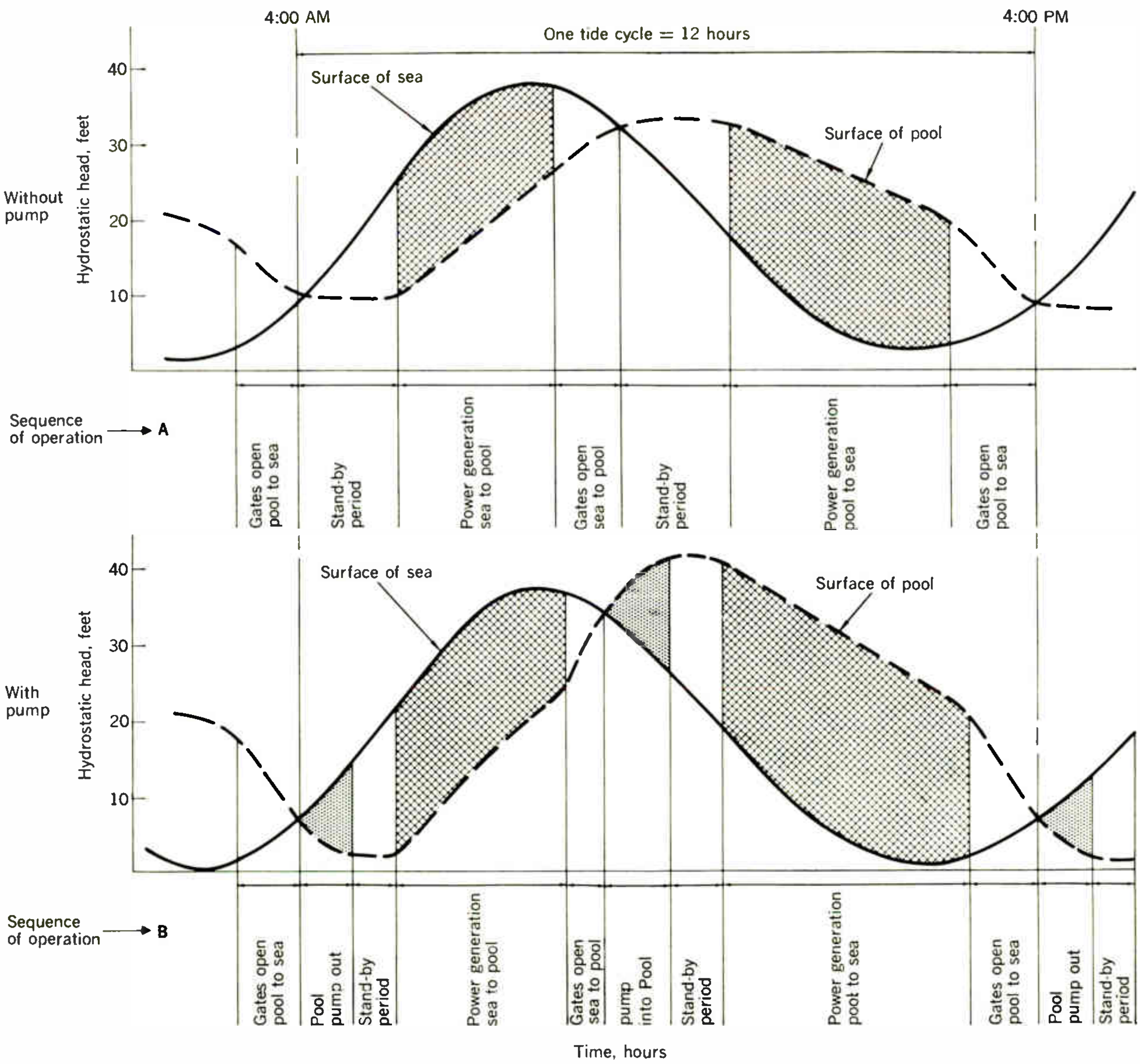
Construction on the la Rance project started in January 1961, after more than seven years of planning, studies, and preliminary investigations. The emptying and filling gates will be like a conventional mobile dam for harnessing low heads. The sluice gates are built to withstand pressure on both the upstream and downstream faces.

The mean tidal range at the site is 28 feet. The range for neap tides is 17.4 feet, 35.8 feet for average spring tides, and 44.2 feet for equinoctial spring tides. During equinoctial high tides, the volume of water cycles four times each 24.5 hours—ebbing and flooding twice.

Corrosion problem of sea water. The French engineers built a test plant that permitted alloys to be selected for the manufacture of corrosion-resistant turbine blades. And a testing station for paints enabled the best products and preparation methods to be chosen for optimum protection for metal surfaces exposed to corrosion by sea water and spray. A laboratory was also provided for the testing of hydraulic concrete.

As may be seen in the Fig. 13 diagram, the first construction stage consisted of building the lock on the left bank, and the six sluice gate openings on the right bank. In the second construction stage, the tidal power plant and dam were built behind a cofferdam enclosure 1640 feet long by 655 feet wide. The cofferdams abut on

Fig. 12. Graphs showing the utilization of the pump-generator cycles over a one-tide period of 12 hours.



the right bank Rock of Chalibert, and on the left bank east of the lock. The north cofferdams on the seaward side were built to allow the estuary to be cut off. Thus, the central section of the south cofferdams, on the landward side, were built in slack water when cutoff was achieved.

The cofferdam cells are of two types—cylindrical, earth-filled gabions of conventional sheet pile type, with connecting arches, and steel sheet piling cells, 69 feet in diameter, in the central sections that were subject to more violent alternating tidal flows. Sheet piling was erected on bedrock in water ranging from 16 to 66 feet deep. The strong tidal currents required heavy metallic formers to hold the sheet piling in place. The sheet piling was erected and removed with pontoon cranes of the type shown in Fig. 13.

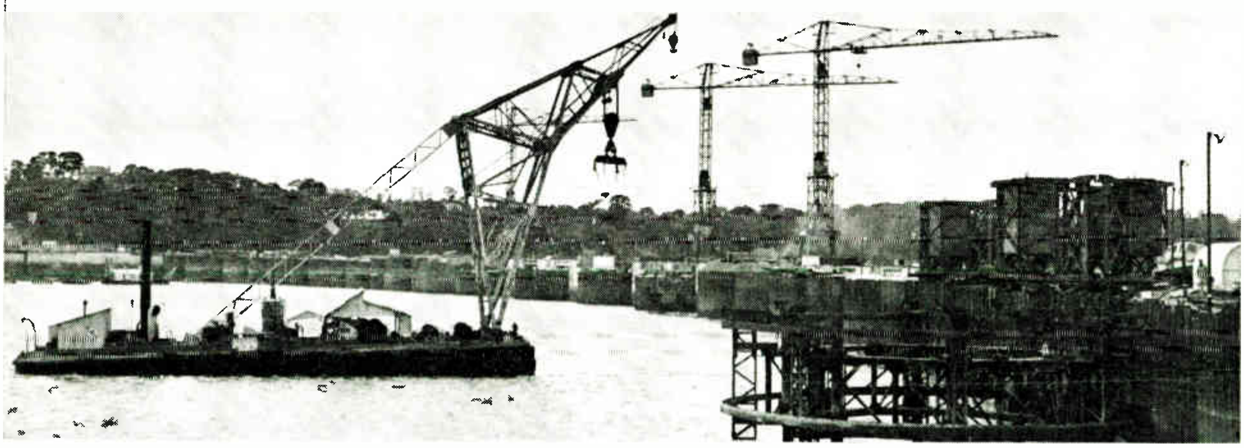
Electricité de France (EDF), the country's power authority, expects power to be generated on the first set of turbogenerators by November 1965, and predicts that all 24 sets will be in operation by July 1967.

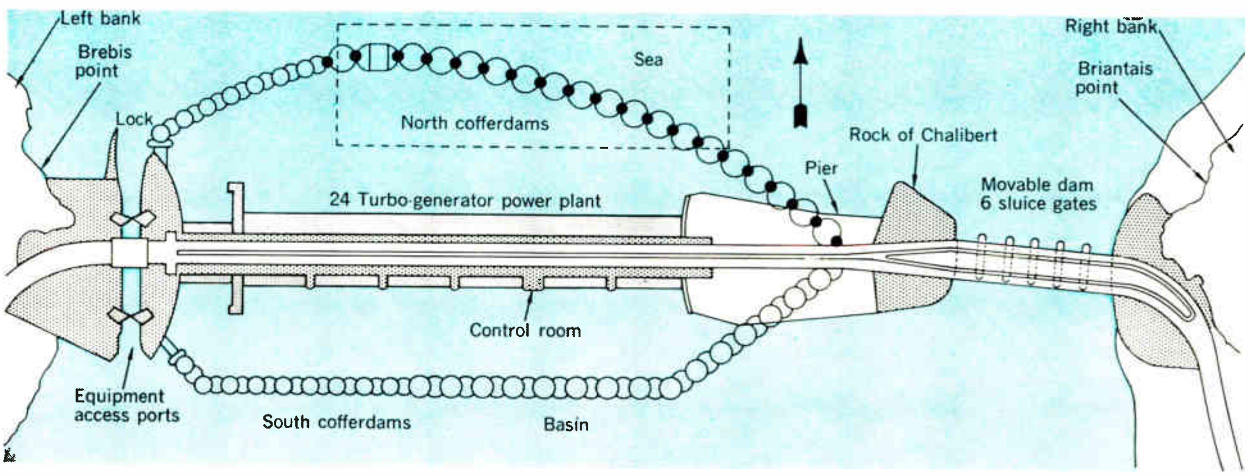
Comparison of la Rance to 'Quoddy

Although the two tidal projects are based upon the same theory of electric power generation, here is where the similarity seems to end. In the first place, la Rance is a compact, single-pool concept, situated in a narrow estuary that is endowed with tides whose average range is greater than 'Quoddy's—28 feet to about 18.1 feet. The total linear length of the dams and power plant at la Rance is about 2500 feet—a mere half mile—compared to the almost seven miles of dam construction, complete with 160 emptying and filling gates, that will be required at 'Quoddy. At la Rance we are talking about water depths that do not exceed 70 feet, while at 'Quoddy the depths of the bays forming the two pools range from 125 feet to 300 feet. The impounding basin, or pool, upstream from the la Rance dam involves only about nine square miles, with a useful storage volume of about 5 billion cubic feet. The two pools at 'Quoddy cover about 142 square miles.

Maritime traffic is not a major problem at la Rance, thus only one navigation lock is required; but at 'Quoddy four large and complex locks will be needed. The volume of excavation required for the construction of the dam and power plant at la Rance would seem like a child's sand pile in comparison to the 2½-mile long by 1¼-mile wide by 40-foot deep combined excavations (see Fig. 3) that would be required for the construction of the two 50-unit power plants at 'Quoddy. Finally, there is the complexity of an international boundary line situation

Fig. 13. Diagram (bottom) illustrates the construction sequences that were used during the building of the la Rance tidal power plant, dams, and other appurtenances, while view (above) shows the construction of the "gabion" type cofferdams that formed the north enclosure for the tidal power plant. Note the pontoon cranes that were used for the erection and removal of the sheet piling.





(United States–Canada) at 'Quoddy that is entirely absent in the French project.

Essentially, the la Rance project may be considered as a pilot model that was conceived and achieved at a relatively small, controllable, and economical scale, and will provide a proving ground—as well as a background of experience and technological know-how—for subsequent projects.

But the economics of the la Rance effort provide the final clincher—about $80 million—compared to estimates as high as $1.2 billion for the combination 'Quoddy and Dickey power projects.

Interior's report of 1963

In response to President Kennedy's review request letter of May 20, 1961, the Department of the Interior advised that:

1. The 'Quoddy project is feasible on current fuel prices—which are essentially the same as those used in the 1961 IJC report.

2. The project is feasible with the change in the engineering plan to provide peaking power on the order of 1000 MW.

3. The project is feasible for development by the U.S. Government, based on an interest rate of 2⅞ per cent as prescribed by the Bureau of the Budget for project formulation.

The major changes in planning developed in the 1963 Interior report, as compared to the plans of the Passamaquoddy Engineering Board in the 1961 IJC report, are:

1. Increasing the 'Quoddy Tidal Power Project installation from 300 MW to about 1000 MW.

2. Operating 'Quoddy for short periods every day for peaking power production to fit the anticipated load pattern of the area.

3. Use of axial-flow type of hydraulic turbines instead of the conventional, vertical-shaft turbines (see Fig. 5).

4. Construction of a major storage and power project at Dickey, Maine, on the Upper St. John River (see Fig. 14), instead of at Rankin Rapids.

5. Some modification of the reregulating dam and power production facilities at the Lincoln School, Maine, site.

Thus 'Quoddy would have an ultimate installed capacity of 1000 MW, and the Dickey project would have an ultimate installed capacity of 750 MW. The coordinated and integrated operation of the two facilities would produce 1000 MW of dependable peaking capacity, and 250 MW of dependable capacity, at 60 per cent load factor, delivered to the load centers. Also, about 1 billion kWh per year of off-peak energy could be generated at 'Quoddy, and about 600 million kWh at downstream hydroelectric plants of the New Brunswick Electric Power Commission. The Government claims the proposal is feasible from an engineering and economic viewpoint, and that the benefit–cost ratio would be 1.27 to 1.0, based on the interest rate of 2⅞ per cent. But although the Canadian Government has common interests in the proposal, the analysis has been based upon the standards and criteria applicable to such developments in the United States.

It is the Government's contention that even if core drillings and additional studies are needed to firm up the estimated cost of the Dickey project, there is ample evidence that the Dickey site is satisfactory for the construction of a storage and hydroelectric plant.

The Government predicts that the first 500-MW power plant at 'Quoddy will utilize every facility envisaged in the IJC report for the development of a 300-MW power plant, and that the location of a second power house at the site to provide an additional 500 MW will be satisfactory.

In the summation of its report, dated July 1963, Interior recommended that:

1. The report be sent to Congress as a basis for early authorization of the International Passamaquoddy Tidal Power Project, and the storage and hydroelectric development on the Upper St. John River by the Army Corps of Engineers, and the marketing of the power by the Department of the Interior.

2. The President instruct the Secretary of State to initiate negotiations immediately with the Government of Canada to arrange the sharing of the power benefits of the St. John River, and the joint development of the 'Quoddy Tidal Project to assure maximum benefit to the interests of both nations.

The economics of 'Quoddy—Interior's estimates

This presentation of the cost estimates for construction, maintenance, and power transmission at Passamaquoddy and the Dickey Power Plant, is taken directly from the Secretary of the Interior's report of July 1963 to the late President Kennedy. The costs are shown and itemized in Tables I through IV.

Transmission costs. For purposes of this estimate, development of the Passamaquoddy–Dickey power combination will be assumed on the following schedule:

Stage I—Construction of Dickey Dam and reservoir, and initial installation of 150 MW of power-generating facilities.

Stage II—Construction of Passamaquoddy tidal basin

I. Passamaquoddy construction costs

Item	Installed Capacity 500 MW	Installed Capacity 1000 MW
Power plant	$157 771 400	$351 375 200
Filling gates	64 585 300	64 585 300
Emptying gates	61 108 300	61 108 300
Locks	20 187 500	20 187 500
Dams	80 261 000	80 261 000
Lubec Channel	633 500	633 500
Fishways	919 100	919 100
Relocations	3 914 000	4 500 000
Lands and damages	1 859 000	2 500 000
Subtotal	$391 239 100	$586 069 900
Contingencies	68 369 400	110 924 500
Subtotal	$459 608 500	$696 994 400
Engineering design, supervision and administration	41 364 800	62 295 000
Total	$500 973 300	$759 289 400

II. Passamaquoddy operation, maintenance, and replacement cost (OM&R)

Item	Installed Capacity 500 MW	Installed Capacity 1000 MW
Operation and Maintenance		
Power plant	$1 385 000	$2 750 000
Switchyard	89 000	225 000
Subtotal	$1 474 000	$2 975 000
Gates and locks	250 000	250 000
Total	$1 724 000	$3 225 000
Replacements		
Power facilities (total)	366 000	742 000
Total OM&R	$2 090 000	$3 967 000

III. Dickey power plant construction cost

Item	Installed Capacity 150 MW	Installed Capacity 450 MW	Installed Capacity 750 MW
Lands and damages	$ 5 116 000	$ 5 116 000	$ 5 116 000
Relocations	150 000	150 000	150 000
Dams	67 250 000	67 250 000	67 250 000
Power plant	22 520 000	59 640 000	95 880 000
Switchyard	1 100 000	2 000 000	3 600 000
Buildings, grounds, and facilities	840 000	840 000	840 000
Access road and railroad	1 252 000	1 252 000	1 252 000
Subtotal	$ 98 228 000	$136 248 000	$174 088 000
Engineering design, supervision, and administration	8 841 000	12 262 000	15 668 000
Total	$107 069 000	$148 510 000	$189 756 000

facilities, installation of 500 MW of power-generating facilities at 'Quoddy, and an additional 300 MW at the Dickey power plant.

Stage III—Completion of the 1000-MW installation at Passamaquoddy, and 750-MW ultimate installation at Dickey.

It is further assumed that construction of Stage II facilities would be completed five years after completion of Stage I, and that construction of Stage III facilities would be completed ten years after the completion of Stage II.

A broad estimate of the anticipated transmission requirements for the project area, based on the July 1963 Interior report, is given in Table V.

The transmission system

The comprehensive project plan foresees a fundamental transmission system that interconnects the Passamaquoddy Tidal Power Plant with the Dickey Plant, and will serve Maine, other areas in New England, and the Province of New Brunswick, and will terminate in Boston. A diagram of the ultimate transmission plan developed by the Bureau of Reclamation is shown in Fig. 14.

Two 345-kV transmission circuits are proposed for power delivery to Boston, with a switching point at Bangor, Maine, for interconnection with three 230-kV transmission circuits from the Dickey Plant to Bangor. These lines would be designed primarily to tie in with the tidal project purposes, but their off-peak capacity could be utilized as supplements to other power systems in the area. The power transmission system is designed for stable operation following double line-to-ground faults near the power plants. The transmission diagram also indicates lines extending to Fredericton, N.B., that could deliver power to Canada, provided suitable agreements could be made.

IV. Dickey operation, maintenance, and replacement cost (OM&R)

Item	Installed Capacity 150 MW	Installed Capacity 450 MW	Installed Capacity 750 MW
Operation and maintenance			
Power plant	$282 000	$742 000	$1 200 000
Switchyard	32 000	58 000	104 000
Subtotal	$314 000	$800 000	$1 304 000
Dam and reservoir	20 000	20 000	20 000
Total	$334 000	$820 000	$1 324 000
Replacements			
Power facilities (total)	63 700	164 400	264 500
Total OM&R	$397 700	$984 400	$1 588 500

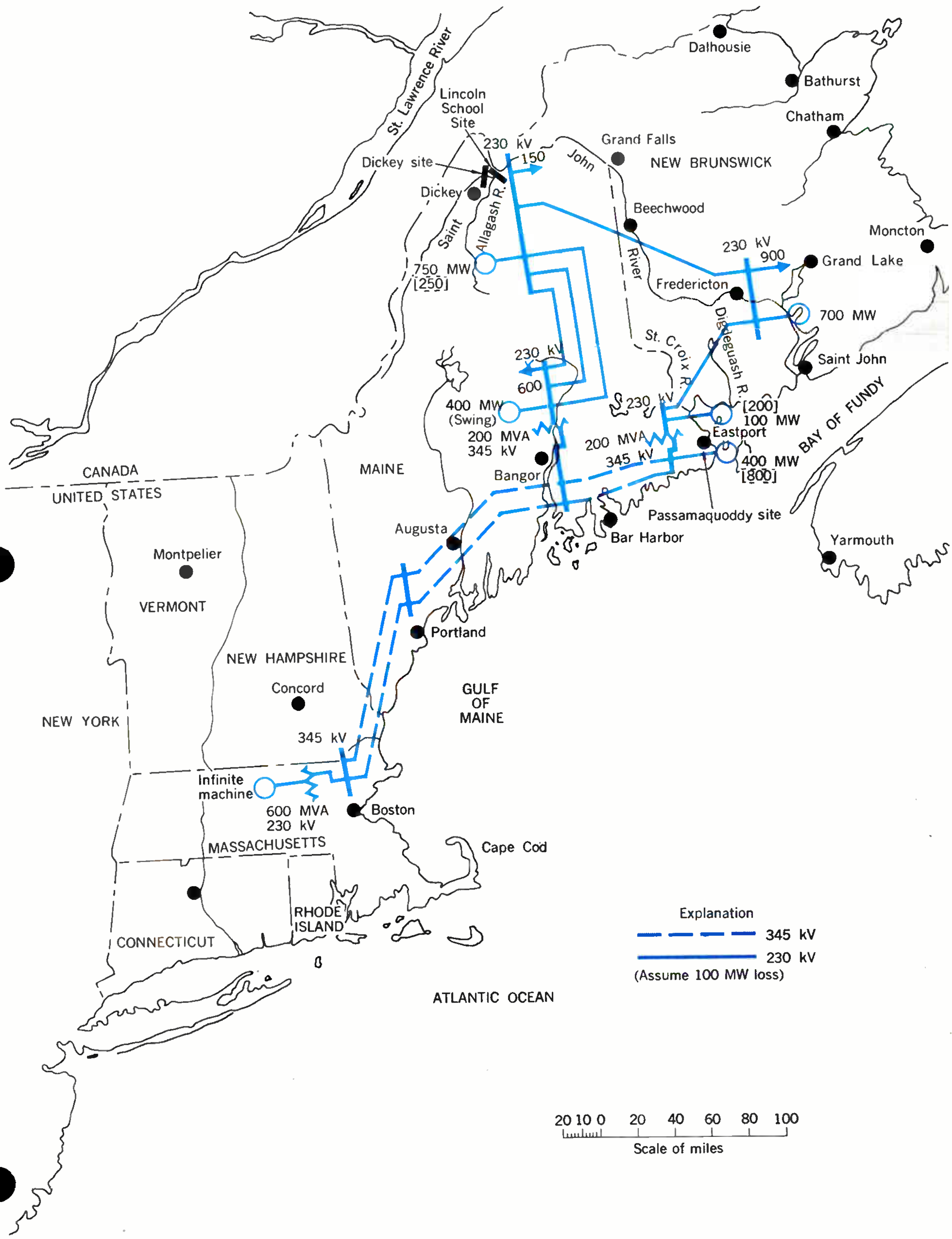
V. Transmission cost estimates

	Stage I	Stage II	Stage III
Construction cost	$18 000 000	$50 000 000	$92 000 000
Annual operation, maintenance, and replacement cost	150 000	439 000	538 000

VI. Predicted benefit-to-cost ratios

	Benefits	Costs	Benefit–Cost Ratio
Stage I	$ 9 845 000	$ 3 856 000	2.55 to 1.0
Stage II	29 235 000	24 427 000	1.20 to 1.0
Stage III	46 849 000	36 872 000	1.27 to 1.0

Fig. 14. Area map indicating the locations of Passamaquoddy and the Dickey auxiliary power plant projects. The ultimate transmission plan as developed by the Bureau of Reclamation is shown in red. This includes 1000 MW installed at 'Quoddy and 750 MW installed at the Dickey site.



VII. Table of unit power values

Item		Value	
Average annual energy	Maine	4.1 mills	per kWh
	Boston	3.2 mills	
	downstream	3.2 mills	
Dickey site			per kW
At-market value		—	
Less transmission		—	
At-site value		$31.20	
Passamaquoddy peaking			
At-market value		29.15	
Less transmission		3.00	
At-site value		$26.15	

It is Interior's claim that the combination construction of Passamaquoddy–Dickey would create equivalent benefits, annual Federal project costs, and benefit–cost ratios as indicated in Table VI (see page 114).

The annual equivalent power benefits from the potential power development are estimated to be $42.1 million. The energy and capacity values used in the Government analysis were based on the alternative costs of obtaining equivalent power in the New England–New Brunswick areas, by utilizing the cost of highly efficient, large-sized, investor-owned thermal plants in the Boston area. Allowance was made for transmission costs in converting the power values to at-site conditions. These are summarized in Table VII.

The estimates of dependable capacity, average annual energy generation, and accrued power benefits for the initial and for the full stages of development are given in Table VIII.

Interior's estimate of power costs

To evaluate the power market for the area to be served by the Passamaquoddy–Upper St. John River development, a complete listing was made of all New England power plants operating during 1961. The results of this study are plotted as average costs of capacity and energy on the Fig. 15 graph. Also shown is the estimated cost of producing power from the overall development at an interest rate of 2 7/8 per cent. According to Interior, this demonstrates the immediate market for these power developments, since power will be produced at $24 per kilowatt of capacity, and energy at 4.0 mills per kilowatt-hour. If Interior's estimates can be accepted, then by comparison, the 1961 actual costs for a New England power plant were $26 per kilowatt for capacity, and 6.36 mills per kilowatt-hour for energy.

Finally, it is Interior's contention that the immediate development of power at 'Quoddy and the Dickey site would provide Maine, the rest of New England, and New Brunswick with a power supply at about 25 per cent less than present cost.

The Main report—an economic rebuttal

At the request of the Electric Council of New England, representing the investor-owned utilities of that area, Chas. T. Main, Inc., the Boston firm of consulting engineers that supervised the design and construction for the St. Lawrence River and Niagara hydroelectric projects, prepared a comprehensive report on its views concerning the 'Quoddy project as proposed in the Interior report of July 1963. The following are some direct quotations from the Main analysis that was submitted in August 1963:

"We can find no evidence in the Report to convince us that it is other than an assembly of figures and misapplied data that show semblance of economic justi-

VIII. Power benefits and related data—Passamaquoddy-Dickey power development

	Initial Stage of Development	Full Development
Capacity, MW		
Dickey	150	750
Passamaquoddy	—	1000
Dependable Capacity—Dickey	150	250
—Passamaquoddy	—	1000
Adjusted for 10 per cent losses—Dickey	136	225
—Passamaquoddy	—	9
Annual energy, MWh		
Total energy		
At-site production—Dickey	751 000	1 250 000
—Passamaquoddy	—	1 318 000
Downstream production	656 000	656 000
Adjusted for 8 per cent losses		
At-site production—Dickey	695 000	1 150 000
—Passamaquoddy	—	1 213 000
Downstream production	607 000	607 000
Total annual power benefits	Total, millions of $	Total, millions of $
Capacity—Dickey	4.24	7.02
—Passamaquoddy	—	23.54
Energy—Dickey-at-site	3.48	5.75
—Dickey-downstream	1.94	1.94
—Passamaquoddy	—	3.88
Total	9.66	42.13

fication for the project to those not familiar with power economics...

"It computes the present cost of power incorrectly, favoring the project and leading to the completely false conclusion that power could be sold 'at a cost of at least 25% lower than the average power cost in 1961'...

"It, in the letter from the Secretary of the Interior to the President, states that the benefit–cost ratio is 1.27 to 1.00 based on power repayment within 50 years, but actually this is the figure for 100 year repayment... We find a benefit–cost ratio of 0.50 to 1.00 for 50-year amortization of the project...

"We find that power would have to be sold for about 21% more than the present cost if the portion of the project cost allocated to power is to be paid off within 50 years...

"It is thus clear and, we believe, irrefutable that the Passamaquoddy Project is not only economically unjustifiable but that the peaking concept proposed by the Interior Department is even less favorable than the concept proposed by the Engineering Board."

Quoting further from the Main report, we come to the nub of its conclusions:

"*Present Power Costs*. The [Interior] Report listed the major power plants in New England, together with cost information from Federal Power Commission Bulletins, and computed the 'average' cost of power in New England in 1961 to be $26.00 per kilowatt of capacity and 6.36 mills per kWh of energy. But this 'average' was merely the numerical average of all the numbers, giving a 3000 kW plant costing $55.30/kW/yr. the same weight as a 457 000 kW plant costing $23.40/kW/yr. Had the computations been done correctly to obtain a true average the results would have been:

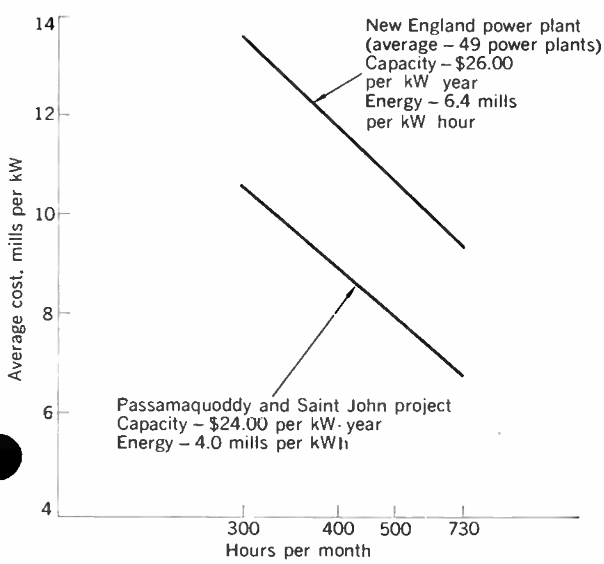
Capacity—22.34/kW/yr
Energy—5.19 mills/kWh

"It will be noted that, assuming the Canadian payment would actually be realizable, power must be sold for $43 020 000 per year to pay out the portion of the project costs allocated to power within 50 years. If sold at the above average, the cost per year would be:

1 125 000 kW @ $22.34	$25 132 000
1 995 000 MWh @ 5.19	10 354 000
Total	$35 486 000

"Thus there would be an increase of $7 534 000 or 21% rather than a saving of 25% as claimed by the Report."

Fig. 15. Graph indicates the Interior Department estimates of power cost at plant—transmission not included—for Passamaquoddy–St. John vs. an average for New England power plants.



The weight of the evidence

With the differences of opinion clearly defined between the advocates of public power development by the Government and the spokesmen of investor-owned utilities, a summation and evaluation of the various arguments, advantages and disadvantages, and political aspects of the 'Quoddy quibble may be enlightening.

At face value, the late President Kennedy's contention that "each day a million kilowatts of power surge in and out of the Passamaquoddy Bay" captures one's attention and imagination. This, plus the sense of urgency to explore all possible sources of electric energy in view of a possible future power deficit favors serious consideration of the 'Quoddy potentials. But in the thirty or more years since 'Quoddy was first considered by the Government, nuclear energy and nuclear power production have come of age. Therefore, it may be argued that perhaps time has bypassed the tides of 'Quoddy. If this be so, are we then pursuing a power solution that is anachronistic in the light of other developments in power technology?

The Department of the Interior claims that New England power costs are the highest in the country. As already shown in Fig. 15, Interior selected 49 New England power plants—irrespective of plant size or age—for its 1961 survey, and came up with a cost of $26 per kW per year, plus 6.36 mills per kWh. But although Interior's estimates for 'Quoddy are $24 per kW per year, plus 4.00 mills per kWh, weighting of plant averages by size and age gives a more realistic figure for New England power of $22.38 per kW per year, plus 5.14 mills. And as newer and more efficient power plants are placed in service, these costs are continually decreasing.

Chas. T. Main, Inc. reported that delivered costs for peaking power would be $10.45 per kW per year, with delivered cost at 3 mills per kWh—if alternative pumped-storage and thermal power projects were developed by investor utilities.

The 1963 Interior report submitted to President Kennedy emphasized the trend in the utility industry toward increased use of both conventional and pumped-storage hydro power for peaking. But in its cost estimates and future projections, only thermal units were considered as the basis for comparison. When questioned about this, Interior claimed that no suitable pumped-storage sites could be found in Maine. Contradicting this statement, however, Chas. T. Main, Inc., reported that there are four practical pumped-storage sites within the state that could be developed for the production of 1000 MW or more firm peaking capacity—and at about one tenth the cost of the combined Passamaquoddy–Dickey projects.

Some other seeming contradictions in Interior's Load and Resources Study include its prediction of a peak demand of 36 000 MW by 1980, of which 4000 MW would be for peaking. Using the Federal Power Commissions figures for planned expansions, Interior calculated a 23 000-MW power deficit for 1980. unless the 'Quoddy project is realized. But the 1980 predicted capacity level is predicated upon investor-utility planned construction only through 1965—with the apparent assumption that private utilities have made no plans for further expansion past that date.

The annual load factor for the expected scheduling of the 'Quoddy–Upper St. John combination would be about 24 per cent, and actual power costs would increase to about 15 mills per kWh, plus transmission costs. This figure would be over 100 per cent more than that of the investor utilities.

The Interior Department claims that total accrued benefits of the 'Quoddy–St. John development would be $46.8 million as compared to annual costs of $36.9 million, and that the benefit–cost ratio would be 1.27 to 1.0. The Main organization, however, in its analysis for a 50-year amortization, finds the actual cost may be nearer $53.2 million, with benefits of only $26.5 million, thereby drastically changing the benefit–cost ratio to about 0.50 to 1.0. Further, it is felt that the estimated interest rate of 2⅞ per cent is unrealistic—and that a more practical figure would be 4 per cent or more.

Another seldom-mentioned flaw in the combination power plan is the extreme northerly location of the Dickey site, and the fact that the Upper St. John River is ice-bound for more than three months of the year.

Critics of the Government plans enumerate and emphasize that:

1. The construction of cofferdams in depths ranging from 125 to 300 feet, and under a head of 75 feet when dewatered, has never been attempted before.

2. A large portion of the construction activity must be crowded into slack-tide periods of 20 minutes each, four times a day—and workers must continually wrestle with the tidal variations at all hours.

3. Once the rock-fill dams are positioned and nearly completed, they must be closed in the face of magnified tidal velocities that may reach as much as 20 feet per second.

4. Because of the great variance in tidal heights at 'Quoddy in any lunar month, it would be necessary to build an auxiliary source of power (Dickey) of more than half the capacity of the tidal project to maintain the maximum peaking capacity of 'Quoddy.

5. The Passamaquoddy area lies in a geologic fault zone, and geological evidence indicates that the preglacial bedrock channel in Head Harbour Passage. between Green Islet and Campobello Island, is about 400 feet below sea level.

6. There is the usual Government tendency to underestimate costs and overestimate accrued benefits. It is felt that the $1.2 billion figure could be much too low.

7. Almost all of Passamaquoddy Bay, where the bulk of the proposed dams, emptying and filling gates. and navigation locks would be located, lies in Canada. Only the two powerhouses, small portions of the dams, and one navigation lock would be in the United States.

Reaction north of the border

The American offer to build the project entirely with American dollars would give the Canadians a free ride. Even so, there is mixed feeling in Canada over the matter. While there is considerable interest expressed by New Brunswick provinicial officials, the Canadian Parliament, as late as this spring, leaned favorably toward the more practical—and less costiy—Chignecto development that would be located 125 miles farther up the Bay of Fundy where tidal ranges are considerably higher than at 'Quoddy. The Canadians claim this project could generate 900 MW—almost the same as 'Quoddy—on a firm, not peaking, basis, and at a cost as low as 2.87 mills per kWh.

The power push on the Potomac

Senators Edmund Muskie (D., Me.), Margaret Chase Smith (R., Me.), Edward Kennedy (D., Mass.), and five other New England senators are sponsoring Senate Bill S. 2573, which was introduced on February 28, 1964. This bill was referred to the Senate Committee on Public Works, and hearings on the matter are now under way. Simultaneously, two House of Representatives bills, H.R. 10179 and H.R. 10180, were introduced by Maine Congressmen Clifford G. McIntire and Stanley R. Tupper, both Republicans. These bills have been referred to the House Committee on Foreign Affairs. It is interesting to note in passing that there is bipartisan sponsorship for this proposed legislation to authorize construction at 'Quoddy in conjunction with the Dickey project.

Interior has jumped into the fray with both feet—despite the charge by the investor-utility spokesmen that the Government wants to get its foot in the door for Federal power for New England at the expense and to the detriment of private enterprise. And, although the Army Corps of Engineers has taken a more conservative viewpoint toward the project, the backing of this branch of the service is also expected. Thus, with strong political backing, the project's proponents are closer to the realization of their aspirations than at any previous time in the past 30 years.

Probably both sides have overstated their cases to obtain both publicity and support. Perhaps the case for 'Quoddy would have a better talking point if it had been preceded by a similar project—such as la Rance—on a successful and much smaller scale.

The ultimate fate of the Passamaquoddy project is anyone's guess at this time. Although its advocates are very optimistic and energetic in their efforts, they are confronted by an opposition that is equally vocal, articulate, and dedicated in its efforts to make sure the project dies a-bornin'. Nevertheless, it would be only fair to give both sides adequate time for a full and comprehensive opportunity to present their arguments at Congressional hearings. Then, after all the evidence is presented, the public has a vested right and interest to expect a decision—one way or the other. And that decision should be final and irrevocable and based on facts.

The author wishes to acknowledge the cooperation and courtesy of the U.S. Department of the Interior, U.S. Army Corps of Engineers, the French Embassy Press and Information Division, Boston Edison Company, Central Maine Power Company, Chas. T. Main, Inc., and the American Society of Civil Engineers in making available various reports, data, and illustrative material that were of immeasurable assistance in the preparation of this article.

Better vocoders are coming

The present state of the art and possible future trends in vocoder development are discussed both on the basis of further improvement to standard techniques and with reference to new approaches

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Synthetic speech systems which are designed to accomplish economies in transmission, or to meet special military needs, traditionally have involved some degree of degradation in the process whenever they involve bandwidth compression. If speech information can be successfully concentrated into narrower bands, the savings in channel capacity accruing from this procedure would be of great economic importance in reducing future capital investment in transmission systems.

A challenge therefore emerges, "What can we give up that we need less than the advantages that can be thus accomplished?" There has been a basic demand for the retention of intelligibility as we know it in the ordinary telephone conversation. Principally, "quality, naturalness, and recognizability" have suffered in earlier attempts to develop workable speech compression systems.

Bandwidth reduction systems that process, transmit, and receive electronically reproduced speech descriptions, based upon spectral or phonetic properties, are generally referred to as "vocoders," (from voice coder). While voice coding has long been regarded as promising, it is only recently that word intelligibility and quality tests under laboratory conditions, supplemented by practical demonstrations over operational circuits, have shown that users may soon expect acceptable performance. The state of vocoder development is advancing rapidly enough now to warrant placing some faith in the belief that both intelligibility and quality will be good enough, at least to satisfy the demands of the armed services. As for the commercial user, for whom naturalness and recognizability are also paramount considerations, the challenge is most severe.

In comparison to the music of a symphony orchestra, human speech is a relatively simple type of signal. Vocal sounds are more like the tonality of a single string of a stringed instrument, since their component vibrations constitute only one fundamental and one series of harmonically related overtones. Thus, according to information theory, speech does not require the full telephone bandwidth that is now used, and it can be subjected to bandwidth compression, or reduction, to accommodate a greater number of telephone conversa-

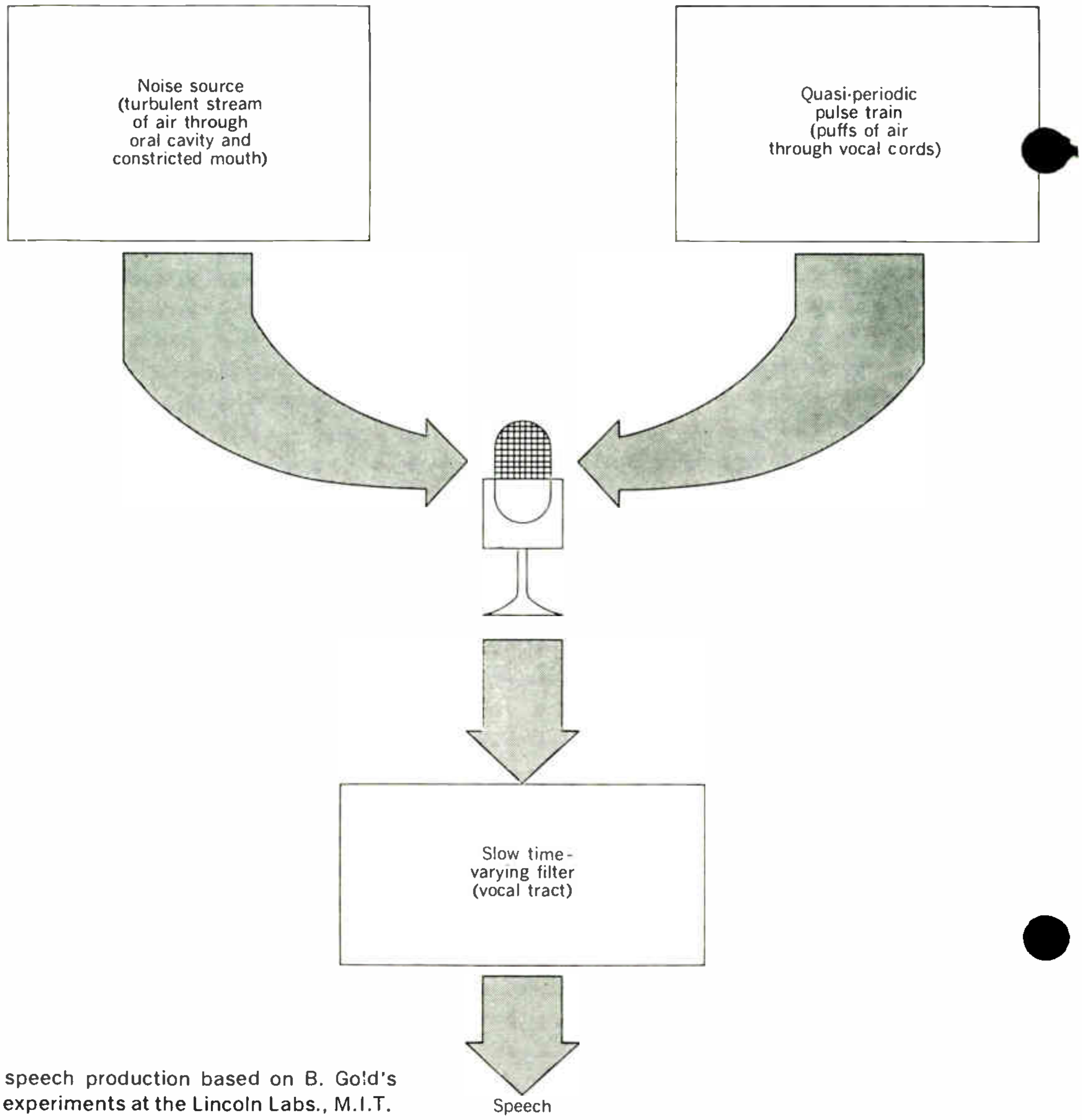


Fig. 1. Model of speech production based on B. Gold's description from experiments at the Lincoln Labs., M.I.T.

tions in simultaneous transmission over existing facilities.

In place of the highly complex waveform produced by the normal telephone transmission device, the vocoder may be designed to produce a simplified output signal, such as a binary digital data stream. The number of bits of digital data which must be transmitted per second to do a satisfactory job of vocoding thus becomes the main point at issue.

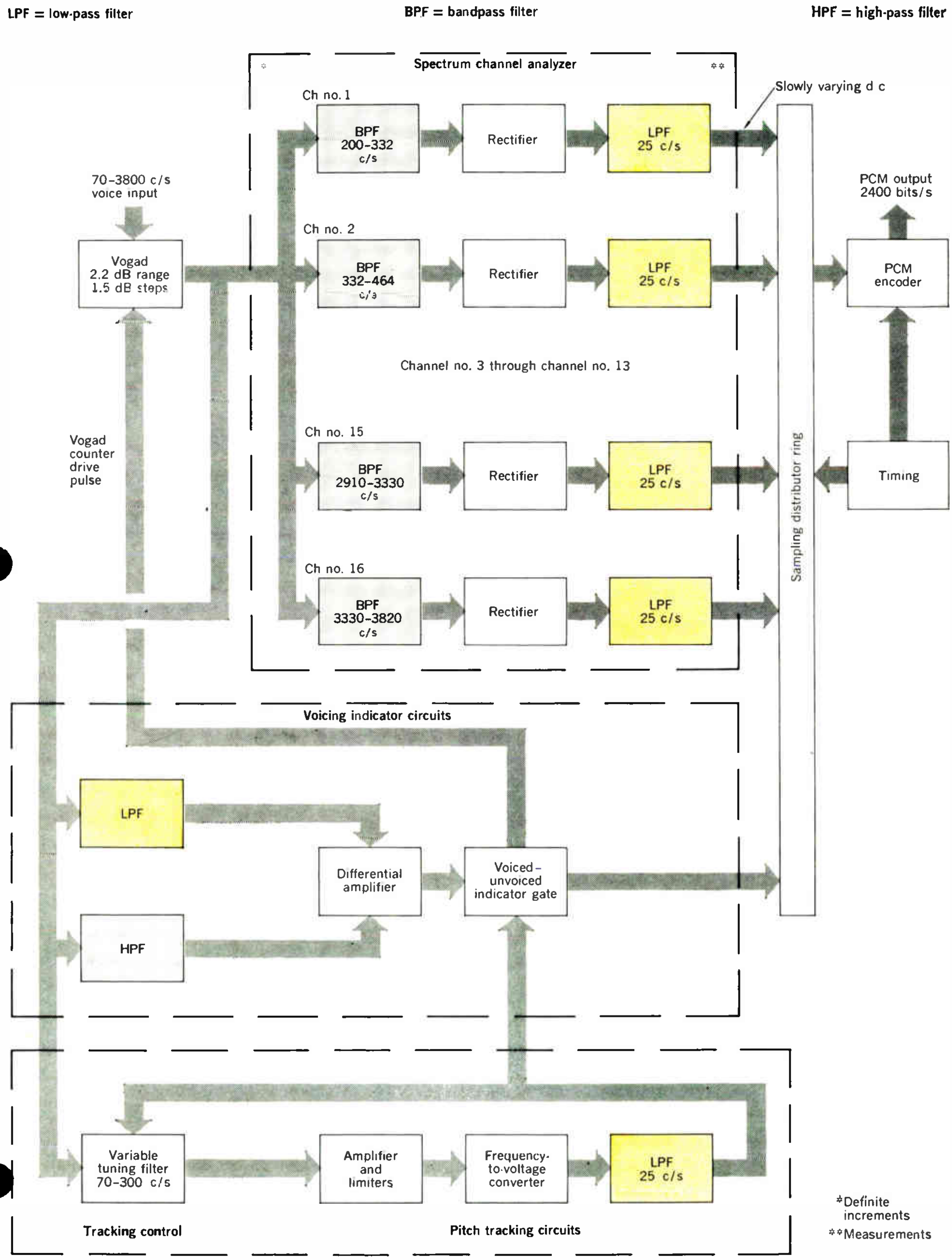
This discussion will give particular attention to speech vocoded for digital data transmission at 1200 or 2400 bits per second (b/s) over standard communication channels that have a bandwidth of from 3 to 4 kc/s. However, higher bit rate cases will be touched upon.

Vocoder's historical background

The first channel vocoder was developed by H. W. Dudley, of the Bell Telephone Laboratories, before World War II. It used a set of contiguous bandpass filters, each of which had a bandwidth of about 150 c/s, with rectifiers and low-pass filters (20 c/s) that produced values of the short-time frequency spectrum for a series of discrete frequency bands. The device was called a *channel vocoder* because it consisted of a parallel set of separately analyzed channels, each of which had its own output that was based upon the speech frequency and amplitude content at any particular time. This pioneer model recognized and differentiated between speech sounds that were either "voiced"—as a vowel—or "unvoiced," as a sibilant, or "S" sound. It also contained a "pitch extractor" that developed a varying voltage output whose amplitude was proportional to the basic pitch frequencies of the voiced sounds. At the receiving end, each channel could be modulated with either a "buzz" or "hiss" generator—the choice being made on the basis of the nature of the speech sound to be synthesized. The speech nature was determined in accordance with the information signaled from the voiced or nonvoiced characteristics at the time and at the frequency of the pitch extractor signal. The filter outputs were summed, and the spectrum of speech was thus recreated. The intelligibility of this early device was reasonably good, but the quality of the reproduced speech was somewhat unnatural.

During the 1930s, work continued on Dudley's idea. The Bell Telephone Laboratories (BTL) developed and

Fig. 2. Channel vocoder analyzer section.



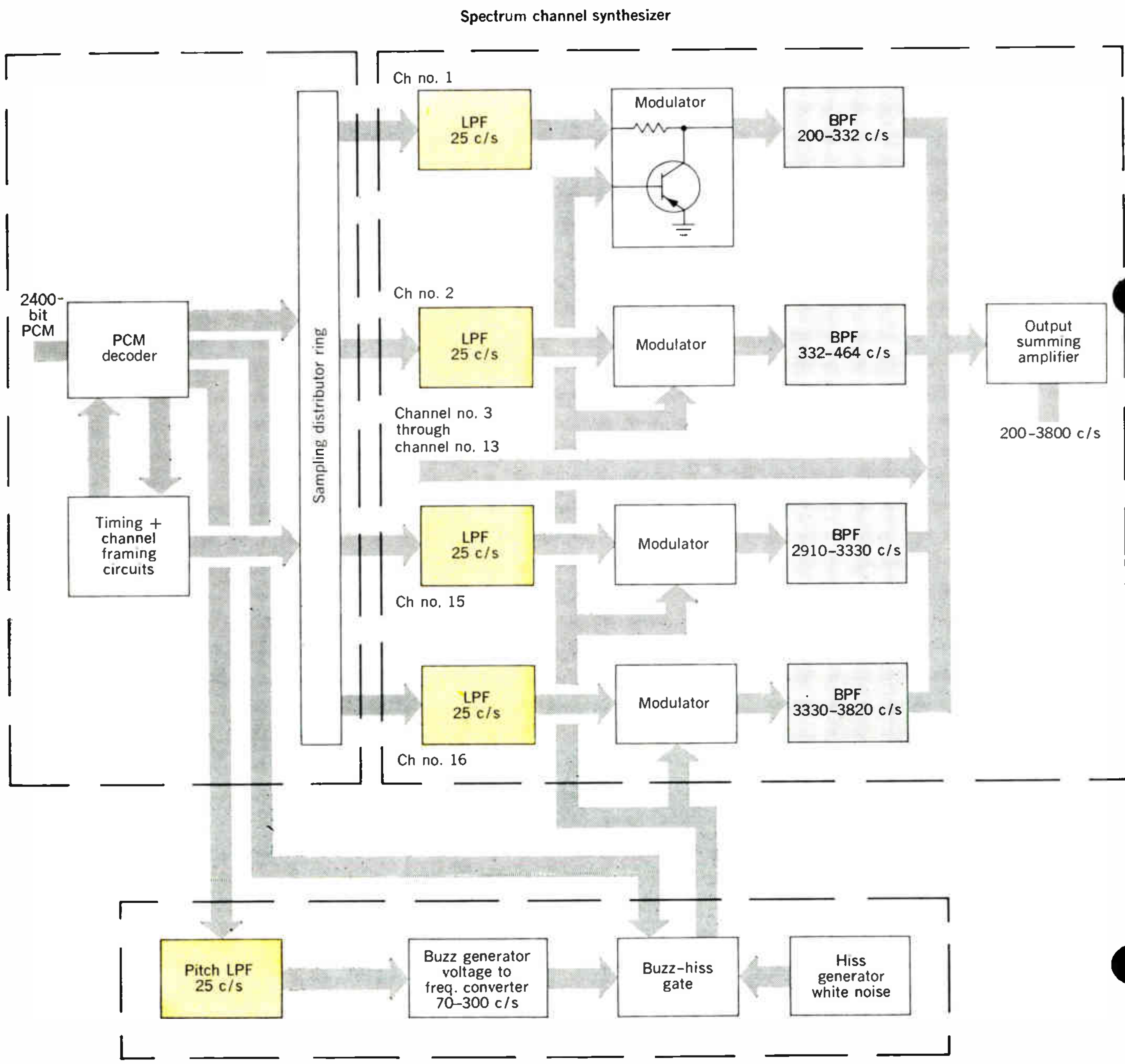
demonstrated a form of voice coder that was exhibited at the 1939 New York World's Fair under the name of "Pedro the Voder." A human operator, at controls that resembled those of a pipe organ, created synthetic speech in the Voder by manipulating these controls.

We are optimistic about several speech compression developmental efforts currently under way that relate quite closely to the early work done by Dudley. Some approaches that have emerged in recent work introduce new methods of pitch extraction, and apply alterations in filter circuitry and characteristics. They also include miniaturization and techniques to ensure structural sturdiness. Performance of some recently developed vocoders evaluated by the Stanford Research Institute, indicate that in the "normal" 2400 b/s digital data mode, speech intelligibility scores of 88 to 95 per cent have been achieved in phonetically balanced (PB) word articulation tests and rhyme tests. These results show an improvement over 2400 b/s vocoders that were tested as recently as two and three years ago when word intelligibility ratings of 70 to 85 per cent were considered very good.

The nature of human speech

To understand the analysis and synthesis of human speech sounds, one must appreciate their natural dynamic and phonetic attributes. We know that when a person talks, a column of air is pushed from the lungs through the vocal tract by muscular action, and it is finally exhausted from the nose and mouth. The vocal cords vibrate to impart speech sound wave components to this air column in the form of variations in amplitude and frequency of tonally voiced utterances. Air passages

Fig. 3. Channel vocoder synthesizer section.



having resonant and nonresonant cavities—some of which are controlled by the speaker—reinforce or cancel certain frequencies, and vary the voice energy of the several frequency components. The physical dimensions of each individual's throat, mouth, and nasal cavities cause his voice to have predominant frequency characteristics that persist as he makes the various sounds within his vocal range. The sounds that originate in the larynx and vocal cords are called "voiced."

The second type of speech sound includes those which require little or no vocal cord action. These are termed "unvoiced." Basically, they have a noise-like or hiss-like quality that is imparted to the moving air column after it has passed the larynx, and is forced through a constricted cavity, such as may be formed by certain positions of the tongue, teeth, and lips.

The generation and pronunciation of the recognizable, separate sounds used in speaking is dependent upon the ability of the speaker to control the vibration, or "buzzing" of the larynx for voiced sounds, to position and shape the sound-conditioning cavities and, in the case of unvoiced utterances, to impart the plosive, fricative, nasal, and aspirative consonants. When speech sounds are combined into an uninterrupted unit of utterance, we have a syllable. Words may be single impulses of speech or syllable combinations. B. Gold, of M.I.T.'s Lincoln Laboratory, has described a simple model[1] of speech production as shown in Fig. 1. About 45 distinct sound changes per second are the maximum that occur in human speech, but normally the rate is less. The pitch period, however, may be as short as a few milliseconds. Also, the rate of transition from one sound to another is not constant. Voiced sounds and sequences of voiced sounds, which occur without intervening unvoiced sounds, have a wide range of rate of transitional change. Yet, it is the slowly time-varying and periodic quality of voiced speech that enables the vocoder to determine fundamental pitch patterns. The simple detection of pitch can be related to the instantaneous amplitude peaks that recur at the fundamental frequencies of voiced sounds. This is a suitable point of departure to investigate the development of the conventional channel vocoder.

Elements of the channel vocoder

To understand the application of speech compression techniques to voice coding on a conventional channel analysis–synthesis basis, a typical channel vocoder is shown in Figs. 2 and 3.

In Fig. 2, the transmit terminal is composed of a voice operated gain adjusting device (Vogad), the spectrum channel analyzer circuits, the voicing indicator circuits, and the pulse-code modulation (PCM) circuits for digital encoding.

The talker's speech signal is generated in a special microphone that has a relatively flat response, and ranges from 70 to 3800 c/s. The signal is fed into the Vogad, which has a 22-dB range of adjustment. This range is controlled in 1.5-dB increments by a digital counter that is responsive to the drive pulses sent to it from the voiced–unvoiced indicator gate in the voicing indicator circuitry. The gate operates at the interval rate set by the precise points of time at which successively articulate segments of speech, occur—and in a fashion that is identifiable in terms of differential amplifier "crossovers." The output of the Vogad is held at a relatively constant value by this automatic gain control.

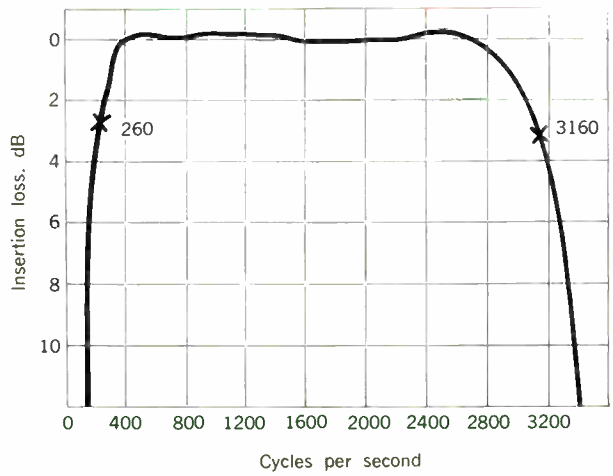


Fig. 4. Graph shown is a plot of typical passband, Type "N" carrier performance.

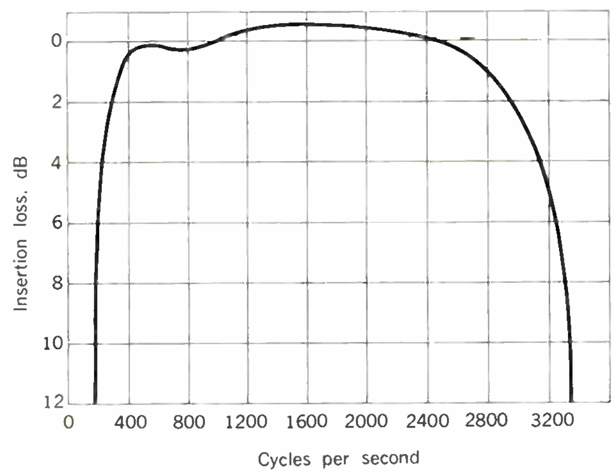


Fig. 5. Graph shows typical passband, Type "O" carrier performance curve.

This vocoder has 16 spectrum channels, each of which contains a bandpass filter, rectifier, and a low-pass filter. Each filter passes a narrow band of voice frequencies, and this energy is rectified and inserted into a 25-c/s low-pass filter. The output of the low-pass filter is a slowly varying signal that describes the energy content during a given period of time in the portion of the speech spectrum to which the channel is tuned. As different sounds are made by the talker, the outputs of the spectrum channels correspond to the spectral distribution of speech energy and to the articulation rate involved. Collectively, the spectrum channels cover the frequency band from 200 to 3820 c/s.

By the use of filters and differential amplifiers, the voicing indicator circuits detect whether the speech input is voiced or unvoiced. The signal from the Vogad is separated into high- and low-frequency segments, each of which is amplified and rectified—one to a positive dc level and the other to a negative dc level. These levels are combined and added in the differential amplifier, and the positive or negative resultant determines whether a

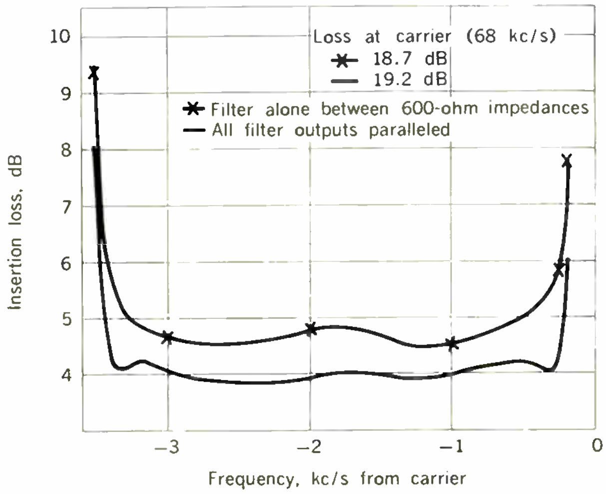


Fig. 6. Graph showing typical insertion losses based on using a Bell Telephone System 561B filter.

voiced or unvoiced condition exists. The option of these circuits is then included in the PCM code for transmission to the receiver.

The pitch-tracking circuitry also receives the signal from the Vogad, and this circuitry includes a variable-frequency filter that automatically tunes to the pitch frequency of the talker's voice by means of a feedback control loop. The output of the pitch-tracking filter is then amplified and limited to detect the lowest frequencies present. A frequency-to-amplitude (voltage) converter is used for driving the low-pass filter. The output of this filter is a voltage that is proportional to the fundamental pitch frequency of the voice, and it controls the frequency of the variable tuning filter. The pitch information is used only when the differential amplifier indicates a voiced condition.

Signals from the spectrum channels, together with the voiced–unvoiced decision and pitch channel, are multiplexed and pulse-code modulated into the output. In this vocoder, each spectrum channel output is represented by a three-bit ($2^3 = 8$ values) code, and the pitch channel is represented by a six-bit ($2^6 = 64$ values) code. The information contained in the 16 spectrum channels and the pitch channel, together with the voiced–unvoiced decision, comprise a 54-bit-per-frame PCM code. At a frame-sampling rate of 44.44 frames per second, a total transmission bit rate of 2400 b/s is attained.

At the receiving terminal (see Fig. 3), the PCM signal—which includes timing synchronization—is decoded and framed for proper channel correlation and extraction. The output of each channel synthesizer low-pass filter is a replica of the corresponding analyzer output before encoding.

The decoded pitch extractor channel signal controls a voltage to the 70–300-c/s buzz-generator voltage-to-frequency converter. Since the voltage output of the pitch detector is directly proportional to the fundamental frequency of the voice, the buzz generator produces periodic pulses that occur at the fundamental voice frequency. The hiss generator, which produces sounds for use in synthesizing unvoiced speech, is essentially a white-noise generator.

The buzz–hiss gate is controlled by the decoded PCM signal element that relates the voiced–unvoiced indication in each frame. The output voltage from each low-pass filter to its associated modulator determines the level of energy fed into each bandpass filter. These receiver filters are identical to their counterparts in the channel analyzer sections of the transmitter. Thus, the output frequencies and energy content are representations of the frequencies and energy inserted into the analyzer filters at the transmitter.

The signals from the 16 synthesizer channels are combined, amplified, and applied to the receiver of the listener's telephone set, and he hears a synthesized replica of the talker's speech.

The selection of the type of pitch extractor to be used in a conventional channel vocoder is dependent upon whether the input to the Vogad includes the fundamental pitch frequencies of the human voice. The frequency input range is a function of the type of microphone that is used. Therefore, we have two conditions that we may consider:

Conventional frequency domain. In this case, a special telephone microphone is used that has a frequency response in the lower end of the speech spectrum—down to about 70 c/s. Here, the microphone will have an output that includes the fundamental frequencies of the voice, and pitch detection can be achieved by means of a variable-frequency tuned filter.

Time domain. In this instance, a standard telephone microphone, with no useful frequency response below 300 c/s, is employed. The pitch extraction must be derived from the time waveform, or by using the summed outputs of full-wave detectors that are placed in the spectrum analyzer channels. The output is a pulsating waveform at the fundamental pitch frequency, and this gives a time-spaced train of pitch markers.

The transmission medium

One informative approach in the investigation of the use of vocoders is to present some broad characteristics of the transmission medium into which they must be placed so that we can define the several operational modes for which these devices must be designed. Broadly speaking, four transmission categories emerge:

Conventional telephone channel. This is widely available in switched long-distance networks; but although it is often referred to as a 4-kc/s channel, it affords much less than 4000 c/s of usable passband. Figures 4 and 5 illustrate the passband performance of two widely used A.T.&T. end link carrier systems. Note that neither gives 3 kc/s between the 3-dB points, and that there is a fairly flat response only between about 400 c/s, on the low side, and about 2500 c/s on the upper side. There is a sharp lower cutoff, and a sloping upper cutoff beyond these points. Figure 6 shows typical filter insertion losses of the type employed in long-haul carrier systems. Here, the passband is a little wider, but still restrictive. It must be remembered that the carrier systems now in use in the Bell System and the independent telephone companies were designed to accommodate analog waveforms where small phase changes were not severely damaging to normal telephonic speech transmission. In data transmission phase and delay distortion is undesirable—particularly since many data modems employ phase-sensitive processes as a fundamental aspect of their means of operation.

The conventional long-distance telephone channel is not expected to accommodate more than 2000 b/s of digital bit stream, with long-term error rates in the order of one part in 10^4, or better. Tests indicate, however, that 2400-b/s vocoders are not rendered militarily unacceptable by quality degradation at error rates of 1 or 2 per cent, and that a 3 per cent error condition might be tolerable. However, for commercial telephone applications, a 0.1 to 0.2 per cent error rate might be regarded as an upper limit. Thus, 2400-b/s vocoders, using this transmission medium, are referred to as operating in the "normal" mode.

Degraded telephone channel. Under this general heading, we can characterize the submarginal communications circuits which will not support 2400-b/s vocoder transmission, but which can carry a 1200-b/s signal at an error rate below 5 per cent. With this medium, the frequency band is narrower, greater delay and phase distortion exist, impulse noise is higher, there are more frequent dropouts, and—in the ratio case—multipath effects are present. On these circuits, quality and recognition of vocoded speech would be decreased, but word intelligibility would have to remain at least at 80 per cent of normal to be "minimum acceptable." Vocoders that must be geared to this transmission situation are said to be operating in a "degraded" mode.

Special high-quality channel. This general category refers to the improved, or extended bandwidth channel, which would have to be provided to meet a 4800, 7200, or 9600-b/s information rate associated with voice excited vocoders and their digital-data modes. Such a "treated," or specially equalized channel, would have low-phase distortion, low-noise level, well-equalized delay distortion over the envelope, and flat frequency response across the passband. In some applications, twin channels might be used, each carrying a portion of the information. Vocoders operated over this type of channel would be in the "high-quality" mode.

Wide-band channels. Digitized speech systems operating with 38- to 50-kilobit wide-band channels, over either long or short distances, are said to be functioning in the "extra-high-quality" mode.

The voice excited vocoder

The presence of noise in the pitch circuitry of the conventional channel vocoder causes a severe degradation of the quality, particularly when the noise is in the range of 70 to 300 c/s. It is possible for the conventional pitch extractor to analyze or extract the true nature of the talker's voice waveform only when the input speech-to-noise ratio is very good. Because of the shaping and conformation of the human vocal tract when making certain voiced sounds, a portion of the total generated sound wave contains voiced as well as unvoiced components. In such cases, the transition between voiced and unvoiced sounds is indistinct, and this may cause the voiced–unvoiced decision to be poorly timed. Often it may be necessary to synthesize both voiced–unvoiced sounds simultaneously, and this is impossible in the typical channel vocoder. What has been needed is a technique that would eliminate the requirement for pitch detection and voiced–unvoiced decision circuitry because of their imperfect performance. The voice-excited vocoder (VEV), with about a 250- to 800- or 1000-c/s directly transmitted baseband has been offered as a solution that would accomplish this. The VEV is insensitive to noise conditions and tends to have a more superior output quality than the conventional channel vocoder—and it is less demanding in the area of low-frequency equalization.

The VEV can, of course, be used for fully coded transmission of speech only when the baseband is digitized along with the rest of the processed signal. When this is done, 4800, 7200, or possibly 9600 b/s may have to be transmitted to meet acceptable standards. In such a case, a wide-band, or high-quality equalized channel, would be required—or the twin channel approach would be necessary.

VEV development work is under way at Bell Telephone Laboratories (BTL), to study the possibilities of reducing the band to 7200—or even 4800 bits, and still hold the quality at high levels. BTL engineers presently have an interesting test and demonstration apparatus with which they can provide a wide variety of combinations of VEV characteristics. An interesting feature of their equipment is the equalization of delays occasioned by the difference in width of vocoder channels. They are able to provide a simulation of two vocoders operating in tandem. Also, they can demonstrate the effect of two talkers speaking into the same vocoder (as might occur in a conference).

The BTL VEV was designed to accommodate a wide range of input voices,[2] including the high-pitched voices of women and children. A baseband of 250 to 940 c/s is used, and this results in an input passband of 690 c/s. There are 17 spectrum channels that cover the range of 940 to 3650 c/s. The lower 14 bands have a bandpass characteristic of 150 c/s each, and the upper three are used to accommodate slightly wider bands. The baseband was first spread to a wider band by rectification, and its shape was found to fluctuate in accordance with the baseband's normal spectral shape. The fluctuating spread spectrum was filtered into several narrow bands, and each one was then clipped in a limiter to remove the amplitude variation. This resulted in a flat excitation spectrum in the limiter output.

In such a VEV system, intelligibility can be made to approach that experienced when talkers are heard over a standard commercial telephone system of the type available for ordinary conversations. Quality, in terms of naturalness and validity of recognition, should satisfy all but the most sophisticated ear. The challenge in the VEV, therefore, is to hold to these standards while keeping the data bit rate as low as practical to eliminate the need for improved telephone transmission channels to permit its use.

'Polymodal' vocoder development

A significant new concept that has emerged in vocoder R&D is the "polymodal" vocoder technique, and it is being studied for the development of a speech communications system to provide an adaptive range of capabilities for digital communication. The polymodal concept provides a number of optional configurations of the vocoder equipment for flexibility in meeting changing requirements and conditions. A high-data-rate configuration of the vocoder would provide high-quality speech for situations where channel capacity for the higher bit rate is available, and its use would be justified. Configurations of lower data rate would provide optimum performance only where limited channel capacity is available, or where transmission economy is a major consideration.

The experimental polymodal vocoder developed for Air Force Cambridge Research Laboratories (AFCRL) by Texas Instruments Inc.[3] represented the first embodiment of these concepts.

The autocorrelation vocoder

Theoretical and experimental studies by various groups in the research community have indicated that autocorrelation speech spectrum analysis systems can be equal in intelligibility and quality to channel vocoders. Studies at the Applied Research Laboratories (ARL) of Sylvania Electric Products Inc., have shown that it is possible to use an orthogonal filter (Laguerre type) composed of simple, cascaded *R-C* sections in lieu of the channel filters of the basic system, and to obtain the advantage of scaling, in frequency, the spectral resolution of the system in accordance with the characteristics of human hearing.[4] A principal objective of this research is to reduce the size and weight of vocoder hardware.

Improving the channel vocoder

When the Air Force decided to improve and develop the conventional channel vocoder into a suitable speech compression system for airborne applications, the initial effort was to identify problem areas and then attempt to make piecemeal improvements. This was implemented through contracts with the Philco Corporation. Performance evaluations of new improvements from these design efforts were made by the Stanford Research Institute.

Fig. 7. Diagram of channel vocoder, integrator-analyzer channel circuitry.

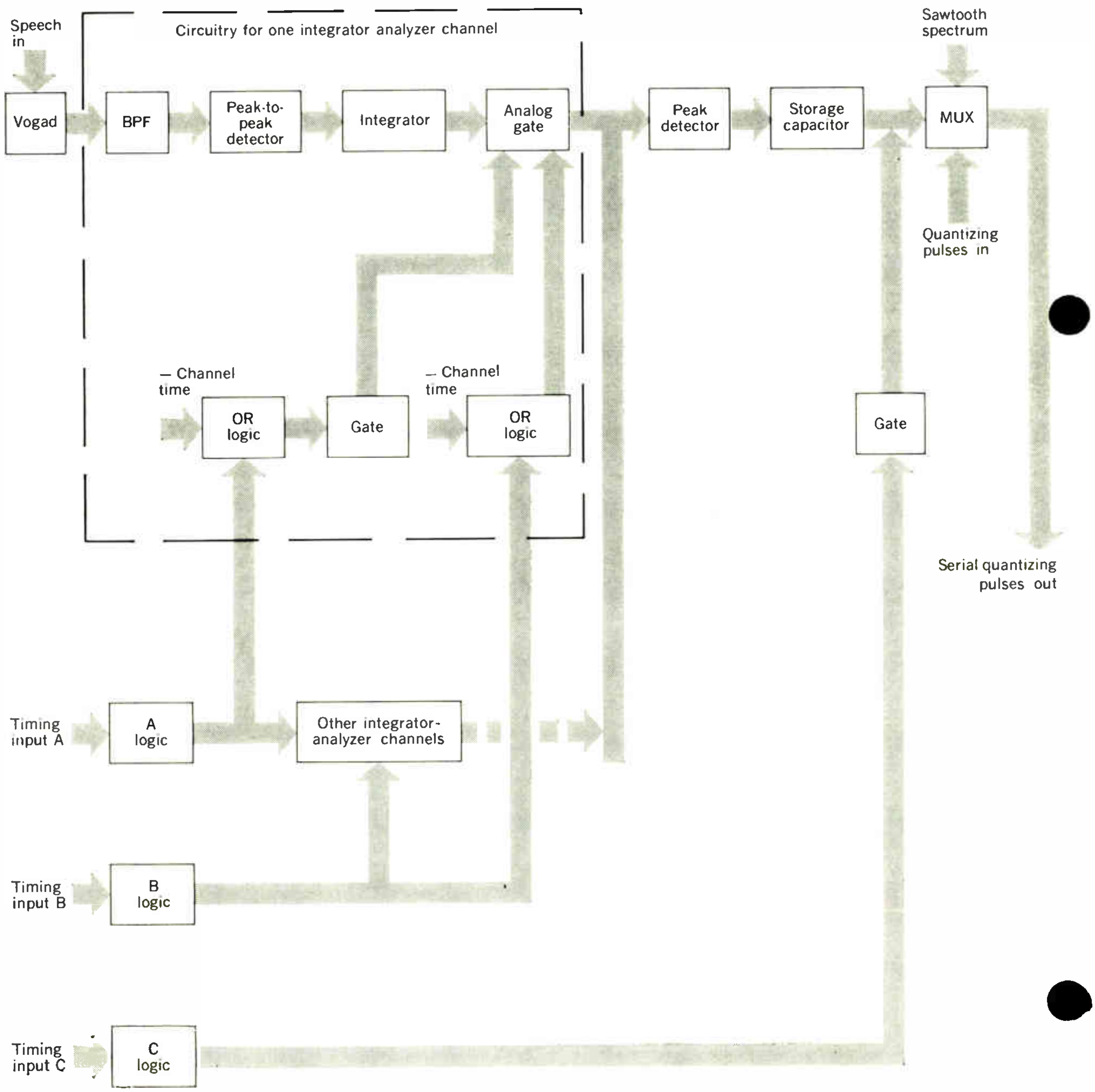
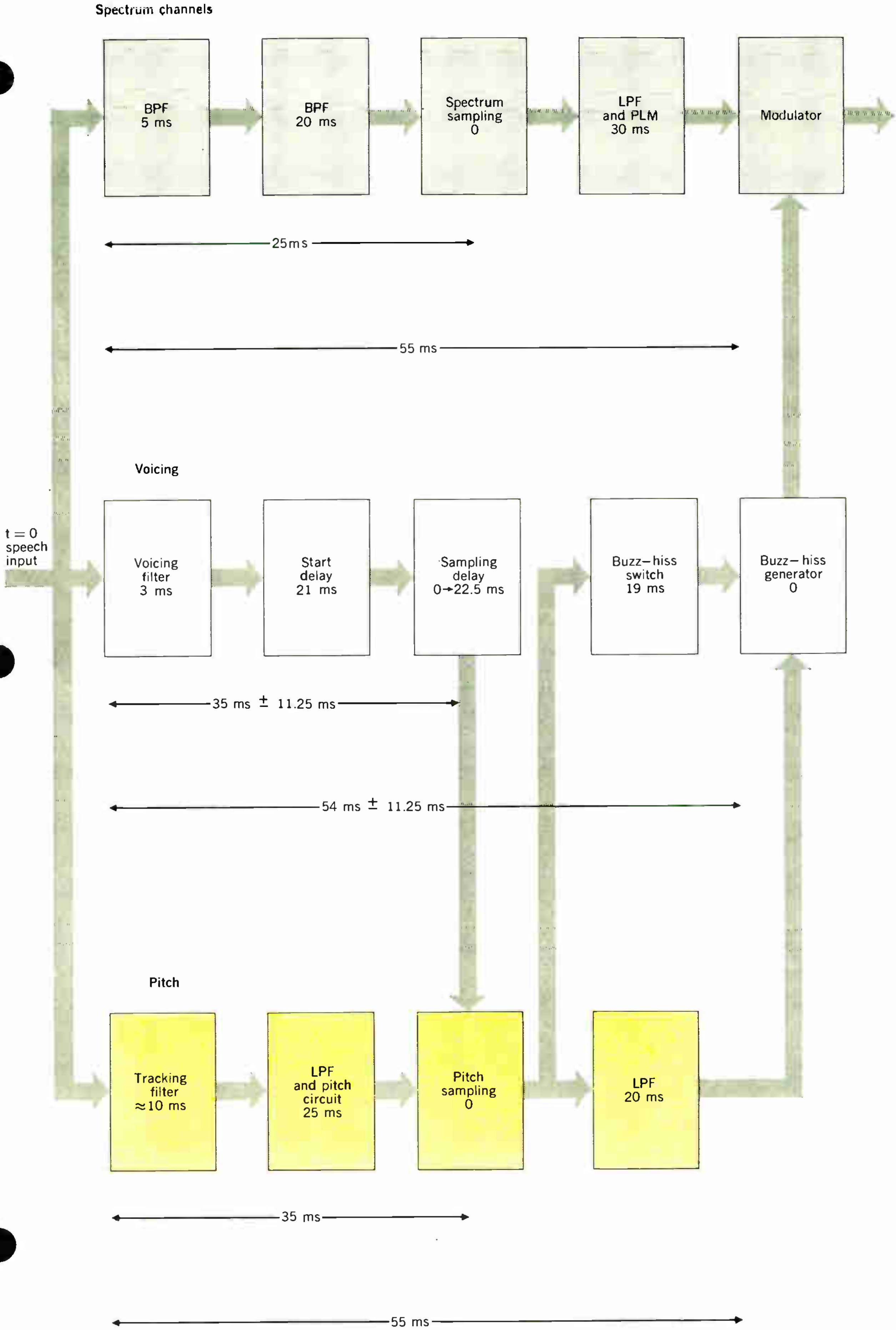


Fig. 8. Conventional channel vocoder delay diagram.



One of the objectives was to redesign the pitch extraction circuitry (see Fig. 2) to provide a relatively constant level to the pitch-tracking circuits, and to confine the input to fundamental voice frequencies. In the new configuration, the low-frequency fundamental pitch circuits are no longer driven from the Vogad output that contains energy from the total spectrum. In the new method, the conventional variable tuning filter is connected ahead of the Vogad. Since only fundamental pitch frequencies are involved, the signal is passed through a 350-c/s low-pass filter before it reaches the pitch- and voicing-indicator circuits. A new squaring circuit, which performs limiting and buffering, gives the desired waveshape and output level. The evaluation of this effort confirmed hopes for a significant quality improvement.

In another case related to the PCM circuitry, the basic conventional channel vocoder used a linear quantizing technique (which needed refinement for closer following of the amplitude variations) in its A/D and D/A converters. The new circuitry, however, which gives improved performance, employs a quantizing technique that more closely and quickly follows the amplitude variations.

A study was made to determine the effect of substituting other circuits for the low-pass filter output system usually employed in channel vocoder analyzers, and it was found that the substituted integrator circuitry was equivalent to the low-pass filter in following amplitude variations. A block diagram of this circuit is shown in Fig. 7. Since it is difficult to miniaturize low-pass filters, and it is easy to miniaturize integrator circuitry, the principal advantages of the modification are in size reductions. Several relatively expensive inductors are eliminated. Also, studies were conducted to determine the effect of replacing the bank of synthesizer channel low-pass output filters with a series of *R-C* circuits. The net effect was a simplification and reduction in weight of the entire synthesizer. The final circuitry worked satisfactorily, and reduced costs without impairing performance.

There are processing time problems in vocoders that have caused trouble in terms of recombining spectrum, voicing, and pitching information in perfect synchronization in the synthesizer. Various circuit routes through the vocoder have different delay patterns that must be ultimately adjusted and accommodated. For example, variable time delays occur in switching to and from, as well as holding and switching, both voiced and unvoiced speech signals. Calculation of time-delay periods over various signal paths through the vocoder show that variable delays up to about 60 ms are possible. This is illustrated in Fig. 8, wherein proper matching of all system delays makes a noticeable improvement in performance.

"Dual filter synthesis" or "spectral flattening"— which are somewhat esoteric terms applied to prefiltering in vocoder synthesizers—was applied to improve synthesizer channel performance. Bear in mind that the buzz inputs, used in conjunction with synthesizer channel outputs, are related to the fundamental pitch of the speaker which, for military male talkers, has been assumed to be in the 70 to 300 c/s range. The white-noise hiss inputs cover the sound spectrum in use in all channels, and high harmonic content is present—with a relatively constant amplitude—over the frequency range used.

Gold and Tierney, of the M.I.T. Lincoln Laboratories, have shown that the harmonics of buzz pulses[5] do not hold to constant amplitudes as the pitch varies. They suggest prefiltering and limiting separate buzz–hiss signals for each synthesizer channel before modulating. In accordance with this philosophy, the buzz–hiss signal input of the improved vocoder is fed on a parallel basis to all channels. The signal in a given channel successively moves through an added first bandpass filter, a limiter amplifier, and thence to a modulator that also receives the normal amplitude control for the channel in question. The final portion of each channel is a regular bandpass filter. This process assures that the frequency spectrum content of the buzz–hiss source introduces proper amplitude harmonics to the channel modulator.

Possible future trends

From the discussed examples, it is obvious that many developers are pursuing a variety of paths toward the improvement of both the quality and intelligibility of vocoder performance. Some researchers are breaking out of the restriction to a voice channel bandwidth for transmission on the line. A salient example is that of digitizing the VEV output, which, as already noted, now requires more digital data bits for transmission than conventional systems.

As an extension of the polymodal vocoder concept, it is believed that an adaptive digital speech equipment is now feasible. The adaptive vocoder system is envisaged by Caldwell Smith of the AFCRL as a polymodal vocoder that operates on a full-duplex link with additional logic so that the level of channel reliability (error rate) is continually sensed during the course of communications. This proposed method of sensing error rate is one of interspersing test messages in the pauses of speech. Should the channel reliability fall below tolerable limits for the data-rate setting, the control system would automatically switch transmitting and receiving systems to a lower data-rate setting that would be appropriate for optimum performance over the channel. Automation of the data-rate selection, in principle, would provide quick reaction to sudden noise or transmission degradation, and would assure the reliability of the speech channel at an optimum level, within the performance limits of the system.

Another important goal is to squeeze more and more bits per second into a particular bandwidth. The most interesting concepts are the use of phase orthogonality and multilevel data-transmission devices. Some developers believe they are close to the accommodation of 4800 b/s in an unimproved voice channel. Such techniques could improve the performance of vocoders by permitting the incorporation of higher bit rates on the assumption that means would be available to use lines which do not require costly equalization to reduce phase and delay distortion. Another desirable possibility for new techniques is the accommodation of existing 50-kilobit encoded systems in existing 48-kc/s group bands.

The Bell System T1 pulse-code carrier[6] might be well suited for two different applications, one of which involves the possibility of group encoding the approximately 1.5 megabit output of a standard 24-channel terminal. This encoded information presumably could be transmitted over the standard T1 repeatered line over a nominal distance of about 20 miles. It is possible to use T1 as terminals for a radio link, in which case the distance would be limited by the propagation capability of the radio link. The other proposed application would be the design of a new T1 terminal to operate with the standard T1 repeatered line—or radio link—to accommodate a number of 50-kilobit encoded outputs and a number of clear channels. The latter suggestion appears to be the more practical, since it does not involve the low-frequency loss limitation imposed by using T1 terminals on a standard basis.

A factor which will have an important influence is the increasing need to switch broadband (48-kc/s groups or 240-kc/s supergroups). There are two reasons for this trend: the subscriber need for 48-kc/s bands; and the problem of broadband restoral under emergency conditions—either push-button manual or automatic—through some form of broadband alternate routing. It is now feasible to obtain commercially, as a special arrangement, a broad band of frequencies that can be directed through the regular switched dial network as a "piggyback" adjunct to a clear voice channel over which the dialing is done.

The use of computers in vocoded speech is being tested at many locations. At the Lincoln Laboratories, B. Gold is working on a program for the combination of tentative decisions made by six speech extractors, and to compute therefrom a more accurate speech.

At BTL, E. E. David, A. M. Noll, and M. R. Schroeder are pursuing studies of the complex nature of speech-induced analog-signal waveforms through the application of a computerized correlation process to distinguish the periodic pulse peaks that correspond to the fundamental pitch frequency of the spoken voice. They refer to this as a "Cepstrum" technique,[7] and their work has been undertaken in conjunction with the development of a computer program that simulates vocoder performance. This method of pitch extraction is said to be extremely accurate and very insensitive to noise in the voicing circuitry. While the verification of this simulation must await validation tests in the laboratory with the use of actual circuitry, the results of the theoretical studies to date indicate that combining almost perfect pitch extraction with the best of other conventional channel vocoder circuitry will lead to the development of a digital vocoder capable of giving superior results at 2400 b/s—or less.

In another BTL development, J. L. Kelly and L. J. Gerstman have devised a computer program which permits them to use a "phonetic code" for 22 consonant and 12 vowel sounds. The program operates in conjunction with a series of nine input control signals that correspond to voice pitch, voice loudness, tongue position, and other speech variables. The output is used to drive a "simulated talking machine."

In conclusion, it appears that the many years of intense inquiry into speech bandwidth compression and digitizing are producing worthwhile results. The outlook is bright for further improvement. While the research community still seeks the optimum design, good vocoded and digitized speech systems for the military are emerging now.

The Mitre Corporation has obtained approval for the release of the information in this report, which was prepared under Contract AF 19-(628)2390 with Air Force Electronic Systems Division, AFSC.

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Project FIST: Fault isolation by semiautomatic techniques

Part II—Detailed instrumentation

This second and final part of the article discusses the details of the FIST test instrument, examines the configurations of some typical transformation networks, and describes the stimulus generators, which are used to furnish the test signal when the normal signal input to a module is inadequate for test purposes

Gustave Shapiro, George J. Rogers, Owen B. Laug, P. Michael Fulcomer, Jr. *National Bureau of Standards*

The method for fault isolation by semiautomatic techniques developed at the National Bureau of Standards, to which the acronym FIST has been applied, is a diagnostic tool for rapidly isolating faults in a modularized, noncomputer type of electronic equipment without removal of the modules from the prime equipment. It seeks to reduce the down time required for maintenance by combining modularized equipment, which minimizes the time and skill required to restore system operation, with a rapid, simple method for isolating defective modules. Although it has been devised to permit the novice technician to check module performance without being required to interpret data, it can also be used by the skilled technician to isolate a malfunctioning module rapidly, without reference to technical manuals and without prior knowledge of the equipment being tested.

Fault isolation is accomplished by measuring the dynamic performance of each of the modules in the prime system and determining if this performance is within the limits required for the correct functioning of the system. The functional relationship between the module being tested and the parts of the FIST measurement system is shown in Fig. 1. The characteristic to be measured is usually a dynamic property such as amplification, pulse rise time, pulse width, frequency, phase shift, etc., but checking module performance may also require measurement of direct currents and voltages, critical properties of the environment within the module, and occasionally values of resistance, inductance, or capacitance.

The hand-carried general-purpose test instrument is capable of simultaneously measuring four properties of the module or of its inputs. Each of the four measurements is made by a comparator, which compares the peak-to-peak amplitude of two periodic voltage waveforms. One input of this two-port device is connected to the signal being measured through the transformation network, and the other to a reference voltage, which may be (1) the internal reference contained within the test instrument or (2) a reference derived from the circuit under test by means of the transformation network.

The transformation networks are used to convert the performance characteristic that is to be measured to a periodic voltage whose amplitude is sensitive to small percentage changes in the characteristic being measured. A voltage divider included in the transformation network reduces this voltage to the level required by the test instrument and sets the acceptance limits of the test based on the performance required of the module being tested. The transformation network thus serves a programming as well as a conversion function.

This use of the transformation network to determine the type of test and its limits permits great flexibility in the variety of parameters that can be measured without requiring complexity in the test instrument. The arrangement is well suited to circuit performance measurements, since in most cases it is necessary only to ascertain if the characteristic is within the prescribed limits, and not to determine its absolute value. Since the determination of the limits is made a function of the transformation network, the operation of the test instrument is simplified.

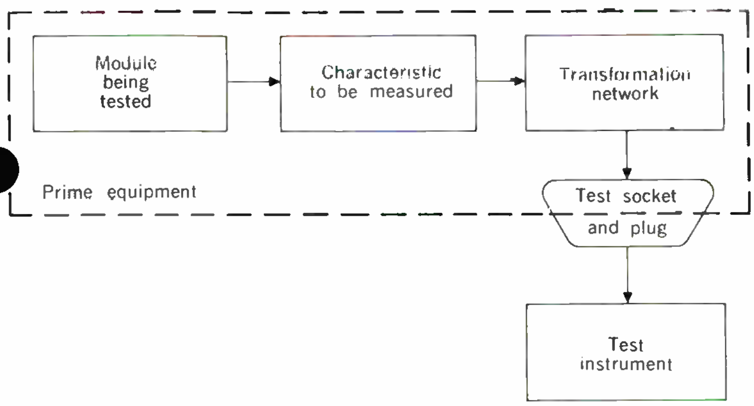
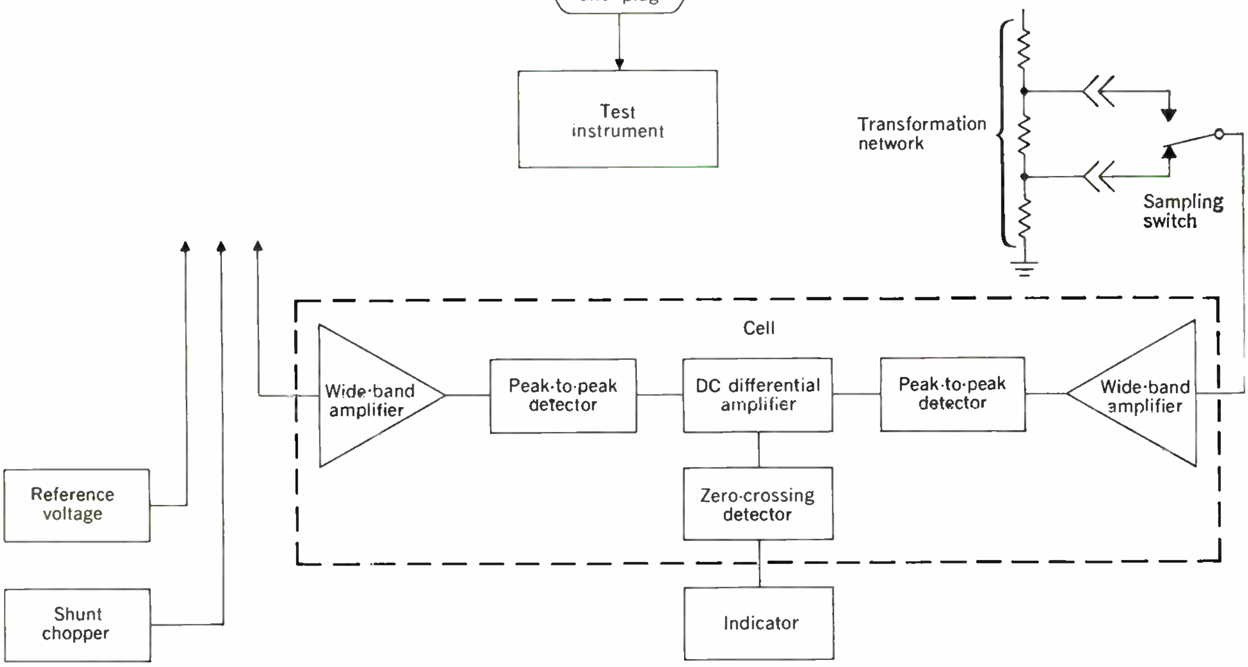


Fig. 1. Functional diagram showing relationship between module being tested and parts of FIST measurement system.

Fig. 2 (below). Basic elements of the one-cell test instrument.



It also places the selection of the characteristic to be measured and its limits under the control of the system designer, who is in the best position to know what characteristics are important to the performance of the module. The system designer, furthermore, knows what limits must be set on these characteristics for the proper functioning of the system of which the module is a part.

Part I of this report, which appeared in the August issue, explained the principles upon which the FIST concept is based, described the features that give the method its flexibility, examined techniques for physically incorporating FIST into the prime equipment, and demonstrated the simplicity of the programming and the speed with which a complex piece of electronic equipment can be checked. Part II will concentrate on some of the practical details of the test instrument; the transformation networks; and the stimulus generators, which are used to furnish the test signal when the normal operating signal is inadequate for test purposes.

Test instrument

Since the test circuitry is divided between the transformation networks and the test instrument, the latter should be versatile enough to accept the output of a large variety of transformation networks. Its operation should be simple and straightforward, and should require a minimum number of controls. To enhance operator confidence in the instrument, it should be capable of self-checking.

Because the maintenance technician is assumed to have a limited knowledge of the test equipment, and possibly no knowledge of the function performed by the prime equipment being tested, the indication of performance must be on a good–bad basis, requiring the operator to make no decisions. It is realized that the use of good–bad indicators must be approached with caution, since a skilled technician may feel that such indicators do not give him enough information about the circuit being tested. However, if he wishes to obtain additional information through the use of conventional test equipment, the test sockets provide numerous convenient access points to the prime equipment.

Basic one-cell test instrument. Figure 2 shows the basic elements contained in the FIST test instrument. This instrument differs from the one shown in Part I in that it employs a different type of indicator and uses a driven sampling switch instead of a potentiometer to connect one input of the test instrument to the output of the transformation network. In Part I, the explanation of the operation of the test instrument was simplified by showing that a "good" indication would be obtained if the potentiometer could be adjusted to equalize the two inputs to the comparator. If it is necessary only to determine whether module performance is within limits, however, it is not necessary to find the nulling point, but only to determine whether a null exists within the range of the potentiometer. A single-pole double-throw switch can be substituted for the potentiometer if the type of indicator is changed as shown in Fig. 2. This sampling switch, which is in the input probe of the test instrument, is a single-pole double-throw reed relay driven by a multivibrator in the test instrument.

The functional blocks enclosed within the dotted border constitute one cell of the instrument illustrated in Fig. 2. Basically, a cell consists of two wide-band amplifiers of identical gain which drive peak-to-peak detectors whose dc outputs, proportional to the peak-to-peak ac input signal voltages, are fed to a differential amplifier. The output voltage of the differential amplifier is proportional to the difference between the two inputs to the cell. This voltage feeds a zero-crossing detector, which drives the indicator. A green light is used to indicate a good module and a red light to indicate a bad one. The wide-band amplifiers provide the gain needed for linear detection of low-level signals. It is important only that the relative gain of the two amplifiers be the same, since the quality of their input signals, rather than the absolute amplitude, is being measured.

When the output of the differential amplifier passes through zero, or changes polarity, the zero-crossing detector causes the indicator to read "good." This change in polarity will occur if the voltage at the input to one of the wide-band amplifiers is between the levels to which the input of the other is alternately connected by the sampling switch. If the output of the differential amplifier does not change polarity, which will occur if both sampling switch voltages are higher or both are lower than the signal level at the other wide-band amplifier input, the lack of a zero crossing will cause the test instrument indicator to read "bad."

Also contained within the test instrument is an ac reference-voltage source available for amplitude measurements. The reference used is a voltage derived from a temperature-compensated reference diode which is converted to a 10-kc/s square wave by means of a conventional astable multivibrator whose transistors, when conducting, operate in the saturation region. When a voltage measurement is to be made, the reference voltage is tied to one input of the cell by means of a jumper wire on the test socket.

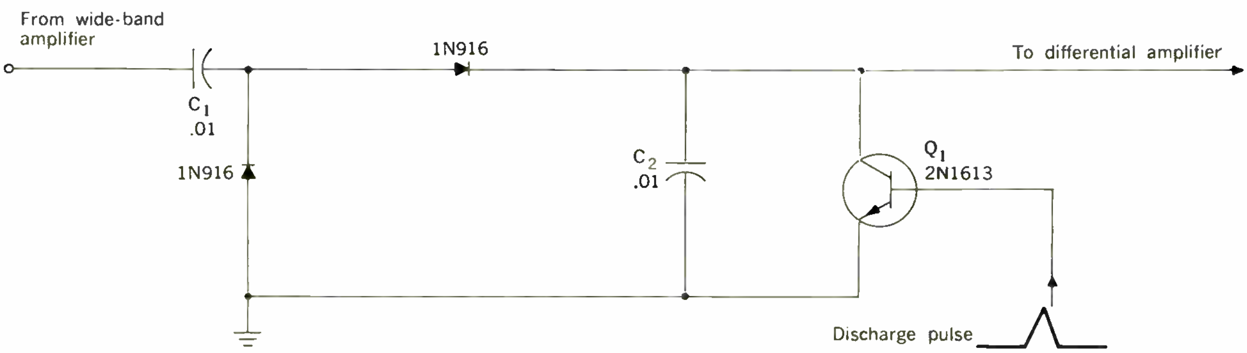
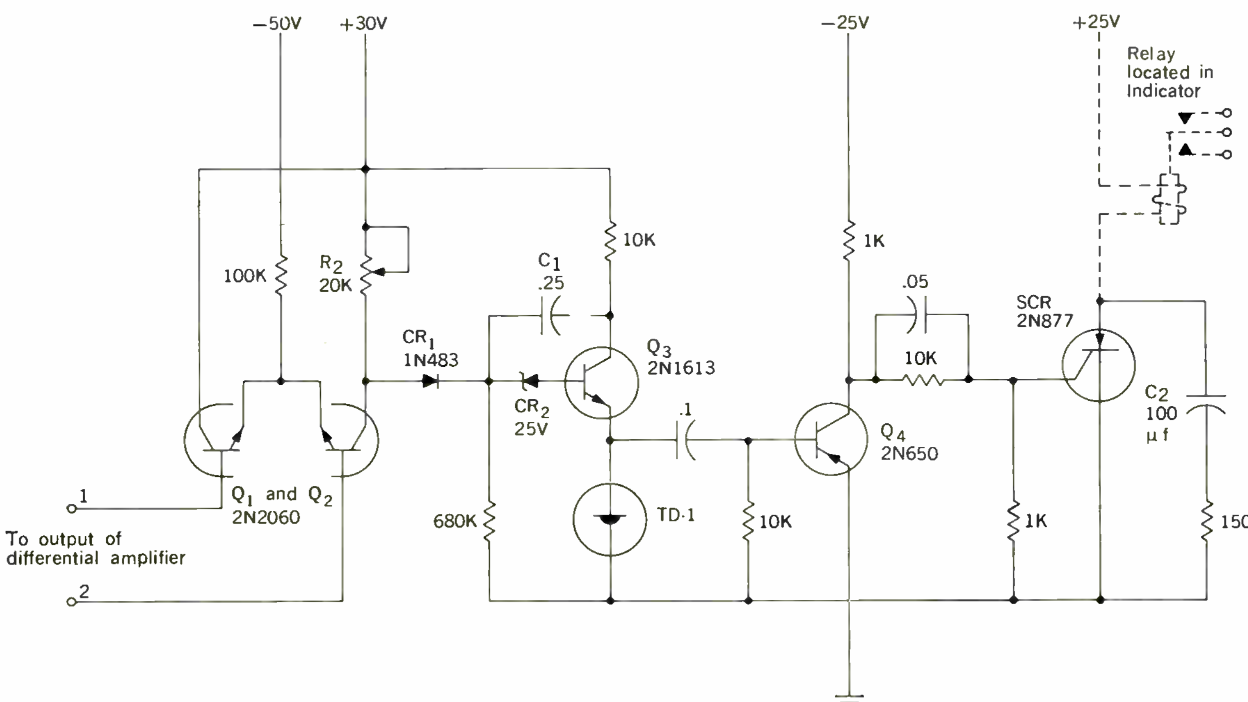


Fig. 3. Peak-to-peak detector and discharge circuit.

Fig. 4. Circuit of the zero-crossing detector.



Ac amplifiers were used in the test instrument because of the many problems associated with direct-coupled amplifier circuits. A practical method of amplifying dc signals is to convert them to a pulsating voltage before amplifying, which can be done by means of a shunt chopper contained within the test instrument.

The use of peak-to-peak detectors allows the amplitude comparison of dissimilar waveforms. The detectors are conventional in design except for a discharging circuit, shown in Fig. 3. Although the charging time of the detectors is short, the discharge time must be long so that the detectors will respond faithfully to low repetition-rate signals. When the sampling switch is changed from one position to the other, the input signal changes in amplitude, but the output level of the detectors can follow the change only if the detector is discharged momentarily to zero at every switching transition and then allowed to charge to the new level. This is accomplished by the discharge pulse, which is generated each time the sampling switch is actuated.

Zero-crossing detector. The zero-crossing detector is one of several unique circuits designed for the FIST test instrument. Its function is to close a relay in the indicator when the output of the differential amplifier passes through zero. The relay in the indicator controls the operation of the green and red lights that indicate the good or bad performance of a module.

The circuit of the zero-crossing detector is shown in Fig. 4. Basically, it consists of an emitter-coupled differential amplifier whose single-ended output is compared with a voltage established by a reference diode. When the relative polarity of the inputs to the differential amplifier changes, a tunnel diode generates a short pulse at the instant that the output of the differential amplifier equals the reference voltage. This pulse is amplified and triggers the gate of a controlled rectifier, which in turn closes the relay in the indicator. The relay remains latched for about one second after the instant of zero crossing.

The differential amplifier uses two high-gain silicon planar transistors Q_1 and Q_2 in one enclosure. This type of construction offers good stability against temperature changes, since the junctions of both transistors are at nearly the same temperature. The exact point of zero crossing is adjusted by the potentiometer R_2 to give an output voltage just equal to the 25-volt reference in the base of Q_3 when the input voltages to the bases of the differential amplifier are equal.

When base 1 becomes more positive than base 2 as a result of crossing zero in one direction, the output voltage of the differential amplifier will exceed the 25-volt reference in the base of Q_3, causing base current to flow and thereby switching tunnel diode TD-1 to its higher stable-voltage state. This positive pulse reverse biases Q_4 and thus is not amplified. However, as base 2 becomes more positive than base 1, the result of crossing zero in the other direction, the output voltage of the differential amplifier will drop below the reference level. This drop cannot occur instantaneously because of feedback capacitor C_1, which tends to delay the change, but this delay is essential to ensure that the narrow pulse which discharges the detectors is not transmitted by the zero-crossing detector to cause a false indication of zero-crossing. After this delay, Q_3 turns off and the tunnel diode switches from the higher stable voltage state to the lower stable voltage state. The negative pulse generated by the tunnel diode is amplified and inverted by transistor Q_4.

The output pulse from Q_4 triggers the controlled rectifier into conduction, thereby energizing the relay and discharging C_2 rapidly. The 150-ohm resistor in series with C_2 limits the peak current through the controlled rectifier to a safe level. The gate of the controlled rectifier returns to a slightly negative voltage at the instant the trigger terminates to ensure turn-off of the controlled rectifier as C_2 charges. This capacitor charges through the relay with a time constant determined by its capacitance and the relay resistance; the length of time the relay remains closed is determined by the *R-C* charging time and the relay drop-out current.

A four-cell test instrument. It is reasonable to expect that over a period of time a technician will become sufficiently familiar with the prime equipment to associate certain malfunctions with particular test sockets. This is particularly true if the assembly associated with that socket is a frequent offender. The technician may wish to check the suspected test socket before following the prescribed testing routine. This is a natural desire which should be satisfied if possible.

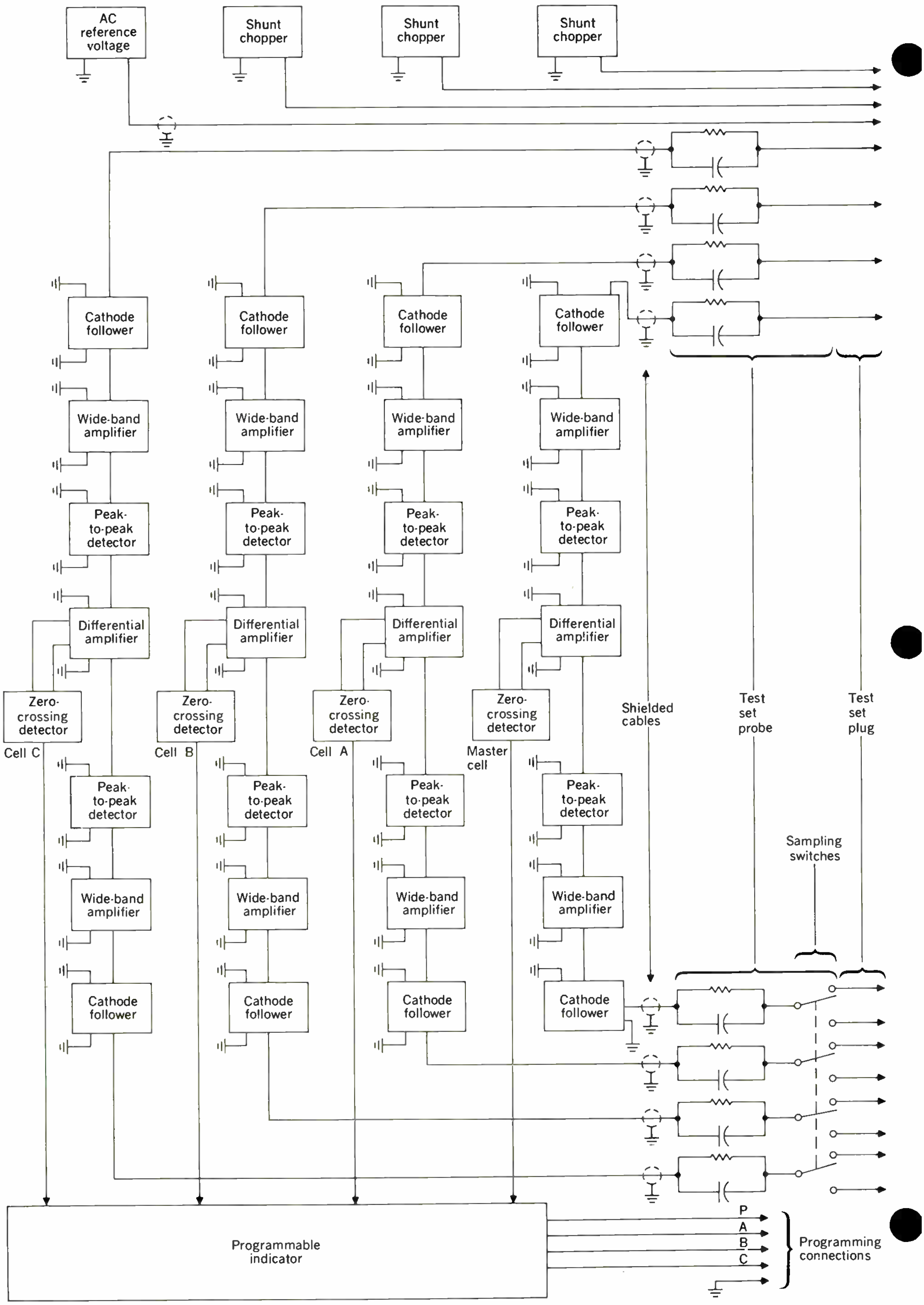
If the technician is to be permitted to test the modules in any order he chooses, however, some refinements in the test instrument are necessary. The normal input signal to the module under test usually furnishes signal for the FIST performance checks. When the modules are checked in the prescribed order, the test socket arrangement assures that all the modules furnishing inputs to the one under test have been checked previously, so that the technician can be reasonably sure that the module under test is receiving the correct inputs.

If the technician deviates from the prescribed order in checking the modules with a one-cell test instrument, he has no assurance that the inputs to the module under test are correct. A module could be good yet produce an erroneous "bad" indication because one of its input signals is either absent or out of limits. Since the purpose of the test is to locate the malfunctioning module, however, a "bad" indication should refer only to the module under test, and not to the condition of its inputs; otherwise, the technician does not know whether or not to replace the module.

To permit the technician to test out of sequence without running the risk of getting an erroneous "bad" indication, additional cells are included in the test instrument to permit the inputs to be checked simultaneously with the performance of the module. These input tests are called qualification tests; the tests on the module itself are called performance tests. If one or more of the inputs to the module under test is incorrect, the qualification test results in a "no-test" indication, which indicates that no test on the module is possible until a malfunction elsewhere in the system has been corrected. The additional information permits the technician to distinguish between a "bad" module and an incorrect input to the module.

The flexibility of FIST is greatly increased by including the additional cells in the test instrument and by making it possible to use any of them for either qualification or performance measurements. Figure 5 shows a block diagram of such an instrument. It consists of four cells, three separate choppers for measurement of three different dc voltages, a reference voltage, and a program-

Fig. 5. Block diagram of a four-cell test instrument.



mable indicator. Each of the four cells is of the type illustrated in Fig. 2, except that all cells share the same "good–bad" indicator.

Programming the four cells for either a performance or a qualification test is accomplished in a very simple manner. The master cell is always used as a performance cell. Any of the other three cells, *A*, *B*, or *C*, can be programmed for a qualification test by grounding its programming connection (*A*, *B*, *C*, of Fig. 5), or any can be programmed for a performance test by connecting its programming connection to the pin labeled *P*. On the other hand, if any of the three cells is not required, its programming connection is left floating. The interconnections among the programming pins are made by prewired jumpers on each test socket in the prime equipment being tested.

Programmable indicator. Figure 6 shows the circuitry used to program the output of each cell for either a qualification or a performance measurement. The relays are energized by the zero-crossing detectors when the characteristic being measured by the cell is within its prescribed limits. They control the indicator lamps through transistors, because it was found necessary to keep the power level in the programming leads low to reduce crosstalk caused by switching transients.

The operation of the programmable indicator is best explained by first assuming that programming connections *A*, *B*, and *C* are left floating. The master cell is then the only one that is active in making measurements. When the test instrument probe is inserted in a test socket, an interlock allows control current to flow into the bases of Q_1 and Q_4. If the master relay is not energized, most of the current, which is derived from a constant current source, will flow into the base of Q_1, causing the red indicator to light. Because of the additional voltage drop across the diode in the base circuit of Q_4, the current flowing into this base will be insufficient to cause the green light to turn on. On the other hand, if the relay that is controlled by the master cell is energized, the connection to the Q_1 base is opened and current is allowed to flow only into the Q_4 base, putting on the green light.

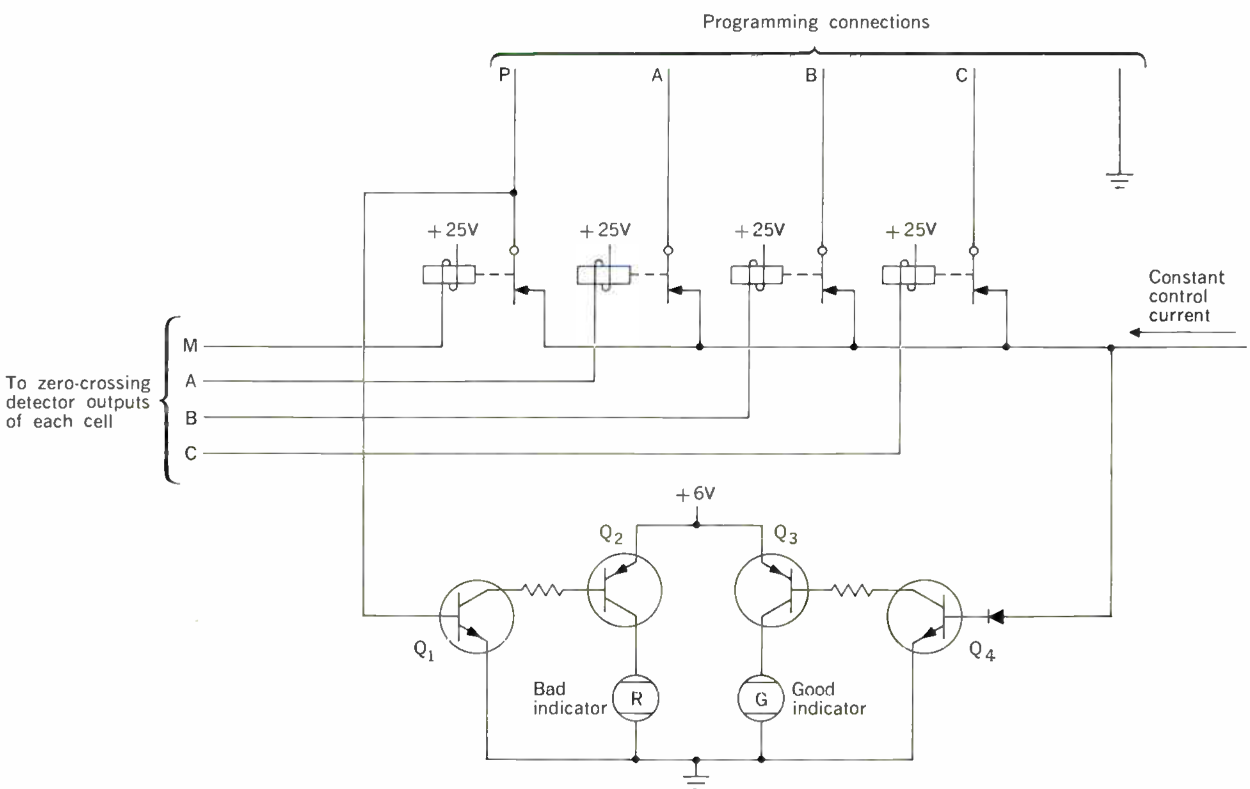
Any of the other three cells can be programmed for a performance measurement by connecting its programming pin, *A*, *B*, or *C*, to *P*. The contacts of all the relays thus programmed are in parallel with the contacts of the master cell relay, so that all of these relays must be actuated before current can flow into the base of Q_4 and turn on the "good" indicator.

Any of the cells, *A*, *B*, or *C*, can be used for a qualification measurement by grounding its programming connection. As long as the corresponding relay is not energized, this grounds the bases of both Q_1 and Q_4 so that neither indicator can light. When the relay is energized, the ground is removed from the transistor bases, permitting the indicators to indicate the results of the performance tests. The contacts of all the relays programmed for qualification measurements are in parallel, so that no indication can be obtained until all the relays thus programmed are energized.

By means of a delay circuit, which is not shown, operation of the indicators is delayed long enough to permit all the relays to complete their switching before either indicator lights. At the end of this delay, one of these indications will be obtained:

1. An illuminated green light indicates a good module. This occurs if the relays of all the cells in use

Fig. 6. Programmable indicator. Each cell output is programmed for a qualification or a performance measurement.



are energized, and indicates that all the characteristics measured for both qualification and performance tests are within their limits.

2. An illuminated red light indicates a bad module. This occurs if the relays of all the cells programmed for qualification tests are energized but at least one relay programmed for a performance test is not. It indicates that all qualification tests are within their limits, but that one or more performance tests are not.

3. Neither lamp lights, indicating "no test." This occurs if any of the cells programmed for qualification tests fails to energize its relay. It means that one or more of the characteristics used for qualifying measurements are outside their limits, and therefore no valid performance measurement can be made.

Self-checking the test instrument. The operator can quickly determine whether or not his instrument is operable by inserting the test probe in the self-test socket located on the instrument. If the green indicator goes on, the test instrument is ready for operation; a red light indicates that the instrument is either defective or needs a balance adjustment.

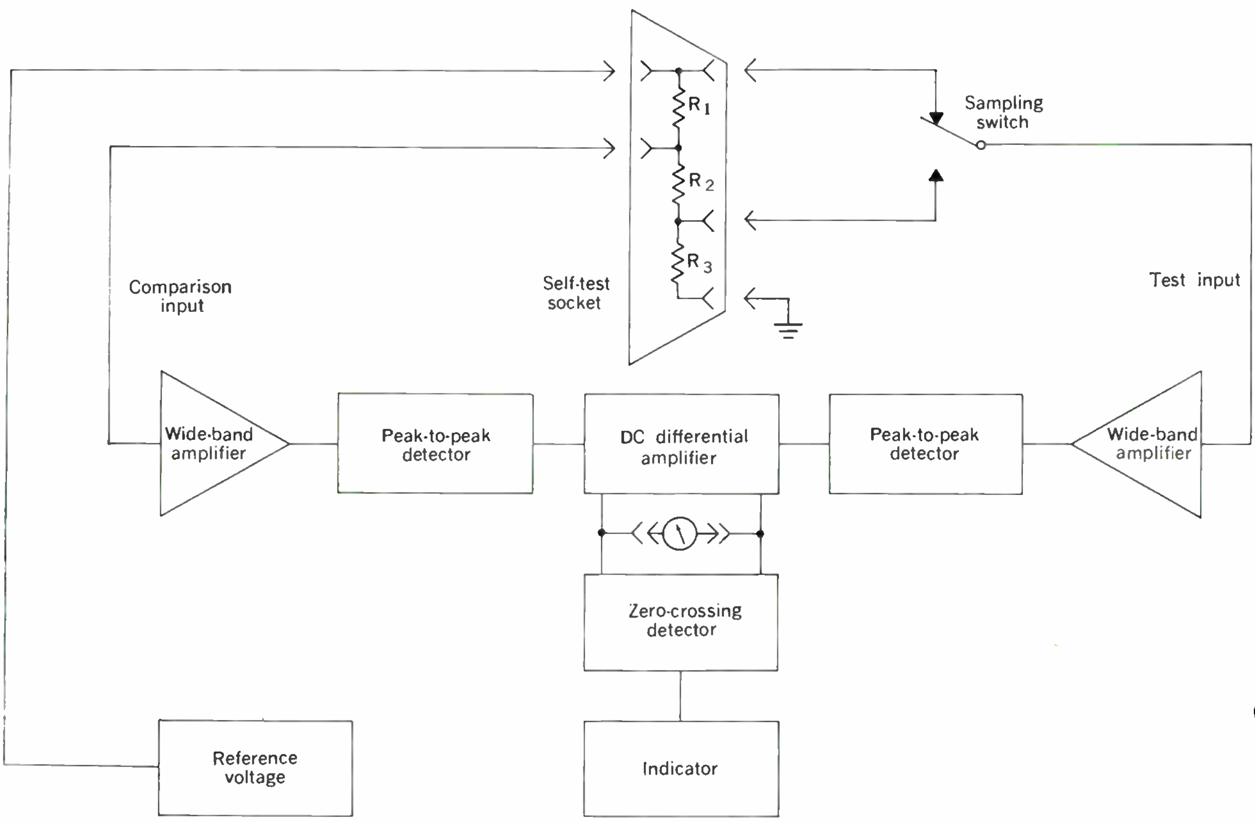
The self-check is accomplished by determining that the gains of the pair of amplifiers in each cell are equal, and by checking for the proper operation of the zero-crossing detector in the cell. Fig. 7 shows one method. The internal reference voltage is connected to an attenuator on the self-test socket from which each cell receives its inputs. When the sampling switch is in the position shown, the test input voltage will be slightly higher than the comparison input voltage. When the sampling switch changes to its other position, the test input voltage will be slightly lower than the voltage at the comparison input. These changes in voltage can be made small and equal by making R_1 and R_2 identical and of very low resistance. If the amplifiers are balanced, the output of the differential amplifier will change polarity each time the sampling switch changes from one position to the other, and the "good" indicator will light. If the amplifiers are unbalanced or the zero-crossing detector is not functioning, a "bad" indication will be obtained.

The supply voltage can also be used to provide the input signal for self-testing. In this case, the reference voltage of Fig. 7 is replaced by the supply voltage and a dropping resistor, and one of the choppers is connected across attenuator R_1, R_2, R_3 to modulate the dc.

With both the reference voltage and the supply voltage to provide input signals, the entire test instrument can be tested with the use of only one self-test socket. One of the cells is connected to the reference voltage, and each of the remaining three cells uses one of the choppers and the supply voltage as a source of test signal. All the cells are programmed for performance tests. Therefore, if any cell is out of balance, or the zero-crossing detector is not functioning properly, or a chopper is defective, or the reference voltage is absent, the "bad" indicator will light. Degradation of the internal reference voltage will usually manifest itself as a complete loss of reference voltage, which is readily detected by the self-check. For those infrequent occasions when it is necessary to calibrate the reference voltage, a digital voltmeter should be used.

Should the self-check result in a "bad" indication,

Fig. 7. A circuit for self-testing one cell of test instrument for gain equality of amplifier pairs and zero-crossing point.



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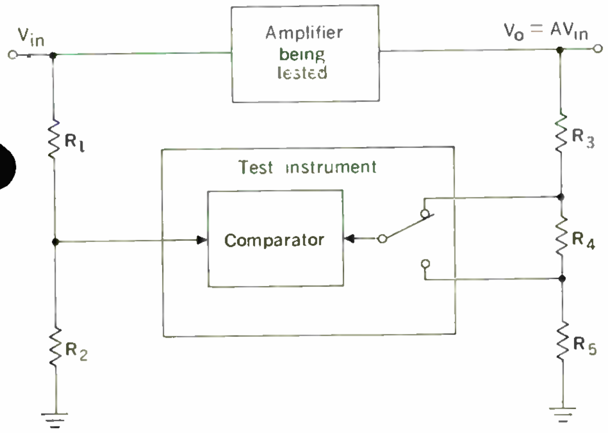


Fig. 8. Transformation network for amplification measurement. Measurement is done dynamically.

each cell can be adjusted individually. For this purpose internal balancing adjustments are provided, as well as a null-indicating meter, which can be switched across the output of any of the differential amplifiers. This meter is not used in the normal operation of the test set. If balancing the gains of the amplifiers does not cause the "good" indicator to light, a skilled technician will be needed to adjust the set for proper operation.

Prototype test instrument. The four-cell test instrument described has been constructed in breadboard form and is presently undergoing preliminary prototype design. The actual instrument will occupy approximately one fifth of a cubic foot and weigh between 12 and 14 pounds. The "good" and "bad" lights will be mounted on the probe.

The following are some of the pertinent overall performance characteristics of each cell in the test instrument.

☐ Input impedance: 5.02 MΩ ± 2 per cent, in parallel with 20 pF ± 10 per cent.

☐ Overall bandwidth (3 dB down): 12 c/s to 22 Mc/s.

☐ Reference voltage level: 240 mV ± 0.4 per cent.

☐ Precision of comparison at reference level: < 0.25 per cent.

☐ Absolute accuracy at reference level for duty factors greater than 10^{-3}: ± 2 per cent.

☐ Useful input operating range: 30 mV to 300 mV.

☐ Average measurement time: 0.75 second.

Transformation networks

Physically, the transformation network is a part of the prime system and forms the interface between it and the test instrument; it includes all the components added to the prime system for the sole purpose of obtaining test information. Most of these components, which are usually small passive elements, are mounted in a cordwood assembly behind each test socket (see Part I, Fig. 8). Since the test instrument is capable of making four measurements simultaneously, these cordwood assemblies may contain from one to four transformation networks. Each assembly usually contains at least two transformation networks, because most modules require at least one qualifying measurement in addition to a performance measurement.

This need for a qualifying measurement is evident in each of the transformation networks described. For example, if amplification is being measured, a failure in a stage preceding the amplifier under test would result in loss of input to the amplifier. In this event, the output of the transformation network of Fig. 8 would cause the test instrument to indicate "bad," which is false since the malfunction is not in the module under test. In addition to this performance measurement of amplification, however, the amplitude of the input signal to the amplifier should be measured as a qualifying measurement. Since the qualifying measurement causes the "no-test" indication to override the "bad" indication obtained from the performance measurement, the test instrument will then correctly indicate that the module is not being tested and that the malfunction must be found elsewhere. Similar qualifying measurements should be made in conjunction with each of the other transformation networks described.

Network configurations. A prerequisite for the design of a transformation network is a knowledge of the characteristics of both the system under test and of the test equipment being used. Once the characteristics of the test set are standardized, however, the transformation network configuration required for each *type* of measurement can be established so that only the component values must be determined to test module performance to the limits required in a specific application. Described in the following paragraphs are examples of transformation network configurations that can be used with the test instrument previously described. They illustrate the general principals employed and are typical of those configurations associated with these properties that can be measured by the FIST system: amplification; bandwidth; capacitance; current; frequency; impedance; inductance; phase shift; power; pulse (amplitude, decay time, delay, droop, duty factor, overshoot, rate-of-rise or decay, repetition rate, rise time, width); radiation (heat, light, X ray, etc.); resistance; sawtooth linearity; square wave symmetry; temperature; variety of physical properties (mechanical, hydraulic, etc.) that can be measured with the use of physical-to-electric transducers; and voltage (ac—with or without dc component—dc, RF).

Amplification. Amplification is easily measured dynamically. If the normal input signal to the amplifier is continuous and its amplitude is greater than the input level required by the test instrument, it can be used as the test signal. The method of measurement is independent of the type of signal being amplified as long as it is within the frequency and duty-factor range of the test instrument.

Both inputs to the comparator are derived from the circuit being tested as illustrated in Fig. 8, the transformation network consisting of a pair of voltage dividers. A reference voltage is derived from the input signal to the circuit under test by voltage divider R_1, R_2, which reduces the signal voltage present at the module input to the level required by the comparator. Divider R_3, R_4, R_5 reduces the output voltage of the amplifier under test to this same reference level for application to the other input to the comparator. The relative values of these resistors are easily determined once the permissible limits of the amplification are known. The total resistance of both dividers should be high enough to avoid loading the circuit under test, and the resistor values should be chosen to minimize the effects of shunt and stray capacitance. In some cases it will be necessary to compensate the dividers. If the resistor values are chosen so that the voltage available at the upper switch position is just sufficient to equalize the inputs to the comparator when the amplification of the circuit under test is the minimum acceptable, and the voltage at the lower switch position is just sufficient to equalize the inputs when the amplification is the maximum acceptable, a "good" indication will be obtained only when the amplification of the circuit under test is between the two limits. For all other values of amplification the unit will test "bad."

For example, assume that the performance of an amplifier is acceptable provided its amplification is between 9 and 11. If its input signal is 10 times the level of that required by the test instrument, the input divider R_1, R_2 must reduce this signal by a factor of 10 to provide a reference for the comparator. If the output divider is designed so that the voltage at the junctions of R_3 and R_4 and of R_4 and R_5 are 1/90 and 1/110, respectively, of the amplifier output voltage, the two voltages so obtained will bracket the voltage obtained from the input divider R_1, R_2 when the amplification is between 9 and 11. For all other values of amplification these two voltages will either both be higher or both be lower than the signal level at the junction of R_1 and R_2. Since the test instrument responds with a "good" indication when it senses that the two signals from the sampling switch lie one above and one below the other comparator input, the "good" indication will be obtained only for amplifications between 9 and 11.

Since peak-to-peak detectors are used in the test instrument, the "good–bad" indication is independent of the relative phase of the two input signals to the comparator, so that the test for amplification is not affected by the phase shift of the amplifier under test, and the results obtained are the same whether the amplifier inverts the signal or not. If the amplification of the circuit under test is less than unity, such as in the case of a cathode follower, the amplifier input must be attenuated more than the output before application to the test instrument, but in other respects the test is the same.

In many cases the maximum amplification is unimportant; the amplifier is acceptable provided its amplification is greater than a specified minimum value. In this case the amplification can be tested to a single limit by eliminating R_5 and grounding the lower end of R_4. The resistance values are chosen so that the voltage at the junction of R_3 and R_4 is just sufficient to equalize the inputs to the comparator when the amplification of the circuit under test is at its minimum acceptable value. The amplifier will then test "good" only when its amplification is equal to or higher than this value.

Voltage amplitude. A voltage may be measured by comparing its amplitude with the internal reference in the test instrument (Fig. 9). The voltage being measured is reduced to a level within the range of the test instrument by voltage divider R_1, R_2, R_3, the resistance values of which are chosen so that a "good" indication will be obtained only when the voltage being checked is within specified limits.

Both ac and dc voltages can be measured. If a dc voltage is to be measured, one of the choppers in the test instrument must be used to convert it to pulsating dc before it is applied to the comparator. (See Fig. 7, Part I.) Ac voltages can be measured in the presence of dc by blocking the dc with a capacitor. The dc component of a signal which contains both ac and dc components can be measured by adding a low-pass filter to the transformation network.

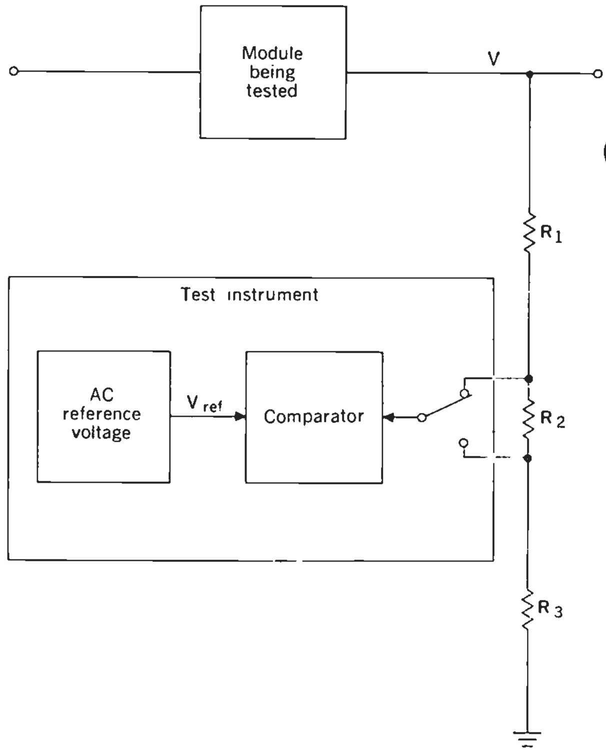


Fig. 9. Transformation network for ac voltage measurement. Amplitude is compared with internal reference.

Pulse amplitudes are measured in the same way as ac voltages, but special precautions may be required when measuring the amplitude of a pulse or square wave in which overshoot or droop is present. Since the comparator is sensitive to changes in peak-to-peak amplitude, it may respond to changes in the overshoot or droop unless the transformation networks are designed to prevent this. The extra components required should be added only when changes in overshoot or droop are likely to cause unacceptable errors in the measurement of amplitude.

If changes in the overshoot are likely to obscure changes in amplitude, the overshoot may be eliminated by adding a low-pass filter section to the transformation network [Fig. 10(A)]. The time constant of the filter R_4, C_1 is chosen to obtain a waveform that is of the same peak amplitude as the original pulse but without the overshoot. If droop must be eliminated, the low-frequency components of the signal can be removed by a high-pass filter [Fig. 10(B)]. The divider resistors are then chosen to reduce the resulting double pulse signal, whose amplitude is independent of droop, to a level that can be compared with the reference.

Pulse rise or decay time. The measurement of pulse characteristics is well illustrated by the transformation network for the measurement of pulse rise or decay time

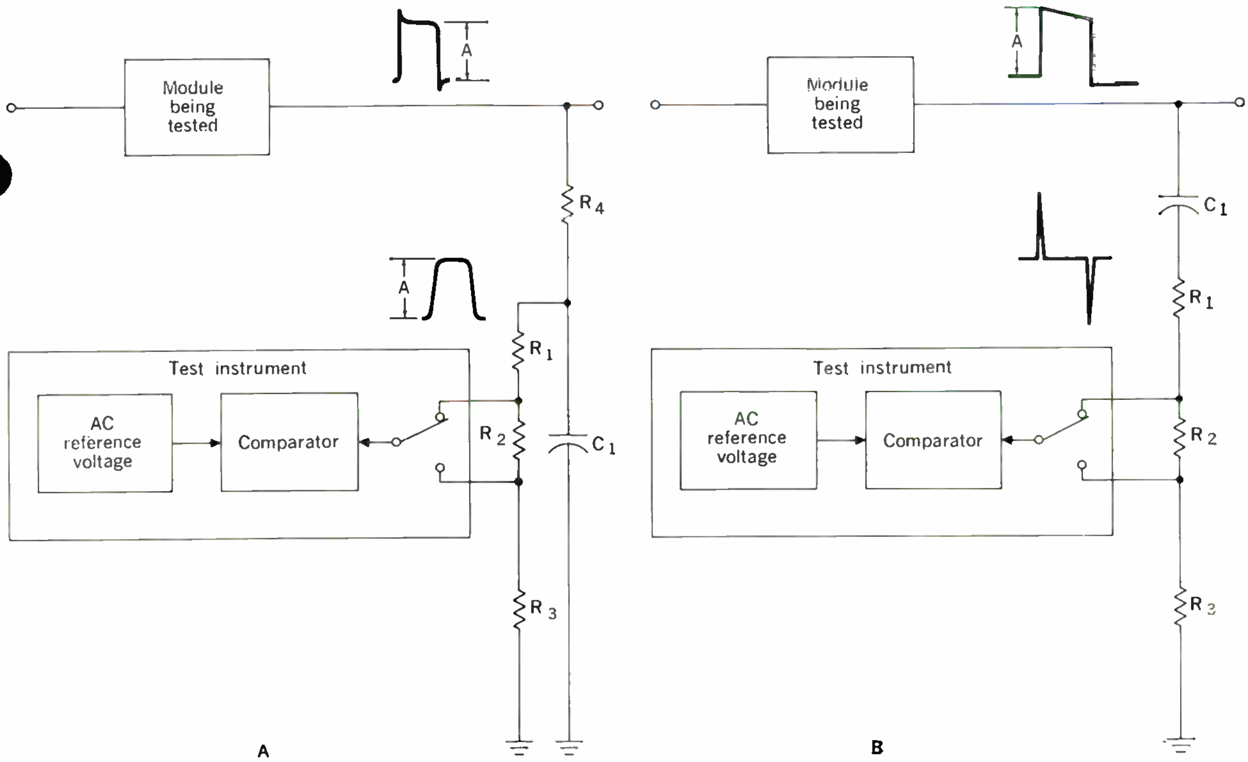
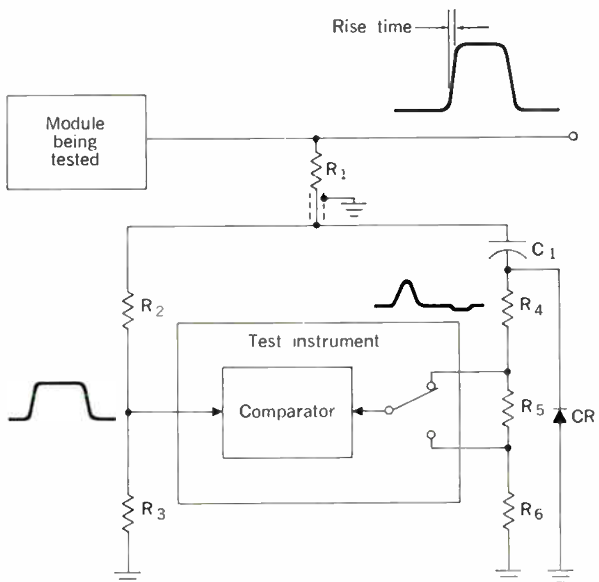


Fig. 10. Transformation networks for the measurement of pulse amplitude in the presence of overshoot or droop. Addition of a low-pass section to network A will eliminate overshoot; a high-pass filter added to network B will eliminate the effects of droop if necessary.

Fig. 11 (right). Transformation network for the measurement of pulse rise or decay time.



shown in Fig. 11. The essential feature of this transformation network is the high-pass filter R_4, R_5, R_6, C_1, the output of which furnishes a signal to the comparator whose amplitude is proportional to the amplitude and transition times of the original pulse. This is compared with a signal derived from divider R_1, R_2, R_3, whose amplitude is proportional to the amplitude of the original pulse being measured but independent of its transition times. Since the amplitudes of both inputs to the comparator vary directly with the measured pulse amplitude, the "good–bad" indication of the test instrument is substantially independent of changes in pulse amplitude, and is a function of transition time only.

When a pulse is fed into an *R-C* differentiating network, the output of the network will be a pair of pulses of opposite polarity, one occurring at the leading edge and one at the trailing edge of the original pulse. The peak amplitude of the first pulse is a function of the amplitude of the original pulse and the transition time of its leading edge (rise time), while the peak amplitude of the second pulse is a function of the amplitude of the original pulse and the transition time of its trailing edge (decay time). Since the two pulses are of opposite polarity, either can be selected by clipping the other by means of a suitably polarized diode. Thus either the rise or the decay time can be selected for measurement.

The time constant of the differentiating network affects both the amplitude of the signal at the input to the comparator and its sensitivity to small percentage changes in the transition time of the waveform being measured. For most applications, a reasonable compromise between the sensitivity and attenuation requirements can be obtained by making the time constant equal to the lower limit (shortest acceptable time) of the transition time to be measured. At the longest acceptable transition time, the peak output voltage of the network will be lower, but its sensitivity to small percentage changes in transition time will be greater. The resistors of divider R_4, R_5, R_6 are chosen so that the output of the divider at the upper position of the sampling switch (junction of

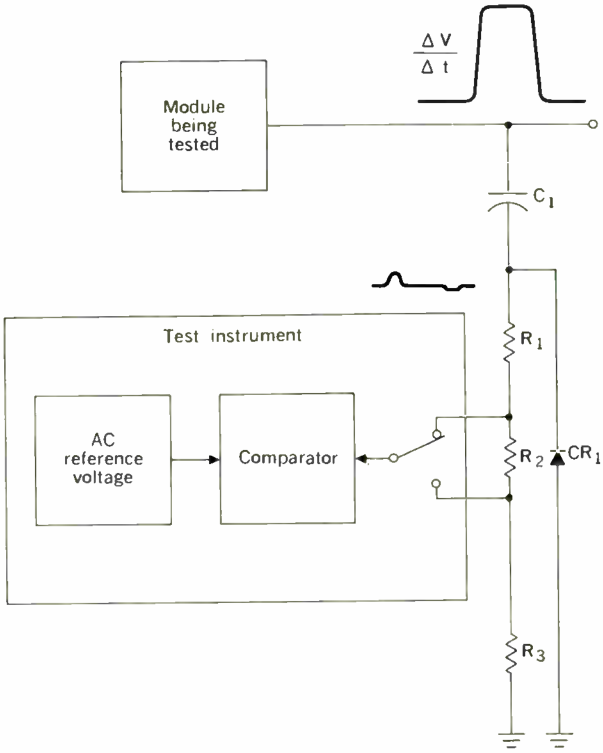


Fig. 12. Typical transformation network used for rate-of-rise and decay measurement.

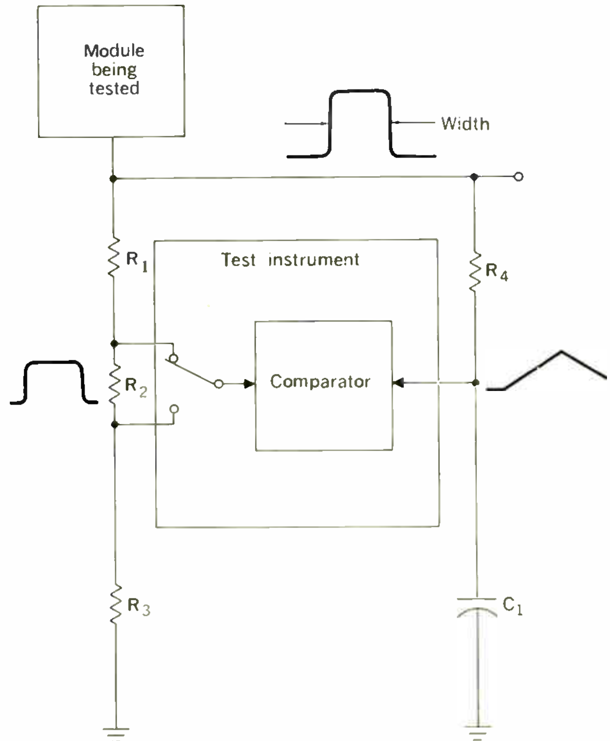


Fig. 13. Typical transformation network used for the measurement of pulse width.

R_4 and R_5) is equal in amplitude to the signal at the comparison input (junction of R_2 and R_3) when transition time is the longest acceptable and the output at the lower switch position (junction of R_5 and R_6) is equal in amplitude to the comparison input signal when the transition time is the shortest acceptable. For any transition time between these two extremes, a "good" indication will be obtained from the test instrument, while a "bad" indication will be obtained for any transition time outside these limits. If no minimum transition time is specified, that is, if the transition time is acceptable provided it is not longer than a specified maximum, R_6 may be omitted. In this case a "good" indication will be obtained for any transition time from zero to the maximum specified.

The rest of the circuit configuration of the transformation network is dictated by practical considerations. Resistor R_1 is used to provide isolation between the module under test and the test socket; it is usually installed at the module socket and connected to the test socket by a shielded lead. In conjunction with R_2 and R_3, it permits a low-impedance driving source to be obtained for the high-pass filter.

Other pulse characteristics. Typical transformation networks for the measurement of other pulse characteristics are illustrated in Figs. 12 through 14. The transformation network used for the measurement of rate of rise or decay, Fig. 12, differs from that used for the measurement of rise or decay time only in the time constant of the high-pass filter and in the method of obtaining the reference voltage. If the time constant of the high-pass filter is made much smaller than the transition time of the signal being measured, the output of the filter will approach the true derivative of its input signal. In practice, a time constant equal to or less than $^1/_{20}$ of the transition time of the signal is satisfactory.

The transformation network for the measurement of pulse width, Fig. 13, is similar to that used for the measurement of pulse rise or decay time except that a low-pass filter is used to transmit to one input of the comparator a signal whose peak amplitude is a function of both the width and amplitude of the original pulse being measured. Since the other input to the comparator is a pulse whose amplitude is also proportional to the amplitude of the original pulse but independent of its width, the output of the test instrument will be a function of pulse width only. The time constant of filter R_4, C_1 is not critical if it is large enough for the rise of output waveform to be a reasonably linear function of time.

Overshoot and droop can be measured by the techniques illustrated in Fig. 14, which measures overshoot and droop as a percentage of the pulse amplitude. In each case one input to the comparator is obtained by passing the original signal through an *R-C* filter section to obtain a signal whose amplitude is proportional only to the amplitude of the original signal. This is compared with a signal that is a replica of the original signal and that contains the same percentage overshoot or droop. The resistances in the divider R_3, R_4, R_5 are chosen so that a "good" indication will be obtained only when the overshoot or droop is within the prescribed percentage limits of the signal amplitude.

Frequency. In the transformation network for the measurement of frequency, either or both of the inputs to the comparator use frequency-sensitive elements to convert frequency changes to voltage changes. The type

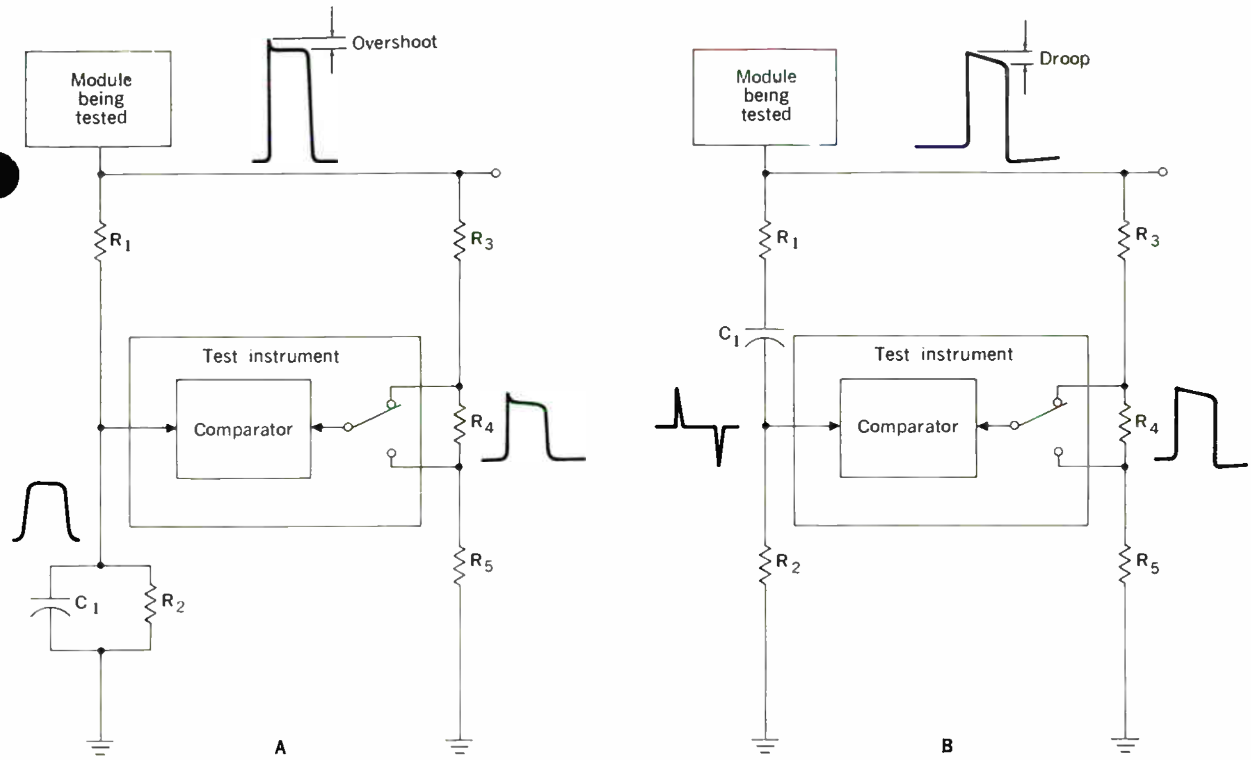


Fig. 14. Transformation networks for the measurement of overshoot and droop: (A) per cent overshoot; (B) per cent droop.

of frequency-sensitive element is determined by the frequency to be measured.

For frequencies in the audio or ultrasonic range, one of the simplest transformation networks consists of an *R-C* circuit to provide the input to one side of the comparator, and a simple resistive divider to provide the input to the other side (Fig. 15). Either a high-pass section (R_4, C_1) or a low-pass section (R_4', C_1') can be used; in either case, the time constant is chosen so that the frequency to be measured lies outside the pass band in the region in which amplitude response is falling off. The output amplitude of the *R-C* section is then a function of frequency, while the output of the resistive divider is not. Both outputs are affected in the same way by changes in the amplitude of the signal being measured, so that the ratio of the inputs to the comparator is affected by changes in frequency only.

For a given attenuation, both the high- and low-pass *R-C* sections have the same sensitivity, where sensitivity is defined as the ratio of the percentage change in output voltage to the percentage change in input frequency. The sensitivity can be doubled by replacing the resistive divider of Fig. 15 by an *R-C* section of the opposite type from the one in the other input to the comparator. That is, if a high-pass section is used in one input, a low-pass section should be used in the other. This is usually a more effective way of increasing sensitivity than cascading two *R-C* sections on one side of the transformation network. When large amounts of attenuation are required, increasing the number of *R-C* sections is an effective way of increasing both attenuation and sensitivity.

The transformation network illustrated in Fig. 16 is used to measure frequencies in the medium- and high-frequency range. In this transformation network, each input to the comparator is obtained from a divider which is composed of resistance in series with a parallel-resonant circuit. As indicated by the curves, which show the voltage amplitude at each input to the comparator as a function of frequency, one of the resonant circuits is tuned to a frequency higher than the frequency being measured and the other to a lower frequency. The resistance in series with each of the tuned circuits is determined by the attenuation required to reduce the amplitude of the signal being measured to the level required by the test instrument. The resistance of R_2 relative to the total impedance of the divider is selected so that a "good" indication will be obtained only when the frequency is within the prescribed range. This requires that the signal amplitude V_3 at one input to the comparator lie between the signal levels V_1 and V_2, which are alternately connected to the other input by the sampling switch. In the example illustrated, this will occur when and only when the frequency being measured is between f_1 and f_2.

Phase shift. The transformation network for the measurement of phase shift makes use of the fact that the sum of two sine waves of the same amplitude and frequency is a sine wave whose peak amplitude is a function of the phase difference between the two. In the vicinity of zero degrees, the amplitude of the sum is relatively insensitive to changes in phase shift, and at 180° no measurement is possible because the amplitude is zero, but within the 180° ± 60° region the sensitivity is good, and the relationship between amplitude and phase difference is almost linear.

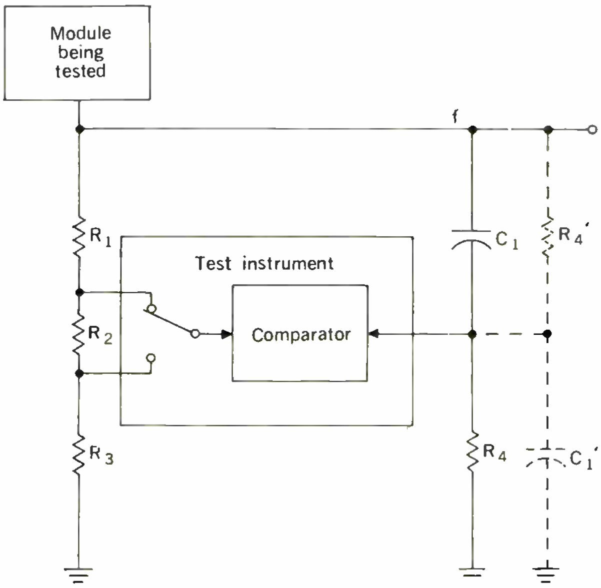


Fig. 15. Transformation network for the measurement of frequencies in the audio or ultrasonic range.

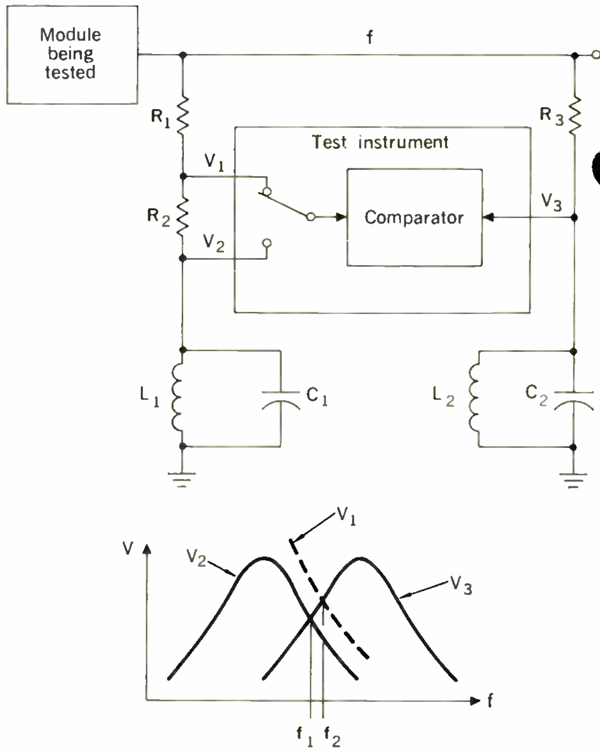


Fig. 16. Transformation network for the measurement of frequencies—medium- or high-frequency range.

A simple transformation network employing this principle for the measurement of phase shift is illustrated in Fig. 17(A). Resistors R_4, R_5, and R_6 form a simple summing network. If R_4 and R_5 are large compared with R_6 and are so proportioned that currents I_1 and I_2 are equal, the voltage across R_6, which is applied to one input of the comparator, will be a function of the phase difference between the input and output voltages of the module under test. The resistors of the reference divider R_1, R_2, R_3 are chosen so that the amplitude of the voltage across R_6 will always lie between the voltage levels at the two positions of the sampling switch if the phase shift is within the prescribed limits. Changes in the signal level at the input to the module under test will not affect the phase shift measurement, because both inputs to the comparator are functions of this signal level.

The problem in checking the phase shift of an amplifier, however, is that the amplification varies within specified limits, with the result that the currents I_1 and I_2 do not remain equal. This introduces errors into the phase shift measurement, which may be very large. But if the phase difference is between 140° and 170° or between 190° and 220°, ±10 per cent changes in amplification will cause errors of less than 2°. (The error is less than 3° over approximately the same range of phase differences for ±20 per cent changes in amplification.) If the phase limits to be measured lie outside this region, a simple *R-C* lead or lag network may be added, as shown in the transformation network of Fig. 17(B), to shift the phase so that the summing network sees a phase difference that is within a region of minimum error.

Resistance, inductance, and capacitance. Although testing to the piece-part level is not advocated, it can be done for special cases by the method illustrated for the measurement of resistance in Fig. 18. If required during the measurement, the component being tested can be disconnected from the rest of the circuit by microswitches, which can be mounted on the rear of the test socket. (See Part I, "Test sockets and transformation networks.")

As indicated by the figure, the transformation network consists of a voltage divider R_1, R_2, R_3, which furnishes one input to the comparator, and a resistor R_4, which, together with the resistor being tested, forms a voltage divider to provide the other comparator input. The ratio of the resistance of R_2 to the total resistance of the divider is chosen so that the amplitude of the voltage across the resistor being measured will be between the voltage levels at the two terminals of R_2 only when the resistance being tested is within the prescribed limits. Voltage for the test may be furnished by the internal reference voltage of the test instrument, or by any ac voltage obtained from the equipment being tested.

This method will probably find most frequent application in the measurement of physical properties rather than in the measurement of resistance. Instead of being a component of the prime equipment, the resistor may be a transducer which is placed in the module to measure light, temperature, pressure, etc. The change in resistance then becomes a measure of the physical property.

Capacitance or inductance can be measured by a similar arrangement if the transformation network is modified by replacing R_3 by a reactive element of the same type as the component being measured.

Inserting a test signal

Except in the case of the transformation network for the measurement of resistance, it has been assumed that the normal input signals to the modules being tested will provide the signals for the fault location tests. This is not

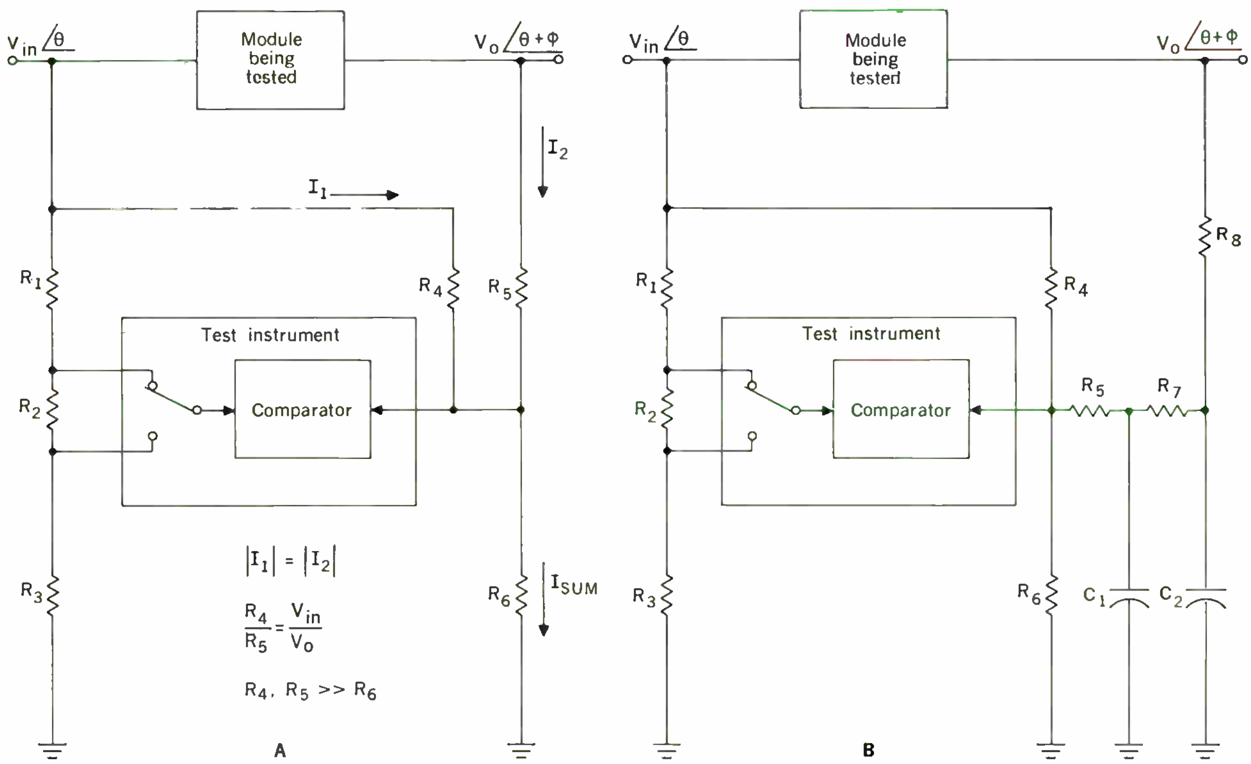


Fig. 17. Transformation networks used for the measurement of phase shift: (A) Basic transformation network; (B) Transformation network to minimize the effect of changes in the amplitude of V_o relative to V_{in}.

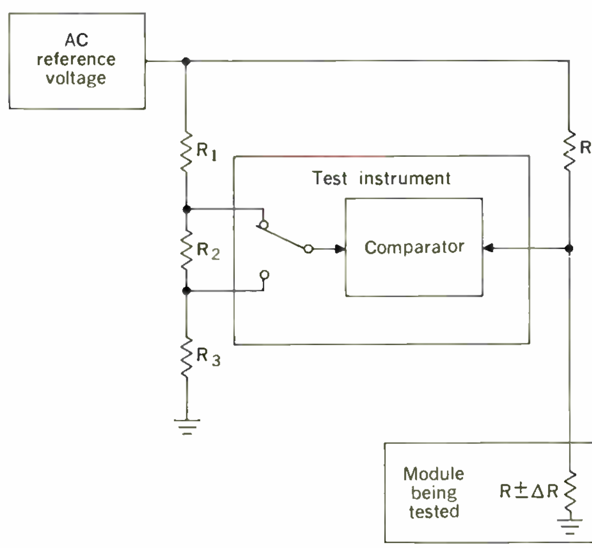


Fig. 18 (right). Typical transformation network used for resistance measurement.

possible when the signal level to be measured is lower than the minimum signal required by the test instrument, or when the characteristics of the normal input signal make it undesirable or impossible to use it, for example, when the signal is discontinuous, as it is in a receiver.

In either of these cases, a "stimulus generator" can be used. A stimulus generator is a module included in the prime equipment solely for the purpose of providing a test signal. In the normal operation of the prime equipment it is not used; it is energized only when the test instrument is connected to those test sockets which require a signal or signals from the stimulus generator for test purposes. It is packaged as a replaceable module which may be tested and replaced, if defective, in the same way as any other module in the equipment.

For the testing of sine-wave amplifiers, the stimulus generator might be an oscillator which provides a signal having the amplitude and frequency required by the circuit under test. The signal could be modulated, if necessary. For testing pulse amplifiers, a stimulus generator that produces pulses having the desired properties would be required. In some cases such a generator might be used for testing *R-C*-coupled amplifiers, even though the normal input to the amplifier was a sine wave. Other types of stimulus generators include sawtooth, square-wave, and noise generators.

The stimulus generator may be connected continuously to the circuit under test and energized only when it is required for testing, or it may be connected only during testing. Jumpers are provided on the test socket for this purpose. Switches can also be provided, if necessary, to isolate the circuit under test from those preceding and following it.

Only a few stimulus generators will be required in the testing of even a complex electronic system. In most systems, the addition of one stimulus generator module to furnish the signal input to the system will permit the entire system to be tested by FIST methods. In radar set AN/SPS-46, to which FIST techniques were applied, a stimulus generator module was added to furnish an input signal for testing the IF strip. The resulting output from the IF strip was then used as the test signal for all the video stages in the signal path between the output of the

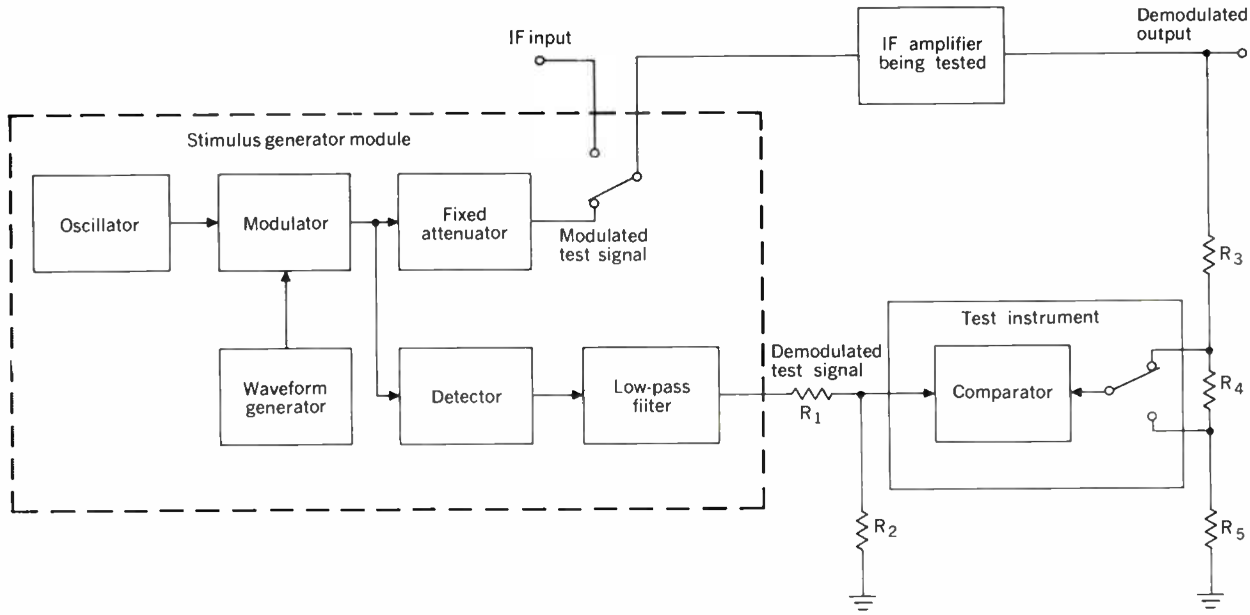


Fig. 19. Use of a stimulus generator to measure the amplification of an IF amplifier.

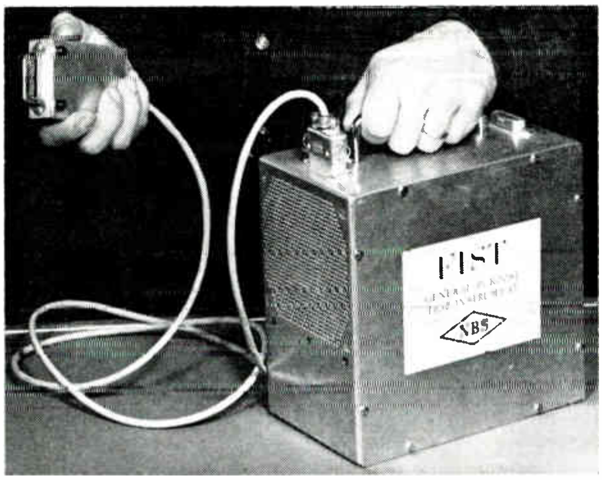


Fig. 20. An indication of the physical size of the test instrument.

IF strip and the indicator. The signals used to test the remaining modules of the system were those generated internally and used in the normal operation of the radar set.

Figure 19 includes a block diagram of the stimulus generator used to provide a pulse-modulated signal at the intermediate frequency to test the radar IF amplifier. The output of the modulator section is a pulse-modulated IF signal a few volts in amplitude. The fixed attenuator reduces this signal to the normal input level of the amplifier being tested, and the detector and low-pass filter provide a demodulated test signal to a second output terminal. Physically, in its longest dimension the stimulus generator module is slightly longer than a paper clip, even though it is built of standard components.

When the stimulus generator is used to measure the amplification of the IF strip, the modulated test signal is connected to the input of the IF amplifier, and the demodulated signal is connected as a reference to one of the comparator inputs in the test set. The demodulated output of the IF strip furnishes the other comparator input through divider R_3, R_4, R_5. The two dividers of the transformation network reduce the signals to the levels required by the comparator. Since both inputs to the comparator are functions of the amplitude of the signal delivered by the modulator of the stimulus generator, reasonable variations in this amplitude will not affect the measurement of amplification.

Except for the fixed attenuator, the stimulus generator module itself can be checked by measuring its pertinent characteristics at the demodulated-test-signal terminal. There is no practicable way of checking the attenuator, since the level of the modulated test signal of the stimulus generator is much lower than the minimum signal level required by the comparator. The fixed attenuator is one of the more reliable components in the stimulus generator, however, so that the reliability of the test will not be seriously impaired by this omission.

Conclusion

FIST is the first comprehensive test concept thus far devised that can be applied by the equipment designer without the assistance of an instrumentation specialist. The simple flexible techniques involved, which are orders of magnitude faster than manual test methods, permit relatively unskilled personnel to maintain complex electronic systems under field conditions. Because the general-purpose FIST test instrument is relatively inexpensive, it is economically justifiable to FIST-maintain even a single piece of electronic equipment. The complement of FIST-maintained equipment in a field installation may be increased or decreased at will without impairing maintenance effectiveness, and the ability to readily update the tests in the field permits maintenance optimization.

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Authors

J. W. Forrester (F) is a professor of industrial management at the Massachusetts Institute of Technology's Alfred P. Sloan School of Management, where he directs research and teaching in the new field of industrial dynamics, an experimental, quantitative philosophy for the design of corporate structure and policies to achieve an organization's growth and stability objectives. Prior to his present position, which he assumed in 1956, Dr. Forrester was head of the Digital Computer Division of M.I.T.'s Lincoln Laboratory. In this capacity he guided the military operational planning and technical design of the Air Force SAGE system for continental air defense. As director of the M.I.T. Digital Computer Laboratory from 1946 to 1951, he was responsible for the design and construction of Whirlwind I, one of the first high-speed digital computers. He is a director of the Digital Equipment Corporation and the author of a book, *Industrial Dynamics*.

John D. Kraus (F) received the B.S. degree in 1930, the M.S. degree in 1931, and the Ph.D. degree in 1933, all from the University of Michigan. From 1934 to 1935 he worked on industrial noise-reduction problems, and from 1936 to 1937 was engaged in nuclear research with the newly completed University of Michigan cyclotron. Following a two-year period as an antenna consultant he joined the Naval Ordnance Laboratory, Washington, D.C. In 1943 he became a member of the Radio Research Laboratory, Harvard University, where he was a group leader engaged in radar countermeasures. In 1946 he joined the faculty of Ohio State University, where he is now professor of electrical engineering and astronomy, and director of the Radio Observatory. He is the inventor of the helical beam antenna, the corner-reflector antenna, and several other antenna types. He is the author of the widely used textbooks, *Antennas* and *Electromagnetics* (McGraw-Hill).

P. G. Edwards (F, L) received the B.E.E. and E.E. (professional) degrees from Ohio State University in 1924 and 1929, respectively. He was granted a first class commercial radio operator's license in 1919. From 1919 to 1922 he was with the Western Union Telegraph Company as operator and wire chief, and from 1922 to 1924 with AT&T Long Lines Department as repeater attendant. In 1924 he joined AT&T's Department of Development and Research, and in 1934 transferred to Bell Telephone Laboratories. In 1961 he retired from BTL and joined the Mitre Corporation. At BTL he was involved principally with toll and local transmission matters, including voice, carrier, microwave, and radio facilities. In 1954 he organized the Merrimack Valley Laboratory at North Andover, Mass., and directed it until his retirement from BTL. At Mitre Corporation he heads the Communication Systems and Techniques Department. Mr. Edwards is a member of Sigma Xi, Tau Beta Pi, and Eta Kappa Nu. He holds 39 patents in the communications field.

J. Clapper, Jr. (SM) retired as a colonel, U.S. Army, in April 1962, and shortly thereafter joined the Mitre Corporation's Communications Systems and Techniques Department as a consultant in general communications. For five years he was a faculty member of military schools, including the Armored School, Fort Knox, Ky., and the Army Command and General Staff College, Ft. Leavenworth, Kans. Pentagon positions included chief, Communications Operation and Planning Branch, OCSIGO; Army coordinator for the Joint Communications-Electronics Committee, Joint Chiefs of Staff; chief, Army Frequency Management Division; chairman, Combined Canada, U.K., and U.S. Frequency Allocation Panel; member, U.S. National Executive Committee, CCIR; and special assistant to the Chief Signal Officer. He attended Creighton University, the University of Nebraska, the University of Maryland, Jackson College in Hawaii, and the Army War College. He holds B.S., M.S., and M.A. degrees.

Gustave Shapiro, George J. Rogers, Owen B. Laug, and P. Michael Fulcomer, Jr. Biographical sketches of these authors appear on page 113 of the August issue.

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Scanning the issues

The Creative Years. Much has been said and written in the last decade on the relationship between creativity and age among scientists and engineers. Several exhaustive studies have all arrived at the same general conclusion: on the average, the likelihood of outstanding scientific achievement peaks beginning in the late 30s or early 40s and thereafter declines.

The peak appears earlier in highly abstract disciplines (mathematics, theoretical physics) and later in more empirically based disciplines (geology, biology). Also, the peaking is sharper for the most outstanding achievements, and flatter for minor achievements. But the fact that this peaking does occur statistically can no longer be denied. Indeed, the time has come to stop debating whether or not the phenomenon occurs, and to begin trying to understand it.

At first blindly attacked, these findings in some circles have come to be just as blindly accepted. A physicist was recently heard to remark, "If you haven't made your mark by 35, you might as well quit the field." This raises an interesting question. Does a scientist's creative potential really fall off substantially after reaching its peak in his late 30s?

It is interesting to note that studies of intellectual abilities do not indicate that intellectual potential as such declines. A favorite alternative hypothesis, pleasing to the scientific ego, is that the more able achievers are drawn off into teaching, administration, and committee work not directly productive of scientific output. A third interpretation is that after the young scientist has struggled hard and built his reputation, he can afford to relax. A fourth hypothesis is that as the scientist becomes an expert in his field, he loses the freshness of viewpoint needed for pioneering breakthroughs. A fifth view is that of technical obsolescence: the scientist loses touch with recent advances.

New insight into the effects of age on scientific achievement has now been provided by a study, conducted from 1958 to 1960, among 1311 scientists and engineers in 11 research and development organizations to determine the effects of research environment on scientific performance.

These studies reveal that a series of saddle-shaped curves with *twin peaks* 10 to 15 years apart, rather than a single peak, consistently appeared in a variety of settings, and for several criteria of performance. Incidence of the peaks and valleys was 5 to 10 years later in development-oriented laboratories (stressing product improvement) than in research-oriented laboratories (stressing scientific publication). The rate of obsolescence thus appeared higher in scientific activity than in development, where cumulative experience continued to be of value.

Advancing years were more of a handicap in the government labs in the sample than in the industrial or university settings, both for Ph.D.s and for non-Ph.D. engineers. However the B.S. "assistant scientists" in Ph.D.-dominated labs survived more successfully in government than in industry.

Scientists who were strongly involved in their technical work resisted the effects of age more successfully than the mildly involved. They rose more quickly to eminence at younger years, and sagged less sharply at older years.

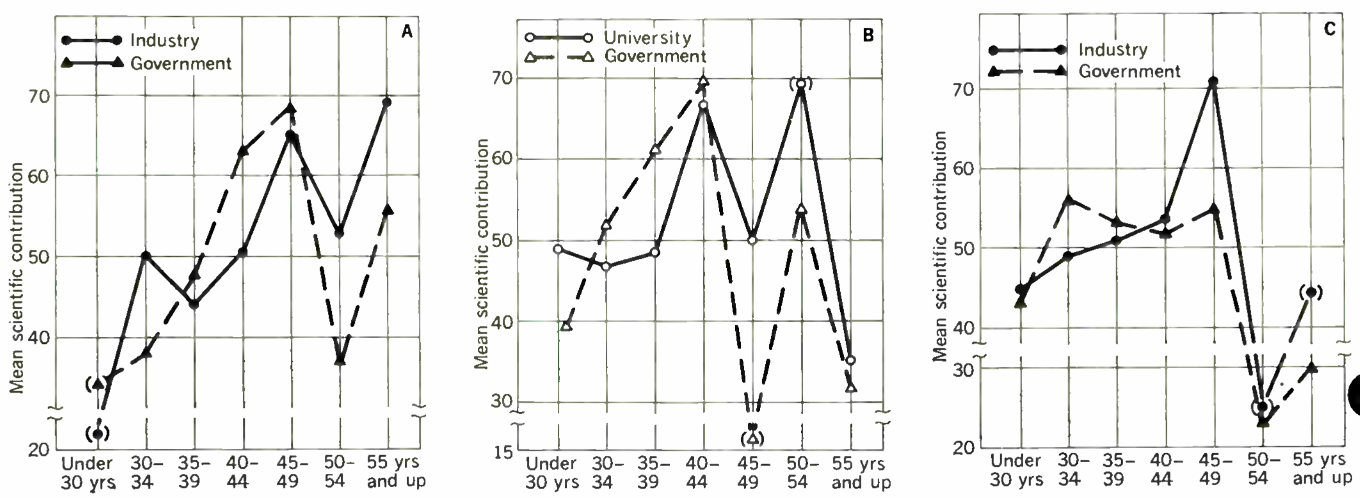
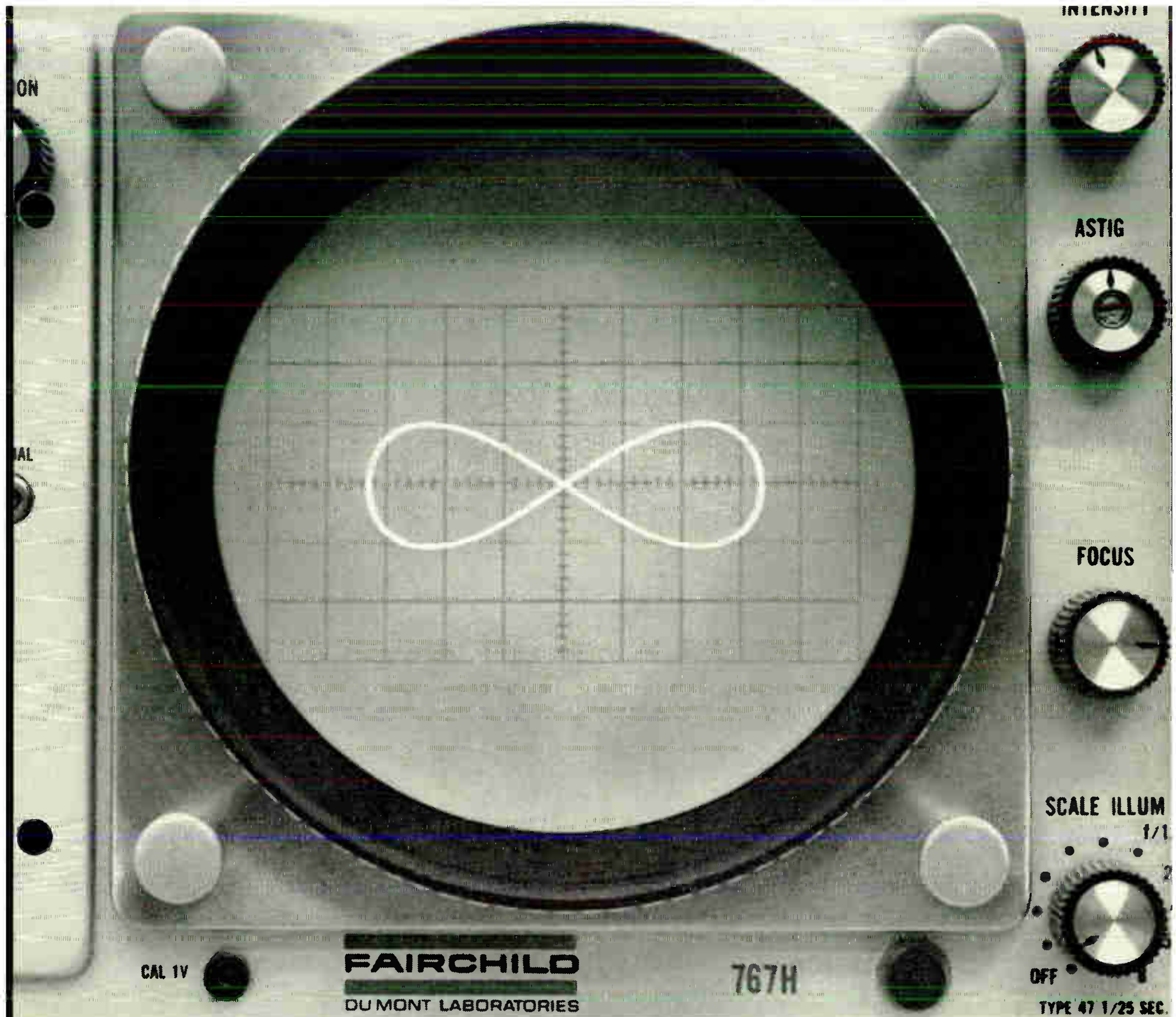
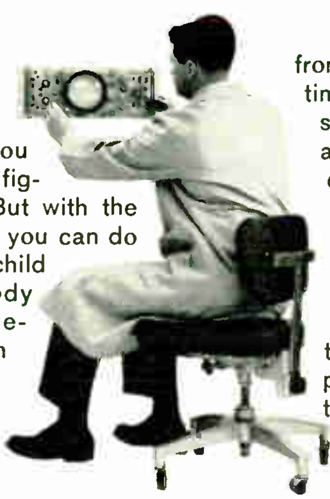


Fig. 1. Scientific contribution (within past five years, as judged by colleagues) in relation to individual's age, in nine research settings. Points enclosed in parentheses are based on fewer than five cases. A—Ph.D.s in development laboratories, B—Ph.D.s in research laboratories, C—"Engineers" (non-Ph.D.s in development laboratories).



Versatility Almost Unlimited



The capabilities of Fairchild's solid-state Series 765H scopes aren't quite infinite (although you can set up this Lissajous figure for fun or profit). But with the many plug-ins available, you can do more with a single Fairchild scope than with anybody else's. For example, frequency may range from DC to 100 mc (3 db down), sweep rates from 5 nsec/cm to 1 minute, rise-times to 3.5 nsec. All Fairchild 765 series plug-ins are interchangeable; among other things, you can get single or multiple X-Y displays by using identical plug-ins in both compartments simultaneously. The main frame of the new 765H series is available in three configurations: bench, rack, and the compact Portascope®. There is also the militarized Portascope. Versatility? Almost unlimited. For more information, write for the Fairchild Instrument Catalog, or ask a field engineering office for a demonstration; there's one in your area. Fairchild Scientific Instrument Dept., Section 911, 750 Bloomfield Ave., Clifton, N. J.

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Correspondence

In defense of dowsing. The article in the May issue, "Is Philosophy Off Limits" by Arthur B. Bronwell, sums up the limitations and attitude of universities, engineers, and scientists," relative to new or "mystic" phenomena. The author mentions the lack of intricate and costly equipment not now available for basic research. However, there are many scientific peculiarities that don't require new, expensive, or exotic equipment and that are begging for investigation, but they receive the "kiss of death" when they are named. These include what is popularly known as ESP (mental telepathy), water dowsing, deleportation, and telekiness. Our present "scientists" sum these up with the comment, "Humbug!" The attitude seems to be that "nothing known can produce such effects, so it is clearly a hoax, misobservation, or fraud."

For instance, water dowsing has intrigued men from Biblical times to the present. Books have been written affirming or denying such a phenomenon. Pro and con arguments have been based primarily on eyeball instrumentation and the degree of success with which the dowser locates water. In recent years (probably the last ten) adequate instrumentation has been available for proof or disproof. The con group contends that the action of the forked twigs, rods, or other devices is caused by muscle movement on a subconscious level.

The writer, utilizing modern instrumentation and a movie camera, produced documentary evidence that the pro side is right. Of course, it's "misobservation," but if you try to get anyone with a "known name" to observe, he doesn't want to risk his reputation!

A lecture on my investigations was delivered to the G-IM, Los Angeles Section, though I had been warned that I was jeopardizing my job and my possible future getting involved in such a crackpotish endeavor. An attempt to have my engineering work on this subject reviewed and continued by one of the local "outstanding" universities led to "I don't know if any undergraduate is interested and certainly the professors aren't."

As ex-chairman of the Los Angeles Section of G-IM (and still a member of its National Board), and present chairman of the G-NS, I would like to point out that I sponsored the local work on water dowsing not for personal aggrandizement but because I feel that the G-IM and other groups could afford to stop presenting trivia and to concentrate on something which could result in a challenge and a possible advancement of the state of the art.

We all know that our brute force method of going to the planets is a poor way of doing business. Yet the subjects of teleportation and telekiness, investigations of which might lead to a crucial breakthrough, are not being investigated.

Alvin B. Kaufman
Woodland Hills, Calif.

Dinosaurs or Birds. In the editorial in the September 1963 issue of ELECTRICAL ENGINEERING, page 549, the question is asked, "Are we dinosaurs or birds?" I am neither. Naturally, I can't speak for others but I know that I am a professional engineer. As a practicing engineer, I have learned and experienced, in several industries, that such a person is differentiated from other educated people principally by virtue of his utilizing energy and materials safely and economically on projects that have an end use. He does so with both his special scientific and engineering knowledge and his judgment.

The editorial contends that these criteria should be eliminated from the definition of engineering and, in fact, suggests doing away with any definition. Naturally, it would then be easy for an educator to put anything into an engineering curriculum whether or not it had a bearing on engineering.

The editorial states that a definition places walls around a person which, therefore, binds him in the area of his discipline. I say there are walls in my house, but they don't prevent me from venturing into my community in all sorts of professional, educational, useful, and esthetic activities. They don't prevent me from participating in student guidance programs of Eta Kappa Nu,

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for instance. They don't prevent me from pursuing continuous education in engineering, in culture, and in business management. They don't prevent me from preparing myself in engineering education.

Frankly, I don't understand this attitude about defining engineering when it seems to be so badly misunderstood by the public. It may be true that I am in the minority with my views on engineering education, the subject of definition being one of them. However, I am confident that if I were in the minority, the definition of engineering would have been modified a long time ago.

Larry Dwon
American Electric Power Service Corp.
New York, N.Y.

Youthful ingenuity. The following is an authentic set of quotations from the laboratory reports of sophomores and juniors at a well-known university. I submit these for your amusement and edification as examples of spelling and thinking at the higher education level.

"In Measuring voltages a certain amount will leak through the voltmeter and the reading will be a little low."

"In measuring current some of it will be stopped by the resistance of the ammeter and the reading will be a little low."

"Most of the laws that we use in circut calculation are ideal and not perfectely true, however, they are accurate enough to be used for practicle purposes."

"The voltage read low caused by constant plugging of equipment by other students."

"If the current in two short circuits are equal, the act as similar circuits."

"The ideal results are different from those experimental results, yet the ideal results are helpful, since it has a very small difference from the experimental results."

"My theoretical graph is similar to my experimental graph but my experimental graph looks more like a theoretical graph than the theoretical graph does."

"The phase shift oscillator proved to be more sensitive since it could not be made to operate at all."

Allan F. Pacela
Senior Scientist
Defence Systems Operations
Lear Siegler, Inc.